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Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA, MERCED

**OPTIMAL REMOTE SENSING WITH SMALL
UNMANNED AIRCRAFT SYSTEMS AND RISK
MANAGEMENT**

by

Brandon Stark

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Electrical Engineering and Computer Science

Committee in charge:
Professor YangQuan Chen, Chair
Professor Shawn Newsam
Professor Joshua Viers

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The dissertation of Brandon Stark is approved:

Professor YangQuan Chen, Chair

Date

Professor Shawn Newsam

Date

Professor Joshua Viers

Date

University of California, Merced

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to my wife, parents, and kittens.

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Portions of this dissertation contains content of material as it appears in [1–10]. The senior co-author listed in these publications directed and supervised the research that forms the basis for this dissertation.

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CURRICULUM VITAE

Brandon Stark

(Last Updated: March 12th, 2017)

Contact Information

667 Sonora Ave
Merced, CA 95340
bstark2@ucmerced.edu

Education

- 2012 - 2017 **Doctor of Philosophy in Electrical Engineering & Computer Science**
University of California, Merced
Advisor: Dr. YangQuan Chen
Dissertation Title: “Optimal Remote Sensing with Small Unmanned Aircraft Systems and Risk Management”
- 2010 - 2012 **Doctor of Philosophy in Electrical Engineering** (not completed)
Utah State University
Advisor: Dr. YangQuan Chen
- 2007 - 2010 **Master of Science in Electrical Engineering**
University of Bridgeport
- 2007 - 2010 **Master of Science in Computer Engineering**
University of Bridgeport
- 2003 - 2007 **Bachelor of Science in Computer Engineering**
Minor: Art History
University of California, Irvine

Employment History

- 2016 - Current **Director, UC Center of Excellence on Unmanned Aircraft System Safety**
University of California, Office of the President

Led the creation of a new department within the University of California, Office of the President in the Office of Risk Services dedicated to managing risk and safety for Unmanned Aircraft Systems across the University of California. Developed UC systemwide policies for UAS activity, developed a UC UAS Safety Management System, implemented effective tracking mechanisms for enterprise risk management and safety assessments.

2016

Graduate Student Teaching Fellow (TF)

School of Engineering, University of California, Merced

Served as primary lecture instructor (1.5 hours a session, 2 sessions per week) for ME142 - Mechatronics.

2013 - 2015

Graduate Student Teaching Assistant (TA)

School of Engineering, University of California, Merced

Developed a project based lab curriculum designed around student learning outcomes developed for the redesigned course - ME142 Mechatronics (4 Units). Designed and developed lab equipment, integrated new technology each year, evaluated Student Learning Objectives each offering. Served as primary lab instructor (3 hours a session, 3 sessions per week) for 2013-2015.

2012 - 2016

Lab Manager (GSR)

MESA Lab, School of Engineering, University of California, Merced

Founding manager. Managed all aspects of the Mechatronics, Embedded Systems and Automation Lab including lab safety, lab hiring, project management, research management, purchasing and inventory control. Developed and conducted a wide range of research projects, including those aimed at mentoring undergraduates. Developed outreach activities, and hosted high profile seminars. Grew membership to 80 undergraduate students.

2010 - 2012

Graduate Student Researcher (GSR)

CSOIS, School of Engineering, Utah State University

Developed and implemented Unmanned Aerial Systems, including autopilot development for fixed-wings and rotary wings, human-factors of UASs and safety systems for UASs. Managed inventory control.

2007 - 2010

Graduate Student Teaching Assistant (TA)

School of Engineering, University of Bridgeport

Developed the curriculum and taught for several lab sections, including analog circuits, digital logic II and FPGA design.

Scientific and Professional Membership

- Member, IEEE (Aerospace and Electronics Systems Society, Circuits and Systems Society, Computer Society, Control Systems Society, Systems, Man and Cybernetics Society, Robotics and Automation Society)
- Member, ASME (American Society of Mechanical Engineers)
- Member, AUVSI (The Association for Unmanned Vehicle Systems International)
- Member, URMIA (University Risk Manager and Insurance Association)

Teaching

Teaching Experience abridged to only UC Merced

Instructor of Record, Primary Lecturer

ME142 Mechtronics (4 units) - Junior level technical elective (Spr 2016)

Lab Teaching Assistant Experience

ME142 Mechatronics (4 units) - Junior level technical elective (Spr 2013, Spr 2014, Spr 2015)

Invited Lectures

ENG065 Circuits - Passive Filters (Fall 2012, Spr 2013, Fall 2013, Spr 2014, Fall 2014)

Independent Study Directed (over 22 student projects)

Senior Capstone Project Advising (4 student projects)

Honors and Awards

- 2016 - Best Paper - International Conference on Unmanned Aerial Systems (ICUAS 2016)
- 2015 - UC Merced Leadership Award - Outstanding Graduate Student
- 2014 - UC Merced Leadership Award Finalist - Outstanding Graduate Student
- 2013 - UC Merced Leadership Award Finalist - Outstanding Graduate Student
- 2011 - Graduate Advisor for AUVSI SUAS Rotary Competition Team (9th Place, 1st team in competition history to do waypoints with rotary-wing vehicle)
- 2010 - Graduate Student Teaching Award, School of Engineering, UB

Institutional Service

- UC ANR IGIS Program Review Committee (2017-)

- Graduate Student Association: President (2014-2015)
- UC Merced Graduate Representative: University of California, Council of Presidents (2014-2015)
- Graduate Student Representative: Academic Senate Committee - Graduate Council (2014-2015)
- Graduate Student Representative: Graduate Student Committee on Research (2014-2015)
- Graduate Student Representative: Graduate Student Social Committee (2014-2015)
- Graduate Student Representative: Graduate Student Professional Advancement Initiative (2014)
- Graduate Student Representative: Vice-Chancellor for Administration Student Advisory Board (2012-2013, 2014-2015)
- Graduate Student Representative: Search Committee for Dean of the School of Engineering (2014-2015)
- Graduate Student Representative: Research Week Advisory Board (2013-2015)
- Graduate Student Representative: Academic Senate Committee CAPRA (2014)
- Graduate Student Representative: Academic Senate Committee Committee on Research (2013)
- Academic Representative: Buhach Colony High Engineering Advisory Board (2013-2014)
- Graduate Student Association: Secretary (2013-2014)
- Graduate Student Representative: Transportation and Parking Services Advisory Board (2013-2014)

Workshops Presented

1. B. Stark, Understanding Risks and Safety for Drones, Workshop in: Bay Area Community College Symposium, Hayward, California, USA, January 9 2017.
2. B. Stark, Unmanned Aircraft System Risk Management for Higher Education, Workshop in: Drone Educator's Conference, San Bruno, California, USA, October 22 2016.
3. B. Stark, B. Smith, Y. Chen, Emerging sUAS Technology for Precision Agriculture Applications (AgDroneTech15), Workshop in International Conference on Unmanned Aircraft Systems 2015, Denver, Colorado, USA, June 9 2015.
4. B. Stark, Y. Chen, Personalizing Mechatronics Education, Half Day Tutorial in 19th IFAC World Congress, Cape Town, South Africa, August 27 2014.

5. B. Stark, B. Smith, Y. Chen, Emerging sUAS Technology for Precision Agriculture Applications (AgDroneTech14), Workshop in International Conference on Unmanned Aircraft Systems 2014, Orlando, Florida, USA, May 27 2014.
6. B. Stark, Z. Li, B. Smith, Y. Chen, Personalizing Mechatronics Education Utilizing an Open-Source Real-Time Control System Rapid Prototyping Platform, Half Day Tutorial in: ASME IDETC MESA2013, Portland OR, USA, August 3 2013.
7. B. Stark, Y. Chen, Iterative Design Towards Improved Fault Tolerance: A Framework for Improved SUAS Airworthiness, Workshop in: Health Management, Fault-tolerant Control, and Cooperative Control of Unmanned Aircraft, ECC 2013, Organizers: Youmin Zhang, Camille Alain Rabbath, YangQuan Chen, Christopher Edwards, Cameron Fulford, Hugh H.-T. Liu, Liang Tang, Didier Theilliol, and Antonios Tsourdos, Zurich, Switzerland, July 16, 2013.
8. C. Coopmans, B. Stark, A. Jenson, Y. Chen, SUAS Airworthiness, Architecture and Human Factors, Half Day Tutorial in International Conference on Unmanned Aircraft Systems 2013, Atlanta, GA, USA, May 28 2013.
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ABSTRACT

Over the past decade, the rapid rise of Unmanned Aircraft Systems (UASs) has blossomed into a new component of the aviation industry. Though regulations within the United States lagged, the promise of the ability of Small Unmanned Aircraft System (SUAS), or those UAS that weigh less than 55 lbs, has driven significant advances in small scale aviation technology. The dream of a small, low-cost aerial platform that can fly anywhere and keep humans safely away from the ‘dull, dangerous and dirty’ jobs, has encouraged many to examine the possibilities of utilizing SUAS in new and transformative ways, especially as a new tool in remote sensing. However, as with any new tool, there remains significant challenges in realizing the full potential of SUAS-based remote sensing. Within this dissertation, two specific challenges are addressed: validating the use of SUAS as a remote sensing platform and improving the safety and management of SUAS.

The use of SUAS in remote sensing is a relatively new challenge and while it has many similarities to other remote sensing platforms, the dynamic nature of its operation makes it unique. In this dissertation, a closer look at the methodology of using SUAS reveals that while many view SUAS as an alternative to satellite imagery, this is an incomplete view and that the current common implementation introduces a new source of error that has significant implications on the reliability of the data collected. It can also be seen that a new approach to remote sensing with an SUAS can be developed by addressing the spatial, spectral and temporal factors that can now be more finely adjusted with the use of SUAS.

However, to take the full advantage of the potential of SUASs, they must uphold the promise of improved safety. This is not a trivial challenge, especially for the integration into the National Airspace System (NAS) and for the safety management and oversight of diverse UAS operations. In this dissertation, the challenge of integrating SUAS in the NAS is addressed by presenting an analysis of enabling flight operations at night, developing a swarm safety management system for improving SUAS robustness, investigating the use of new technology on SUAS to improve air safety, and developing a novel framework to better understand human-SUAS interaction. Addressing the other side of safety, this dissertation discusses the struggle of large diverse organizations to balance acceptance, safety and oversight for UAS operations and the development of a novel implementation of a UAS Safety Management System.

Chapter 1

INTRODUCTION

1.1 Dissertation Roadmap

The development of Unmanned Aircraft System (UAS) has grown dramatically over the past several years, with significant advances in technology and regulations. However, there remains significant challenges to overcome before the full potential of UASs are realized. Of the many challenges, two in particular are of significant interest within this dissertation: validating the use of Small Unmanned Aircraft System (SUAS) for remote sensing applications and improving safety and management of UAS operations. Deploying an SUAS for a remote sensing application is a relatively new challenge and while it has similarities with other remote sensing platforms, the dynamic nature of an SUAS introduces new advantages and challenges, but their effectiveness still requires validation. Moving to take advantage of some of the new advantages of SUAS such as operations at night or multi-vehicle operations, however introduces new challenges on safety and management that must be addressed before new regulations can be implemented. This dissertation presents a collection of advances to solve the challenge of optimal remote sensing with SUASs and risk management.

1.1.1 Unmanned Aircraft Systems

The integration of UAS into the National Airspace System (NAS) is slowly, but surely progressing with the enactment of regulations to enable small UAS, defined as weighing less than 55 lbs. This first step has been a highly-anticipated advancement within the UAS industry. For many research applications, both UASs and SUASs have been proposed and encouraged, but the challenges associated with their use and regulations has slowed their adoption. Though UASs in general were declared as the next big thing in 2012, many of the proposed ‘big’ successes, such as delivery services have failed to materialize before the regulations were enacted in 2016. Though SUAS are only a subset of the UAS industry, it is seen as the most immediate need and potentially largest component.

In 2013, the Association of Unmanned Vehicle Systems International (AU-VSI), estimated that up to 80% of UASs operating in the US will be purchased for agricultural applications [11]. Many of these applications were obvious: crop

dusting and land surveillance were two of the most commonly cited examples. The technology for these two applications had already been well developed and their adoption was suspected to be eminent. However, the more advantageous agricultural applications, while they had been demonstrated, were considered to be several years away from deployment.

In the following years, these applications became the subject of many research projects. The more rigorous scientific applications of crop yield estimations, soil moisture monitoring, pest management, or soil salinity control require a level of robustness, reliability, and precision that many platforms are unable to satisfy. Current platforms for researching these aspects have typically been developed specifically for these purposes; however, this is not a sustainable effort. If wide-spread adoption is to be achieved, researchers must be able to focus on the research project at hand, and not on the development of the platform. While much research can be accomplished with the large, full-scale sized UASs, the greatest avenue to applications remains in the use of the SUASs as these platforms are currently the most accessible to researchers and for agricultural applications and have the highest variation in quality.

1.1.2 SUAS-Based Remote Sensing Applications

Led by the development of small, high resolution cameras as well as suitable multispectral cameras, SUASs have demonstrated a significant level of capabilities for both agricultural and environmental applications [12]. There are large varieties of applications being investigated that are enabled by the high-resolution imagery provided by SUASs including irrigation timing control [13], canopy coverage and yield estimation [14], and disease and pest management [15]. Highly desirable metrics such as crop water stress estimation have also been investigated using SUASs [16]. Utilizing established remote sensing indices such as Normalized Difference Vegetation Index (NDVI) has also enabled a variety of applications valuable for agricultural such as yield estimation [17], and crop harvest yield attributes [18]. Multispectral indices such as Photochemical Reflectance Index (PRI) [19] as well as more complex analysis utilizing hyperspectral imagery [20] have also been demonstrated to be effective estimators for metrics such as water stress.

Environmental applications, including conservation efforts, are also a prime example of the value of SUASs. They have been utilized frequently for a variety of applications, including wetland mapping [21] and rangeland management. The land classified as rangelands comprises of over half of the usable land in the world and has significant agricultural and economic value. Conservation and management of these lands can be a challenging task due to the wide variety of activity and large areas [22]. Satellite imagery can be used for decision support, but the resolution of the imagery is typically insufficient. Finer details such as individual vegetation and small water features are impossible to see and become difficult for management.

Accurate assessment of small features, such as dead matter or litter have been identified as one of the most important indicators for assessing long-term sustainability of the land [23]. Current methods, using satellites or field-crews, suffer from high costs and limited actionable intelligence due to the sparse nature of the evaluations. SUASs provide a new and cost efficient method for data collection for better range-land management [23–25]. These autonomous systems have several advantages over satellite imagery or manned aircraft. They can fly at very low altitudes, enabling high resolution imagery, can accomplish a wide variety of mission, can have a higher revisit frequency and can be much safer and cheaper to operate. As a result, remote sensing applications for SUASs have seen significant growth as their utility gains credibility.

In general, the use of SUAS technology for agriculture or environmental monitoring is an extension of existing methodology utilizing aerial or satellite imaging for monitoring crops. Literature is well-established on the effectiveness for such applications as pest, weed or disease monitoring or damage assessment. The advent of SUASs, paired with Global Positioning Systems (GPSs) and high resolution cameras provides the ability to utilize imagery, such as that seen in Figure 1.1, to improve that methodology and enable improved practices.

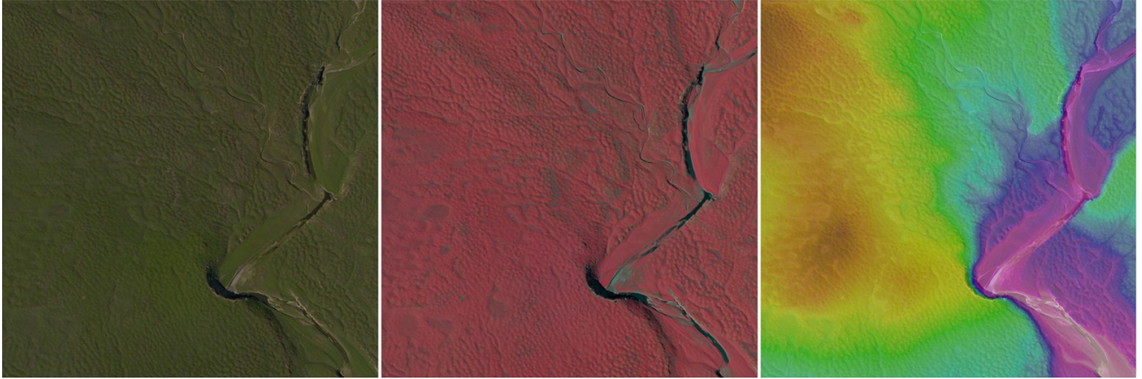


Figure 1.1: Aerial imagery collected by SUAS over Merced Vernal Pool and Grassland Reserve, March 4th, 2015. (a) Color (b) False Color NIR Composite (c) Elevation Map

While there has been a recent interest of the agricultural implications of high-resolution or multispectral imagery, there remains a significant amount of work. Many of the solutions found in literature utilize specialized equipment, controlled environments, and rely on analysis expertise. These solutions are currently not implementable at any level of commercial operation and further development is necessary. The majority of existing methodology described in literature for SUASs was developed for low resolution satellite imagery or through the use of handheld

hyperspectral sensors with high spectral resolution, meaning that these are not optimized for use by SUASs, which can provide high resolution imagery with limited spectral resolution and potentially with a higher temporal resolution [26]. In some cases, methods developed for satellite-based remote sensing were found inconclusive for SUAS remote sensing [27]. Realizations such as these have led to more detailed investigations into developing SUAS data test sites [28], and further analysis into developing SUAS specific solutions [29].

1.1.3 UAS Regulation History

However, in order to utilize UASs or SUAS for any purpose, there are regulatory and safety hurdles. In the U.S., the FAA is the official agency that governs the use of the NAS. Utilizing federal regulations, standards and policies, the Federal Aviation Administration (FAA) develops and enforces strategies and rules that promotes air safety and an efficient use of the NAS. While UASs have been in existence since the early 1930's, regulations regarding their use have only existed since 2005.

In 2005, the FAA published AFS-400 UAS Policy 05-01. This provisional report established the first official sanctions of UASs allowing UAS operators to apply for a Certificate of Waiver or Authorization (COA) that permits the use of a specific unmanned aircraft or a class of unmanned aircraft to specific operational bounds. These COAs are only offered to military or public agencies and only for U.S. government functions. This definition includes state agencies and research institutes such as public universities. However, this policy excluded the option of sanctioned civil or commercial use [30].

In 2008, the policy was updated with the Interim Operational Approval Guidance 08-01 report. This document continued the offering of COAs to public agencies, but also included a mechanism for civil operators to apply for a Special Airworthiness Certificate in the Experimental Category, subject to strict limitations and to the applicable regulations of 14 Code of Federal Regulations (CFR) parts 61 and 91 [31].

An early attempt to develop regulations for civil use was published in 2009 to address the rules and operations for SUASs. The 'Comprehensive Set of Recommendations for SUAS Regulatory Development,' written by the SUAS aviation rulemaking committee (ARC) proposed similar operations as its predecessors such as IOAG 08-01, but stricter limitations and regulations on use. In this report, SUASs are proposed to strict altitude and lateral distances of 400ft and 1200 ft respectively while utilizing visual line of sight (VLOS) as the primary method of mitigation for mid-air collisions [32]. Limitations on flight altitude and lateral distance, 400 ft and 1200 ft, were recommended due to the limited capability of visual observers for conflict detection and resolution services. The report does not consider Sense and Avoid Systems (SAASs) such as real-time video links or real-time air traffic monitors to aid in situational awareness to allow extended flights in terms of distance, altitude and

duration. The recommendations by the SUAS ARC also includes a primary means of collision avoidance by recommending that an SUAS dive to a lower altitude and yield right-of-way, as a pilot would expect a similarly sized bird do as a manned aircraft approaches [32]. Due to the visibility challenges of an SUAS, it was decided that a vertical evasive maneuver would prove to be the optimal maneuver to avoid the collision volume.

In addition to the operational bounds, the recommendations posed by the SUAS ARC include additional qualifications for operation in each available class of airspace. SUAS operations typically occur in Class E or G airspace, where air traffic is sparse and where visual flight rules (VFR) are allowed during visual meteorological conditions (VMC), a common aviation term that quantifies the safe operational weather and visibility. Other airspace classes may be used, but the altitude limitations keep this usage to a minimum, applicable only when near the Class C and D airspace extends to the surface around airports. Operation near these airports are recommended to be prohibited unless special authorization is given from the local Air Traffic Control (ATC) and ATC contact is maintained [32].

The FAA revisited the issue of UAS operations in a Concept of Operations (CONOPS) for Unmanned Aircraft Systems report, first issued in 2011 and updated in 2012, to address the necessary requirements that a UAS must meet to be worthy of integration into the NAS [33]. In this report, the FAA shares their view of a UAS operating safely and efficiently with other air traffic by utilizing a ‘file-and-fly’ approach; filing a flight plan similar to existing instrument flight rules (IFR) flight plans before receiving flight authorization, without the need for creating a segregated airspace specifically for UASs [33]. However, as with many of the other mentioned reports, the FAA CONOPS for UASs specifically excludes describing operations for SUASs as not fitting within their concept narrative.

One of the major steps towards UAS operations was the FAA Modernization and Reform act of 2012 that introduced several legal definitions for UAS, SUAS, pushed for the integration of civil UAS into the NAS and introduced two significant regulations, commonly known as Section 333 and Section 336 [34]. These two sections introduced a process for the FAA to allow civil UAS flight operations after a safety review (Section 333) and established the regulations for recreational UAS flying, which includes the definition of ‘model aircraft.’

It was not until 2015 that progress had been made on civil UAS operations. In February, the FAA released a Notice of Proposed Rule Making (NPRM) for SUAS operations. Building off some of the proposals from the 2009 recommendation report, it promoted a safety-based approach rather than a technical standard based approach. The regulations were finalized in August 2016 in Title 14 of the CFR, Part 107 [35]. This set of regulations primarily enabled the use of SUAS within Class G airspace while introducing a new remote pilot in command (RPIC) certificate and introduced a SUAS rating. In contrast to a Public Agency COA or Section 333 COA,

the new regulations did not require an aircraft airworthiness certificate or the use of a Visual Observer (VO). However, the new regulations placed an increased emphasis on risk and safety management, and placed the responsibility of maintaining safety squarely on the RPIC.

Unlike previous proposals for SUAS operations, the FAA introduced an airspace authorization process and a waiver process for flight operations beyond the limitations within 14 CFR 107. The airspace authorization enables SUAS operators to request airspace authorization in Class B, C, D and surface E airspace. The waiver process enables SUAS operators to request waivers to specific regulations in 14 CFR 107, provided the applicant made a sufficient case to ensure an Alternate Means of Compliance (AMOC).

1.1.4 UAS Safety and Management

Throughout the process of developing UAS regulations, the FAA began to shift many safety responsibilities from the aircraft manufacturers and the FAA to the UAS operators. This can be seen in the relaxation of aircraft certification standards (a manufacturer required component in earlier COAs) to no longer being required under 14 CFR 107, though specifically for SUAS. However, this places additional consideration to be thorough with safety on the part of the operator.

As a result, the role of UAS safety management has grown significantly as more UAS enter the NAS. In the simple cases enabled under 14 CFR Part 107, such as Class G airspace, integration into the NAS has been relatively straight forward. However, as more operators propose flight operations under the 14 CFR 107 waiver process, additional safety research is necessary. Areas such as determining safety standards for non-standard flight operations [7], balancing multi-aircraft health and safety [4], improving UAS traffic management [2] and exploring human factors [1] are key components to improving UAS safety [36].

Beyond improving UAS safety as more aircraft enter the NAS, the reliance on operator judgment has changed the way that UAS safety needs to be managed. For large organizations, UAS operations may pose significant risks as a wide range of users and aircraft may be deployed. While the FAA transfers risk to the UAS operators, in practice, all of this risk is transferred to the organization as the operators are acting on behalf of the organization. As a result, UAS risk and safety management are expected to play significant roles in the coming years.

1.2 Research Motivations and Approach

The UAS industry is rapidly growing, however, as presented previously, there are significant gaps that remain to be addressed. In this section, these gaps are identified and their approach to resolution is described.

1.2.1 Lack of a General SUAS Remote Sensing Methodology

The use of SUASs in remote sensing applications is still in need of maturation. As more and more applications are developed and documented, the need for a guide for the development of an SUAS remote sensing methodology has become apparent. A well-developed methodology is critical for project success as it defines with clarity, the end goal, the implementation, the data collection strategy and provides metrics for success and project completion. Failure to accurately develop a methodology can lead to significant development delays, spiraling costs, or complete project failure [8].

Addressing this general challenge requires an investigation of the advantages and disadvantages of SUAS operations and their remote sensing equipment to better inform the reader. While many view SUAS operations as an alternative to satellite based imagery, this is an incomplete view. This is especially true in the use of other remote sensing equipment such as Thermal Infrared (TIR) [5] and Short Wave Infrared (SWIR) imagers [6].

1.2.2 Sources of Error

The data processing workflow for UAS-based Remote Sensing is currently a multi-staged process of data collection and several layers of calibration and corrections. Sensor corrections such as noise cancellation, radiometric calibration and lens corrections as described in [37] have commonly been employed to generate ‘accurate’ data. Alternatively, *in situ* calibration techniques have been employed [38].

However, this workflow is subject to the introduction of errors at every stage of processing that may inadvertently result in poor quality results. The question is posed, is it even possible to collect perfect results? What are the limiting factors that influence data accuracy and what can be done to mitigate their influence? One such source of error is found in the wide field of view (FOV) cameras commonly deployed on SUAS and is shown to have profound impacts on data accuracy [10].

1.2.3 Lack of Optimized Data Collection

In addition to requiring several layers of corrections to extract calibrated data, the current processes for data collection are still significantly inefficient or possibly insufficient. Even in the best cases, despite all the processing, significant amounts of the collected data may go unused in the final analysis stages or are of minimal value. An example flight output such as in Figure 1.1 is generated from upwards of 30 GB of image data for less than 300 acres of coverage at 8 cm resolution. If the desired data was to determine the spatial pattern of large features, the research question posed is could less data be collected and still provide meaningful results? However, in order to address optimized data collection, defining ‘meaningful data’ is necessary and is the subject of the next challenge, optimizing the data analysis processes. This can be expanded into a more general question of optimality. How is an optimal SUAS flight defined with regards to data collection? What are the

factors that influence data collection from an SUAS and how can it be adjusted? It can be shown that an optimality framework can be developed from spatial, spectral and temporal factors [9].

1.2.4 Changes in UAS Safety and Risk Management

As described previously, the rapid growth of the UAS industry and the changes in the U.S. regulatory environment has shifted SUAS safety responsibilities from the FAA to the SUAS operator. This transfer of responsibility has profound impacts on future expansions of UAS and SUAS operations and on the oversight responsibility for large organizations in particular. In order to realize the full potential of all UAS operations in the NAS further analysis of some of the barriers to more complex cases is required. For the large organizations, a whole new structure of safety management is necessary.

1.3 Dissertation Contributions

The major contributions of this dissertation include, but are not limited to the following:

1. Described and enumerated the unique challenges and requirements in developing a specific SUAS methodologies for multispectral remote sensing applications.
2. Introduced the use of SWIR for SUAS-based remote sensing applications.
3. Analyzed the introduction of error in SUAS based remote sensing platforms from the bidirectional reflectance distribution function (BRDF).
4. Established a framework for optimizing remote sensing data collection with regards to spatial, spectral and temporal factors.
5. Developed the first SUAS safety case for flight operations at night.
6. Investigated the use of Automatic Dependent Surveillance-Broadcast (ADS-B) as a SAAS.
7. Developed and implemented the first UAS Safety Management System (SMS).

1.4 Dissertation Organization

The dissertation is organized as follows. The research motivations and contributions are introduced in Chapter 1. Chapter 2 addresses the challenges of SUAS remote sensing methodology and the use of TIR and SWIR imagers. The effect of the BRDF on the accuracy of data collected by SUAS is analyzed in Chapter 3. The optimality of multispectral remote sensing is investigated in Chapter 4 with the development of a generalized framework with regards to spatial, spectral and temporal factors. Chapter 5 changes direction and discusses the safety challenges of

the integration of UAS into the NAS. The development and implementation of a novel SMS specific for UAS operation management is discussed in Chapter 6. Finally, Chapter 7 concludes the dissertation with discussions of future research directions.

Chapter 2

SMALL UNMANNED AIRCRAFT SYSTEM BASED MULTISPECTRAL REMOTE SENSING METHODOLOGY

2.1 Introduction

The use of Small Unmanned Aircraft Systems (SUASs) has rapidly developed into a promising tool for remote sensing applications. From archaeology and coastal monitoring to wildlife conservation, end-users have found significant value in these new aerial sensing platforms, especially as a component of cyber-physical systems [39]. Their adaptability for a wide range of capabilities, such as low altitude flights or extended operations and automated flight controls, enables data to be collected that was previously unobtainable. Unfortunately, the challenge of SUASs are just as much in their use as it is in their technology. The multitude of platforms and sensors, coupled with a lack of standards and validation has led to questions over their reliability as data collection platforms [8]. This challenge of collecting meaningful, accurate and cost-efficient data is nontrivial, and establishing an effective methodology is an effective tool to address this challenge. It is clear though that an understanding of SUAS, their applications and their sensor payloads is necessary.

In this chapter, a guide to developing an effective methodology for SUAS-based remote sensing operations is presented. This chapter serves as the background and foundation for discussions on improving data collection from SUAS from analysis of data error and optimizing data collection. The remainder of Section 2.1 introduces the concepts of remote sensing methodology and its formulaic development. Section 2.2 introduces SUASs and core concepts of Unmanned Aircraft System (UAS) based remote sensing applications. Section 2.3 introduces common UAS remote sensing payloads and their attributes to guide selection. Special attention is given to the use of Thermal Infrared (TIR) and Short Wave Infrared (SWIR) imagers in Sections 2.4 and 2.5 respectively. Section 2.6 discusses the advantages and disadvantages of SUASs. While there are a multitude of different types of UASs and sensors, this chapter focuses on specifically SUAS (< 55 lbs) and optical based remote sensing as an example, though the overarching message is applicable for any UAS and sensing technique.

2.1.1 Methodology and Project Management

Remote sensing is a relatively new field and driven by technological developments, it has expanded quickly. It is easy then to get caught up in the latest technological tool without a clear focus of the research methodology to use the tool efficiently or even correctly [26]. While methodology typically does not describe specific procedures, an effective methodology serves as a guideline for solving a problem, outlining what the activity of the research is, how to proceed, how to measure progress and what constitutes as success. Though public interest has fostered technological innovation, literature has been sparse of addressing how to use SUAS effectively and ensuring that the results are scientifically valid. It has become necessary to promote methodology for the development of new applications and the maturation of the field of SUAS-based remote sensing [8].

As with any research project, an important challenge for the SUAS project developers is to translate layman statements such as “Let’s use a drone to improve land management practices” into “Let’s use a remote sensing platform carrying radiometrically calibrated optical imagers in the visible and near infrared spectrums for the bare ground classification of a 10 sq. mile area with a desired optical resolution to discern the endemic population of Meadowfoam (*Limnanthes alba*).” The first statement is a wishful goal; the second introduces the methodology necessary to ensure a successful application and that the initial development and equipment purchases will lead to an effective solution. The challenge with SUAS is that the capabilities and limitations are frequently misunderstood. The following approach breaks down the steps such that these knowledge or technical gaps can be identified.

2.1.2 Formulaic Development

An effective methodology defines the end goal, the activity, the implementation of the activity, the measurement of progress and the success of the project. It provides a guideline for solving the targeted problem with specific tasks, components and metrics. An incomplete or poorly defined project methodology can lead to development delays, spiraling costs, purchases of incorrect equipment or complete project failure. In practice, many project developers find it useful to formulate a project methodology in terms of a series of questions such as the following (as adapted from [40]):

- What is the purpose of the project?
- What is the stated goal of the project?
- Is the goal quantitative or qualitative?
- Does this project utilize the scientific method or the technological method?
- What objects or events are the desired outcomes related to?

- Are there specific relationships found within the object or event of interest that can be utilized or must be taken into consideration?
- What data is necessary to address the problem?
- How should the data be collected?
- What procedures should be used to analyze the data?
- Are there available models/procedures sufficient to analyze the data?
- Does it require developing new models/procedures?
- What efforts must be undertaken to ensure the validity and reliability of the project?
- What ethical issues need to be addressed?

Addressing the questions above and/or other clarifying questions about the proposed project is designed to help form connections between goal and implementation and identify specific methods that will enable the successful completion of the application or project.

The first step in any project is to understand the goal with the intended purpose of narrowing down the language to actionable items. Simple classifications such as separating the goal between quantitative goals and qualitative goals are often useful in this regard. This step often requires a thorough understanding of the desired goal which may not always align with the wording of the stated goal. For example, a project with a purpose of ‘improving crop yield’ utilizes language that implies a qualitative goal, but in practice would require quantitative goals such as ‘improve yield by 5’ that implies accurate measurements to be achievable.

The method or body of techniques of the project is another example of a way to provide guidance to the development of an effective methodology. For SUAS remote sensing applications, the scientific method and the technological or engineering method are the most common. Whereas the scientific method strives to advance knowledge, the technological method addresses specific problems or issues. If the scientific method is about knowing, then the technological method is about applying [40]. The two methods may overlap at times and utilize similar approaches and equipment, but the differences play a role in the development of an SUAS remote sensing methodology.

The scientific method can be described as a set of techniques based on empirical and measurable evidence with principles of reasoning and inquiry to arrive at new knowledge. It is a cycle of observations, refining hypotheses and testing, until a thoroughly vetted understanding can be presented as knowledge. Environmental research SUAS applications typically fall under this category with the assumption

that the technical capability of the SUAS-based remote sensing is sufficient. In contrast, the technological method is an application of research, directed at a specific target goal or desired state. In this approach, the enabling technical capability is the target end goal. Validation and testing become methods to measure progress rather than part of the implementation. In some projects, both methods may be employed such as answering a scientific inquiry while developing the underlying technical capability. Clarifying the goals and the methods of the project can help put realistic targets and progress metrics within the context of the project end-goals, and prevent cost-control problems from inadequate detail planning.

Examining the relationships of the desired objects and events of the goal is another aspect of forming a methodology. Keeping track of strong correlations and dependencies can be valuable. In some cases, the target goal, for example, ‘measuring chlorophyll content’, might show a positive correlation with a reflectance ratio calculation known as Normalized Difference Vegetation Index (NDVI) [41]. Thus utilizing NDVI might be an effective method. However, a thorough methodology may identify that NDVI also shows a strong correlation with leaf area index [41], which may complicate the desired goal measurements if the influences of the two correlations cannot be separated.

Understanding the goals and ways that the desired data can be collected provides some guidance for equipment, software and workflow requirements, but selecting the right pieces can still be a significant challenge. There are a wide variety of platforms, sensor packages, software solutions at an equally wide range of costs and capabilities already commercially offered, but even still many researchers and developers end up implementing their own custom solutions [26]. This application-centric approach, choosing equipment based on the specific requirements of the application, is common given the narrow and specialized applications proposed. However, this drives up costs and delays projects when incorrect equipment is purchased or developed.

Once the project’s data goal is selected, the data must be collected. Data collection strategies vary significantly based on equipment, though there are plenty of examples of the use of modified equipment [42–44]. However, one of the major challenges for remote sensing applications of SUASs is the lack of standardized processing procedures. As many developers and researchers have discovered, specialized workflows are often necessary to process their data. Unfortunately, this poses problems in addressing whether the results of the project were valid and reliable. It is not an uncommon problem though, especially for remote sensing operations, where different data generating processes can create data that may not be comparable with other sources [45].

Ethical and legal issues are significant topics that require addressing with an effective methodology. The current legal environment, especially in the US, is

particularly challenging to traverse. However, it is important that SUASs applications are developed with the legal restrictions and limitations in mind and with an understanding of how they may affect the data collection process and feasibility of the proposed goal. A challenge may arise from addressing privacy concerns. A common technique is to employ a ‘Privacy by Design’ approach [46], incorporating privacy considerations into the technology and methodology that addresses it at all stages from data collection, data management to data dissemination.

2.2 Small Unmanned Aircraft Systems and their Remote Sensing Applications

It is clear from the requirements of an effective methodology that the effective utilization of SUAS requires an understanding of SUAS, SUAS applications, different optical sensors and the data that they collect. While there exist many similarities between satellite-based remote sensing and SUAS-based remote sensing, there are distinct differences that must be accounted for.

2.2.1 Small Unmanned Aircraft Systems

Unmanned aircraft are nearly as old as aviation, though primarily serving military purposes such as surveillance and training targets. It was not until after World War II that the aerospace industry began to utilize them for testing and research purposes [47]. Starting in the early 2000’s, interest in SUAS grew dramatically and by 2013, it was declared a multi-billion-dollar industry [11]. However, it is significantly more difficult to provide a detailed description of what a UAS is. By legal definitions, a UAS describes a total system, including ground control equipment, of an unmanned aircraft, which is described simply as an aircraft that is operated without the possibility of direct human intervention [34]. An SUAS is further defined as a UAS in which the unmanned aircraft weighs less than 55 lbs [34]. There is no definition of an SUAS’s shape, motor configuration, color, flight altitude or crew size.

This ambiguity in its definition underscores both its advantages and challenges. SUAS vary significantly in a multitude of critical subcomponents and features such as propulsion systems, autonomous behavior, operator controls, flight endurance and lift characteristics. While this gives SUAS operators significant flexibility, the variability in cost (ranging between \$500 and \$100,000 USD), is indicative of a low barrier to entry, but not affordability for all combinations of characteristics. That is not to say there are not some commonalities within SUAS. Most SUAS are categorized as either fixed-wing or rotary-wing platforms, arbitrary weight categories and payload type [26].

2.2.1.1 Fixed-wing SUAS

An example of a fixed-wing SUAS is the AggieAir Minion, originally developed and built at Utah State University (Figure 2.1). With a 2.4 m wingspan and a total flight endurance of 60 minutes, it is capable of covering up to 400 ha acres per flight at 213 m above ground level (AGL) with a payload capacity of 1.5 kg. While in operation at UC Merced, it accumulated 45 flights and a total of 20 flight hours between May 2014 and December 2015. It is equipped with an autopilot system, an Inertial Measurement Unit (IMU), a Global Positioning System (GPS) receiver, a real-time data telemetry and control link through a computer and a secondary transmitter for manual control and safety takeover. It can be flown manually, programmed to fly to waypoints or programmed to complete autonomous flight patterns. While it has a highly adaptable payload bay and navigation software, due to its size and flight characteristics, it lacks the ability to finely control its forward flight speed, operating between 12 m/s and 20 m/s, depending primarily on weather conditions. With payloads with slow image rates, this limits effective data collection to above 122 m AGL. Due to its large size and weight, it utilizes a catapult system for launches (described in Chapter 5). As a result, deployment takes between 1-3 hours to set up for a flight. While it has significant extra complexity, it is capable of being utilized for a variety of different applications and payloads.

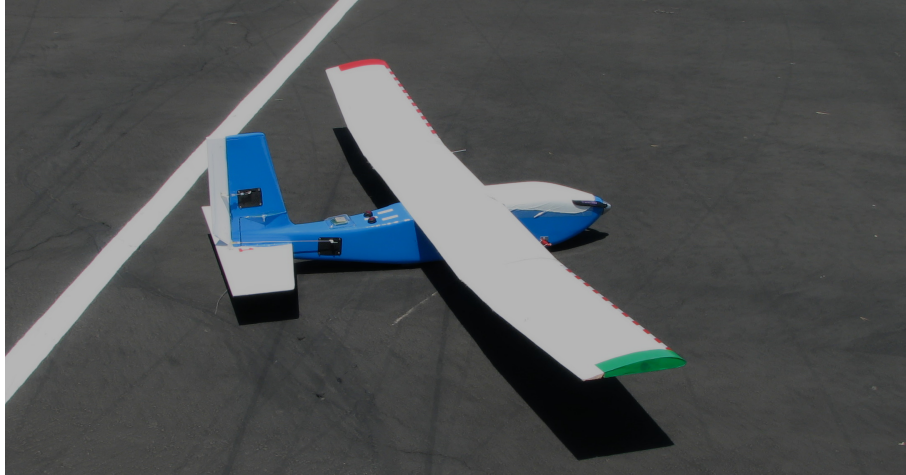


Figure 2.1: AggieAir on runway.

2.2.1.2 Rotary-wing SUAS

In contrast, the Kespry Drone 2, recently released by Kespry [48] is marketed as complete aerial solution for industrial applications such as construction and architecture. This is a rotary-wing platform with a motor to motor length of 30 cm, weighs 2 kg and boasts a flight endurance of 30 minutes. Flying at 122 m AGL,

it is capable of covering more than 50 ha within a single flight. Equipped with the latest technology, including a high-performance ground receiver in addition to the standard IMU, GPS and other flight sensors, it is designed to be a complete solution with a built-in 20 MP camera and automatic uploads to its cloud-based post processing system. Unlike AggieAir, the Kespry Drone 2 is flown completely autonomously from launch to recovery; it does not have a secondary transmitter for manual flight control. Programming is accomplished by selecting the region of interest and the autopilot calculates the flight pattern and altitude. While this removes the fine control of operation from the SUAS pilot in command (PIC), this platform is marketed towards groups with a single purpose, as opposed to general research purposes like AggieAir.

2.2.2 Core Concepts in SUAS Remote Sensing Applications

As evidenced by the variability of SUAS platforms, SUAS applications are equally as diverse. In general, SUAS remote sensing applications can be grouped by data goals into three major categories: Detection or Counting applications, Identification or Localization applications and Analysis Applications. Detection or Counting applications are focused on detecting or counting targets. Unlike the other types of applications, the data in these applications are in the form of contrasts, such as person vs not-person. Identification or Localization applications are focused at understanding the contextual information associated with a target. Rather than looking for a herd of cattle, the size and location of the herd is vital to the application. Analysis applications require further investigation of the data and contextual information to create calibrated and meaningful or actionable information, though these applications can be very complex to establish. In general, the increasing complexity of the application is proportional to the costs, both in time and money.

2.2.2.1 Detection/Counting Applications

The detection or counting of targets is a common and valuable wide-area monitoring SUAS application. Conceptually, the goal of such applications is simple: to find the existence of the desired target. The significant challenge is to determine the optimal way to separate the target from the rest of the scene, either of which could be static or moving. The target is the primary goal; thus, the accuracy of the separation or classification is paramount to success rather than the accuracy of the image or other measurements. The separation or classification of the target can be accomplished in any variety of ways by focusing on finding specific characteristics such as color, texture or shapes that are unique for the target. Additional contextual information, such as location, time of day or *a priori* knowledge may also be valuable for improving the accuracy, and could require the use of data fusion techniques or statistical modeling to reduce errors. However, in contrast to the accuracy

requirement of the detection, the collection of the characteristic or contextual information is reliant on precision, or the repeatability or reproducibility of the collection of the information. This is an important distinction to make because it may affect equipment choice. For example, if the goal is to find hogs on property [49], a TIR camera is an effective tool, but the temperature measurement of the hog is not of value, only the contrast of hot and cold. A lower cost precise TIR imager may be utilized rather than a more expensive accurate TIR imager. More information on TIR imagers is presented in Section 2.4.

Identifying the characteristics or contextual information necessary for detection influences equipment selection. Many characteristics such as texture and shape often require a high spatial resolution to discern small features. Contextual information, such as location and size and depth, can be inferred from motion determined from images with a high temporal resolution such as individual frames in a video. Automated low-level control found in many cameras and video systems such as color balance, auto-focus, aperture and shutter speed control can be effective at maintaining the visibility of the image for characteristics to be discerned.

The time sensitiveness of the application also plays a role in the equipment selection, more so in detection and counting applications than the others [50]. Often an immediate reaction is desired at the detection of a target, such as returning home or changing search patterns. This level of visual feedback into the system often requires real or near real-time communication and systems with a high frame rate are best suited [51]. The desire to have an independently operated imaging system also often requires the same level of visual feedback as well. For these reasons, video systems are more common for detection and counting applications where immediate visual feedback is prioritized over image quality and resolution.

The processing of the data can be automated, or manually done with a human operator. Automated machine vision algorithms have been utilized and demonstrated widely, though human operator monitoring is common place. Search and rescue operations, especially, are staffed with human operators due to scene complexity and ease of implementation [52].

However, there are specific challenges to detect and counting applications. For automated machine vision systems, the data processing increases significantly with image resolution, but too low of a resolution limits the ability to discern details such as texture. Human operators monitoring real-time video also have a number of challenges, as documented by studies on human factors for search and rescue operations with teleoperated robotics [53]. Operator fatigue and sensory overloads are common issues that lead to decreased detection and counting accuracy [?]. Long operations may be limited by SUAS platform capabilities, so proper selection of the desired platform is another key for success [26]. In addition, the data bandwidth of the video system is often much greater than the rate of detection, leading to a significant amount of wasteful redundant data. From that challenge, it is important

to recognize the value of optimal path planning and optimal sensing strategies [54].

2.2.2.2 Identification/Localization

In many situations, the characteristic or contextual information of a target is a part of the data goal. This transforms the application into an identification or localization application, where instead of asking ‘Is it there?’ the question is ‘what is it?’ Characteristic or contextual information commonly includes location and surroundings, but may also include size, time, color or texture. These attributes often require a higher spatial resolving capability of imagery, though not necessarily always a faster temporal resolution. The addition of this information enables classification or identification of a number of items such as plants, animals, vehicles or sustained damage. However, the challenge of classification introduces the need for repeatability and consistency from image to image.

A wide variety of sensor equipment can be utilized for identification or localization applications. Video systems can be utilized effectively as described in firefighting efforts [55, 56]. Digital cameras often can provide a higher resolution and many are affordable solutions where real-time is not necessary. Other specialized equipment such as TIR imagers, multispectral imagers or hyperspectral imagers are also effective equipment, though are often a costly investment. Remote sensing applications may also utilize non-imaging sensors for air quality measurements and the inclusion of localization data enables the creation of detailed spatial maps.

Whereas some detection applications can be accomplished without specialized equipment, identification and localization applications often require contextual information to be stored during image collection and additional processing to fully utilize it. UAS payloads may employ camera systems with embedded GPSs to record image locations. Photogrammetry software such as Pix4D [57] or Agisoft Photoscan [58] are commonly a part of the workflow.

The tracking of moving targets is another common SUAS application that combines the challenge of object identification and localization [59]. Challenges such as multi-object tracking may require the use of real-time data downlinks or significant on-board computing power. As with detection and identification applications, the use of auxiliary processing and data fusion algorithms may be useful for improving results at the expense of cost and complexity.

2.2.2.3 Analysis

Analysis applications are typically complex and require significant development and a strong methodology. While identification applications ask ‘what is it?’ analysis applications are designed around the question ‘what does it mean?’ In essence, they are designed for the purpose of transforming remote sensing data into meaningful or actionable intelligence. The counting application will return with the information that there are 12 trees in the grove. The identification application will

return with the location and size of each tree. The analysis application will generate the data to make estimations on the health of the trees and how much fruit will be produced.

In analysis applications, often the data produced is not the image, but rather a mapping or visualization of the optical sensor measurements. As such, sensor calibration, radiative transfer models, ground control points and bias corrections are standard elements of the analysis application workflow in an effort to relate at sensor measurements to physical features. Commercially available point and shoot digital cameras may not always be well suited for these applications as they typically lack the ability to record at sensor measurements. Multispectral cameras and hyperspectral imagers are commonly implemented and have demonstrated effectiveness in agricultural applications such as crop monitoring [60] and environmental applications such as invasive weed monitoring [61].

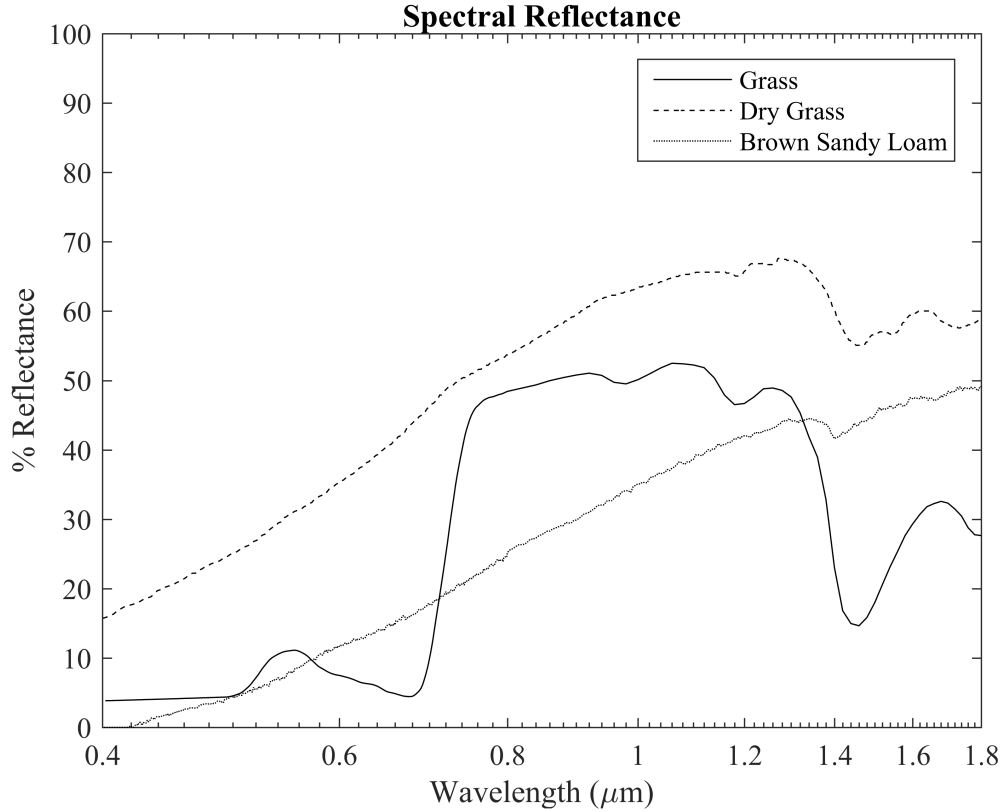


Figure 2.2: Spectral reflectance in the visible and near-infrared region. Data courtesy of ASTER [62].

The value of calibrated imaging equipment can be interpreted in the spectral

reflectance of grass, dry grass and brown sandy loam (Figure 2.2). Live vegetation, including grass, has a distinctive pattern of spectral reflectance, or the amount of light that is reflected. Vegetation typically appears green to the human eye because it reflects more light in the green spectrum (0.53-0.58 μm) than red or blue. Most vegetation is also highly reflective in the Near Infrared (NIR) which is in the range of 0.7-1.0 μm , beyond what the human eye can see. An imaging system that can measure the reflectance of an object at multiple wavelengths would be able to very clearly determine the difference between grass and dry grass, which has a different spectral signature as depicted in Figure 2.2. However, if a sensor was uncalibrated and suffered from an unknown bias, the different materials may be separated, but not identified.

2.3 SUAS Imaging Equipment for Remote Sensing

The development of an effective SUAS remote sensing methodology requires knowledge of various equipment available and their capabilities. Rather than focus on specific technological metrics, the following discussion focuses on the common qualities of selected imaging equipment types. Without specifying existing imaging resolutions or shutter speeds, it is still valuable to examine the different defining aspects and how they dictate the remote sensing workflows and best practices. The following section examines common SUAS payloads such as video systems, digital cameras, calibrated digital imagers and with a discussion of the implementation strategies and methodology development. Special attention is given to the roles of TIR and SWIR imaging equipment found in Section 2.4 and 2.5 respectively.

2.3.1 Video Systems

Video systems can be a simple payload to integrate into an SUAS. It can be as simple as affixing a small high definition (HD) video recorder to the SUAS but also as advanced as a remotely operated gimbaled video system with real-time communication and control (Figure 2.3). The wide range in capabilities enables project developers the ability to decide on the best system, balancing performance and cost with functionality.

Image quality and resolution vary significantly with quality and price, though in general, they are not at the same level as digital cameras. However, the key aspect of video systems is the high frame rate rather than optical quality. For human viewers of live or recorded video, the implied motion visible from the rapid progression of frames provides significant contextual information such as movement direction, relative size and orientation of visible objects, and object depth that are difficult to discern from still imagery at lower frame rates.



Figure 2.3: Frame of real-time video footage, Merced 2013.

With machine vision algorithms and automated processing, the high frame rate enables superior object tracking and coverage area with faster moving vehicles. The use of a controllable gimbal system provides improved situational awareness for human operators [51], a valuable capability for search and rescue operations, though at the cost of added complexity. While video systems typically have a lower image resolution than digital cameras, the use of a narrow field of view lens or a controllable zoom lens can enable a similar high spatial resolution at the tradeoff of a smaller viewing area.

Implementation of video systems into a project workflow is straightforward. Typically, they do not require pre-flight calibration, or image correction as the information goal is to obtain visual references of objects or of characteristic information. Setting up ground control points can be utilized for post processing georeferencing. Depending on the desired autonomy, video processing can be done on-board or on the ground, though typically the computer power is greater on the ground.

2.3.2 Digital Cameras

Digital cameras are effective for many SUAS operations that require high spatial resolution but do not require immediate visual feedback or a high frame rate. Many cameras, even those that are commercially available, have advanced automated features such as automatic focus, color balance, white balance and image stabilization that ensure excellent pictures are generated. Overall, digital cameras provide excellent resolution for quantitative measurements of many characteristics such as small features and object texture, making them ideal for identification or localization applications.

The additional of contextual information such as known ground control points (GCPs) or recording the position the picture was taken in, can enable accurate spatial measurements as well. With a sufficient coverage, a mosaic can be generated from the set of pictures over the targeted area (Figure 2.4). Combined with the contextual information, this enables high resolution georectified orthophotos that can be used for applications such as mapping fire damage [56] and rangeland management [25]. In the example orthophoto from the Merced Vernal Pool and Grassland Reserve (MVPGR), the discoloration of soil is apparent in the area surrounding the water tower located on the right side of the orthophoto, which was caused by sediment leakage.

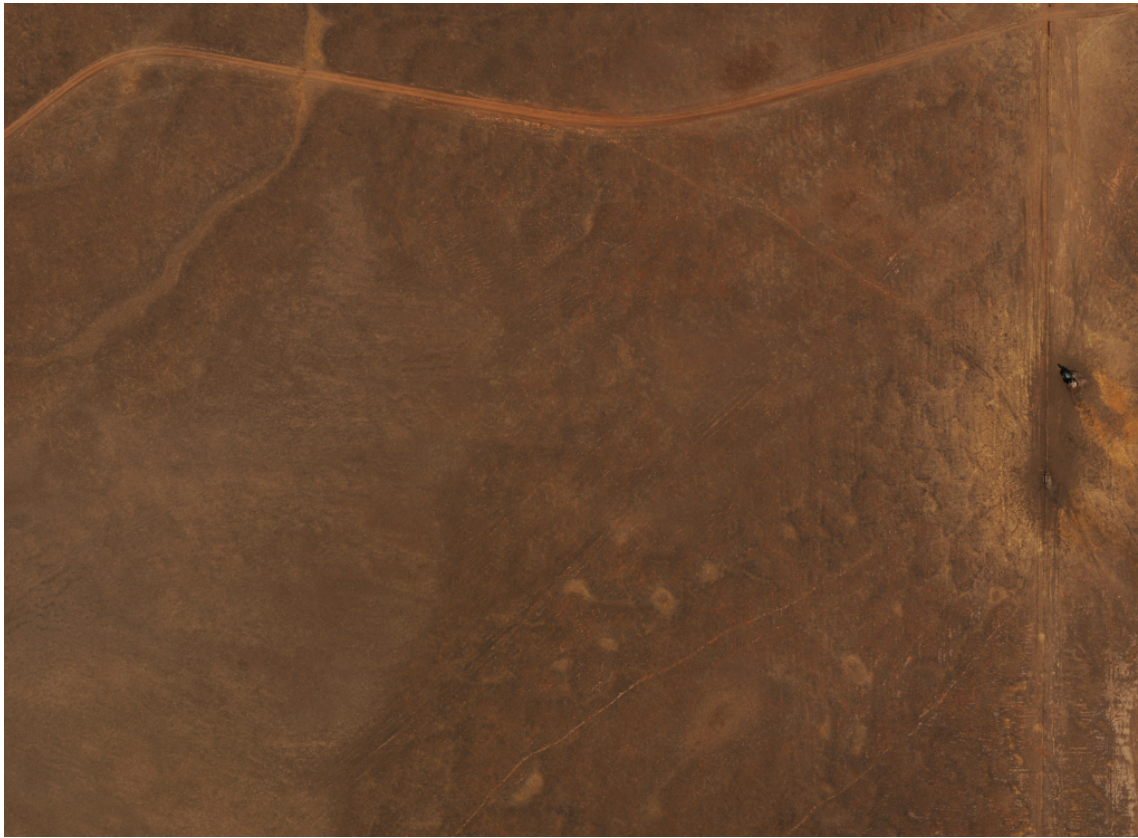


Figure 2.4: Example orthophoto from SUAS.

The pictures generated can also be used with a photogrammetry technique of generating 3D surface models from aerial images (Figure 2.5). Utilizing sufficiently overlapping pictures, image points from a Structure from Motion (SfM) algorithm are matched together to generate pixel depths and stitched together to form a digital surface model. These digital surface models have been presented as both accurate and precise [63] enough to be utilized for applications such as modelling river topology [64] and mapping ice flows [65]. In Figure 2.5, the digital surface model depicts the abundance of sediment mounds that characterize the formation of the seasonal vernal pools in the MVPGR.



Figure 2.5: Example digital surface model with hillshade added for clarity.

While digital cameras have a number of advantages, they are less suited for applications where immediate responses are needed or quantitative spectral measurements. The automated features that enable high quality pictures obscure accurate reflectance radiation measurements by dynamically adjusting color, light and introducing artifacts through lossy compression.

2.3.3 Digital Cameras as Calibrated Imagers

Quantifiable spectral measurements are a powerful analytical tool and the basis for most satellite remote sensing applications. While satellites suffer from low spatial resolution, low temporal resolution and atmospheric interference, SUASs can be utilized to counter these issues.

Calibrated systems are designed to provide accurate radiometric measurements, typically of the radiation emanating from the surface [41]. Rather than looking at images in terms of colors, images are comprised of the intensity of energy received at particular wavelengths. Whereas a red object may appear slightly pink or orange depending on the time of day, camera orientation, or camera settings, a

calibrated system is designed to isolate only the object's reflectance and provide a consistent measurement across multiple settings and viewings.

Digital cameras can be utilized as radiometrically calibrated imagers, though additional procedures are required for calibration. In Figure 2.6, an example workflow for using digital cameras as calibrated digital imagers is depicted. Field data collection is often a necessity for most workflows for radiometric calibration. Camera identification is also a process done prior to the flight operation, though may not be necessary prior to each flight. Lens calibration calibrates for the optical qualities. Flat field calibration provides for adjustments from non-uniform image collection (vignetting, nonlinear response, dead pixels). Spectral sensitivity enables radiometric data to be collected for spectral signature matching which often requires ground control points and spectral control points. The data processing workflow includes the integration of metadata for spatial processing and raw band separation to adjust for band to band registration.

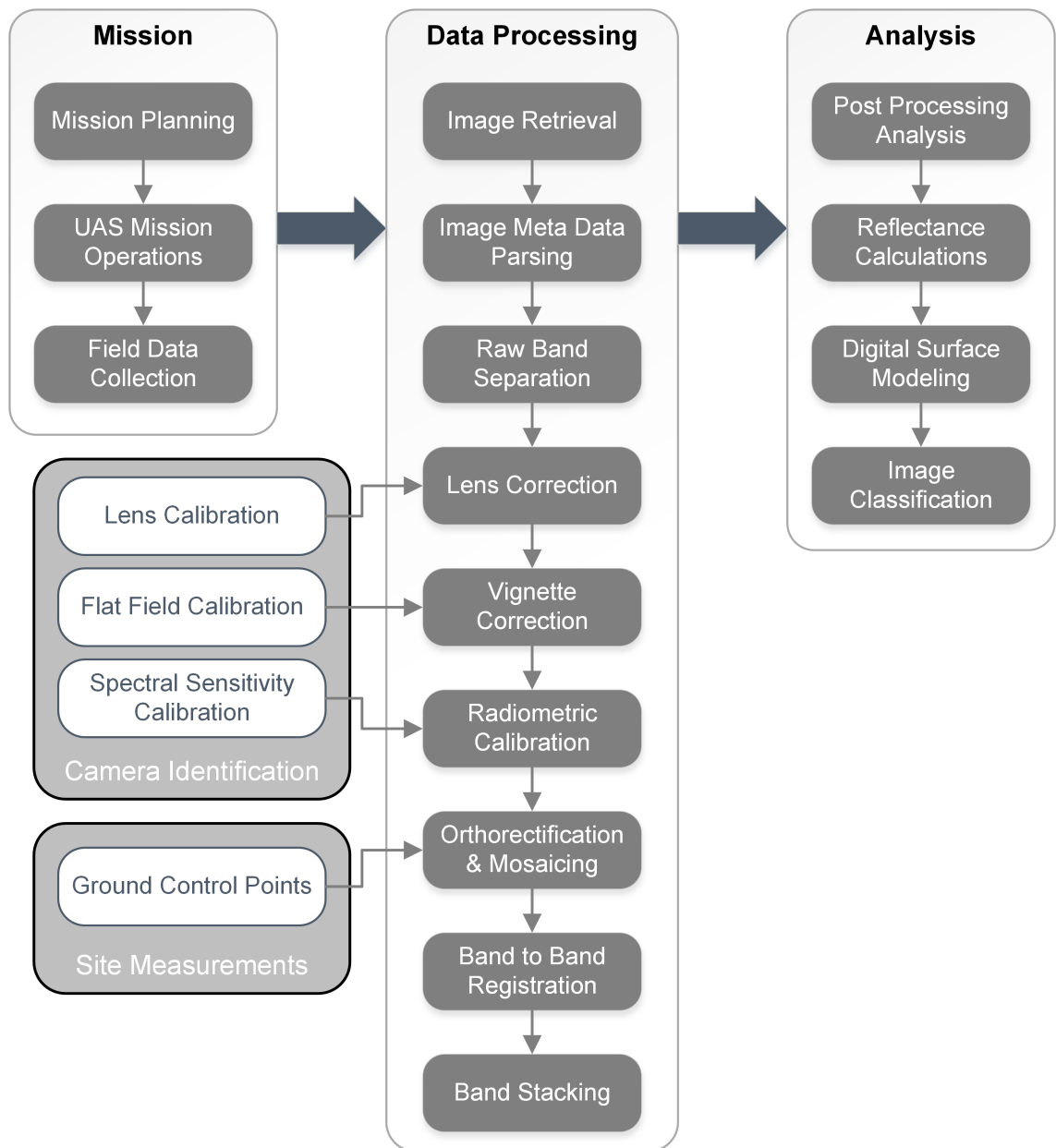


Figure 2.6: SUAS analysis workflow for converted digital cameras.

2.3.4 Multispectral and Hyperspectral Imagers

Imaging equipment that specialize in measuring the reflected radiation at specific wavelengths are either considered multispectral or hyperspectral imagers. Multispectral imagers are typically only a handful of selected wavelengths, while

hyperspectral generate upwards of 60 channels of selected wavelengths, typically at much narrower bands than multispectral.

Advances in technology has led to the feasibility of the use of multispectral imagers such as those developed by TetraCam [66] and MicaSense [67]. For applications that rely on spectral signatures of targets, often these systems are a necessity. A variety of agricultural applications such as crop water stress [19] and identifying citrus greening disease [15] have demonstrated the effectiveness of these systems for both multispectral and hyperspectral imaging.

Many of the implementation strategies of calibrated digital cameras can be similarly applied to these calibrated imagers. As with other optical systems, corrections such as background noise, radial distortion and vignetting are required for accurate radiometric measurements [38]. Multispectral sensors based on CMOS or CCD sensors utilize the sensor's wide range of spectral sensitivity and utilize optical bandpass filters such as those sold commercially by Androver [68] or Edmund Optics [69]. The advantage of these specialized sensors is in the quality of the spectral measurements. While calibrated camera systems have broadband spectral responses, the specialized imagers are capable of measuring specific spectrum.

2.4 Thermal Imagers for SUAS

Thermal imagery, derived from the far-infrared or TIR light spectrum, has shown promise as the missing element to derive the critical actionable intelligence for many applications. Unlike near-infrared imagery, TIR imagery requires a special dedicated and costlier sensor which has slowed its adoption. As the TIR imager technology has decreased both in size and weight, it has become more and more presentable as a suitable sensor for a remote sensing SUAS. While the use of TIR imagery from an SUAS is not new or revolutionary, its use has primarily been for military or law enforcement applications. Only in recent years has its impact as a scientific tool for domestic applications been fully investigated. Despite the cost and the challenges, TIR imagery can provide valuable information, most notably in agricultural applications.

Infrared light is the electromagnetic radiation with wavelengths that range from the edge of visible red (700 nm) to roughly 1mm. While the NIR (700 nm - 1.4 μm) and short-wave infrared (1.4 μm - 3 μm) spectrums are primarily from reflective radiation, TIR (3 μm - 15 μm) is primary composed of emitted radiation. This allows for a sensitive radiation measurement sensor to estimate the kinetic surface temperature of an object by the amount of emitted radiation the object emits, isolated from any reflected radiation. Section 2.4.1 provides an overview of TIR applications, organized by their core concepts. A short introduction to TIR equipment is presented in Section 2.4.2.

2.4.1 Current TIR Applications

While there is a multitude of SUAS applications, those utilized for remote sensing operations can be classified by the level of sophistication of the desired final goal as described in Section 2.2.

Table 2.1 contains a sampling of TIR SUAS application publications, sorted by mission type and year of publication. The majority of published research on TIR SUAS applications are related to the more complex missions of identification and analysis. This, however, is not a reflection on the number of TIR SUAS applications.

Table 2.1: Sampling of TIR SUAS application publications, sorted by mission type and year of publication.

Ref	Year	Type	Mission
[55]	2003	Detection	Demonstrate Effectiveness of an SUAS in fire-fighting operations
[70]	2011	Detection	Used a TIR camera for counting roe deer fawn with an SUAS
[71]	2004	Identification	Proposed using a TIR camera to detect frost forming on crops overnight
[72]	2007	Identification	Added TIR imagery to human identification and tracking algorithms for SUASs
[73]	2008	Identification	Implemented automated human detection for search and rescue operations with an SUAS
[74]	2010	Identification	Implementation of a TIR camera for environmental monitoring applications
[56]	2011	Identification	Advances in mapping TIR imagery for firefighting decision support operations
[75]	2011	Identification	Development of a hyperspectral mapping SUAS that include TIR imagery
[76]	2011	Identification	Automated real-time people and vehicle detection with TIR imagery
[77]	2012	Identification	Used TIR imagery to calculate surface water temperature of streams
[78]	2013	Identification	Identification of subsurface hotspots in a coal mine
[79]	2013	Identification	TIR mapping of coal fires
[80]	2006	Analysis	Correlated TIR imagery from an SUAS with crop health in cotton
[81]	2007	Analysis	Utilized TIR imagery for measuring soil water content
[82]	2007	Analysis	Correlated TIR imagery with crop water stress
[83]	2009	Analysis	Used TIR imagery from an SUAS to calculate Crop Water Stress Index (CWSI)
[60]	2009	Analysis	Compared SUAS calculated Crop Water Stress Index (CWSI) with other vegetation indices
[13]	2012	Analysis	Correlated TIR imagery with crop water stress
[84]	2012	Analysis	Applied SUAS calculated CWSI to peach trees
[16]	2012	Analysis	Applied SUAS calculated CWSI to almond groves
[85]	2012	Analysis	Compared SUAS calculated CWSI with other vegetation metrics from SUAS imagery
[86]	2013	Analysis	Applied SUAS calculated CWSI to five fruit tree species

[87]	2013	Analysis	Used TIR indicators to detect faults in drip irrigation systems
[88]	2013	Analysis	Used SUAS TIR imagery for the early detection of invasive fungus in olive crops
[19]	2013	Analysis	Compared and correlated SUAS TIR imagery with other vegetation indices

2.4.1.1 Detection

The primary motivation for the utilization of TIR imagery for SUASs have historically been within the military or law enforcement applications. In these situations, TIR imagery provides a new layer of information that improves or enhances performance. Bringing this ability to civilian applications leads to the use of TIR imagery for search and rescue applications or firefighting applications [55].

In all of these applications, the utilization of TIR imagery is to be able to see heat signatures. The payload processing complexity is significantly reduced compared to the other classifications. In these detection missions, the user (a ground control or payload operator) is tasked with the higher-level decision making, relying on human expertise rather than system automation. In many of these types of sensitive situations, it is not uncommon for a human to be more trusted than a computer [51]. As such, these detection missions are reliant on real-time information provided to the human operator, with minimal processing delay.

While the previously mentioned law enforcement, search and rescue, and fire-fighting applications are the more common applications for TIR imagers on SUASs, there are several other applications that fit into the detection mission category. Environmentalists and conservationists have regularly utilized SUASs for their efforts, with the SUASs providing a cost-efficient method for counting or monitoring wildlife [70]. On the other hand, SUASs equipped with TIR imagers have also been utilized harmfully, for instance to hunt down wildlife [49]. Thermographic inspection of buildings has also utilized SUASs for aerial vantage points, enabling users to spot or detect anomalies in temperatures [89].

2.4.1.2 Identification

SUAS applications centered around identification missions require further processing than those centered around a detection mission. Whereas detection missions look to see if something is there, identification missions seek to classify information.

Unlike detection missions, the absolute temperature recovered from a TIR imager is frequently utilized in automated classification systems. Real-time processing can still be an important aspect of an identification system, but total information often takes precedence over real-time. In addition to precise temperature information, identification missions often fuse multiple information sources, such as localization information or other spectral imagery to aid in identification.

Applications that utilize spatial information and other spectrum information are abundant, though there remain significantly more applications. In one application, an SUAS with a TIR imager was used to identify subsurface hotspots in open cut coal mines [78]. In [78], a TIR infrared camera was used to create a high-resolution temperature map that enabled the identification of several subsurface hotspots that otherwise would not have been visible. Similarly, a TIR imager was used on a NASA UAS to identify areas within a vineyard that suffered from frost damage [71]. A third mapping case utilized a TIR imager to map the surface temperature of a creek to identify stagnate zones [77]. In these applications, the precise temperature information and the precise location are utilized to reach the desired end goals.

Automated tracking systems such as the ones found in [72], [76] and [73] utilize TIR imagery in combination with the visual light spectrum to enhance human and car identification and tracking systems for SUASs.

2.4.1.3 Analysis

Analysis missions for SUASs with TIR infrared imaging systems require an additional level of processing. Moving beyond simple detection and identification, the goal of analysis missions is to provide actionable intelligence for action based on sound science. The majority of the agricultural and environmental applications of SUASs fall under this large category.

The key attribute of an analysis mission is a reliance on calibrated, georectified, and multispectral imagery. It is this information that actionable intelligence can be calculated from for the end user or further automated control system. Whereas the identification mission answers where a hot spot is, for example, the goal of an analysis mission is to explain why that area is hotter than the surrounding area and what it means to the surrounding area.

While agricultural applications are expected to play a major role for civilian SUASs, the literature is sparse with actual implementations with the exception of those that utilize TIR infrared imagery. The biggest goal of agricultural applications for SUASs is to find ways to identify crop stress and health before the crops are significantly damaged. While the use of just the visible and near-infrared light spectrum has not been effective, it was noted that TIR imagery shows a correlation between the minor changes in water stress that NDVI imagery could not [13]. In [83], it is noted that a TIR index known as CWSI can be calculated from TIR imagery from an SUAS. While CWSI has been established as an accurate indicator of crop water stress, it has not been widely adopted because it requires a significant number of temperature measurements. Satellite imagery has been regarded as having too coarse of a resolution to provide useful information for CWSI. However, with the advancement of SUASs carrying TIR imagers, use of CWSI can be regarded as practical [83]. In [60], further developments of an SUAS demonstrated

that other vegetation metrics such as leaf area index (LAI), Chlorophyll Content (C_{ab}) and water stress could be calculated and validated with the use of TIR imagery. Similar results were found with cotton crops [82], peach trees [84] and almond trees [16]. Initial work on the identification and definition of water stress thresholds for improved management was published in [86].

2.4.2 TIR Imaging Equipment

TIR camera systems are not as diverse as other optical imaging systems, though there exist some variations, especially within resolution and output. A typical TIR imager will range in price from \$2,000 to \$50,000 depending on the quality and functionality. While the prices have decreased significantly over the past few years, they are still significantly more expensive than most commercially available off-the-shelf camera systems. A list of example camera systems in 2014 can be found in Table 2.2. This listing is not exhaustive, though is representative of many possible solutions.

Table 2.2: Available TIR cameras in 2014.

Camera	Resolution	Weight	Output	Spectral Band	Max Frame Rate
FLIR T450sc	320 x 240	880 g*	USB, NTSC	7.5 μm - 13.0 μm	30 Hz
FLIR A325as	320 x 240	700 g	Ethernet	7.5 μm - 13.0 μm	60 Hz
Gobi-384 (Scientific)	384 x 288	500 g*	NTSC, Ethernet, CameraLink	8.0 μm - 14.0 μm	50 Hz
ICI 7640 P-Series	640 x 480	127.6 g	USB 2.0	7.0 μm - 14.0 μm	9 Hz
InfraTec mobileIR M4	160 x 120	265 g*	NTSC, USB 2.0	8.0 μm - 14.0 μm	60 Hz
Optris PI400	382 x 288	320 g*	USB 2.0	7.5 μm - 13.0 μm	80 Hz
Pearleye LWIR	640 x 480	790 g*	CameraLink, Ethernet	8.0 μm - 14.0 μm	24 Hz
Tamarisk 640	640 x 480	121 g	NTSC, CameraLink, USB 2.0	8.0 μm - 14.0 μm	30 Hz
Tau 640	640 x 512	110 g	NTSC	7.5 μm - 13.5 μm	30 Hz
Thermal-Eye 4500AS	640 x 480	108 g	NTSC	7.0 μm - 14.0 μm	30 Hz
Thermoteknix MIRICLE 370K	640 x 480	166 g	NTSC	8.0 μm - 12.0 μm	240 Hz

*denotes TIR Camera weight including housing and lens

As with other optical systems, the final mission objective dictates the minimum image quality [90]. However, unlike the large assortment of digital optical equipment, TIR cameras have a much more limited range of quality. The majority of commercially available TIR cameras have a resolution of 640 pixels by 480 pixels; significantly less than commercially available off-the-shelf point and shoot cameras that have resolutions typically above 4200 pixels by 2800 pixels. As will be discussed in Chapter 4, this has significant effects on mission implementation strategies.

2.5 Shortwave Infrared Imagers for SUAS

SWIR imaging systems or imagers are increasingly becoming commercially available, enabling their integration into SUASs. These unique imagers measure light in the SWIR region of the electromagnetic spectrum, typically defined as between $1\text{ }\mu\text{m}$ and $3\text{ }\mu\text{m}$, beyond the visible light spectrum ($0.4\text{ }\mu\text{m}$ to $0.7\text{ }\mu\text{m}$) and beyond the near infrared region ($0.7\text{ }\mu\text{m}$ to $1\text{ }\mu\text{m}$), but before the thermal region ($7\text{ }\mu\text{m}$ to $15\text{ }\mu\text{m}$). While the NIR spectrum can be measured by CMOS or CCD technology even though it is invisible to the human eye, the SWIR spectrum requires a different detector, such as an Indium Gallium Arsenide (InGaAs) detector. The manufacturing challenges and costs has slowed its adoption in commercial applications. In comparison to other visible light or TIR imagers, the cost for SWIR systems are typically higher and suffer from significantly reduced resolution and increased weight. However, its unique properties can provide valuable information where visible, NIR or TIR imagery are ineffective.

While the SWIR is beyond NIR, it still primarily responds to reflected electromagnetic energy as opposed to emitted energy, and thus is not normally used for thermal measurements [41]. The majority of energy in the SWIR spectrum is either reflected or absorbed by objects, similar to the light properties in the visible and NIR spectrum.

The SWIR spectrum is recognized for its significant absorption by water, and bands of absorption by water vapor and CO_2 . Water vapor has significant impact on the transmission of light in the atmosphere in the SWIR spectrum with bands of absorption around $0.935\text{ }\mu\text{m}$, $1.13\text{ }\mu\text{m}$, $1.38\text{ }\mu\text{m}$, $1.88\text{ }\mu\text{m}$ and $2.68\text{ }\mu\text{m}$ [41]. However, the strong absorption by water in the SWIR spectrum results in SWIR imagers exhibiting significant sensitivity to moisture. In Figure 2.7a, the water in the bottle appears dark rather than transparent. Next to the bottle, the darker spot on the apple is a visible marker of a bruise, which released moisture under the skin of the apple. In the visible spectrum, such bruising would not be visible. Man-made objects, such as clothing also typically reflect highly in the SWIR spectrum as can be seen in Figure 2.7b.



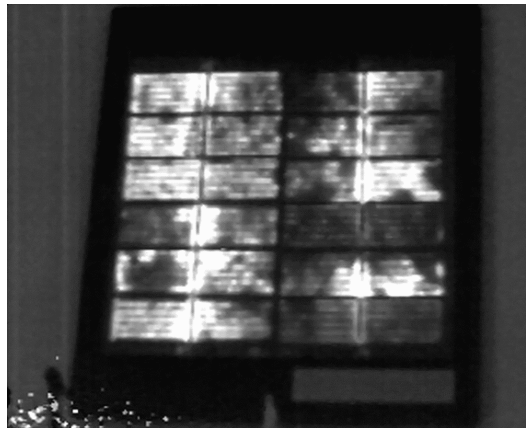
(a) Water and bruised apple.



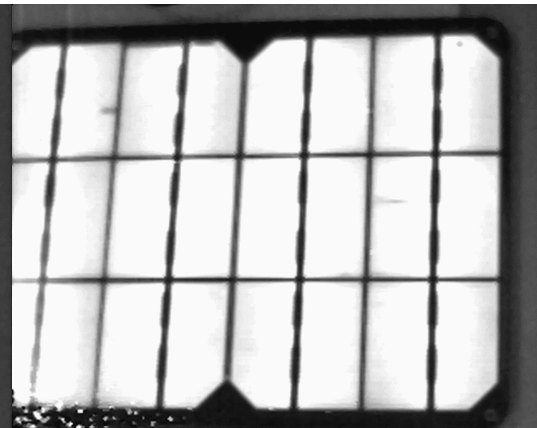
(b) Person wearing black jacket.

Figure 2.7: Short Wave Infrared (SWIR) examples.

While silicon-based CCD or CMOS image sensors are unable to measure SWIR spectrum energy, silicon electroluminescence occurs in the SWIR spectrum. Applying a voltage across a silicon-based solar cell will illuminate the cells, similar to applying a voltage across an LED will illuminate the LED. This property can be used in solar cell inspection. Figure 2.8a and Figure 2.8b depict the difference in electroluminescence (EL) between a poorly performing solar cell (Figure 2.8a) and a well-performing solar cell (Figure 2.8b) as measured by a SWIR imager.



(a) EL of a poorly performing solar cell



(b) EL of a well performing solar cell

Figure 2.8: Comparison of EL of solar cells.

2.5.1 Current SWIR Applications

The unique properties of the SWIR spectrum and SWIR imagers have led to a wide variety of applications. While there are many valuable applications in industrial processing such as solar cell inspection or art analysis, the following section will focus on existing applications where SUAS integration may further enhance operation or provide additional capabilities. In this section, existing surveillance applications and remote sensing applications are introduced.

2.5.1.1 Detection

Recent advances in SWIR imagers have made them viable for military applications [91] such as surveillance or detection applications. A comparison of visible, NIR and SWIR spectrum imagers for military applications was presented in [92]. The authors identified several potential uses where SWIR imagers have an advantage over visible and NIR cameras: haze penetration, forest and oil fire penetration, maritime and ground target contrast and long range visibility. While SWIR imagers suffer from low resolution, they are comparable to many currently available TIR imagers.

While the SWIR spectrum is a reflected spectrum, similar to visible and NIR spectrums, the longer wavelength of SWIR results in an enhanced visibility because it is less affected by the Rayleigh scattering effect. While small particles (such as in haze or smoke) scatter visible light, SWIR passes through relatively unscattered. This ability to see through haze is the key advantage for enhanced long range visibility in surveillance applications in comparison to visible light cameras. In the case of fire penetration from forest fires or oil fires, the ability of SWIR to ‘see’ through smoke particles has significant value.

SWIR imagers have also been shown to demonstrate a capability for low-light or night vision [93]. The high quantum efficiency of many SWIR imagers enable useful low-light operation. When combined with an SWIR illumination source, invisible to human eyes, night visibility is possible with an SWIR imager. On clear nights, the phenomenon of airglow, the faint emission of light by the atmosphere, can provide enough illumination in the SWIR spectrum to enable night time visibility for very sensitive SWIR imagers [93].

2.5.1.2 Identification and Analysis

Images in the SWIR spectrum are also abundant in identification or analysis applications, especially within remote sensing. Many satellites have imagers with specific regions of spectral sensitivity, referred to as bands, within the SWIR region. For remote sensing applications, the SWIR spectrum is recognized for its sensitivity to moisture, which can be correlated to important metrics such as leaf water content and other crop canopy physiological statuses [94]. Over the past decades, researchers have used SWIR bands to indicate leaf and canopy moisture [95], plant water stress

[96], the remote sensing of vegetation liquid water [97] and forest fire burn severity [98].

A list of common satellites and their SWIR bands can be found in Table 2.3. While the majority of SWIR bands are in the region between 1.55 μm and 1.75 μm , some satellites have bands in the atmospheric window between 2.1 μm and 2.4 μm and around 1.25 μm . Landsat 8 OLI introduces a new SWIR band between 1.36-1.38 μm , notable because it exists at a region where water vapor is not transparent [99]. The result is that high-altitude clouds reflect highly compared to the dark background of water vapor in the earth atmosphere, which then can be used to correct other satellite imagery distorted from these high-altitude clouds.

Table 2.3: Satellite SWIR bands between 1.2 - 2.3 μm .

Satellite	Resolution	Band Regions (μm)
ASTER	30 m	1.6-1.7, 2.145-2.185, 2.185-2.225, 2.235-2.285
AVHRR/3	1.09 km	1.58-1.64
EO-1 ALI	30 m	1.2-1.3, 1.55-1.75, 2.08-2.35
Landsat 7 ETM+	30 m	1.55-1.77, 2.09-2.35
Landsat 8 OLI	30 m	1.57-1.65, 2.11-2.29, 1.36-1.38
MODIS	500 m	1.23-1.25, 1.628-1.652, 2.105-2.155, 1.36-1.39

Many of the applications utilize a common spectral vegetation difference index in the form of

$$Index = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}} \quad (2.1)$$

where ρ_{NIR} is the reflectance in the NIR spectrum band, ρ_{SWIR} is the reflectance in the measured SWIR spectrum. There are several indexes identified, each with different applications utilizing difference SWIR bands provided by different satellite systems. The availability of SWIR wavelengths for SUASs enable these indices to be calculated at a higher spatial resolution than previously available by utilizing optical bandpass filters. Literature describes three major spectral indices that have been identified. The Normalized Difference Water Index (NDWI) utilizes the shorter wavelengths within the SWIR spectrum (1.2 μm - 1.3 μm) and is recognized as a way to measure vegetation liquid while being less sensitive to atmospheric effects than NDVI [97]. The Normalized Difference Infrared Index (NDII) uses the SWIR spectrum between 1.55 μm - 1.75 μm and has been used to identify historic (up to 10 years) fire scar damage [100] as well as an indicator of canopy water stress [95]. The Normalized Burn Ratio (NBR) utilizes the longer SWIR spectrum between 2.05 μm - 2.45 μm to map forest burns and burn severity [98].

2.5.2 SWIR Imaging Equipment

Although not as common as digital cameras or TIR imagers, SWIR imagers have become available commercially. Currently, most SWIR imaging sensors are made with InGaAs detector arrays. Although there are other detectors such as Germanium (Ge), Indium Antimonide (InSb), and Mercury Cadmium Telluride (HgCdTe) detectors, InGaAs arrays have been more practical due to their higher quantum efficiency and low dark current at room temperature, although these sensors are typically only effective between the $0.9\text{ }\mu\text{m}$ to $1.7\text{ }\mu\text{m}$ wavelengths [93]. A plot of the quantum efficiency of an InGaAs detector can be found in Figure 2.9 [101]. As with most electronics, the drive for miniaturization has led to the availability of small and light-weight systems, many suitable for integration into SUASs.

While some satellite imagery is limited by atmospheric transmission windows, an SUAS with a SWIR imager with appropriate bandpass filters would be able to collect a wider range of spectral measurements. This has been shown to be valuable for improved spectral indices for water stress detection or soil moisture measurements [102].

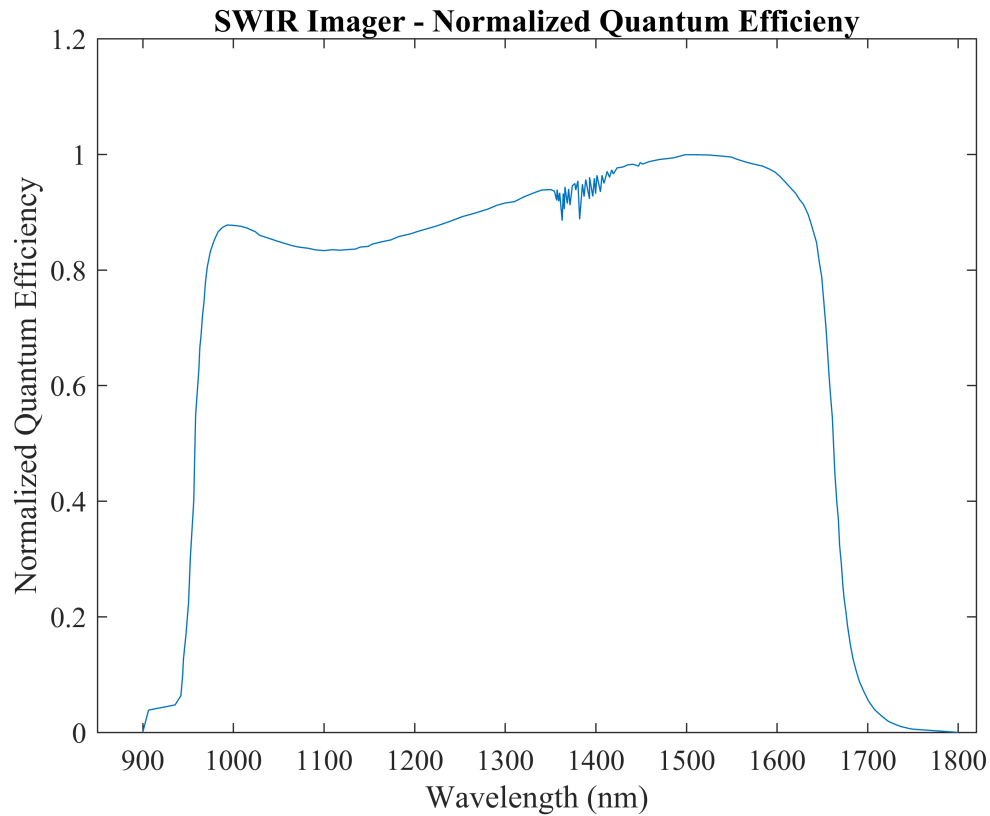


Figure 2.9: SWIR quantum efficiency. Courtesy of ICI [101].

2.6 Common Advantages and Disadvantages of SUAS

The key to utilizing SUAS effectively is in understanding the platform and payloads. While it is difficult to address the wide variety of SUAS, there are some generalities that can be used to guide understanding [26].

2.6.1 Key Advantages

- On-demand data collection
- Multiple payload solutions available
- Can be portable
- Often flies at low altitudes which can enable uniform high resolution coverage
- Capable of data collection in some atmospheric conditions
- Can be low cost

- Many can operate without any permanent infrastructure
- Often battery powered and relatively quieter compared to full-sized aircraft
- Significantly less risk to operators than manned aircrafts
- Controllable data collection

2.6.2 Challenges

- Lack of standardization and quality control
- Subject to local weather conditions
- Often has limited flight endurance (<30 minutes)
- Often only effective in small areas (<60 ha)
- Data collection is not instantaneous for an area
- Often flies under 10 m/s
- Challenging legal framework

2.6.3 Identifying the Niche of SUAS

In general, while SUAS have a number of advantages, their biggest limitations have relegated their operation to scales under 60 ha. However, they are capable of filling a niche gap between ground sensor systems and aerial and satellite based remote sensing. Figure 2.10 depicts a handful of different categories and their position on relevant spatial and temporal scales. As an example, infrastructure and construction processes tend to occur on a spatial scale between sub meters (small components) to 100s of meters (full construction sites), and on a temporal scale between months to years for development. Satellite systems such as Landsat 8 and Advanced Very High Resolution Radiometer (AVHRR) lack the spatial resolution to monitor but would have the temporal resolution. Higher resolution systems from the Worldview - 3 satellite, SUAS or ground sensors would have sufficient spatial and temporal resolution, however with dramatically increasing data density. In contrast, SUAS may not be suitable for fast moving systems (such as tracking live wildlife) or systems that work on large scale, such as weather or land cover analysis.

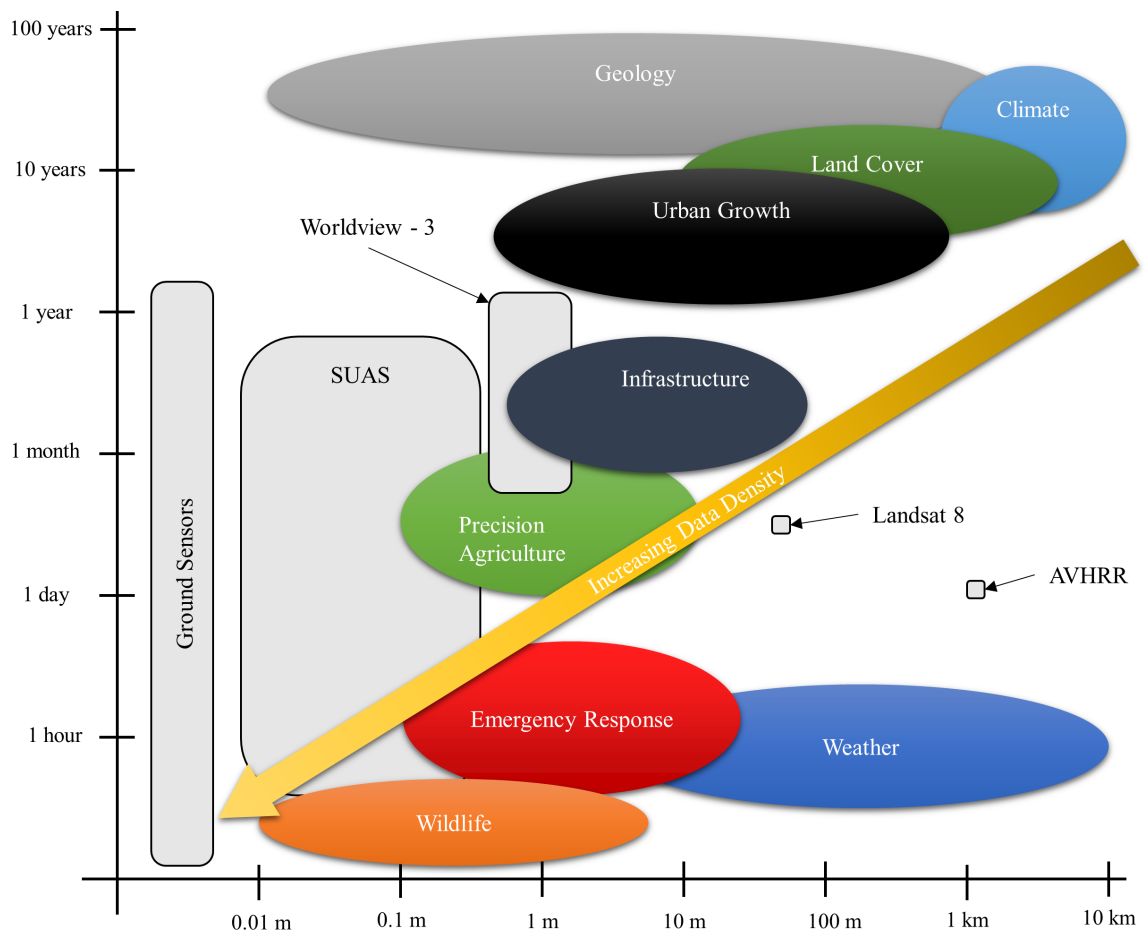


Figure 2.10: Illustration of different spatial and temporal scales relevant to remote sensing.

2.7 Chapter Summary

The use of SUASs as a tool has a number of significant advantages to complement existing technology and methodology and fulfill a niche in remote sensing. However, as new capabilities are developed, there is a need for describing how to utilize and capitalize them efficiently. As more and more applications are developed and described, SUAS methodology will mature and effective projects will be the norm. For many applications, such as those based around detection or identification applications, existing technology is capable. While it is tempting to use SUASs as a direct replacement for satellites for analysis applications, there are additional challenges that need to be addressed especially towards accurate spectral measurements. One such issue will be addressed in the following chapter.

Chapter 3

DATA ACCURACY SUBJECT TO CAMERA FIELD OF VIEW AND SOLAR MOTION

3.1 Introduction

The growth of Small Unmanned Aircraft System (SUAS)-based remote sensing has heavily borrowed from existing methodology from satellite-based remote sensing. However, as described in Chapter 2, while there are many similarities between satellite- and SUAS-based remote sensing, there are also many differences that have a profound effect on data collection, processing and usage. Unlike the high quality and robust sensors found in satellites, sensors in SUASs can vary between low-cost commercial off-the-shelf ‘point and shoot’ cameras to high precision hyperspectral sensors. This variability has introduced a significant new component to an existing problem in remote sensing: How accurate is the data compared to within set variation and how comparable is one dataset to another? This prompts further investigation into the long-term reliability and accuracy of the datasets generated by SUAS.

This has led to an increased interest in data accuracy improvements such as establishing an effective methodology [8], data collection optimization [3], noise cancellation [37], and calibration techniques [103]. Hyperspectral data in particular requires significant calibration [104]. However, the majority of these approaches focus on the means and methods to improve sensor calibration and accuracy. Few address other potential sources, such as those from atmospheric transmittance effects [105].

In this Chapter, two unique challenges are evaluated: the use of a wide field of view (FOV) camera and the effect of solar motion on data accuracy during an SUAS flight. It can be shown that the wide FOV negatively effects data accuracy due to angular variation in reflectance, but solar motion within a sufficiently short flight duration does not drastically introduce error [10]. It can also be shown that solar intensity and spectrum variation is a more significant contribution to data error. The chapter concludes with recommendations to minimize error due to angular variations in reflectance. The rest of the paper is organized as follows. The role of angular variations in reflectance is introduced in Section 3.2. Section 3.3 introduces the SUAS Remote Sensing Model used to simulate the effects of the bidirectional

reflectance distribution function (BRDF) of a simulated environment. The methodology of the simulation analysis is presented in Section 3.4. In Section 3.5, the results of the simulation sets are described. Finally, implications to SUAS-based remote sensing are presented in Section 3.6.

3.2 Angular Variation in Reflectance and the Bidirectional Reflectance Distribution Function

It is well-described in literature that for non-Lambertian surfaces, the reflectance of an object is a function of the angle of view, angle of illumination and wavelength. This is mathematically defined as the BRDF and can be written as follows:

$$f_r(\theta_i, \phi_i; \theta_o, \phi_o; \lambda) = \frac{dL_r(\theta_o, \phi_o, \lambda)}{dE(\theta_i, \phi_i, \lambda)} \quad (3.1)$$

where the response is a function of the illumination zenith and azimuth angles (θ_i, ϕ_i) , observer zenith and azimuth angles (θ_o, ϕ_o) , and wavelength (λ) . L_r is the spectral radiance leaving the surface and E is the overall spectral irradiance.

In existing literature, such as projects on precision agriculture [60] and field-based phenotyping [106], SUASs are utilized to provide high resolution multispectral orthomaps from which inferences about the biophysical properties of the crops are made. The methodology, derived from satellite-based remote sensing, assumes that the aerial images taken are sufficiently modeled as strictly nadir (or straight down) and that any variation in viewing angle is minimal after orthomosaic reconstruction. In satellite-based remote sensing, the FOV is assumed to be sufficiently narrow that any variation in angular reflectance is assumed to be minor at the scale of imagery [41].

However, this assumption does not hold true for SUAS that fly at significantly lower altitudes and use cameras with a wider FOV to compensate. Additionally, as SUAS may collect imagery over a non-insignificant period of time, the solar illumination angles may vary between time of first image to time of last image. As seen in Figure 3.1, the viewing angle within an imaging system can drastically differ within an image, even in a strictly nadir image. In Figure 3.1, although the direct illumination is parallel, the observer zenith angle (θ) varies across the field-of-view of the imaging system. As the SUAS conducts its data collection mission, the illumination angles are also in motion.

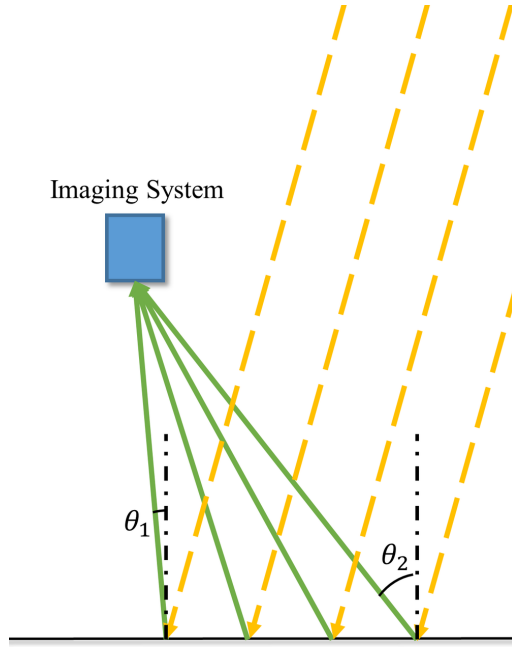


Figure 3.1: Viewing angle variation within an image.

A two-dimensional representation of angular variation in observer zenith angle can be seen in Figure 3.2. In this simulated model of a flat terrain, the observer's zenith angle varies radially from the center by as much as 30° . The imaging system simulated in Figure 3.2 has a 61.6° FOV horizontally and a 46.4° FOV vertically, matching the vertical field-of-view of a Canon S100 camera, a commonly used camera in SUAS remote sensing applications. Many other SUASs may utilize camera systems with a FOV that range between 28.75° to over 100° in wide angle systems.

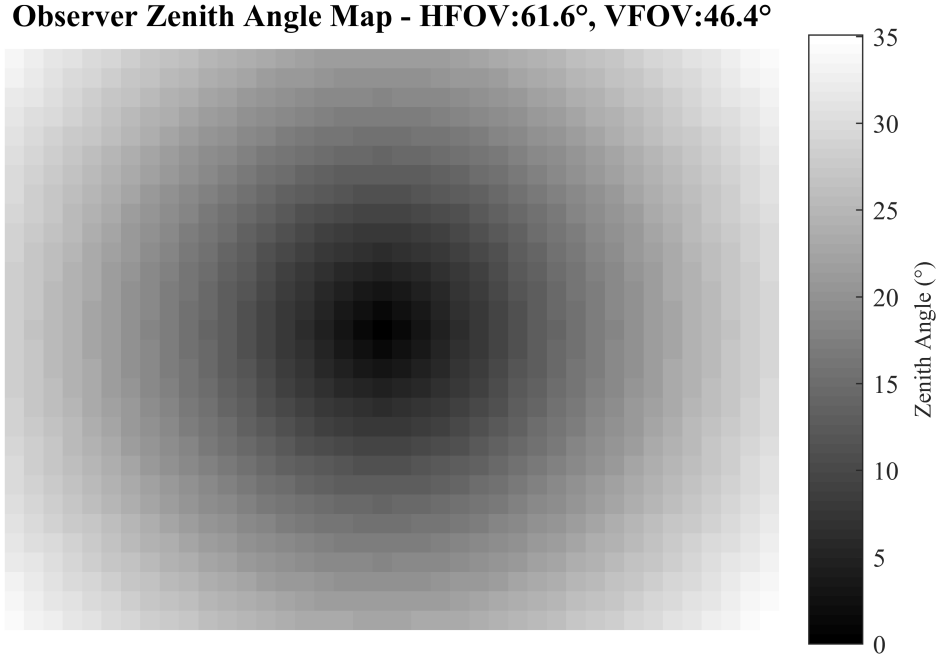


Figure 3.2: The observer zenith angle varies radially from the center of the image. The degree of its variation is dependent on the imaging field-of-view.

As evident in Figure 3.2, the zenith angle variation is too significant to be neglected in analysis. This effect is often drastically apparent in aerial imagery in the form of hotspots or darkened corners. While vignetting effects may have a similar appearance, the wavelength dependence can be visible in multispectral cameras, such as in Figure 3.3 in which the tree canopies in the far right side of the image are not only a different intensity, but also a different color than those on the left. Unlike vignetting effects, this radial variation may be centered anywhere in the image or out of frame.



Figure 3.3: The wavelength dependence on reflectance variation can be visually seen by the change in color of the trees from the right to the left of this image taken with a G-B-NIR modified camera (ELPH110).

The challenge of characterizing BRDF for vegetation has drawn increased interest with the growth in high resolution remote sensing data sets. SUASs have recently been investigated as a novel platform as a goniometer, a device to measure the reflected light at precise angular positions to characterize BRDF [107]. Other methods have derived mathematical models of BRDF based on models or empirical measurements and have been employed in vegetation canopy radiative transfer models (RTMs) to simulate hyperspectral reflectances [41].

3.3 SUAS Remote Sensing Model

In order to effectively isolate the specific effects of BRDF introduced by the wide field of view of a camera and solar motion, a SUAS remote sensing model and

simulation was developed (Figure 3.4). The parameters found within the model can be found in Table 3.1.

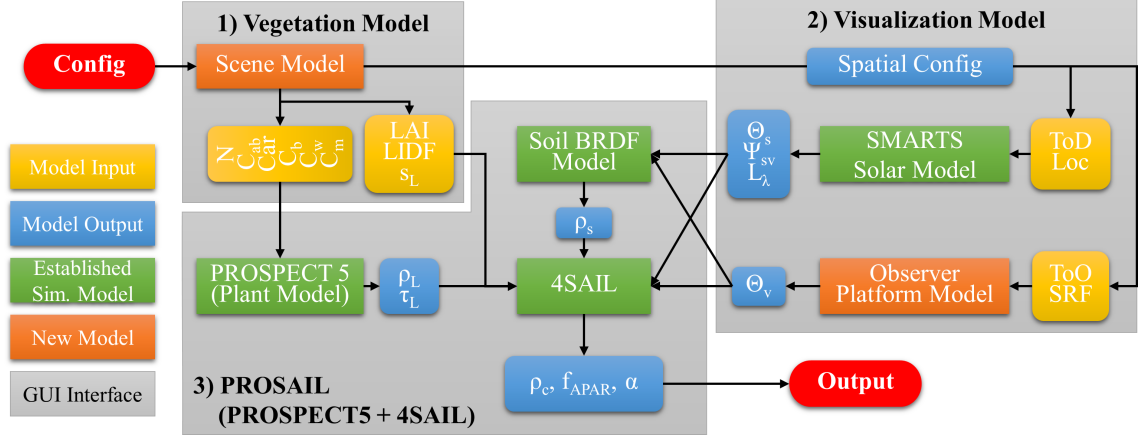


Figure 3.4: SUAS simulation model.

Table 3.1: Parameters in SUAS simulation model.

Config	Simulation Configuration	τ_L	Leaf Transmittance
N	Leaf Structure Coefficient	ρ_s	Soil Reflectance
C_{ab}	Chlorophyll Content	ρ_c	Canopy Reflectance
C_{ar}	Caretenoid Content	α	Canopy Albedo
C_b	Brown Pigment Content	Θ_s	Solar Zenith Angle
C_w	Equivalent Water Thickness	Ψ_{sv}	Relative Azimuth Angle
C_m	Dry Matter Content	L_λ	Solar Irradiance
LAI	Leaf Area Index	Θ_v	Viewing Zenith Angle
LIDF	Leaf Inclination Distribution Function	ToD	Time of Day of Observation
S_L	Hot Spot Parameter	LoC	Location on Earth of Target
ρ_L	Leaf Reflectance	SRF	Spectral Response Function of Sensor
ToO	Time of Observation from First Observation	f_{APAR}	Fraction of Absorbed Photosynthetically Active Radiation

The model utilizes three established models combined with an SUAS model that enables simulation of SUAS remote sensing data collection. At the leaf level, an RTM called PROSPECT5 model provides leaf optical properties in the form of reflectance across a wide spectrum as a function of leaf biochemistry, such as chlorophyll, water, and dry matter content [108]. This RTM is commonly combined with the Scattering by Arbitrary Inclined Leaves (4SAIL) canopy reflectance model to provide a simulation of both the spectral and directional variation of canopy reflectance [109]. The solar spectral irradiances and solar position are simulated with the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) [110].

The combination of PROSPECT5 and 4SAIL is commonly referred to as

PROSAIL, and is frequently used for spectral sensitivity analysis as well as directional sensitivity analysis [109]. Reference [109] provides a survey of existing studies that utilize PROSAIL, as well as validation studies. In particular, [111] demonstrated that top-of-atmosphere hyperspectral radiances under multiple view angles could be accurately predicted.

In the simulation, a scene model is described as a $m \times n$ array of pixels, where each pixel can be assigned an individual vegetation model, including biochemical parameters and canopy parameters as described in [109]. An SUAS mission scene model is utilized to describe the date, time, location, altitude, and camera field-of-view. The outputs of both the vegetation model and the SUAS scene model are fed into PROSAIL and $m \times n$ hyperspectral simulations are run. The important parameters of interest fed into PROSAIL in this study are $\theta_i, \phi_i; \theta_o, \text{ and } \phi_o$ which are outputs of the SUAS and solar model.

3.3.1 Selection of Subcomponent Reflectance Models

The validity of the SUAS simulation model depends on the validity of the sub-model components. At the leaf-level, PROSPECT pioneered the simulation of leaf directional-hemispherical reflectance and transmittance [109]. While the accurate simulation of real-world environments requires measurement of biochemical content (chlorophyll, water and dry matter content, etc), it is assumed that the real-world accuracy is not a needed component for this analysis. The validity of the PROSPECT model to generate plausible hyperspectral reflectance is the only condition that is needed to be met.

The validity of the selection of 4SAIL as a canopy reflectance model is dependent on the following assumptions. Of canopy reflectance models, two models were investigated: 4SAIL and FLIGHT. 4SAIL, one of the earliest canopy models, simulates the BRDF of turbid medium plant canopies by solving the scattering and absorption of four upward/downward radiative fluxes [109]. Since the model does not include parameters for canopy structure, the model is more similar to a homogeneous scattering of leaves over a soil. In contrast, FLIGHT is based on a Monte Carlo simulation of photon transport, where the foliage is represented within crowns based on structural parameters which allows for accurate modeling of scattering effects [112]. Both canopy models are well-regarded and their selection depends on the object of interest. In this study, 4SAIL was selected as the composition of each pixel more resembles the assumptions in this model. Given the high resolution of SUAS aerial imagery, individual canopies are commonly identifiable, but the leaf level resembles a homogeneous scattering within a pixel.

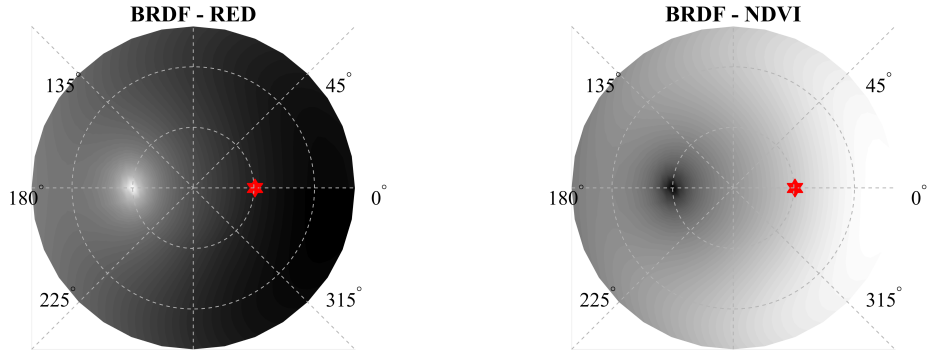
3.3.2 Validation of SUAS Remote Sensing Model

The results of the model match previous published research on BRDF effects [41]. Utilizing the simulation to generate visual representations of the BRDF (Figure

3.5), the significant variation of reflectance is depicted. The variation is also depicted in the calculation of the Normalized Difference Vegetation Index (NDVI) calculated as

$$NDVI = \frac{\lambda_{800nm} - \lambda_{680nm}}{\lambda_{800nm} + \lambda_{680nm}}$$

This variation is indicative of the wavelength dependence of BRDF. While both Near Infrared (NIR) (centered at λ_{800nm}) and red (centered at λ_{680nm}) exhibit a ‘hotspot’ at a specific viewing orientation, the intensity of the reflectance of the red wavelengths decreases at a different rate than NIR.



(a) Polar plot of BRDF at 680 nm.

(b) Polar plot of BRDF of NDVI.

Figure 3.5: Visual representation of BRDF in a polar plot of observer zenith and azimuth. Sun location marked with a star at a zenith angle of 20°.

This effect is similarly shown in Figure 3.6. In this figure, the Normalized Nadir Anistrophy Factor (NANIF) depicts the variation across the wavelengths for a given azimuth viewing angle. This is calculated as

$$NANIF = \frac{BRDF(\theta_i, \phi_i; \theta_{20^\circ}, \phi_{AZM}; \lambda)}{BRDF(\theta_i, \phi_i; \theta_{nadir}, \phi_0; \lambda)}$$

for a given illumination direction (θ_i, ϕ_i) across different viewing azimuths and wavelengths.

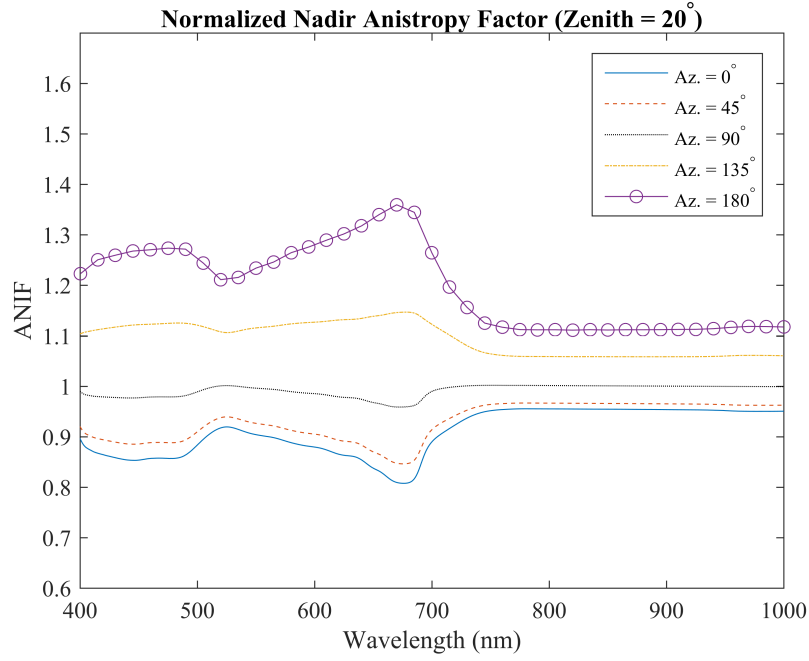


Figure 3.6: Normalized nadir anistropy factor depicts the variation in normalized scale factor as a function of wavelength.

3.4 Methodology

In order to characterize the effect of angular variation in reflectance as introduced by the unique characteristics of SUASs, two sets of analyses were conducted. First, the angular variation in reflectance as a result of a wide viewing angle (46.4°) was analyzed by a set of simulations of a single image. The second analysis was conducted over a series of images taken over a specified time period. In both sets of analyses, several assumptions and simplifications were made to isolate the parameter of interest.

In all images, the terrain was assumed to be perfectly flat and that any variation in viewing angle is due to the imaging equipment field-of-view. In practice, this assumes a perfect radial correction and a perfect lens imperfection correction. The resulting hyperspectral measurements are assumed to be accurate top-of-canopy measurements, neglecting any atmospheric affects or sensor inaccuracies. The measurements are also assumed to be accurate absolutely, assuming a perfectly calibrated sensor. The top-of-canopy measurement is assumed from a static solar spectrum irradiance, irrespective of the time of the day or day of year. In the second set of simulations, this ensures that the only parameter change over the series of images is the change in location of the sun. As an added source of variation, each image

is assumed to be subject to minor variations in aircraft pitch and roll (Normal distribution: $\mu = 0^\circ, \sigma = 2.25^\circ$, calculated from averages from existing data sets) to simulate a typical SUAS flight.

In this study, two biophysical variables within the vegetation analysis are used to introduce variability of the hyperspectral response: Chlorophyll Content (C_{ab}) and leaf area index (LAI). While many factors may be used, C_{ab} and LAI are among the most common variables analyzed with the PROSAIL vegetation model [109]. Since the goal of the study is evaluate the effect of angular variation in reflectance as a function of camera FOV and sun motion, the accuracy of the variables to a real-world system is unnecessary, only that the variables are plausible. As a comparison, each simulated aerial image is compared to a simulated satellite image, which assumes a zenith angle of 0° .

To study the effect of a wide FOV, four sets of simulations were developed: Flat, C_{ab} , LAI and C_{ab} +LAI. In the Flat simulation, the region simulated is considered perfectly homogeneous with static parameters. In the C_{ab} simulation set, the chlorophyll content is taken from a normal distribution with the mean at $35 \mu g/cm^2$ and a variance of $4 \mu g/cm^2$. The LAI simulation set contains a normal distribution of the LAI centered at 3 with a variance of 0.5. The final simulation set contains a combination of both variation in both parameters.

To study the effect of a prolonged flight or multiple flights within a data collection mission, each of the four sets of simulations were run again with three time intervals: All Day (30-minute intervals), Morning (8:00 am - 8:30 am, 2 minute intervals) and Afternoon (12:30-1pm, 2 minute intervals).

3.5 Results

The results of the simulations show a significant impact of the angular variation in reflectance introduced by the wide FOV. While data errors exist in the all-day time simulations, errors were minor in both the morning and afternoon shorter intervals.

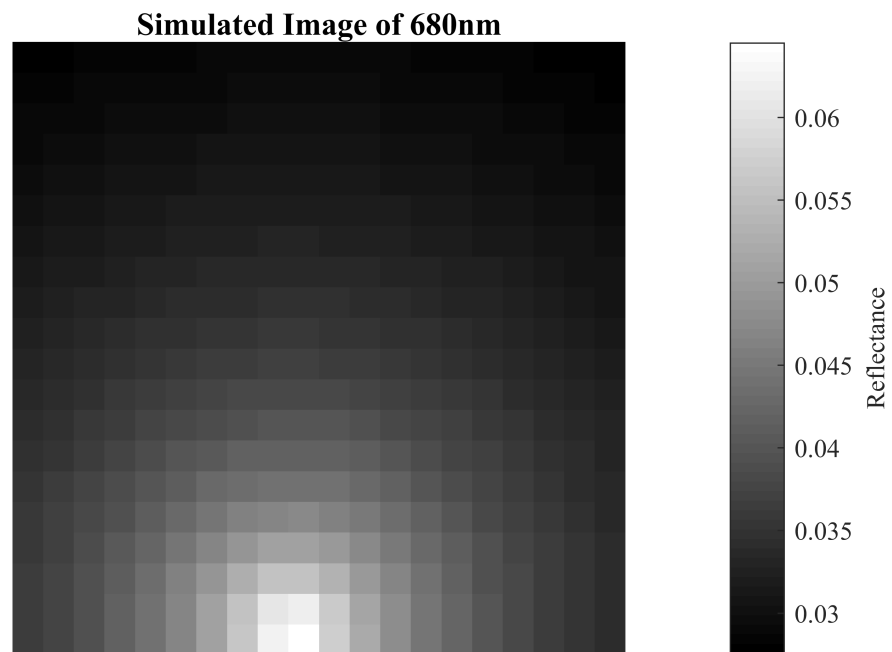


Figure 3.7: Simulated aerial image highlighting the effect of camera FOV on red reflectance.

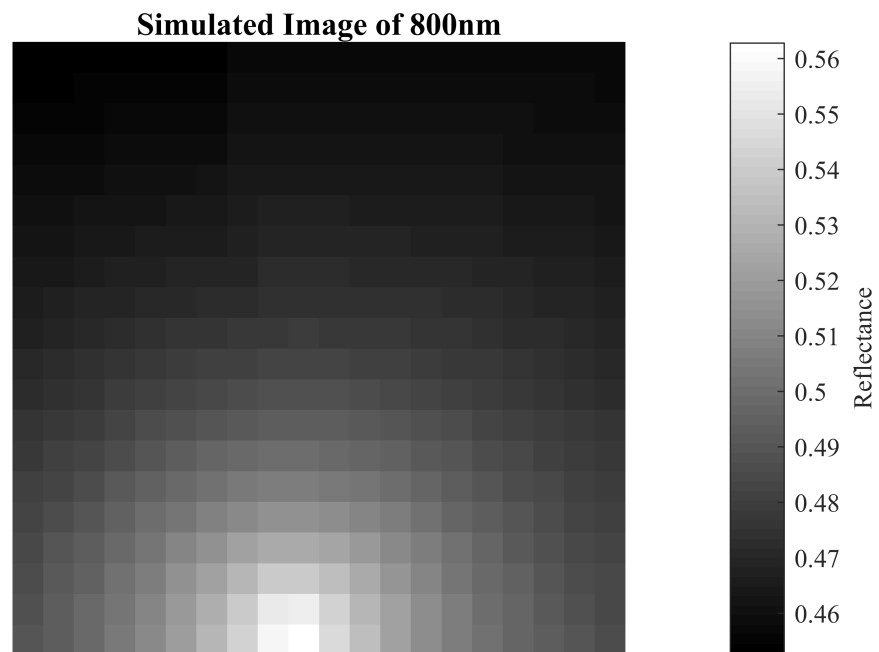


Figure 3.8: Simulated aerial image highlighting the effect of camera FOV on NIR reflectance.

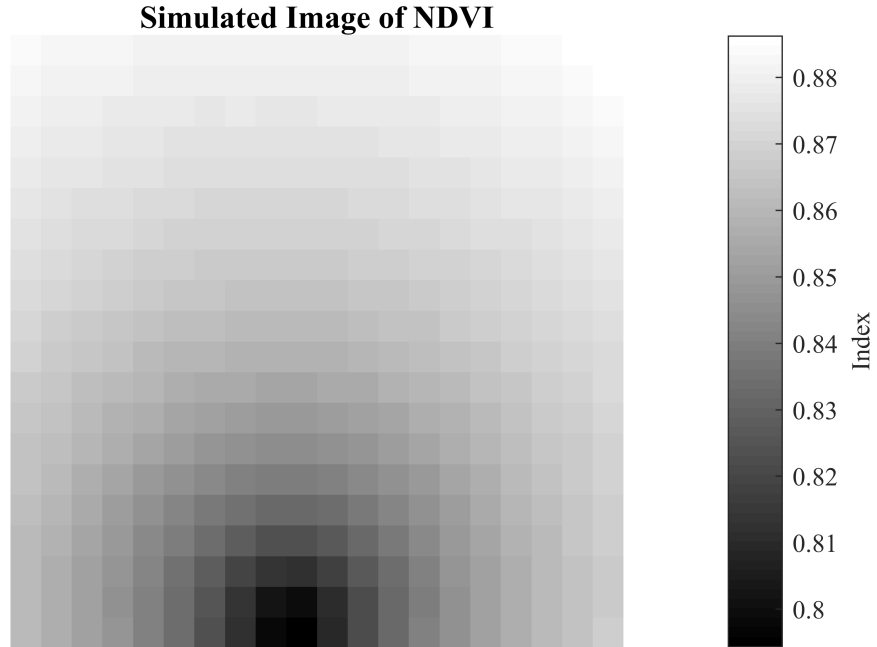


Figure 3.9: Simulated aerial image highlighting the effect of camera FOV on NDVI.

3.5.1 Analysis of Wide FOV

The effect of a wide FOV from a typical SUAS imaging payload can be readily seen in the analysis in the variation in reflectance and NDVI in the four simulation sets. Figures 3.7-3.9 depict the spatial variation at 680 nm (Figure 3.7), 800 nm (Figure 3.8), and the resulting NDVI (Figure 3.9). In the resulting simulated image, the NDVI varies by as much as 10%, with an apparent cold spot in NDVI occurring at the ‘hotspot’ or antisolar point at 680 nm and 800 nm. The wavelength variation manifests in this NDVI variation as previously seen in Figure 3.5. It is important to note that the cold spot seen in Figure 3.9 does not align with the zenith angle map used in the simulation, seen in Figure 3.10. In this case, simply utilizing vignetting corrections to correct the resulting NDVI is not appropriate.

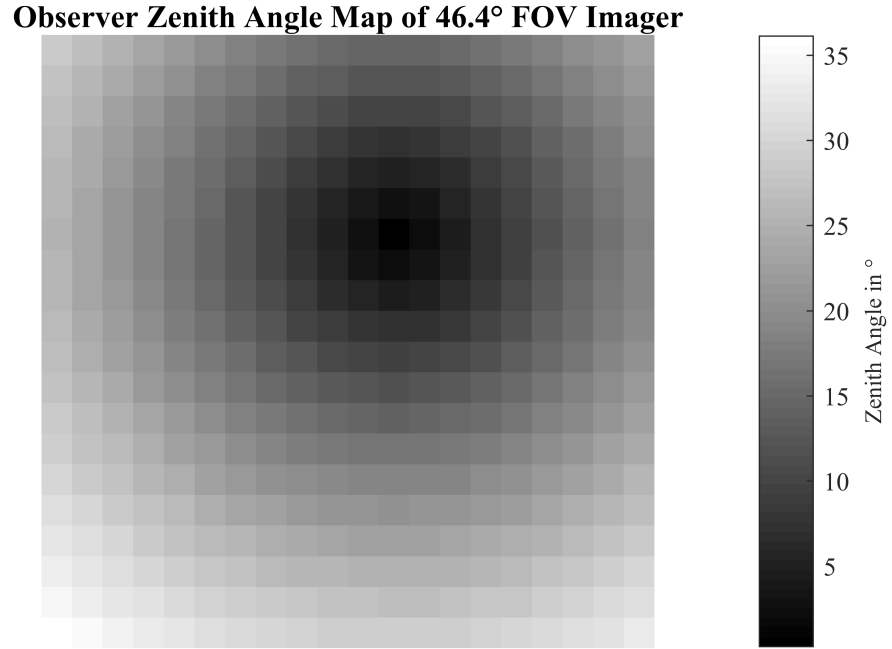


Figure 3.10: Simulated aerial image highlighting the effect of camera FOV.

The variation in reflectance is more pronounced in the other data sets. Table 3.2 depicts the variation in NDVI, as described using a Five-Number-Summary to describe the asymmetric spread: Min, 1st Quantile (Q1), Median, 3rd Quantile (Q3), and Max. It is evident that the introduction of camera FOV results in a different distribution in the calculations. This is apparent in the box plots of satellite imagery (Figure 3.11) and SUAS imagery (Figure 3.12).

Table 3.2: The variation of NDVI in the simulation sets due to wide FOV.

Satellite					
Sim	Min	Q1	Med	Q3	Max
Flat	0.8458	0.8458	0.8458	0.8458	0.8458
C_{ab}	0.8232	0.8426	0.8457	0.8479	0.8528
LAI	0.6558	0.8204	0.8443	0.8621	0.9001
C_{ab} +LAI	0.6573	0.8238	0.8451	0.8636	0.9074

Image					
Sim	Min	Q1	Med	Q3	Max
Flat	0.7902	0.8512	0.8636	0.8725	0.8874
C_{ab}	0.7870	0.8481	0.8607	0.8702	0.8941
LAI	0.6430	0.8300	0.8588	0.8782	0.9148
C_{ab} +LAI	0.6818	0.8322	0.8590	0.8778	0.9193

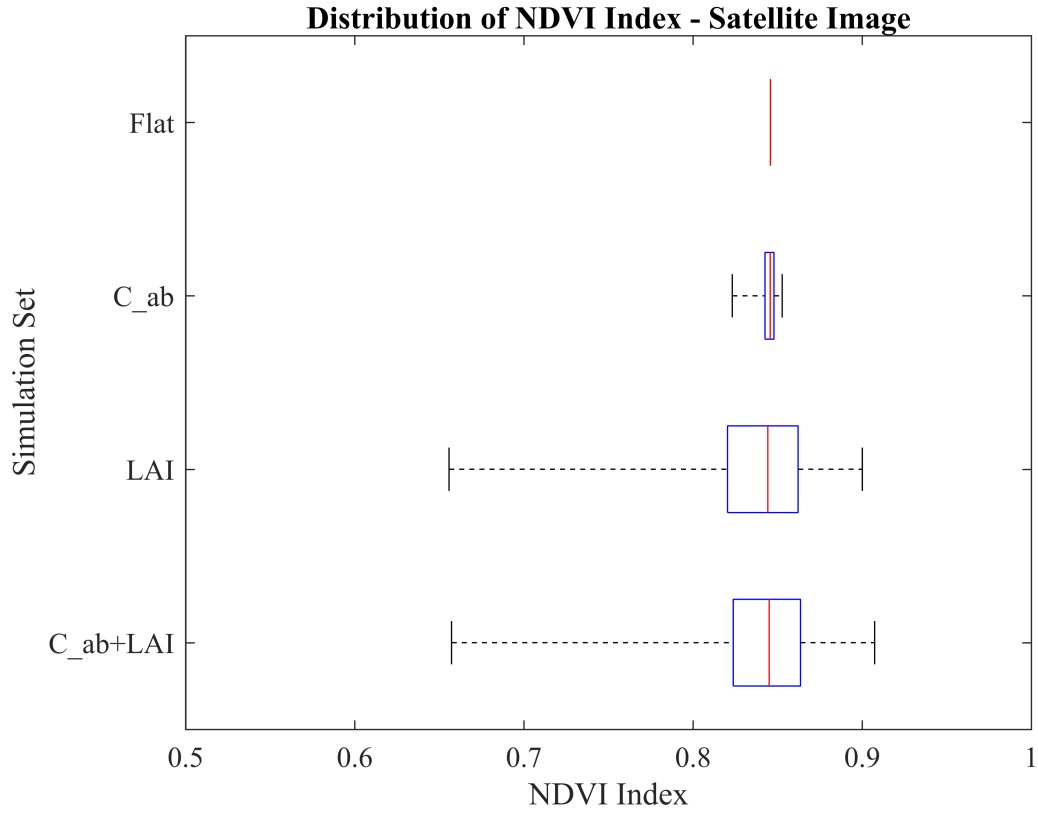


Figure 3.11: Distribution of NDVI from satellite imagery.

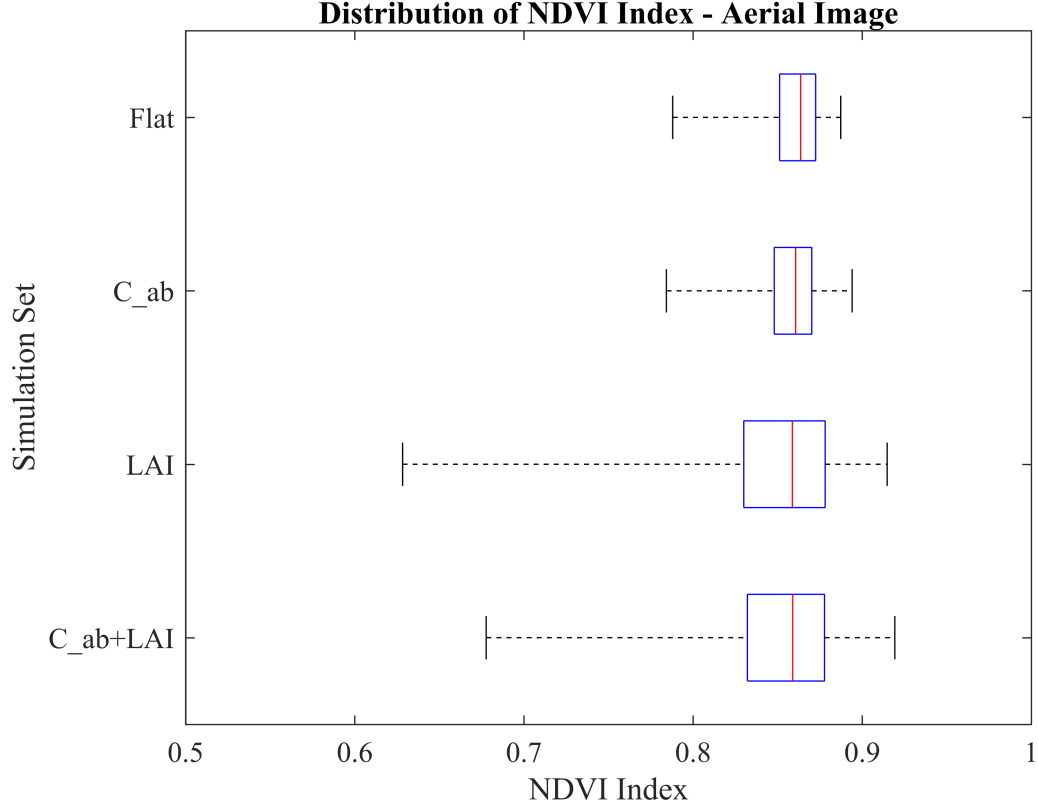


Figure 3.12: Distribution of NDVI from SUAS imagery.

Figures 3.13-3.15 depict the relationship between the simulated satellite imagery and simulated aerial imagery of the resulting calculation of NDVI. While the impact from a wide FOV did not significantly change the resulting NDVI relationship as seen in Figures 3.14 and 3.15, it introduced significant variability and error. Figure 3.13 depicts a significantly poorer performance, this may be attributed to the insensitive relationship between chlorophyll content and resulting NDVI as described in literature [41].

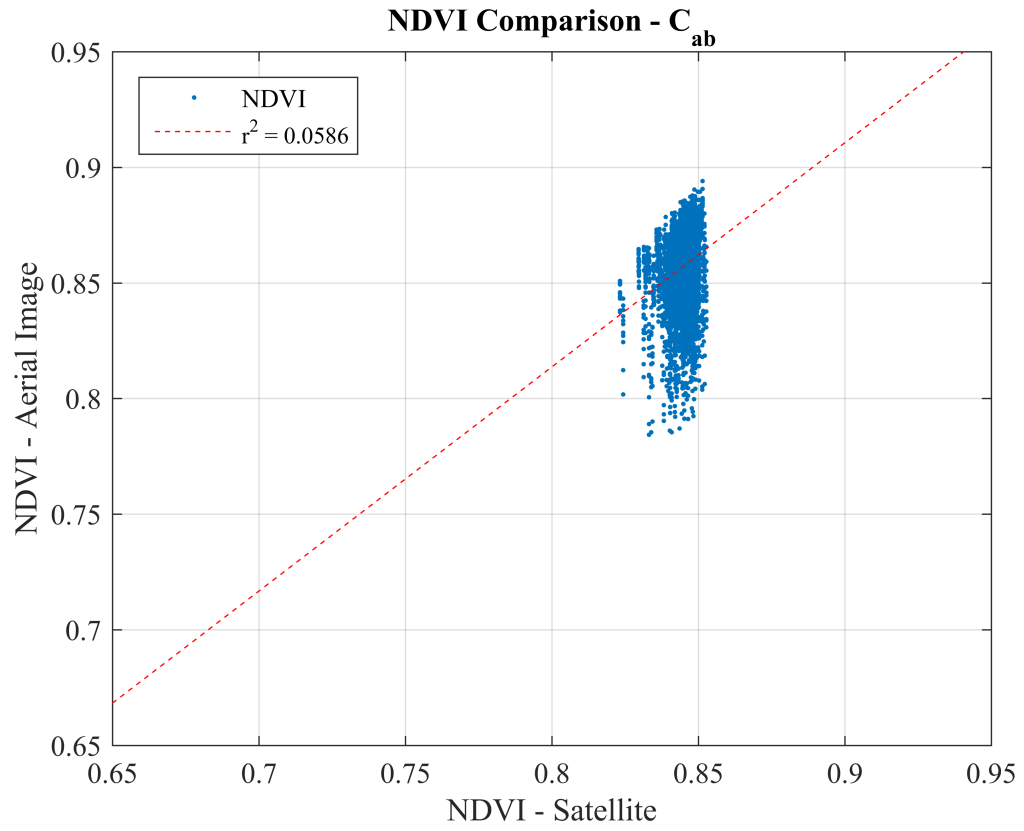


Figure 3.13: Comparison of satellite and SUAS calculations of NDVI - C_{ab} . When C_{ab} is varied, the source of error introduced by the wide FOV obscures the relationship with NDVI.

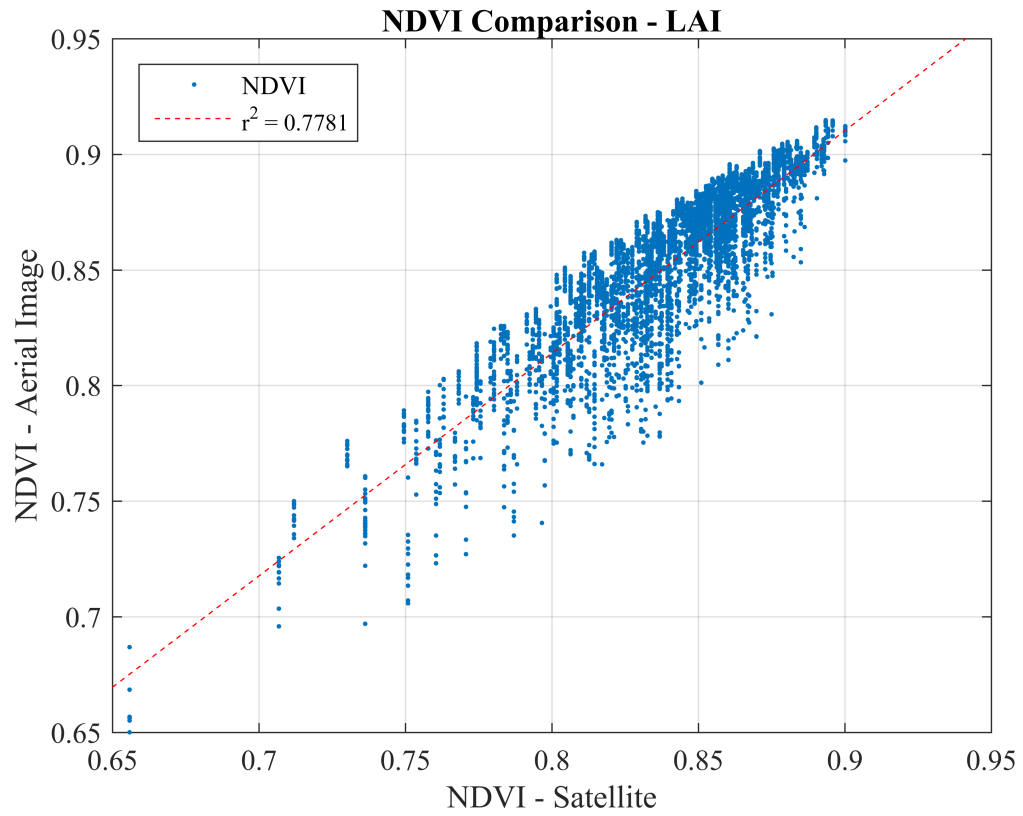


Figure 3.14: Comparison of satellite and SUAS calculations of NDVI - LAI. NDVI is more sensitive to changes in LAI and the wide FOV does not obscure the relationship.

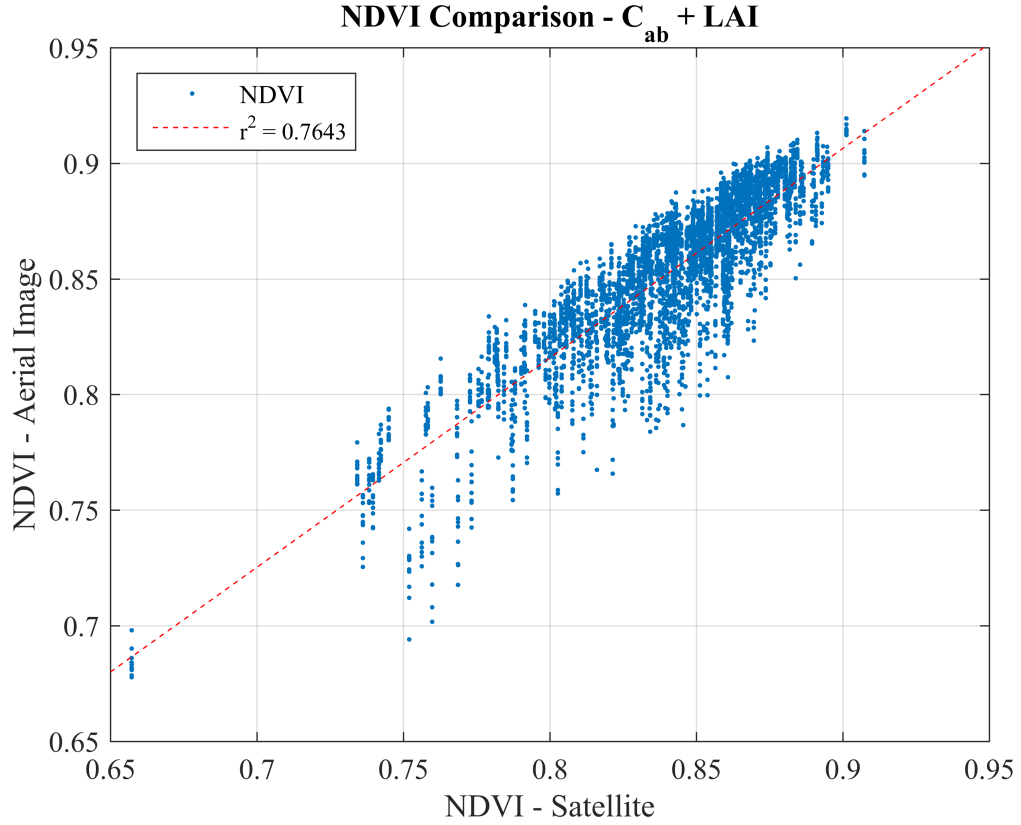


Figure 3.15: Comparison of satellite and SUAS calculations of NDVI - C_{ab} + LAI. The sensitivity of NDVI to changes in LAI masks the relationship with C_{ab} , however the introduction of error from a wide FOV is still significant.

The impact from a wide FOV can be more readily apparent when using NDVI with parameter inversion to predict biochemical properties. Figures 3.16, 3.17, and 3.18 depict the relationships between the C_{ab} , LAI and NDVI. As expected, the simulated satellite image depicts well-defined relationships, suitable for inversion. However, the simulated aerial imagery is much less defined though the relationship is coherent enough to be recognizable. In the case of LAI in the simulation set C_{ab} +LAI, the R^2 goodness of fit reduces from 0.9864 to 0.7476 in the presence of angular variations in reflectance introduced by a wide FOV.

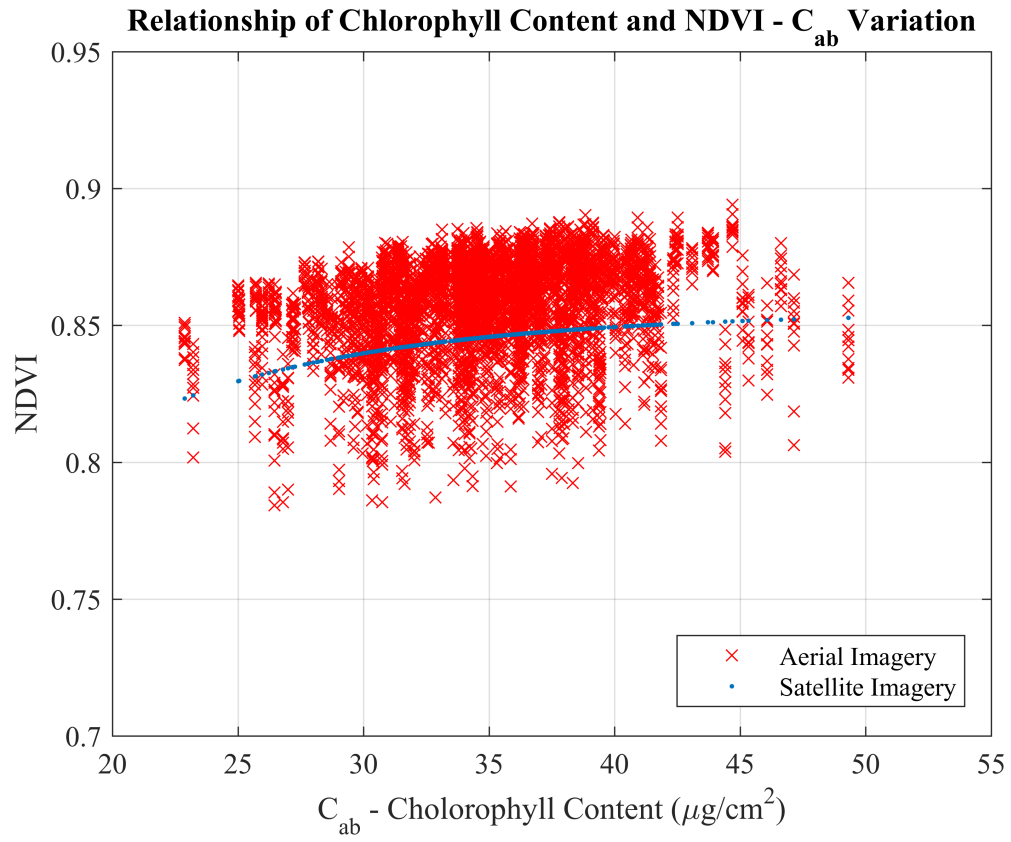


Figure 3.16: Comparison of satellite and SUAS relationships of C_{ab} and NDVI - C_{ab} variation. The relationship between C_{ab} and NDVI is easily obscured by the error introduced from a wide FOV.

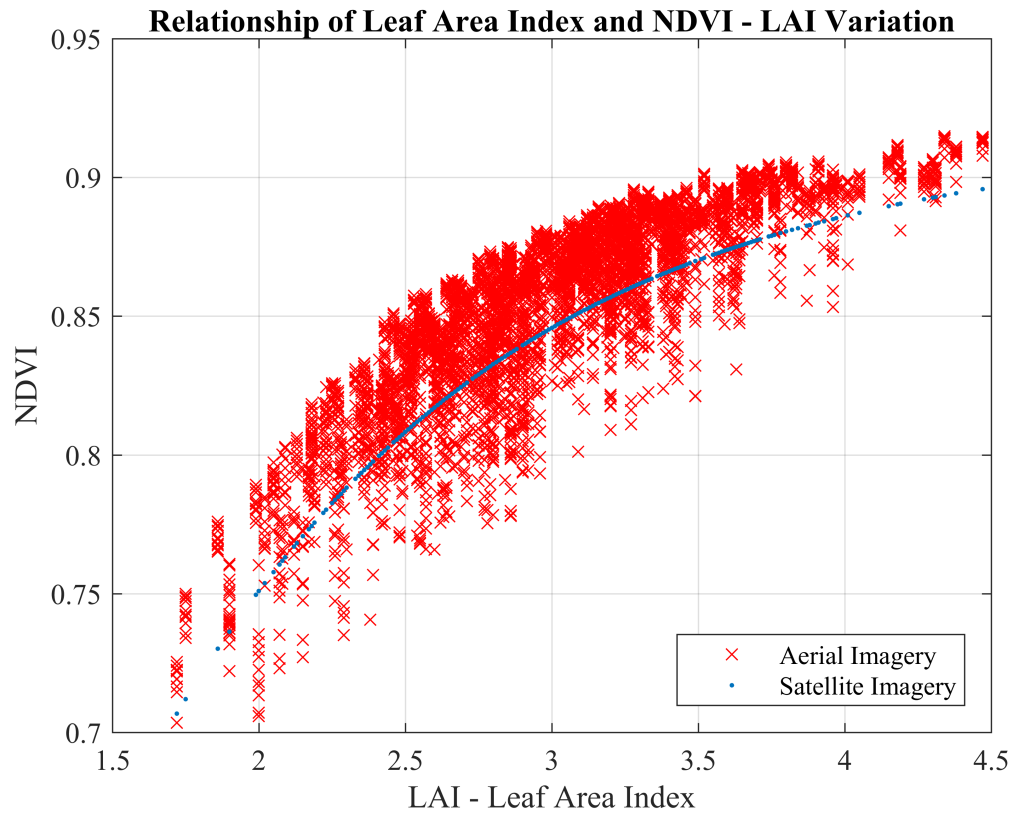


Figure 3.17: Comparison of satellite and SUAS relationships of LAI and NDVI - LAI variation. The relationship between LAI and NDVI is recognizable in the presence of a wide FOV, but with a noticeable loss of accuracy.

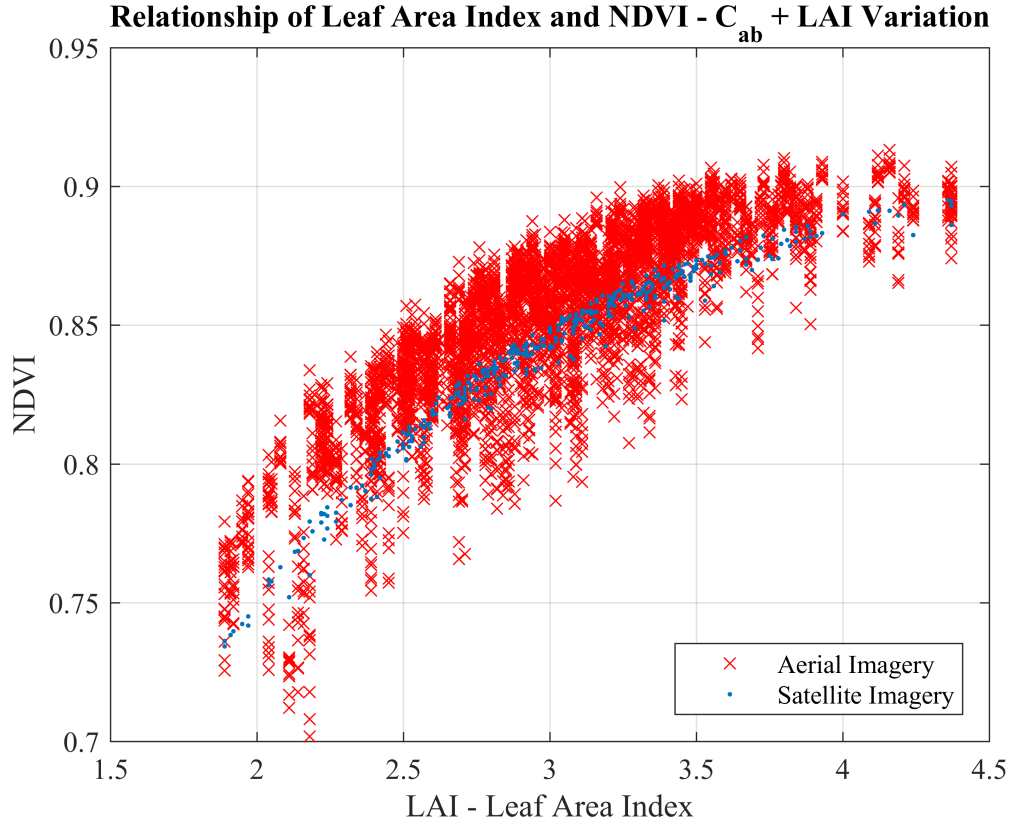


Figure 3.18: Comparison of satellite and SUAS relationships of LAI and NDVI - C_{ab} + LAI variation. The addition of a second variable (C_{ab}) slightly reduces the inversion accuracy, but not to the degree that the wide FOV does.

The effect of the angular variation in reflectance in wide FOV cameras clearly introduces error. In order to understand its implication for SUAS-based remote sensing, an analysis of the error is necessary to answer the question: At what FOV does the introduced error become significant?

This question is significantly more challenging to address. From the BRDF equation, it can be seen that the error is dependent on the angular variation of reflectance of the object of interest and the planar rotation of the object of interest. In the next set of calculations, the simulation visualized in Figure 3.15 (C_{ab} +LAI at solar noon) is analyzed as a function of FOV.

To identify the role of FOV on data accuracy, the mean error percentage between the reference satellite imagery and an increasing camera FOV is calculated (Figure 3.19). Within 5° , the mean error is close to 0%. At 12° , the error begins to rise linearly. As reference, the vertical FOV of several common cameras deployed

on SUAS are indicated. Though the TetraCam cameras have the narrowest FOV, they still introduce error.



Figure 3.19: Mean error between satellite imagery and an increasing camera FOV. Common camera vertical FOV are provided as reference.

The mean error percentage is not a completely accurate measure of fit. The distribution of error is skewed positively as the FOV increases (see Figure 3.9). The value of NDVI increases with the distance from the anti-solar point.

Another description of error is calculated as the change in goodness of fit between the reference satellite imagery and an increasing FOV as depicted in Figure 3.20. As many SUAS are calibrated using a two-point system (light target and dark target, based on known reference points), this correlation mimics the calibration of SUAS remote sensing data.

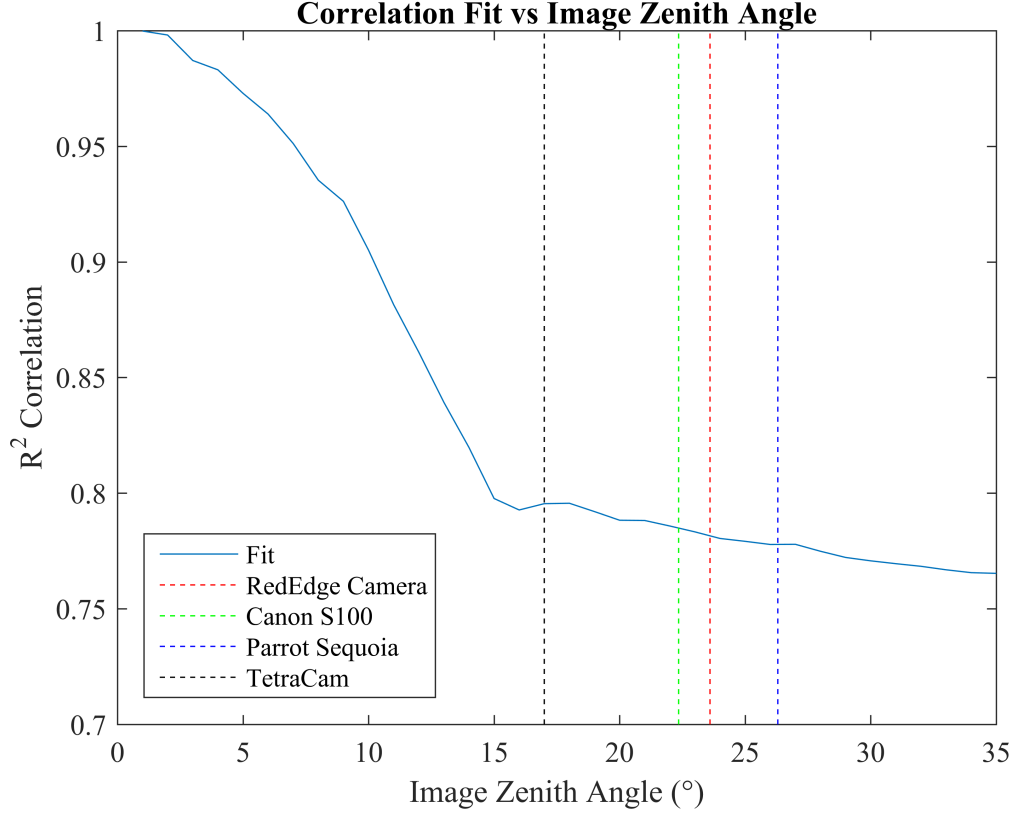


Figure 3.20: Correlation fit between satellite imagery and an increasing camera FOV. Common camera vertical FOV are provided as reference.

The goodness of fit R^2 correlation decreases as the camera FOV increases. It decreases significantly until 15° after which it decreases at a slower rate. This implies the FOV affects accuracy in calibration fit even under 5° , but after 15° the distribution of error does not significantly change, only its pixel count.

The effect of FOV can be traced further into the accuracy of parameter inversion. Figure 3.21 depicts the correlation of LAI and NDVI as simulated for satellite imagery, and aerial imagery with different FOV. When the aerial imagery FOV is under 5%, it closely follows the satellite imagery. However, when the FOV is expanded to 15%, the relationship degrades significantly (as implied by Figure 3.20). After $\text{FOV} > 15\%$, the relationship continues to degrade, but not as significantly.

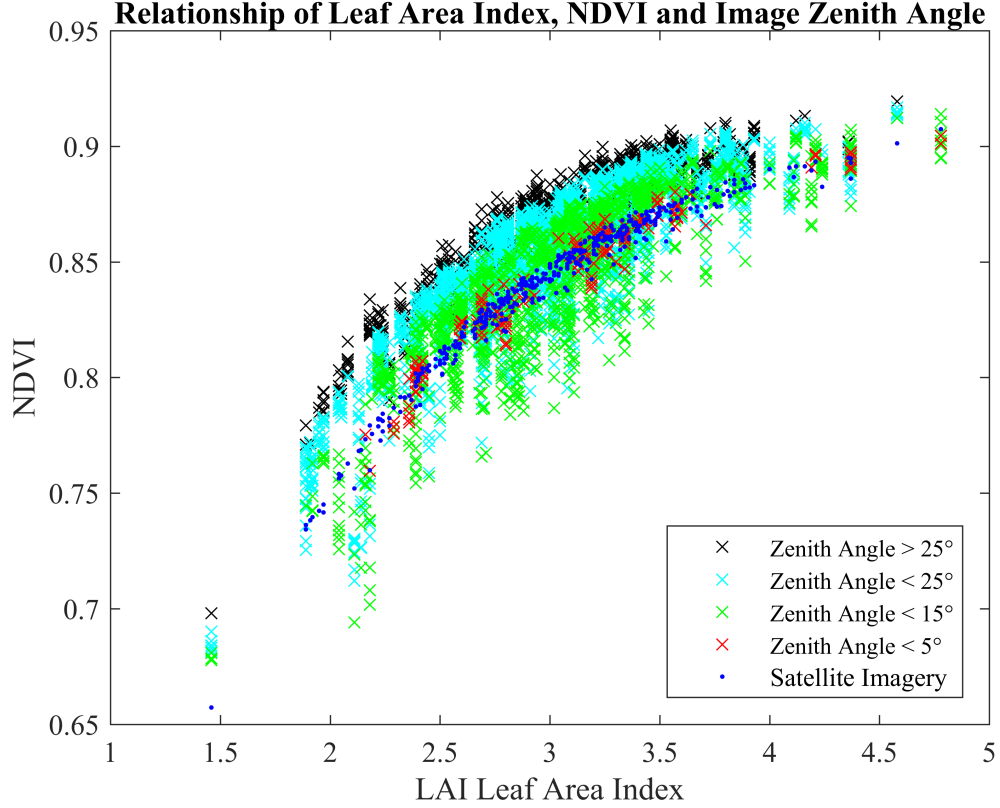


Figure 3.21: Comparison of satellite and SUAS relationships of LAI, NDVI and image zenith angle.

3.5.2 Analysis of Solar Motion

The effect of the solar motion during an SUAS flight or mission is shown to be significant but manageable. Across a whole day, the NDVI varies significantly as a function of the solar position. The set of four full-day simulations can be seen in Figures 3.22-3.25. In all four simulations, the NDVI varied from a maximum mean and minimal variance in the late afternoon to a minimum mean with a maximal variance around noon. The boxplots depict that the distributions have a spread as much as 25%. The added effect of the wide FOV is apparent in a comparison of the simulated aerial imagery and the simulated satellite imagery.

The variance throughout the day is significant and unrelated to solar intensity or albedo. The variation in reflectance is a function of solar illumination direction, as the solar irradiance and intensity was kept constant for the simulation sets. The result of this depicts that solar motion plays a significant role in data accuracy and should not be neglected.

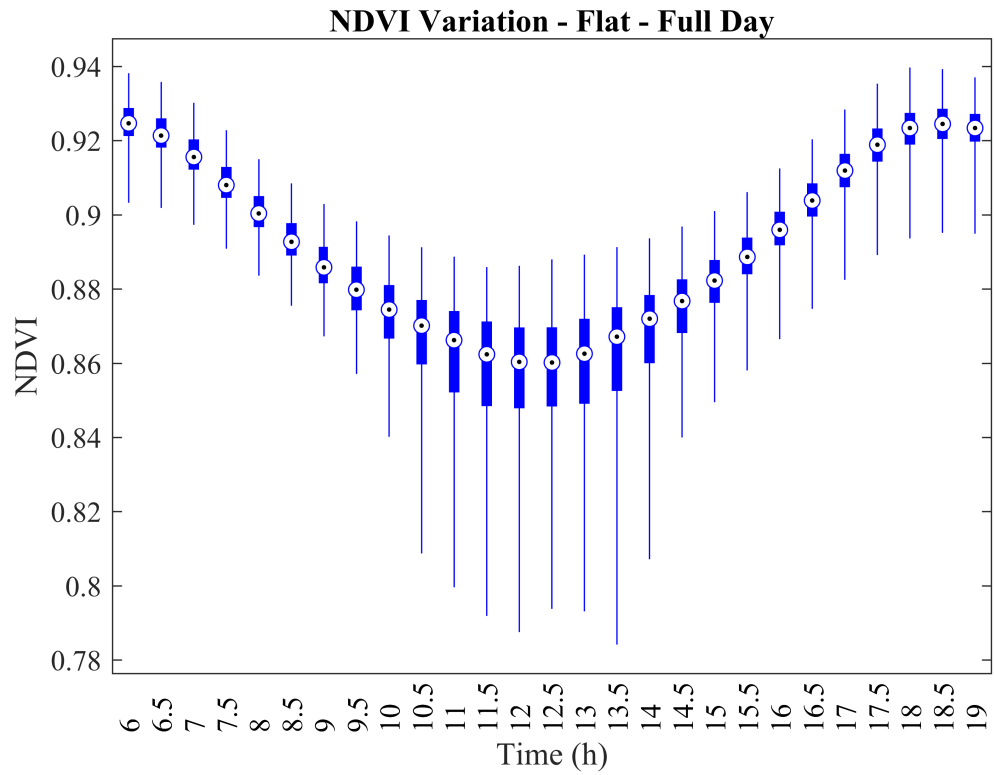


Figure 3.22: Variation in NDVI from an SUAS - Flat - Full Day. The variation is minimal throughout most of the day, until the sun reaches its apex around noon.

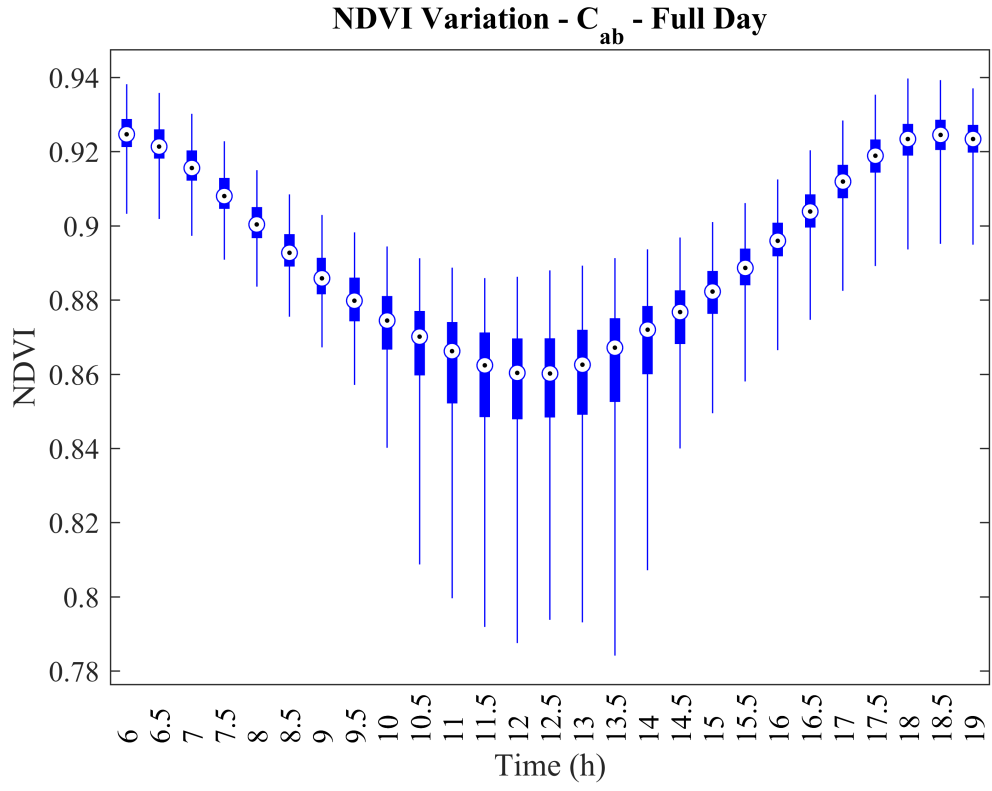


Figure 3.23: Variation in NDVI from an SUAS - C_{ab} - Full Day. Variations in C_{ab} has a minimal effect on NDVI but a similar dependence on solar motion is apparent.

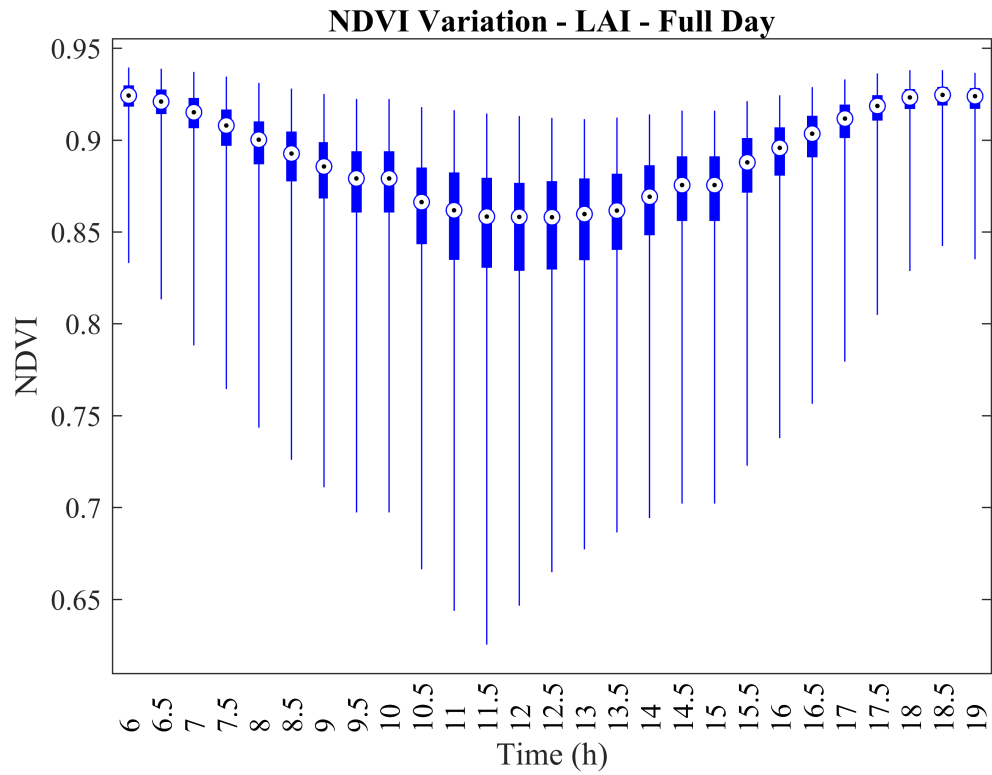


Figure 3.24: Variation in NDVI from an SUAS - LAI - Full Day. Variation in LAI has a larger effect on NDVI, but the time variance due to solar motion is clear.

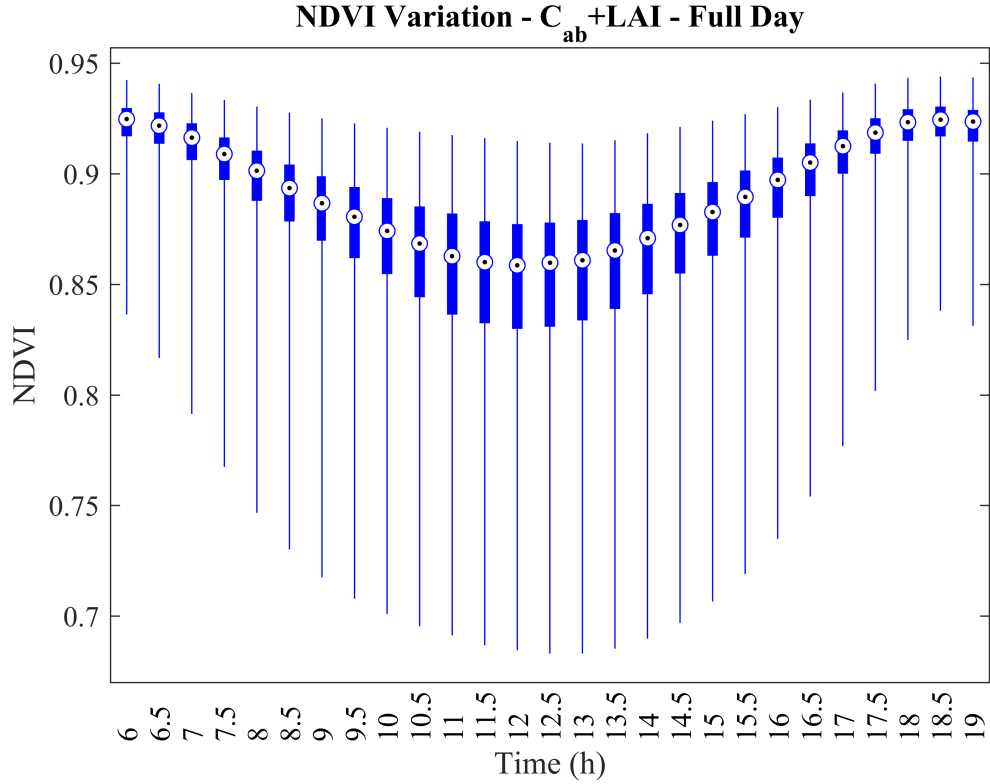


Figure 3.25: Variation in NDVI from an SUAS - C_{ab} + LAI - Full Day. The combination of both C_{ab} and LAI with solar motion and image FOV introduces a significant variance in NDVI.

The results from these simulations indicate that it is unsuitable to directly compare imagery from one time-span to another time-span without correction for both solar motion and image FOV.

The effect of solar motion significantly affects the accuracy of parameter inversion as well. Figs. 3.26 and 3.27 depict the relationship of C_{ab} and LAI respectively over the course of an entire day. As expected, the inversion of C_{ab} directly from NDVI is unfeasible given the variation in solar motion, even from the simulated satellite imagery. The inversion of leaf area index also suffers from poor performance, though the time variation from solar motion can be seen in the patterns of the relationship.

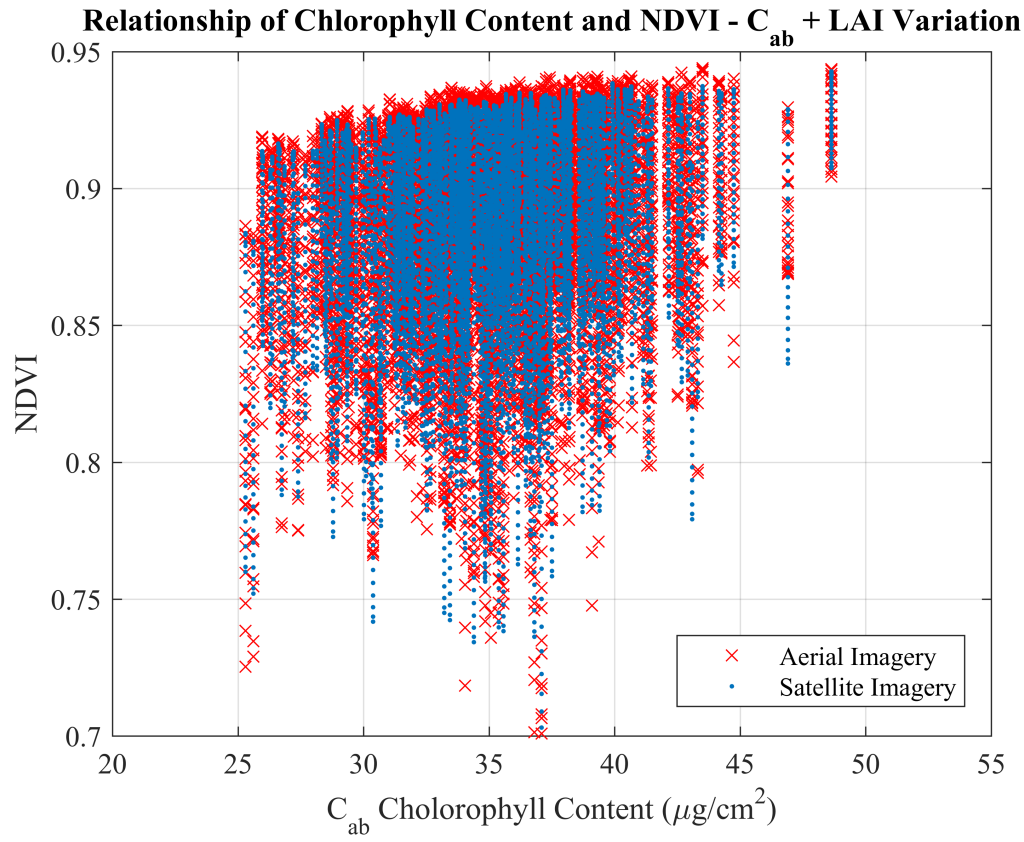


Figure 3.26: Relationship between C_{ab} and NDVI in satellite and SUAS imagery - Full Day. The relationship between C_{ab} and NDVI is obscured by noise from wide FOV and solar motion.

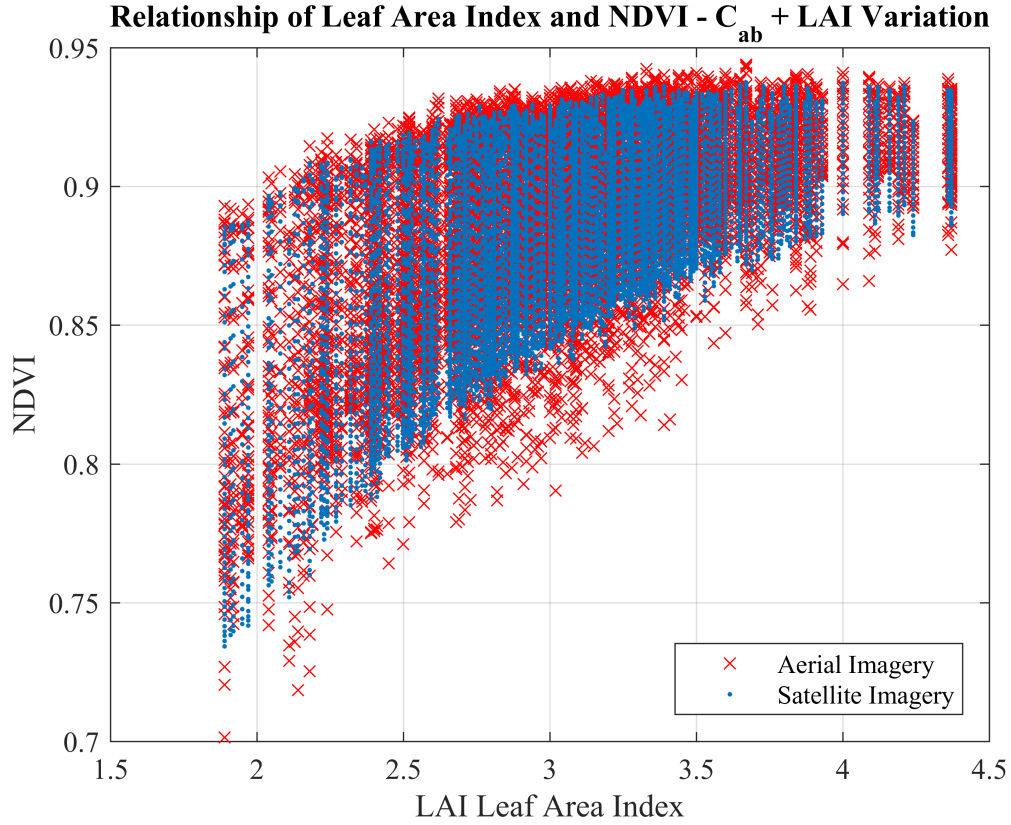


Figure 3.27: Relationship between LAI and NDVI in satellite and SUAS imagery - Full Day. The relationship between LAI and NDVI is visible, but the effect of solar motion introduces error in both simulated satellite and aerial imagery.

The results from the simulation over the course of an entire day depict the severe role that solar motion plays on remote sensing measurements. Special care should be taken when collecting aerial imagery over the course of an entire day, as is common when using an SUAS over a large area. Comparison across time-periods, even with accurate spectral sensor measurements, is subject to errors at top-of-canopy measurements.

In the final set of simulations, the variation in reflectance is evaluated within a 30-minute window, such as would be common in a short SUAS flight.

While the variation in solar motion is significant over the course of an entire day, the variation is nearly unnoticeable at both the morning and afternoon windows. Figs. 3.29 and 3.28 depict the variation within the images during their time windows, from the simulations with variance in both C_{ab} and LAI. The stability of the NDVI

measurements indicate that with a static solar intensity, the solar motion does not play a significant role in data errors.

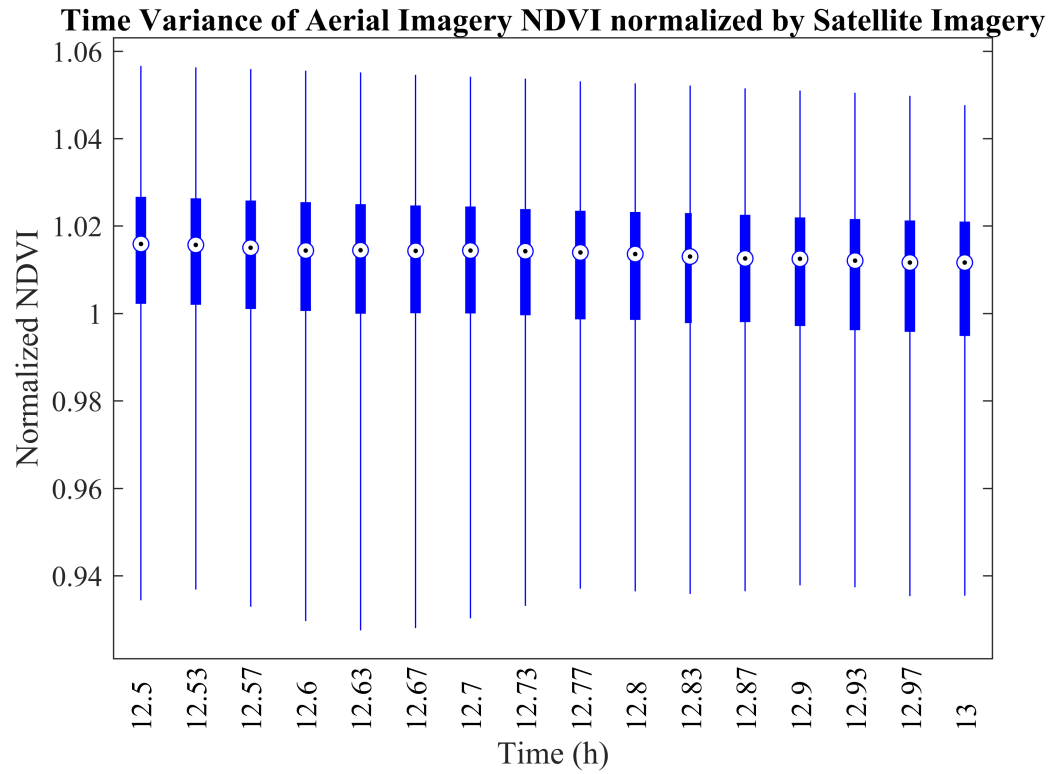


Figure 3.28: Boxplot of NDVI variance in the afternoon (12:30pm to 1:00pm).

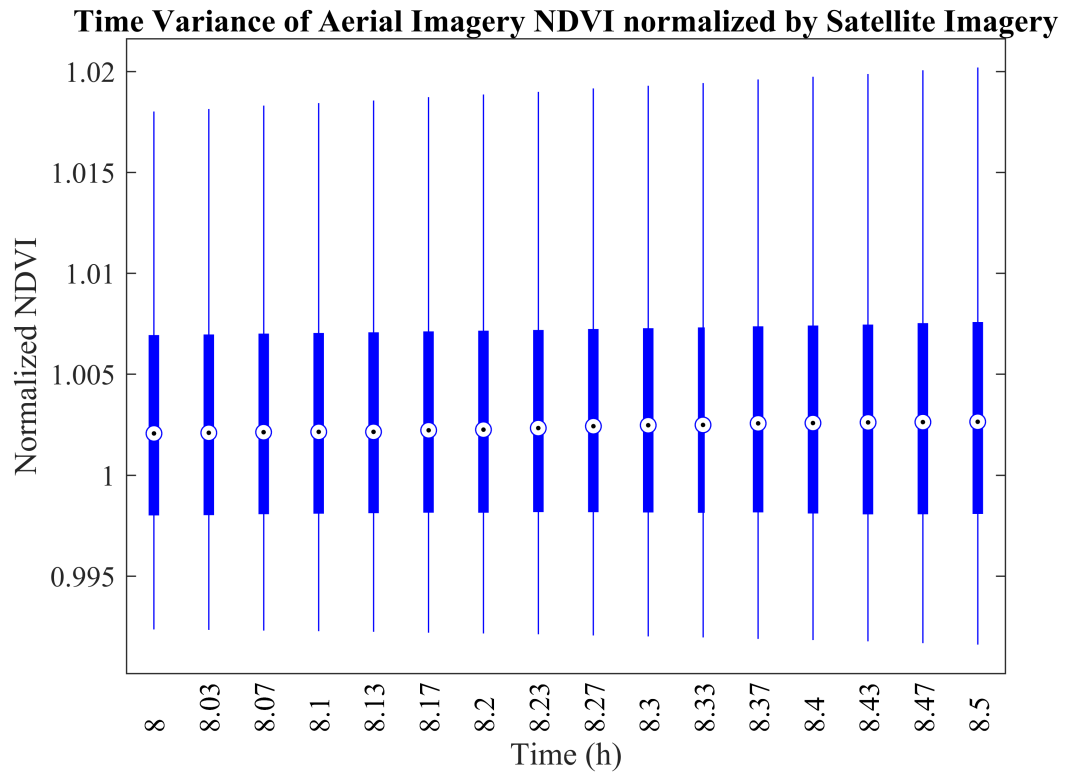


Figure 3.29: Boxplot of NDVI variance in the morning (8:00am to 8:30am).

While the boxplot depicts a stable response of NDVI during a 30-minute time-window, a closeup of the relationship of simulated satellite imagery and simulated aerial imagery depicts the variance and clear time dependence of reflectance measurements (Figure 3.30). Within a short time-window, these patterns may not play a significant role, but may become significant in larger time-windows.

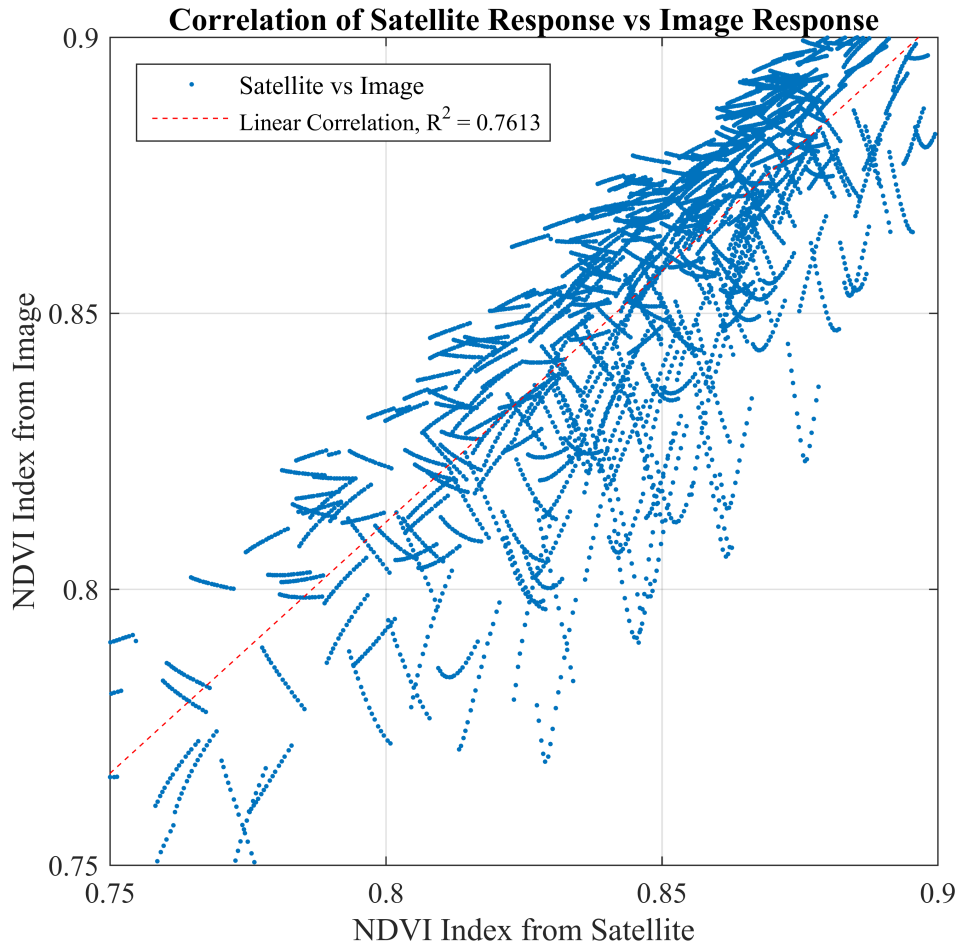


Figure 3.30: Variation in NDVI correlation over a 30 minute interval.

The results of these simulations indicate that solar motion can be a source of error for data collection across multiple time frames, whether it is within the same day or across several days or months. It must be noted that the solar intensity and solar spectrum was kept constant across the entire day. This mimics solar intensity and spectrum calibration which can be enabled by embedded luminosity sensors. It is clear then that solar intensity and spectrum calibration alone is insufficient in enabling long-term reliability and comparability.

3.6 Chapter Summary and Implications to SUAS Remote Sensing

The field of remote sensing with small unmanned aircraft systems is starting to grow, however, there remains significant questions over the accuracy and validity

of the data generated. SUASs can provide significant advantages over traditional satellite imagery, however, the validity of the data must be assessed. However, the results from these analyses have strong implications for future SUAS-based remote sensing.

- SUAS aerial imagery is only comparable to nadir satellite imagery within a narrow FOV. In this simulation set, only within a FOV of 5%.
- The errors due to a wide FOV camera introduce significant inaccuracies even assuming perfect lens calibration and spectral calibration. This propagates to difficulties in parameter inversion.
- SUAS aerial imagery taken across an entire day is subject to significant error due to solar motion, even if the imagery is calibrated to solar intensity and solar spectrum.
- SUAS aerial imagery taken across multiple days may not be comparable due to solar motion.
- SUAS aerial imagery can be comparable within a 30 minute window without significant error from solar motion.
- Straight down imagery to replicate satellite imagery may not be the most optimal use of an SUAS.

Chapter 4

OPTIMAL MULTISPECTRAL REMOTE SENSING FRAMEWORK FOR SMALL UNMANNED AIRCRAFT SYSTEMS

4.1 Introduction

In the development of an effective methodology for Small Unmanned Aircraft System (SUAS)-based remote sensing and analyzing sources of error from common SUAS payloads, it is evident that many techniques may be inefficient, or worse, inaccurate. Many strategies deploy an unmanned aircraft to collect as much data as possible like a satellite without a clear analysis of whether the data provides the ‘best’ data [8]. This raises the issue of how to conduct remote sensing with an SUAS in an optimal sense with regards to the data quality and constrained by technical or logistical limitations [9]. While previous literature has discussed the concept of reconfigurable multispectral data collection with multiple aircraft solutions [43], this still does not fully address the variety of data or the accuracy of the data that can be collected.

In the most general sense, the optimal remote sensing problem stems from the assumption that if an entity under investigation can be characterized by aggregate features such as shape, color, scale, or texture, then there must exist a measurement, range of measurements or set of measurements that provide the most complete representation of the entity. Then this measurement or set of measurements can be defined as the optimal measurement. In this chapter, a conceptual framework is presented for describing optimality as a function of spatial, spectral and temporal factors that provide the best representation.

The remainder of this section addresses the problem of remote sensing and the optimality criterion. Section 4.2 briefly discusses the optimality of spatial factors. The optimality of spectral factors is introduced in Section 4.3 with examples in the Short Wave Infrared (SWIR) spectrum. Section 4.4 investigates the optimality of temporal factors with an example method of optimizing data collection for vegetation analysis. Section 4.5 examines complex joint optimality in spatial, spectral and temporal factors with an application in roosting bird counts.

4.1.1 Optimality in Remote Sensing

As previously discussed, while SUAS-based remote sensing has many similarities with satellite-based remote sensing, there are many unique attributes, both positive and negative. In general, many characteristics in satellite-based remote sensing, such as resolution, spectral response and data collection rate, are static. However, with an SUAS, these may be tunable parameters. This level of customizability can potentially enhance the value of the data, such that it could be possible to collect ‘optimal’ measurements. As in any multi-variate problem, the solution relies on finding the ‘optimal’ set of parameters.

This problem can be formulated as described in [9]. Let $\Omega \subset R^2$ be any arbitrary polytrope defining the area of interest. A series of band density functions η_λ are defined as $\eta_\lambda(q, t) \in [0, \infty) \forall q \in \Omega$, defining the spectral response at any point q of size δ^2 in the region for a spectral wavelength λ , at any time t or bounded set of $t \in [t_1, t_2]$. The usefulness of a mapping from Ω to a given number of η_λ bands is dependent on the proper selection of spatial resolution δ , spectral bands $[\lambda_1, \lambda_2, \dots, \lambda_n]$, and time t .

4.1.2 Development of Optimization Criteria

If an entity can be represented in terms of aggregate features, characteristics, and scale, then there must exist a measurement that provides the ‘best’ representation. This optimality can be defined using the definition of remote sensing described in Section 4.1.1. By extension, there must exist some values of δ, λ , and t that provide the optimal η bands that provide the optimal representation of the entity of interest. It is then the goal of optimal remote sensing to obtain these factors to obtain the best representation given the constraints and limitations afforded by the platform.

Remote sensing optimality must be described with respect to the minimization of an optimality criterion and subject to the technical and physical constraints of the implementation. As described in [9], the minimization of an optimality criterion can be generically described by

$$\min_{u \in \mathcal{U}} J = \left| \frac{\text{cost}(x, u)}{\text{performance}(x, u)} \right| + \phi[x_0, u_0] \quad (4.1)$$

where $\text{cost}(x, u)$ and $\text{performance}(x, u)$ are some arbitrary cost and performance function of SUAS remote sensing at state x , and input u . The state x includes, but is not limited to the aircraft position or other internal states related to the payload and the environment. The set $\mathcal{U}$ contains, but is not limited to the parameters listed in Table 4.1, and $\phi[x_0, u_0]$ describe initial or boundary conditions at state x_0 and initial parameters u_0 .

Table 4.1: Optimality criterion arguments.

Flight Parameters	Sensor	Environmental
Flight Alt. (h)	Resolution. (P)	Time of Flight
Flight Spacing	Pixel Pitch (PP)	Duration of Flight
Overlap %	Pixel Size (PS)	Scale of Interest
Airspeed	Focal Length (F)	Reflectance Response
Flight Patterns	Interval t_{sensor}	Environmental Dynamics
Overlap %	Spectral Sensitivity	Weather Conditions

The optimal remote sensing control law π then satisfies

$$\pi = \arg \min_{u \in \mathcal{U}} \left\{ \left| \frac{cost(x, u)}{performance(x, u)} \right| + \phi[x_0, u_0] \right\} \quad (4.2)$$

However, there is no uniqueness to the control law solution. The minimum in the optimal remote sensing may be achieved for multiple arguments in set $\mathcal{U}$. Thus, there may exist multiple solutions for an optimal remote sensing operation.

In order to understand the optimality in terms of δ, λ , and t , $cost(x, u)$ is described as a weighted product of $cost_\delta$, $cost_\lambda$, and $cost_t$ for a given value of δ, λ , and t . This can be represented as

$$cost(x, u) = \prod_{i \in [\delta, \lambda, t]} \alpha_i \cdot cost_i(x, u) \quad (4.3)$$

where α_i is an arbitrary weight specified by the remote sensing application. Likewise, $performance(x, u)$ can be described as

$$performance(x, u) = \prod_{i \in [\delta, \lambda, t]} \alpha_i \cdot performance_i(x, u) \quad (4.4)$$

The minimization equation can be rewritten as

$$\min_{u \in \mathcal{U}} J = \prod_{i \in [\delta, \lambda, t]} \left| \frac{\alpha_i \cdot cost_i(x, u)}{performance_i(x, u)} \right| + \phi[x_0, u_0] \quad (4.5)$$

It can be seen that (4.5) may be rewritten as some function of δ, λ , and t within the solution space $S(\delta, \lambda, t)$, such that for a solution space $J(x, u)$ there exists a mapping T where $T : J(x, u) \leftrightarrow S(\delta, \lambda, t)$.

4.2 Spatial Optimization

In remote sensing imagery, the spatial sampling scale is a fundamental aspect to analysis as well described in literature [113]. Simply put, if an object can be characterized by visible features, then there must exist some optimal spatial resolution at which corresponds to the scale and aggregation level characteristic of the geographical entity of interest. This definition and corresponding methodology, requires the need for a predefined geographical entity of interest and *a priori* identification of the aggregate data that optimally defines the entity of interest. This is not a trivial step, and is key to a sufficient SUAS-based remote sensing methodology [26]. In this section, spatial optimization is discussed in general sense and is focused on the balance between spatial resolution and flight characteristics.

4.2.1 Image Resolution

While higher spatial resolution may always be preferred, there are many associated costs. Unlike a satellite, an SUAS has the ability to maneuver to a desired altitude to affect spatial resolution or the sensor focal length could be adjusted to provide a chosen spatial resolution. In general, the spatial resolution, or ground sampling distance (GSD) is a function of the image footprint (FP) and sensor resolution (P), and is given by

$$GSD = \frac{FP}{P} \quad (4.6)$$

where FP is given by

$$FP = \frac{h \cdot PP \cdot PS}{F} \quad (4.7)$$

where h is the flight altitude above ground level, PP is the sensor's pixel pitch, PS is the sensor's pixel size, and F is the sensor's focal length. Boundary conditions typically constrain the set of sensor parameters (P, PS, PP, F) given a limited number of available sensors and technology.

However, as flight altitude decreases, so does the image footprint FP which may impact total flight coverage given a finite flight endurance, necessitating a need to optimize. The following set of equations (4.8-4.11) can be used as constraining equations during optimization to describe the flight spacing (S), Mission Time (MT), Max Area (A_{max}), or Max Airspeed (v_{max}) of an SUAS flying a grid pattern for a given set of parameters of the sensor and desired performance:

$$spacing = FP \cdot (1 - overlap) \quad (4.8)$$

$$MissionTime = time_{track} \cdot n_{tracks} \quad (4.9)$$

$$MaxArea = v \cdot spacing \cdot MT \quad (4.10)$$

$$MaxAirspeed = \frac{FP_{vert} \cdot (1 - overlap)}{t_{sensor}} \quad (4.11)$$

where *spacing* is the spacing between parallel flight tracks, *overlap* is the desired image overlap percentage, $time_{track}$ is the flight time per track, n_{tracks} is the number of flight tracks needed to cover an area, v is the SUAS's airspeed, and t_{sensor} is the sensor's set imaging interval.

The optimization is most commonly described as a balance between resolution and coverage area given a finite flight duration. Other factors may play a role, as *a priori* known spatial resolutions can dictate sensor requirements and require balance between flight altitude and coverage. In practice, aircraft constraints play a significant role in the set of solutions.

4.2.2 Identification of the Object of Interest

Determining a suitable spatial resolution is often straightforward. Existing literature addresses image quality requirements for a variety of types of object recognition or other computer vision algorithms [8]. In many cases, the highest possible resolution is often preferred, however this may not always be necessary.

In a simple scenario, an SUAS can be deployed to count the number of canopies in a farm. The typical size of each tree canopy is known *a priori* at approximately 60 cm in diameter. Accurate tree canopy counts may be possible with resolution as coarse as 20 cm, but automated segmentation algorithms may perform significantly better at higher resolutions. The optimal resolution may be defined as the resolution that provides the highest resolution while covering the full entirety of the farm. While the problem is still a spatial resolution optimization, the optimization criteria can be reduced to the maximizing of the coverage area with respect to the finite flight duration.

4.3 Spectral Optimization

Spectral optimization follows a similar set of characteristics as spatial optimization. If there exists spectral characteristics that can uniquely define an object, then there must exist an optimal set of spectral responses, defined by their spectral resolutions to view the spectral characteristics. As with spatial resolution, there are methodologies presented in literature to define optimal spectral resolutions and optimal spectral measurements [41, 114, 115]. Much like spatial optimization, spectral optimization is related to the spectral separability of the desired entity of interest and the minimization of perturbing features of external factors such as atmospheric disturbance and soil reflectance.

4.3.1 Spectral Sensitivity

An understanding of spectral sensitivity is an important quality for proper measurement of reflected radiation. For optical imaging systems, a simplified model of the measured light radiation for each channel or band can be described as the integration of the camera's sensitivity, scene illumination and the scene's reflectance over the spectral range as described in [8],

$$I_{k,x} = \int_{\lambda_{min}}^{\lambda_{max}} C_k(\lambda) L(\lambda) R_x(\lambda) d\lambda \quad (4.12)$$

where k is a channel, x is a spatial position, I is the measured intensity, $C_k(\lambda)$ is the imager sensitivity for band k , $L(\lambda)$ is the spectral power distribution of the illuminate, and $R_x(\lambda)$ is the spatial reflectance of point x . The $C_k(\lambda)$ of the imager sensitivity can be measured or estimated through a variety of means [116]. The illumination can be measured or estimated with existing solar models. The goal for most analysis application involves solving for $R_x(\lambda)$ given $I_{k,x}$, which is a challenge due to the low intrinsic dimensionality. However, the solution for $R_x(\lambda)$ can be approximated when the camera sensitivity is sufficiently narrow, as with multispectral or hyperspectral imaging sensors.

When the channels or bands are not sufficiently narrow, a common solution utilizes colored panels or objects with a known spectral response. To calibrate for scene illumination, in situ measurements either concurrently with the imagery or immediately prior or after are used [117]. The calibration of the imager with known reflectance values ensures an accurate ratio between bands, rather than accurate radiation measurements.

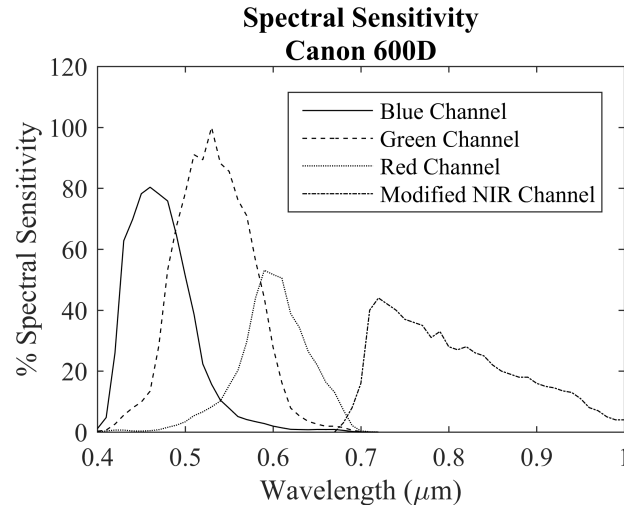


Figure 4.1: Spectral sensitivity for a Canon 600D Camera. Modified NIR channel on a second camera. Data courtesy of [116].

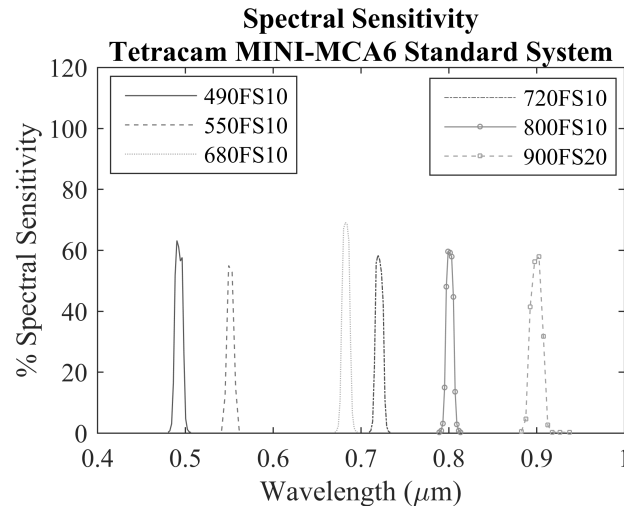


Figure 4.2: Spectral sensitivity of standard filters of a Tetracam MINI-MCA6 Standard System. Data courtesy of [66].

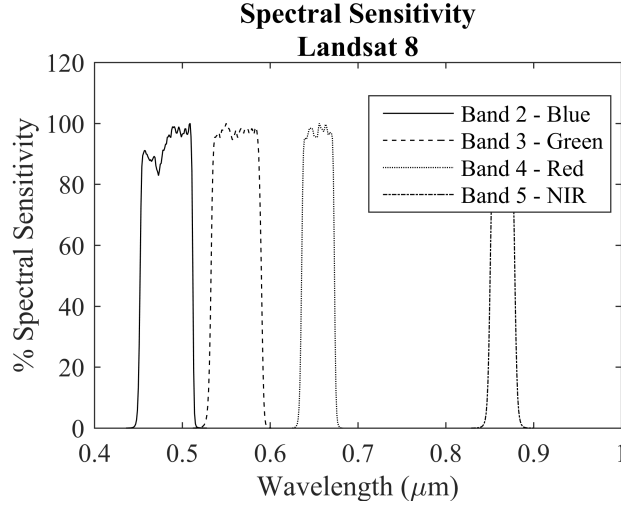


Figure 4.3: Spectral sensitivity of Landsat 8. Data courtesy of [99].

Although the intended effect of calibrated imagers is to provide satellite-like measurements of particular wavelengths, in practice the differences in spectral sensitivity of the imagers pose a challenge for a unified dataset. The following plots of the spectral sensitivity of a Canon 600D digital camera (Figure 4.1), Tetracam miniDC6 (Figure 4.2) and the Landsat 8 Satellite (Figure 4.3) depict the significant variation. For common calculations such as NDVI, the differences in spectral sensitivities of the imaging systems can have significant differences in the final calculations even with satellite systems [45]. As these differences play a large role in the accuracy of the data, care should be taken in the proper selection of the sensor sensitivity to the desired data goal.

It can be seen that from Chapter 3, that the simplified model is an incomplete view as it neglects the angular variation in reflectance which is found in both imager field of view (FOV) and solar motion. The simplified model also neglects the time-variance of solar spectral illumination.

4.3.2 Measurements of Spectral Response

As in spatial optimization, *a priori* knowledge of the spectrum of the entity of interest is required. Many relationships of biophysical properties and spectral reflectances have been identified in literature, and many vegetation indices (VIs) have been developed as a result [41], utilizing a wide array of different spectral wavelengths. Four common VIs can be found in Table 4.2, where the number specifies the central spectral wavelength in μm . The Δ signifies the variability within the λ bandwidth that may be a tunable parameter.

Table 4.2: Common Vegetation Indices.

Indices	Formula
Normalized Difference Vegetation Index (NDVI)	$\frac{\rho_{(800+\Delta)} - \rho_{(680+\Delta)}}{\rho_{(800+\Delta)} + \rho_{(680+\Delta)}}$
Green NDVI	$\frac{\rho_{(800+\Delta)} - \rho_{(550+\Delta)}}{\rho_{(800+\Delta)} + \rho_{(550+\Delta)}}$
Normalized Difference Water Index (NDWI)	$\frac{\rho_{(980+\Delta)} - \rho_{(1240+\Delta)}}{\rho_{(980+\Delta)} + \rho_{(1240+\Delta)}}$
Photochemical reflectance index (PRI)	$\frac{\rho_{570} - \rho_{531}}{\rho_{570} + \rho_{531}}$

The most common vegetation indices utilize the response in the red and near-infrared regions of the spectrum. As discussed in Chapter 2, the sharp difference in reflectance between the two spectrums in vegetation is significant compared to the gradual spectral variation in soil or dead grass. These relationships form the basis of optimal spectral remote sensing, especially realized in the form of narrow-band vegetation indices [41].

However, unlike spatial optimization, spectral optimization has a limited number of degrees of freedom. Commercially available off-the-shelf cameras collect broadband measurements in three channels that obscure fine spectral details. Recently, scientific imagers have been developed for SUAS to mimic the effect of satellite measurements, however many suffer from limited spectral band options. Hyperspectral imagers, such that are needed for narrow-band indices, are not readily available for SUASs due to their cost and weight. In this aspect, spectral optimization may be temporarily limited by technological boundary conditions. However, physical boundary conditions, such as the limitations of analysis techniques for certain vegetation biophysical properties are more difficult to address and to optimize.

4.3.3 Use of Shortwave Infrared as an Optimal Spectral Solution

The use of SWIR imagers for SUAS applications is relatively unexplored and few applications have been documented. However, SWIR provides additional available spectrums for optimal spectral optimization. In particular, two specific potential applications will be discussed that highlight the unique capabilities of SWIR: soil moisture measurements and shallow vernal pool identification and analysis.

4.3.3.1 Soil Moisture Measurements

Recently, as much as forty-six percent of California has been classified as in an exceptional drought. As water conservation becomes ever more important in the state, agricultural regions will need to be as efficient as possible with resource

allocation. To improve water conservation efforts, wide-scale water usage monitoring is necessary with sufficient spatial resolution. The use of an SUAS with an SWIR imaging system is one of the many methods proposed to provide the necessary monitoring [6].

Moisture effects on soil reflectance in the SWIR spectrum has been well documented with spectrometers in laboratory settings. Within the visual spectrum, wet soil reflects significantly less light than dry soil, a process that is both familiar and well-studied. However, measurements of soil moisture is difficult in this range as the amount of light reflected does not vary after some level of moisture, usually within 1-2 of volumetric water content. The reflectance response to varying levels of soil moisture begins to exhibit larger separation in the Near Infrared (NIR) and SWIR range. Previous studies have identified an exponential model relating soil moisture and reflectance [118],

$$R = R_{sat} + (R_{dry} - R_{sat}) \times \exp(-c \times wc) \quad (4.13)$$

where R_{sat} is the reflectance of saturated soil, R_{dry} is the reflectance of dry soil, c describes the rate of change because of soil moisture, wc is the water content (expressed as volumetric content) and all values are wavelength dependent.



Figure 4.4: Example image of soil moisture data collection.

The model from Equation 4.13 can be shown to be valid with SWIR images in addition to hyperspectral measurements. In [6], 10 cups were filled with sand and mixed with distilled water (Figure 4.4). Water content was measured by volume at 2%, 5%, 8%, 11% and 15%. The set of soil samples were imaged with an SWIR imager with a full spectrum lens referred to as broadband (sensitivity between 900 nm to 1700 nm), a 1100nm lens with a bandwidth of 12 nm and a 1600 nm lens with bandwidth of 50 nm. Soil samples were intentionally not smoothed to simulate real-world conditions. Radiometric calibration was accomplished with a National Institute of Standards and Technology (NIST) calibrated white panel from LabSphere [119] and distilled water as the black body. Using the full spectrum of an SWIR imager (broadband) resulted in the highest nonlinearity, whereas the use of the 1600 nm centered bandpass lens resulted in the most linear relationship (Figure 4.5). All three lenses resulted in an R^2 fit to the described model above 0.9. The result of this experiment validated the use of the previously described model (4.13) and validated the use of 1600 nm centered bandpass filter as the filter that would provide the most linear response to soil moisture as a function of volumetric content.

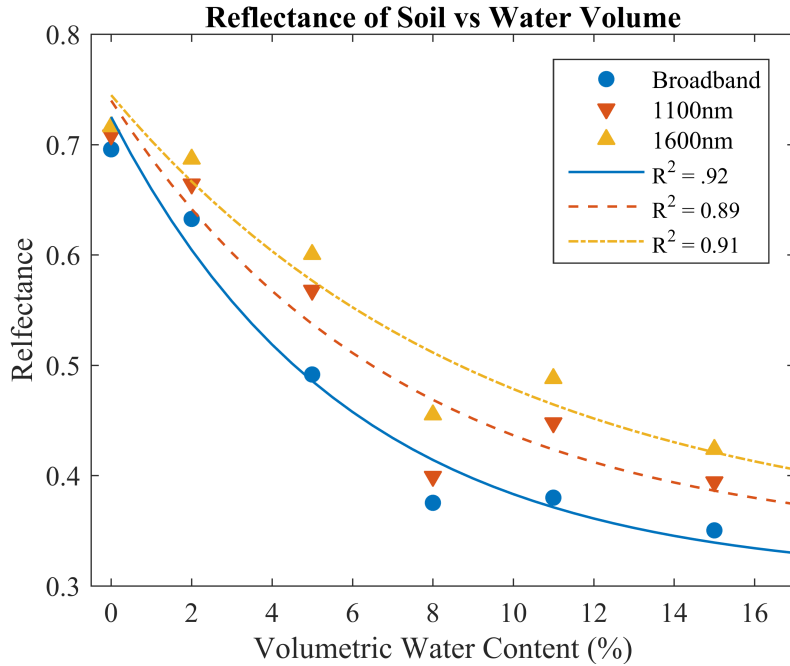


Figure 4.5: Reflectance of soil in SWIR as a function of water volume comparing three lens configurations. Reflectance measurements depict a more linear relationship when using a bandpass filter lens with a center wavelength at 1600 nm.

Future SUAS missions could combine ground truth measurements of top soil

moisture with SWIR aerial imagery to validate the use of the described model for soil moisture estimation. While this application would only be effective when the soil is bare and when looking at the top layer of soil, the information would be valuable for understanding the hydrological connectivity in semi-arid environments, where many rare and endangered species of flora and fauna congregate.

4.3.3.2 Vernal Pool Identification and Analysis

In Central California, brief seasonal rain occasionally concentrates forming what is known as vernal pools. These vernal pools are critical complexes teaming with unique endemic flora and fauna. Some of these pools may only be several centimeters deep and exist for a brief week, but are a valuable ecological resource. Within Central California, the majority of the original vernal pool habitats have been destroyed through farming and urban development. Ecological monitoring and conservation of vernal pools are critical for maintaining this part of the California ecosystem. The monitoring of ecosystem properties in these ephemeral habitats requires high spatial resolution and high temporal frequency sensing. Traditional approaches to remote sensing fail in these systems because the identifying features are too small or change too rapidly. The use of SUASs have the potential to both provide the high spatial resolution and the high temporal resolution to both identify and quantify these vernal pools [6].

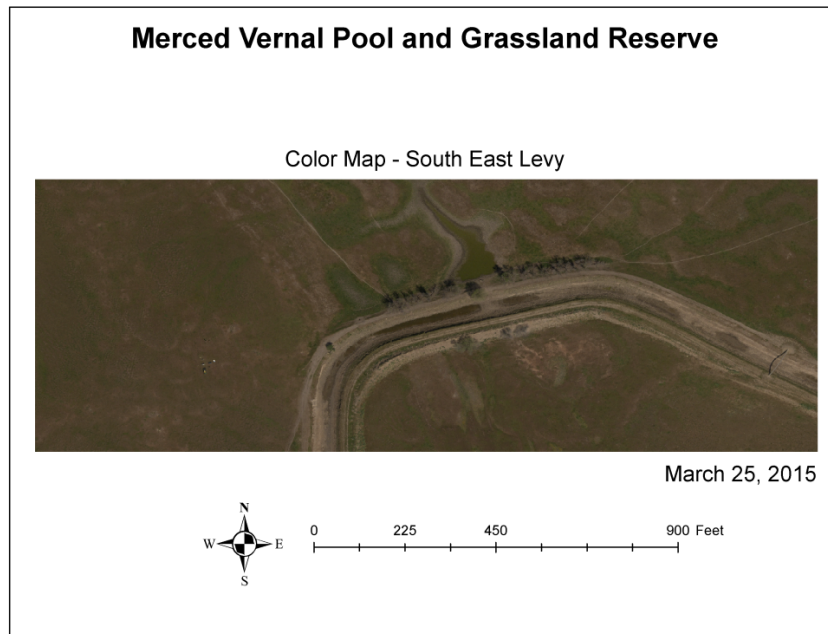


Figure 4.6: Orthomosaic in color.

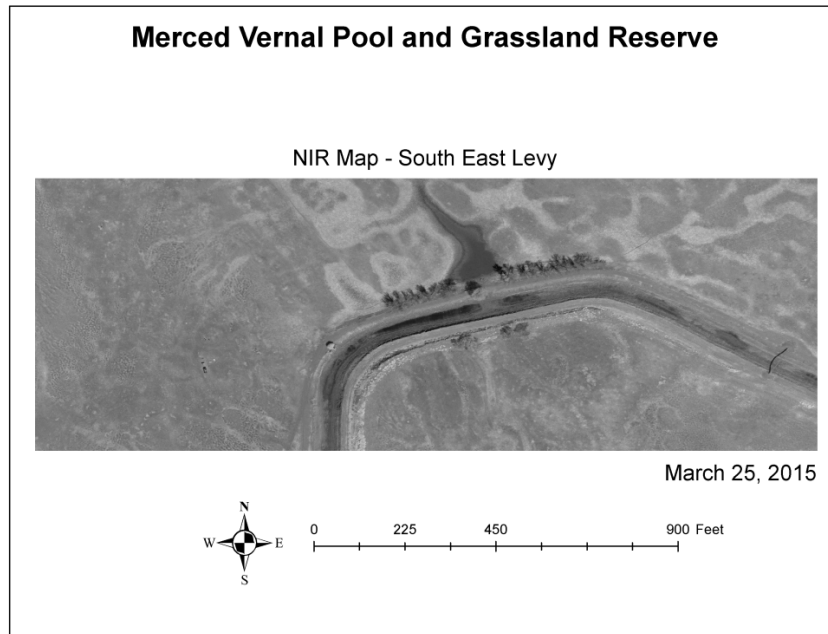


Figure 4.7: Orthomosaic in NIR.

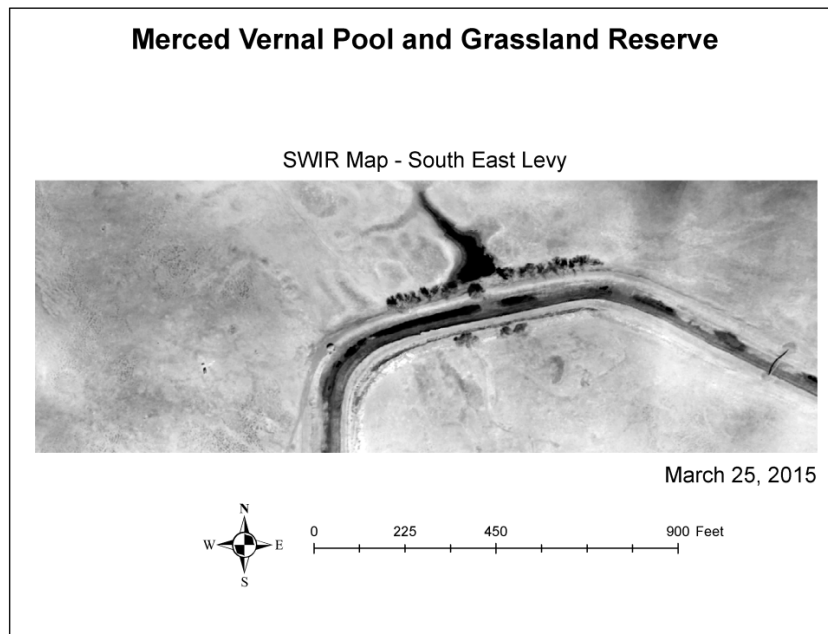


Figure 4.8: Orthomosaic in SWIR.

As described in [6], while NIR imagery can be used for mapping water features, energy in the NIR spectrum is not fully absorbed in water less than 1 m. A subset of SUAS imagery collected in Color, NIR, and SWIR is seen in Figures 4.6, 4.7 and 4.8. The shallow pool outside the levy is indistinguishable in color imagery and is faint in NIR. However, the full outline of the water level is clearly depicted in SWIR. In contrast, the deeper water pool within the levy is more apparent in NIR, however, the even more shallow ponds are indistinguishable from soil and bare-ground. The increased sensitivity of SWIR to water enables accurate water feature measurements which is a critical need for conservation efforts.

4.4 Temporal Optimization

The concept of finely optimizing the temporal resolution is unique to SUASs. Unlike other remote sensing technology, the time and date of data collection with an SUAS may be finely controlled. The temporal scale for data collection with an SUAS may be over the course of a year or as small as over the course of an afternoon or shorter. Literature has remarked on this ability to collect finely controlled aerial data by collecting multiple data sets in a day [60] or optimizing data collection for a specific time [3]. The optimization of the temporal axis may be deployed as a means to minimize identification overlap or to show the changes of a system dynamic over time.

While an SUAS may be more finely flexible in the time of data collection, there are several boundary conditions. Unlike a satellite, the time it takes for an SUAS to collect the necessary aerial imagery is not trivial. Flights with a fixed-wing SUAS may take as long as 1 to 2 hours, limiting the temporal bandwidth of data collection. On the other hand, rotary-wing vehicles typically suffer from significantly reduced flight times, generally on the order of 15-20 minutes. These factors provide strict limitations on the total availability of the data. In addition, as discussed in Chapter 3, during the time of data collection, solar motion can introduce errors and introduce challenges on long-term data reliability and comparability.

4.4.1 Optimal Image Collection to Minimize Shadowing

Taking advantage of the on-demand capabilities, researchers can now exert a greater level of control over when imaging data can be collected when using an SUAS. If the time at which imagery data is collected can be controlled, then there is some methodology that can be applied to find the optimal time for imagery collection. Shading effects have known negative effects on vegetation and soil metrics and subsequent calculations and classifications that are necessary for analysis [41, 120, 121]. In areas with sparse, non-uniform vegetation, the minimization of shadows in imagery is especially valuable.

The minimization of shadows in imagery is intended to improve the performance of many remote sensing classification techniques. With pixel based classification strategies, often the difference between two adjacent parts of a shrub is equal to the difference between the shrub and a rock. This lack of separability results in poor classification performance, even with the use of high resolution imagery that an SUAS is capable of providing.

A similar problem of separability was apparent in the classification of land cover for forest fire management mapping of potential fuel types [122]. Utilizing light detection and ranging (LIDAR) data in the form of vertical density distributions including the canopy height model with surface reflectance data increased the performance of their classification techniques. Unfortunately, for many SUASs, a LIDAR unit is both too costly and too large to implement as a payload simultaneously with imaging equipment. As SUAS operations have matured, operators have begun leveraging a second major form of photogrammetry technique of utilizing sufficiently overlapping images to generate a digital elevation model (DEM) [121]. The generation of a DEM can be done either through simultaneous imaging from a stereo pair of cameras or through Structure from Motion (SfM) algorithms from a single camera. In either method, image points are matched from each pair of images to generate a mapping of pixel distances from the camera. With proper ground control points (GCPs) and georectification, a georectified DEM can be generated [63,64,121].

Recent research has validated the use of SUASs for DEM generation by demonstrating an adequate level of accuracy [63,64]. In [64], researchers utilized a commercially available software package, Agisoft Photoscan, to achieve a respectable level of accuracy compared to ground truth measurements with improvement possible with additional processing and GCPs. Another study indicated that the greatest factor in the accuracy of a DEM generated by an SUAS was the flight altitude [63]. Other studies have shown similar results using SUASs for DEM generation for mapping ice flows [65] and post damage analysis [123]. One significant advantage of the process of generating a DEM is that it can be accomplished through the same set of imagery utilized for spectral reflectance indices or classification, maximizing the use of a single set of imagery collected from an SUAS operation.

The use of a DEM has been shown to provide additional data to the object-based classifier in the form of a shadow estimator and enables the collection of imagery at the optimal time [3]. Given a location's latitude and longitude, the NOAA Solar Calculator can plot the sun's azimuth and solar elevation for any given day [124]. A shadow estimation for a generated DEM can be run over the set of azimuth and solar elevation angle for a given day and time. The optimization can be reduced into a minimization function to solve for t in the following problem:

$$\min_t Shadow(x, y, \alpha, \phi) \text{ for } \forall x, y \in \mathcal{I} \quad (4.14)$$

where the sun's estimated α and ϕ can be calculated through the NOAA Solar calculator, and $x, y \in \mathcal{I}$ represents all pixels within image $\mathcal{I}$. The shadow estimation can be calculated through any means. The minimization function is designed to find the time t at which there is the least amount of shadowing on the image. In many cases, the minimization is achieved at solar noon, however in many topographically challenging locations, this may not be the case.

The result of the optimization run on a small hill (Figure 4.9) can be seen in Figure 4.10. As expected, as the sun reaches its solar noon (at $t = 12.26$ hr), the shadow intensity decreases. However, the optimal time for collecting imagery for the date of February 15, 2014 would be at 13:00hr or 34 minutes after solar noon. This discrepancy can be attributed to the orientation of features. As a reference for time scale, the process for data collection of this imagery set took approximately 10 minutes including the takeoff and landing.

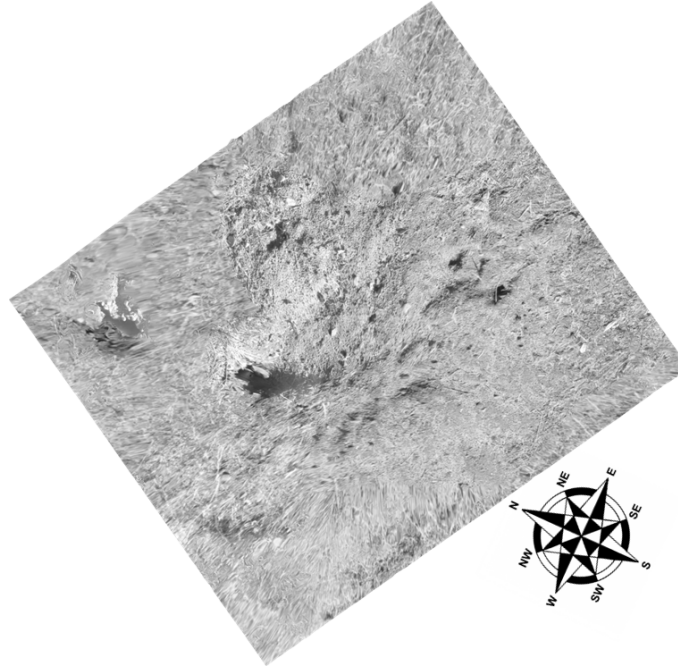


Figure 4.9: Reference NIR image.

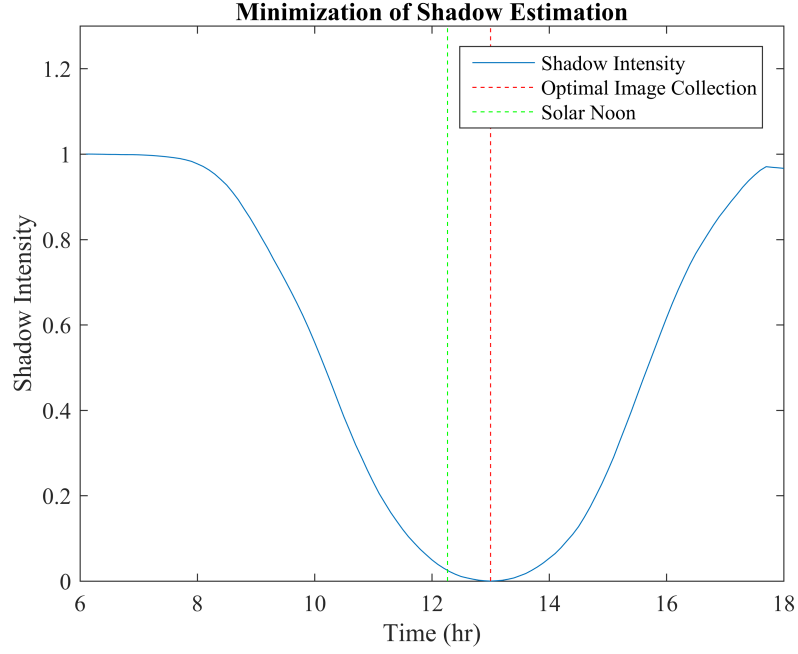


Figure 4.10: Time at which shadows are minimized for reference NIR image.

4.5 Optimizing Bird Counts using a TIR Camera at Night

An example of the importance of the optimization in remote sensing can be found in the following investigation on the use of an SUAS to conduct Sandhill Crane surveys. Sandhill Cranes are an endangered migratory crane that fly up and down California every year. The collection of regular and accurate counts of Sandhill Cranes that utilize the roosting sites in the Sacramento-San Joaquin River Delta is an important metric for conservation efforts. As the birds are only stationary at night, the current methods for estimating numbers involve on-site visual counts, in the early morning or evening. The combination of weather, low-light conditions, variations between volunteer observers and other difficulties pinpointing exact counts leads to a wide-range of errors. The potential exists for under-reporting, missing roosting sites, or failure to detect site trends, all of which may hamper further conservation efforts.

A potential solution exists in the use of an SUAS with a Thermal Infrared (TIR) camera. An SUAS could be flown at night while the Sandhill Cranes are roosting, and use a thermal infrared camera to identify the birds. The birds primarily roost on shallow water rather than on land, to protect them against predators. This temperature differential between the cranes and the water has been previously demonstrated, providing enough contrast to count [125]. However, the use of small rotary-wing Unmanned Aircraft System (UAS) provides approximately 20 minutes

of flight time, not enough to provide coverage for an effective census count. This is a typical situation where the need for optimization is critical to the mission's success. This mission can be framed as a joint optimality problem in optimizing the spatial resolution and temporal factors to ensure the optimal identification of the roosting birds. In this section, the optimization challenge is separated into two components: flight coverage optimization and time of flight optimization.

4.5.1 Flight Coverage Optimization

The use of a TIR camera for the purposes of counting Sandhill Cranes has been previously demonstrated [125]. However, in order to conduct a complete survey, the SUAS must cover larger areas than the 10 ha area a rotary-wing platform could cover. The goal of the mission is to provide accurate survey counts in an area of greater than 1200 ha. The smallest area of coverage of value must be comparable to the existing field counts, done on plots which range from 40 to 200 ha. In order to cover this size of area, AggieAir, a fixed-wing SUAS was selected, capable of 60 minutes of flight time with a nominal flight speed of 17 m/s. It is apparent that multiple flights are necessary. For the spatial resolution challenge, existing TIR cameras contain a 0.3MP sensor and a narrower FOV compared to common camera payloads. With an image resolution of 640 x 480 pixels, the aircraft must balance flight altitude and flight coverage to ensure that the resulting GSD is suitable.

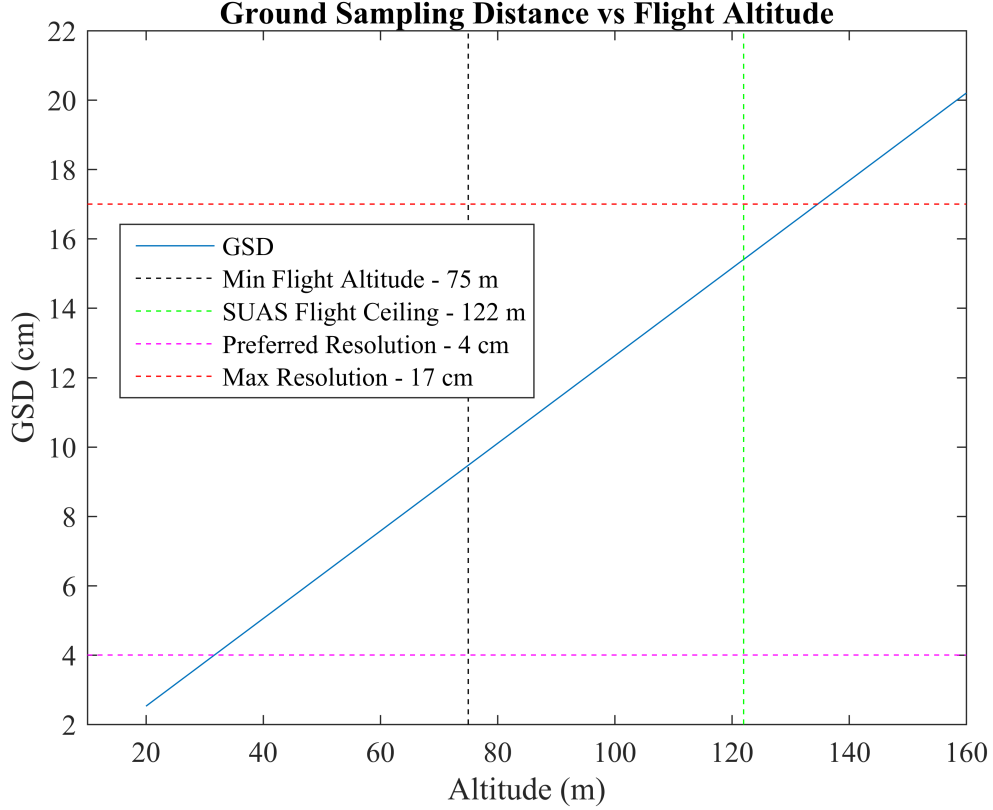


Figure 4.11: Flight altitude and ground sampling distance.

When roosting, the birds appear as an ellipse between 50-60 cm in length and 17-23 cm in height. A preferred GSD would provide for 2-4 pixels in the shortest dimension, in this case roughly 4 cm. With the stock lens of the TIR camera providing a static FOV of $44^\circ \times 33^\circ$, GSD is directly influenced by flight altitude (Figure 4.11). However, given this TIR camera, it is impossible to reach the preferred GSD as the minimum flight altitude is 75 m. This would provide a potential solution with a GSD of 9.5cm. In the worst-case scenario, it may be possible to detect roosting birds with a GSD as high as the smallest dimension (17 cm), but measurement accuracy would be suspect. At the max legal flight altitude of 122 m above ground level (AGL), the resulting image ground resolution or GSD is 15.24 cm, well above the preferred resolution.

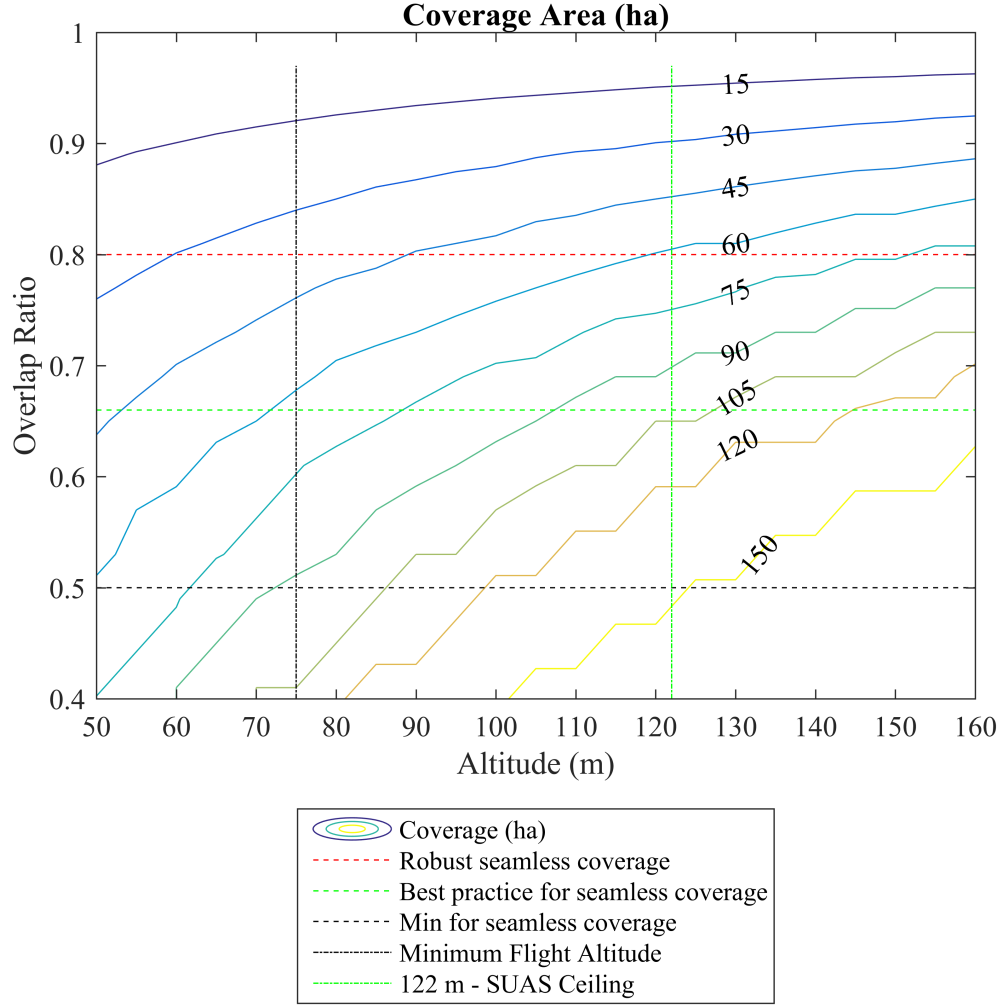


Figure 4.12: Acreage coverage per flight and image overlap.

However, the flight coverage area is influenced by flight altitude as seen in Figure 4.12. As described in Section 4.2.1, image overlap parameters can be utilized to provide seamless coverage or provide sufficient multi-angular views for robust scene reconstruction, and also influence flight coverage area. In many flight operations, best practice is to ensure that each spot on the ground is imaged in at least 9 images which corresponds to 0.66 image overlap ratio (2/3rds of each picture is repeated both vertically and horizontally).

In this scenario, at altitudes below 122 m AGL, the coverage area dramatically decreases, ranging from 60 ha to 37 ha with an overlap ratio of 0.8 (Figure 4.12). If the conditions for overlap enable a lower ratio, up to 100 ha can be covered per flight.

If the goal of the analysis is to be able to identify different roosting bird species in the area, then further analysis is needed. A table of estimated roosting sizes of the various bird species found in the selected roosting site in the Sacramento-San Joaquin River Delta can be found in Table 4.3 (estimated from staff personnel).

Table 4.3: Estimated bird characteristics.

Bird Species	Length	Population Variance	Estimated sleep- ing length ratio	Sleeping Width
Crane	100-120 cm	5 cm	50%	17-23 cm
Canadian Geese	76-110 cm	13 cm	66%	17-23 cm
Small Geese	50-64 cm	5 cm	66%	15-18 cm
Tundra Swan	140 cm	8 cm	62.5%	23-28 cm
Mallard	50-66 cm	3.75 cm	87.5%	10-14 cm

The challenges of separability can be visualized with a population distribution simulation as shown in Figure 4.13 and image simulations shown in Figures 4.14a-4.14d. These images depict that accurate size measurements may be useful to separate larger bird species from the smaller species, however there is insufficient information from a silhouette for accurate species identification. It is shown in Figure 4.14d that despite the low resolution, it is possible to detect roosting birds but not identify species at an altitude of 122 m from a spatial resolution aspect.

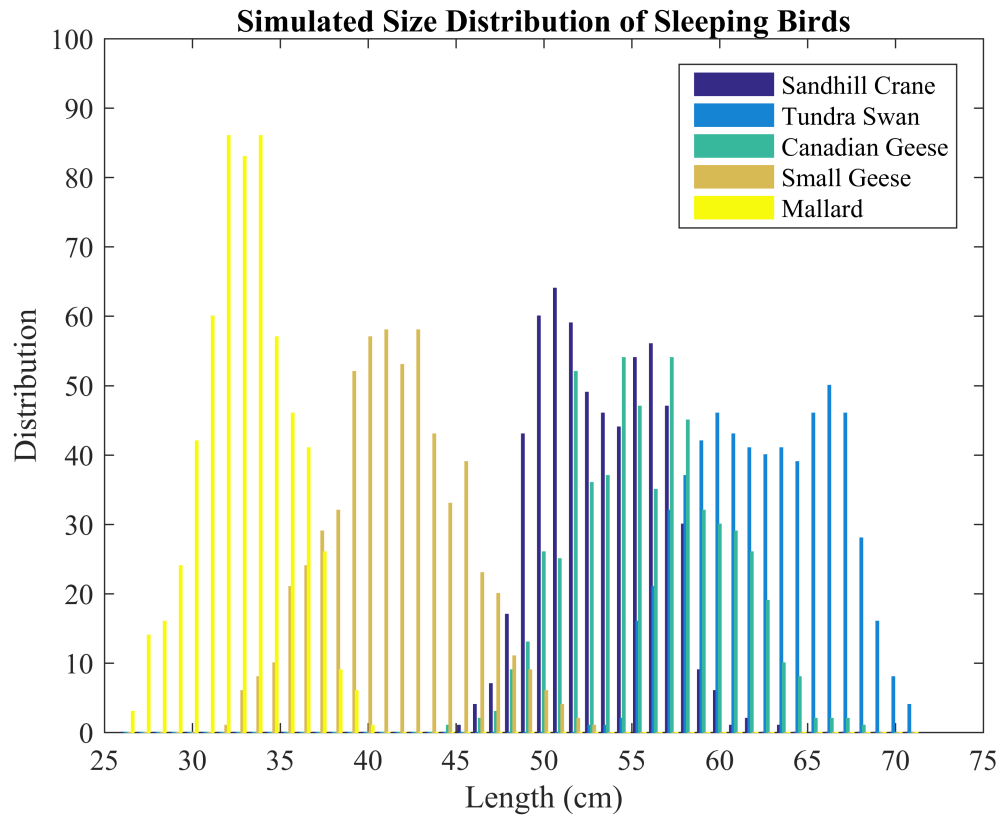


Figure 4.13: Simulated distribution of sleeping bird length. The simulation displays significant overlap between the Sandhill Crane, Canadian Geese and other bird species that will reduce species identification accuracy based on sleeping length alone.

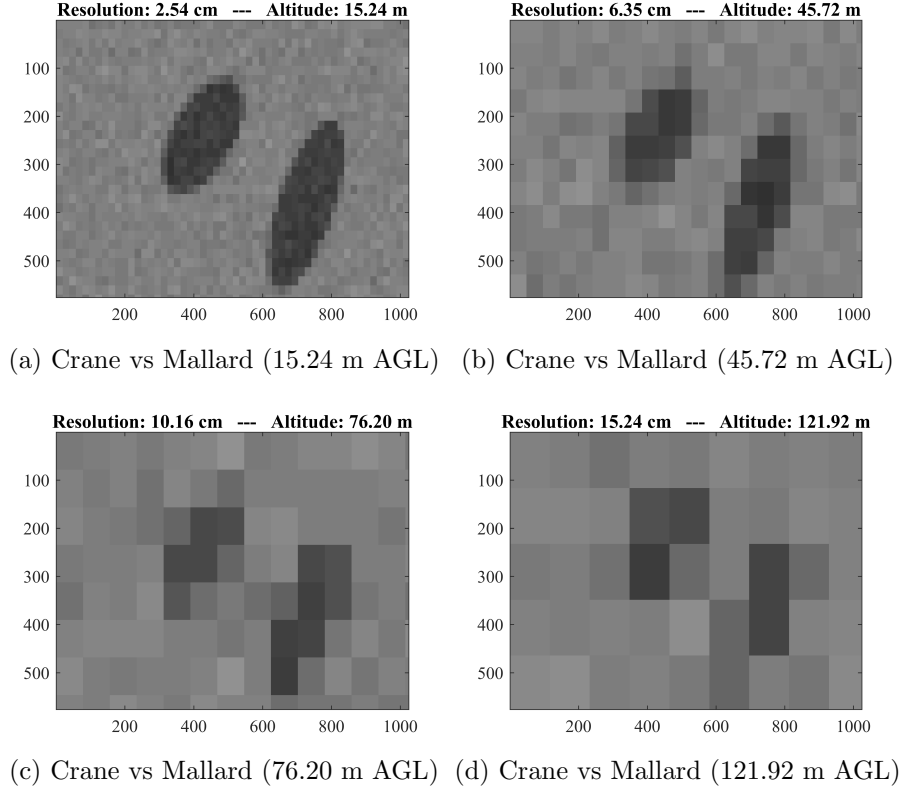


Figure 4.14: Simulated images set of crane and mallard.

4.5.2 Optimization of Time of Imagery Collection

As described previously, the detection of roosting birds at night utilizes a TIR camera to identify a temperature difference between roosting birds and the surrounding environment in which the standing pools of water had a warmer temperature than that of the roosting birds. However, the temperature of the birds was unknown and the thermal effects of the standing water was unmodeled prior to the project. The understanding of the temporal and thermal characteristics proved to be an important aspect to the successful completion of the project.

In several image sets, the collection of data was successful, as in Figure 4.15. The birds in this figure are clearly visible ranging from small dots to silhouettes of birds in flight.

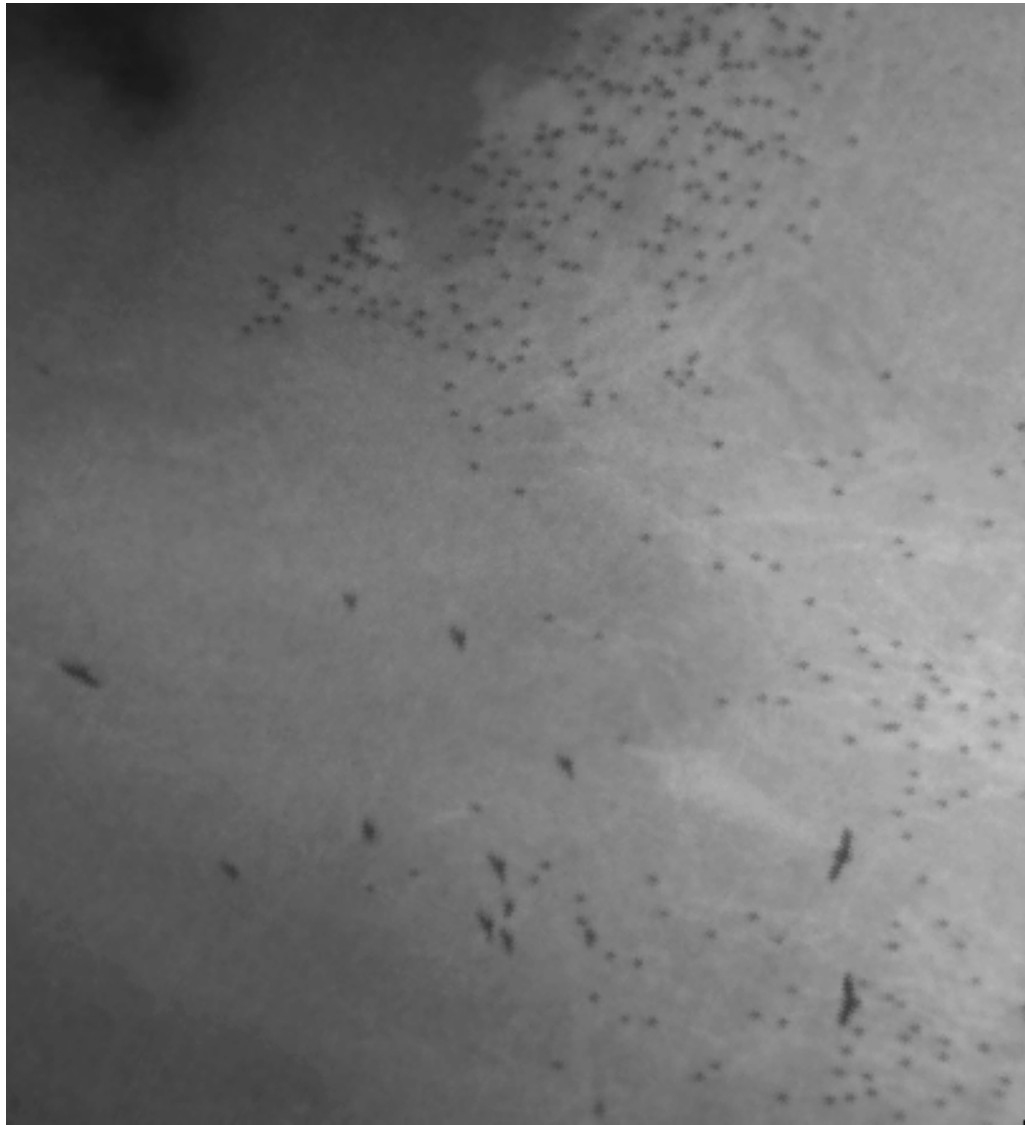


Figure 4.15: Closeup on TIR image from March 5th, 2015. Bird silhouettes are clearly visible as colder than the surrounding water.

However, in many of the imagery collected, it was apparent that the unmodeled thermal characteristics could introduce significant errors. In theory, during the day, the water in the flooded fields where the birds roost will be warmed from the sun, and will slowly cool at night. The smaller objects such as vegetation and the birds will cool with the ambient air temperature and the soil will cool rapidly due to evaporative cooling. However, in Figure 4.16, birds are visible as both warmer and colder than the surrounding water. When the birds are disturbed, their body heat

is observable from a slightly elevated temperature. This scenario is not satisfactory for detection or identification purposes as it decreases the observability of the birds. The spatial temperature variability of the water is also apparent which further complicates the detection process. The thermal dynamics of the environment introduces the need to optimize the data collection time to optimize the observability of the birds.

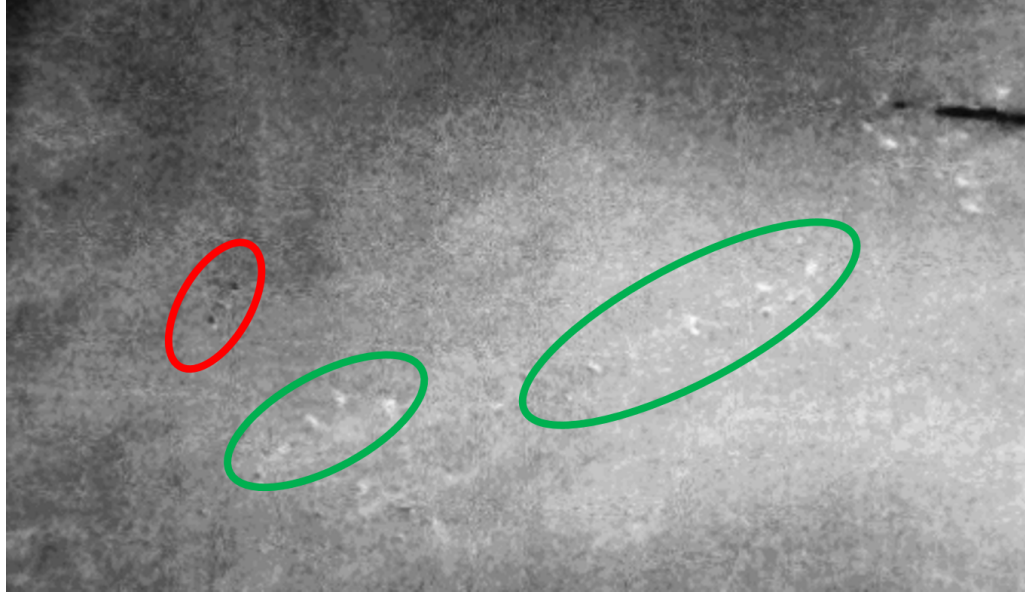


Figure 4.16: Closeup on TIR image from Nov 13th, 2014. Unidentified birds show up as both colder (circled in red) and warmer (circled in green) than the surrounding water.

The temperature contrasts between the birds, water, soil and vegetation are paramount to the project's success. A sampling of the various temperatures found during the flights as measured by the TIR imager can be found in Table 4.4. The average temperature of positively identified objects (typically 3-5 instances per image) was compiled across 10-15 images per flight.

Table 4.4: Various average temperatures as measured from TIR imagery.

Date	Flight	Air (°F)	Water (°F)	Bird (°F)	Soil (°F)	Veg. (°F)	Day (°F)
11-16-2014	1	58.0	52.17	51.43	49.25	46.50	65.00
11-16-2014	2	54.0	49.47	47.97	38.53	48.32	65.00
11-16-2014	3	45.0	50.49	48.74	46.27	47.85	65.00
12-18-2014	2	49.0	47.50	46.91	46.76	46.76	60.00

The assumption that bird temperature follows or correlates to the ambient

air temperature is not validated in the data compiled from the SUAS nighttime flights (Figure 4.17). On the other hand, there is a strong correlation between bird and water temperature. These results may be indicative of poor resolution where pixel mixing between birds and the water may create an artificial correlation.

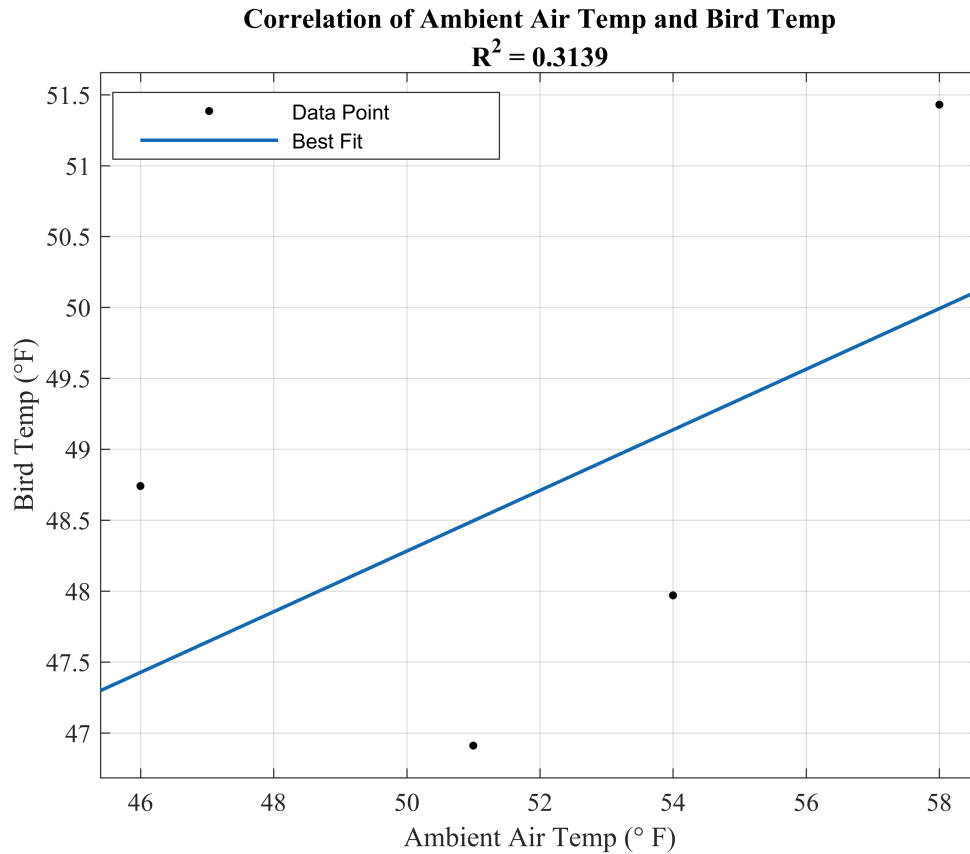


Figure 4.17: Correlation between air and measured bird temperatures.

However, the temperature difference between the birds and water showed a strong correlation between the temperature difference of the daytime temperature and the temperature at the time of flight (Figure 4.18). This matches the assumption that the daytime sun heating up the water generates the temperature contrast of the birds on the water and validates the assumption that flying later in the night will result in better contrast than early in the evening.

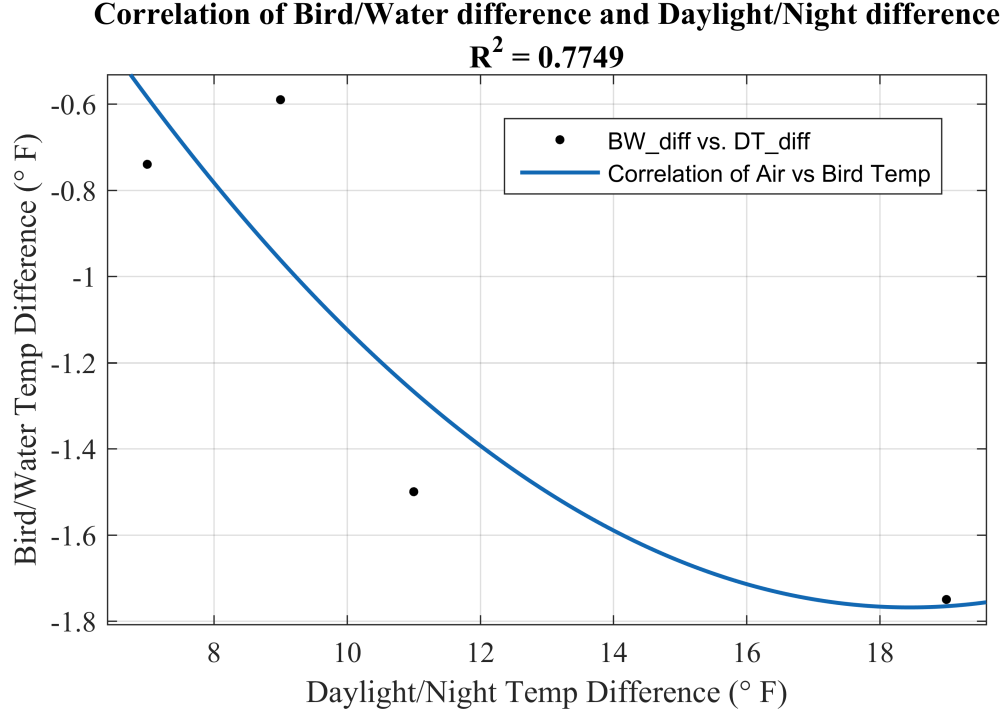


Figure 4.18: Correlation between air temperature and measured bird temperature.

The temperature correlations found prompt further investigation into the optimal time for thermal data collection. Intuitively, the warmer the day is and the colder the night is, the better the temperature contrast between the birds and the water. However, there does not seem to be a strong correlation between ambient air temperature and the bird temperature as was previously assumed.

Additionally, the thermal capacitance of the flooded fields is likely also influenced by the size of the pooling of water. The river on either side of the island had a significantly higher temperature than the standing water in the pool. It could be assumed that the thermal imagery process of detecting birds may not be effective in small areas of water or in areas that do not get significant sunlight.

4.6 Extending the Framework

While the examples presented thus far has focused on singular solutions, the framework is capable of addressing optimality as a time-varying solution as needed to address the issue of data accuracy in Chapter 3. Consider a case where the remote sensing goal is not uniform across the region Ω , instead the desired δ is spatially dependent or the desired η band mapping of λ varies with t . Unlike traditional remote sensing, an SUAS or a fleet of SUASs, may be developed in such a manner

where the data collection could be optimal at every point q instead of optimal for the region Ω .

This framework may also be advantageous in the expansion to $\Omega \in R^3$. Incorporating three dimensional spatial, spectral, and temporal data into the remote sensing framework has also recently started to gain traction and SUAS are poised to become significant data generators for spatially complex areas. The value of optimal data collection will become even greater with an additional dimension of spatial data collection that may exponentially increase data processing and analysis time unless properly accomplished.

4.7 Chapter Summary

The challenge of optimizing remote sensing operations with SUAS is a significant step towards improving data collection and analysis. While data storage is not a significant reason to optimize data collection, there are many other factors that may necessitate optimization strategies as discussed in this chapter. Given the large data sets now possible, the data analysis can be a significant bottleneck when the remote sensing strategies are not optimized. In other situations, usable data for the operation goal may not be obtainable unless the flight parameters are optimized, as in the example case of counting roosting birds in Section 4.5 that required optimizing spatial and temporal factors to identify a suitable solution.

Compounding the issue of optimization is that many parameter relationships may be specific and goal dependent, and as a result, their relationships have yet to be developed or generalized. This does not imply that considering optimality is not of value, but rather indicates that there the current use of an SUAS for remote sensing is still in its infancy and there is more still yet to be explored.

SUAS-based remote sensing has been shown to be an up and coming tool, but its potential has yet to be fully realized. Many projects are still developed around existing methodologies that revolve around obtaining high resolution images and analyzing the resulting images. But SUASs are capable of acting as part of a dynamic system, rather than measuring moments in time. There are significant capabilities that can change the approach of remote sensing along spatial, spectral and temporal factors. The conceptual framework presented here attempts to highlight and establish the foundation for these future endeavors. However, while this conceptual framework examines what could be, as will be discussed in the next chapters, there are many technical, legal and safety related challenges for SUAS-based remote sensing to be fully realized.

Chapter 5

CHALLENGES FOR THE INTEGRATION OF SMALL UNMANNED AIRCRAFT SYSTEMS INTO THE NATIONAL AIRSPACE SYSTEM

5.1 Introduction

The rise of Unmanned Aircraft Systems (UASs) into the commercial mainstream has coincided with smart phones and the exponential development in technology. However, a common remark has been that while smart phones have been unconstrained, UAS technology has been significantly held back by Federal Aviation Administration (FAA) regulations. The statement is largely an exaggeration, though there is some truth to it. Even early in the history of UAS, the FAA struggled to keep up with the pace of technology that comprised this new technology looking to gain access into the National Airspace System (NAS). Guidance documents such as AFS-400 UAS Policy 05-01 [30] and AIR-160 Interim Operational Approval Guidance 08-01 [31] (released in 2005 and 2008) offer insight into the early attempts of understanding and addressing the use of UASs. The focus of these two documents were to answer the question ‘what makes a safe UAS operation in the NAS?’ These early attempts of answers followed a familiar pattern in aviation, focusing on identifying potential hazards and categorizing risk.

As early as 2007, the FAA identified that although a pilot in command (PIC) of a UAS is not within the vehicle, the PIC still serves a vital and unreplaceable role as the one fully responsible for the safety of the aircraft, its immediate airspace and those below on the ground [126]. While this statement does not sound significant nearly 9 years later, it was a profound statement to declare that an operator on the ground, who may be miles away from the aircraft, was still responsible for ensuring the safety of the NAS. It was a precursor to discussions over liability in accidents and how much faith to place in automated systems when it came to human life. This led to the decision to require minimum standards and qualifications for the PICs of UASs and the basis for the FAA’s policy interpretation that ‘no person may operate a UAS in the NAS without specific authority’ [126]. And due to this requirement, that the existing Advisory Circular (AC) 91-57, which opined on model aircraft, was not suitable authority for UAS use by ‘persons or companies for business purposes’ [126]. With this notice of interpretation, the nascent UAS industry suffered. Until October

2014, over 7 and a half years later, when the first Section 333 exemptions were granted, civil UAS were prohibited from entering the NAS, singlehandedly holding back any commercial usage by UASs. The one exception was in the public sector, where the FAA had a different oversight requirement that enabled public agencies an opportunity to apply for a Certificate of Waiver or Authorization (COA) on a case-by-case basis for a specific aircraft, specific location and specific purpose for up to a two-year approval. However, in higher education, this led to unequal access. While public universities such as the University of California and Utah State University were able to earn COAs, private universities such as Stanford and BYU were forced to halt all UAS activity.

The rational for the steep restriction on UAS was rooted in safety and risk analysis. In the Interim Operational Approval Guidance 08-01 [31], the FAA established the first official guidance document on what is needed for a safe UAS operation. Over the years, additional guidance documents such as FAA National Policy N 8900.207 [127] and ATO Organization Policy N JO 7210.846 [128] continued to develop a clearer picture of addressing safety. As shown in Table 5.1, these safety issues can be roughly grouped into four major categories: procedural and operational challenges, technical challenges, aircraft safety, and crew certification & training.

Table 5.1: Compilation of safety issues described in [30–33, 126–129].

Risk Categories	Specific Issues
Procedural & Operational Challenges	Night Time Flights Risk Mitigation Procedures Visual Observation Alternate Means of Compliance (AMOC) Sense & Avoid Procedures Air Traffic Deconfliction Emergency Procedures Accountability
Aircraft Safety	Aircraft Airworthiness Aircraft Standards Measures of Performance Continued Airworthiness Ground Safety Dropping Objects/Hazardous Material
Technical Challenges	Automatic Dependent Surveillance-Broadcast (ADS-B) Sense & Avoid Technology Autonomous Operations

	Failsafe Robustness Communication, Command & Control Spectrum Allocation
Crew Certification & Training	Human Factors PIC Certification PIC Training Requirements Medical Standards Testing Standards Visual Observer & Other Ground Crew Requirements

However it was clear that the term UAS was a significantly wide category and that a piece by piece approach was necessary. This was detailed in the FAA’s ‘Integration of Civil UAS in the NAS Roadmap’ [36], where they finalized the decision to focus on the integration of Small Unmanned Aircraft System (SUAS) as a priority while the safety challenges (such as those expressed in Table 5.1) were addressed. In August 2016, the FAA enacted the finalized regulations for the operation of SUASs within the NAS in Title 14 of the Code of Federal Regulations (CFR), Part 107 [35]. This set of regulations primarily enabled the use of SUAS within Class G airspace while introducing a new remote pilot in command (RPIC) certificate and introduced an SUAS rating. In contrast to a Public Agency COA or Section 333 COA, the new regulations did not require an SUAS airworthiness certificate or the use of a Visual Observer (VO). However, the new regulations placed an increased emphasis on risk and safety management, and placed many of the responsibilities of maintaining safety primarily on the RPIC.

For flight operations beyond the bounds of 14 CFR 107, the FAA introduced an airspace authorization process and a waiver process. The airspace authorization enables SUAS operators to request airspace authorization in Class B, C, D and surface E airspace. The waiver process enables SUAS operators to request waivers to specific regulations in 14 CFR 107, provided the applicant made a sufficient case to ensure AMOC. As of Dec 2016, the most common requested and approved waivers were for flight operations at night, while requests for other waivers have been regularly denied.

Though this waiver process enables many more opportunities, it does not provide a safety standard or AMOC that can be generalized into more cases. These safety challenges are nontrivial and much of the work necessary to address the items in Table 5.1 remain unresolved. All of these are big open-ended challenges that require a combination of engineering, regulatory and safety expertise. In the following chapter, an element from each of the categories from Table 5.1 is evaluated. The procedural and operational challenges of flying SUASs at night is presented in Section 5.2. In Section 5.3, distributed control of SUAS with real-time health monitoring is

investigated to address balancing aircraft safety and operational goals. Section 5.4 discusses the use of ADS-B in SUAS as a solution for aircraft traffic management. Finally, a model for analyzing the human-SUAS interaction is presented in Section 5.5.

5.2 Flight Operations at Night

One of the most requested waiver to the regulations in 14 CFR 107 is to enable flight operations at night. Many have looked at utilizing SUAS for missions such as frost damage detection [71], surveillance, firefighting [130] and wildlife counts. However, the regulations prohibit flight operations at night due to many safety challenges, primarily the degradation or complete loss of visual line of sight and related hazards. The waiver process enables proponents to make a safety case, but is limited in scope and there is no standardized definition of visibility or AMOC. In this section, a comprehensive analysis of enabling flight operations at night is presented. The work presented in this section was developed in September 2014 for the work presented in Chapter 4. At the time of writing in January 2017, this remains the only fixed-wing SUAS approved for flight operations at night. To put this in perspective to the fast moving SUAS industry, in the same timeframe, the FAA has granted 5,551 Section 333 exemptions (from October 2014 to August 2016), granted over 30,000 RPIC certificates (from August 2016 to December 2016), and 272 waivers for flight operation at night (from August 2016 to December 2016).

Despite the popularity of flight operations at night, addressing the full scope of the challenges has only received minor attention over the years. Previous works coordinated to establish ‘no fly-zones’ with the FAA [71], were significantly limited in scope as in the Part 107 waivers or worked without FAA authorization, either internationally or in restricted airspace. The Academy of Model Aeronautics (AMA) has long supported flying model aircraft at night and includes it within their Model Aircraft Safety Code [131]. However, within their requirements, they assert that hand-held illumination is insufficient and that an illumination system is required that provides ‘the pilot with a clear view of the model’s attitude and orientation at all times’ [131]. However, to meet AMOC towards the FAA safety standards, significantly more details are required.

In this section, the development and design of a suitable SUAS lighting system, operation protocols and regulatory recommendations are presented. In Section 5.2.1, an introduction to existing FAA regulations for flight operations at night is presented. The proposed lighting system suitable for an SUAS and the appropriate operational adjustments are described in Section 5.2.2. Section 5.2.3 discusses the implementations and regulatory recommendations learned through the development of flight operations at night.

5.2.1 Existing Regulations for Flight Operations at Night

Existing regulations provide guidance towards the development of both a lighting system installation and protocols for flight operations at night for SUASs. In this section, a brief overview of existing standards and regulations as enforced by the FAA for domestic aircraft within the U.S., specifically for flight operations at night. The regulations regarding aircraft lighting, PIC requirements and protocols are discussed in detail where they relate to SUAS operations. While Part 107 enacted specific regulations regarding SUAS, however it provides no additional regulatory standards for approving flight operations at night [35]. Part 107 introduced the requirement of anti-collision lights to be used in civil twilight, but in the regulation justification noted that the FAA had insufficient knowledge whether this would be acceptable or necessary for flights after twilight [132].

5.2.1.1 Aircraft Lighting

The regulations related to aircraft lighting systems can be found in 14 CFR Part 23 - Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes, in Subpart F - Equipment [133]. The lighting of the aircraft has different design developments for internal lighting and external lighting. The regulations regarding the internal lighting system (§23.1322, §23.1381) are not applicable in an SUAS and will not be discussed. Instead, the focus of the section will be on the regulations regarding the external lighting of an aircraft (§23.1383 – §23.1401).

The configuration of positional lights are described in §23.1385 and are depicted in Figure 5.1. Navigation lights are placed on the wing tips and tail of the aircraft. The left wing light color is red, the right side is green and the tail light of the aircraft is white. These navigation lights are used by other air traffic to determine heading enabling the identification of potential threats. In a situation where a PIC sees a green position light on an aircraft to the PIC's 'red' side, it is an indicator of a potential collision. Conversely, green-to-green and red-to-red indicate low or no threat of collision. However, these position lights are not intended to be omni-directional as seen in Figure 5.1. Regulation §23.1387 defines the directionality of the position lights. The lights on the wingtips are oriented forward and extend 110°, only slightly behind the aircraft. The tail light is designed to only be visible from behind the aircraft, covering a span of 140°.

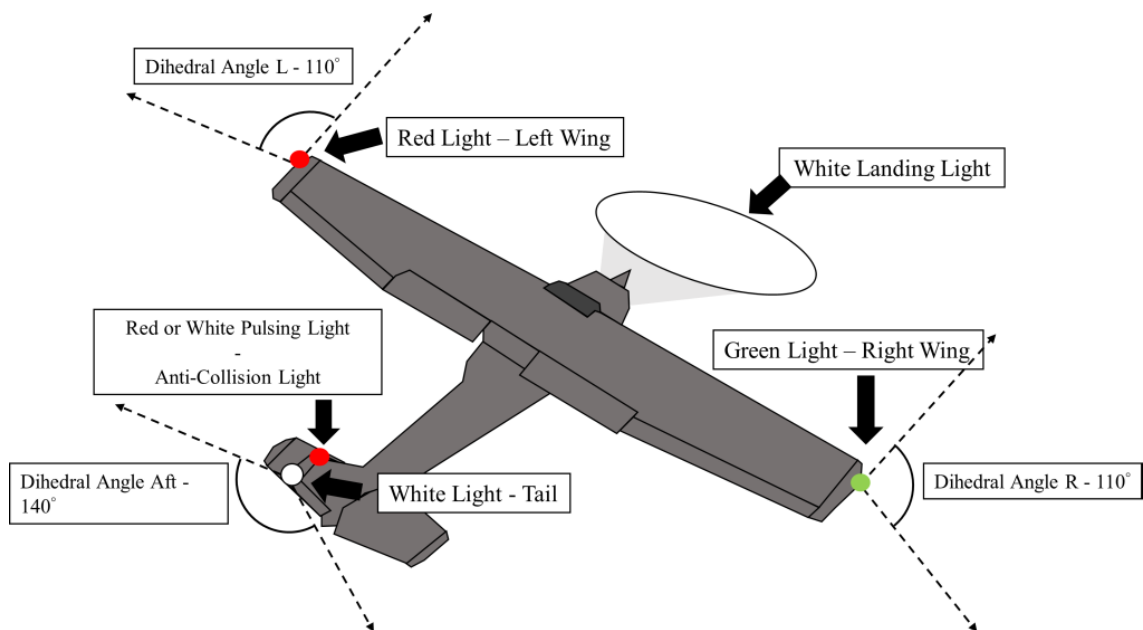


Figure 5.1: Diagram of existing aircraft light regulations §23.1383, §23.1385, §23.1387 and §23.1401.

Additionally, aircraft are required to install anti-collision lights as defined by §23.1401. Anti-collision lights, located either on the wing or fuselage, are used to improve the aircraft's visibility with bright flashes of light. The color of the light is white or red and it pulses between 40 and 100 cycles per minute. Within §23.1401, the minimum intensity and viewing angles are also defined. Additionally, taxi or landing lights are commonly used to increase visibility for the PIC to see the runway, though they are only minimally defined by §23.1383. Regardless if it's day or night, the landing lights are 'on' when approaching landing.

Regulations §23.1389 – §23.1395 relate to the required minimum light intensities across the range of visibility for each light. Regulation §23.1397 defines the color of each light according to the CIE colorspace coordinates, while §23.1399 defines the minimum requirements for anchor or riding lights if installed on an aircraft.

The FAA regulations regarding aircraft operation are found in 14 CFR 91 - General Operating and Flight Rules [134]. In regards aircraft lights, §91.209 asserts that no person may (a)(1) operate an aircraft unless it has lighting position lights; and (b) operate an aircraft without a lighted anti-collision light system, unless the PIC determines that it would be in the interest of safety to turn the lights off [134].

5.2.1.2 Protocols and Pilot Requirements

Aircraft operations at night differs significantly from daylight operations as there exists an abundance of safety challenges. The addition of aircraft lighting enhances aircraft visibility, but introduces additional operational requirements and PIC training.

In order to adjust to operating in dark environments, PICs are taught to wait at least 30 minutes in the dark environment before beginning operations [135]. Once in the air at night, different scanning techniques are often recommended. During daylight, PICs are taught to engage in focused scanning, however at night, PICs are taught to utilize their peripheral vision more as their peripheral vision is more sensitive in low-light situations.

Due to the additional training, PICs are required to fulfill additional currency as defined by 14 CFR 61 [136]. Flight operations at night requires currency of three takeoffs and three landings to a full stop. The night currency is to be completed during the period of one hour after sunset to one hour before sunrise.

During night operations, PICs are required to have three hours of night training. This also includes flight over 100 nautical miles and at least 10 takeoffs and landings to a full stop [136].

5.2.2 SUAS Flight Operations at Night

While there are parallels between operations of SUAS and manned aircraft, there are plenty of differences between flight operations at night that have not been thoroughly addressed in literature. Since the RPIC of an SUAS is no longer inside the aircraft, many regulations and best practices commonly discussed for protocols, such as cockpit instrumentation visibility and PIC scanning, are not applicable. In an SUAS mission, the main operator is considered the RPIC and is often supplemented with VOs to provide the RPIC with additional situational awareness. Using the previously described existing regulations related to aircraft lighting and operations as a guideline, both an SUAS lighting system and protocols for flight operations at night is developed. In this section, first an overview of the various issues regarding visibility and observability for night time operations of SUASs are introduced, followed by a description of a proposed lighting system and additional protocols.

5.2.2.1 Risk Assessment for Flight Operations at Night

In this section, a risk assessment is presented in the following tables (Tables 5.2-5.4) to enumerate a wide variety of potential risks associated with night time operations, along with potential solutions. While a handful of the risks presented pose a minimal or acceptable level of risk, it is clear that there are many that can be mitigated through the use of a properly designed lighting system and additional requirements for night time operation planning and management.

The flight operations at night risk assessment is broken down into three phases of operations: Pre-Flight Preconditions (Table 5.2), Launch & Recovery Operations (Table 5.3), and Standard Mission Operations (Table 5.4).

Table 5.2: Pre-flight preconditions.

Potential Risk	Resolutions
The RPIC is not sufficiently trained.	Require sufficient proficiency in flight operations at night prior to SUAS operation.
The ground crew is not sufficiently trained.	Require sufficient proficiency in flight operations at night prior to SUAS operation.
The ground crew is unable to view ground equipment.	Provide additional illumination.
The ground control station operator is unable to view control station.	Provide additional illumination.
The additional illumination from the ground crew is distracting to the RPIC or visual observer(s).	RPIC and/or visual observer(s) must be distanced from illuminated ground crew operation.
The RPIC and/or ground crew are distracted and forget critical safety checks due to fatigue or prolonged exposure.	Limit exposure and operation to prevent excessive operations.
The SUAS lighting system is inoperable.	Add SUAS lighting subsystem checks to pre-flight checks.
The SUAS, after returning from a mission, has suffered damage that requires repair before the next flight.	Increase the rigor of flight status inspection for night operations.

Table 5.3: Launch & recovery operations.

Potential Risk	Risk Severity	Probability	Resolutions
The RPIC encounters flight control issues due to environmental disturbances.	Minor	Probable	Acceptable risk, exists in current operations.
The RPIC is unable to see SUAS performance issues.	Major	Probable	Supply specific illumination for launch phase.
The RPIC is unable to see SUAS disengage from launch mechanism.	Major	Frequent	Supply visible indicator for successful release.
SUAS launch is too shallow.	Minor	Probable	Acceptable risk, exists in current operations.
The RPIC is unable to determine SUAS altitude as it descends.	Major	Probable	Ensure lighting system is sufficient. Ground control station to announce SUAS altitudes.
The RPIC does not have sufficient distance for a safe landing.	Minor	Remote	RPIC and visual observers to inspect recovery location prior to twilight.
Ground crew too close to recovery location.	Hazardous	Remote	Require sufficient proficiency. Improve flight planning.
The RPIC is unable to determine SUAS heading upon approach.	Minor	Probable	Utilize strip lighting on wings that improve heading orientation observability.

Table 5.4: Standard mission operation.

Potential Risk	Risk Severity	Probability	Resolutions
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The RPIC lost visual sight of SUAS due to distance.	Major	Probable	Ensure SUAS lighting system provides sufficient visibility. Establish clear visibility limits and improve mission planning.
The RPIC lost visual sight of SUAS due to obstruction.	Major	Probable	Improve flight planning operations. Require RPIC and visual observers to inspect for potential obstructions prior to twilight. Utilize secondary visual observers.
The RPIC lost visual sight of SUAS due to SUAS lighting system failure.	Major	Remote	Add SUAS lighting subsystem checks to pre-flight checks.
The RPIC is unable to determine SUAS orientation due to lack of training.	Major	Probable	Require sufficient training on determining orientation from lighting system. Ensure adequate visibility.
The RPIC is unable to determine SUAS orientation due to distance.	Minor	Probable	Require sufficient training on determining orientation from lighting system. Ensure adequate visibility.
The RPIC is unable to determine SUAS orientation due to changes in visibility or external factors.	Minor	Remote	Utilize secondary visual observers. Ground Control provide supplementary information.
SUAS flight performance has changed.	Minor	Remote	Analyze the lighting system integration to minimize changes to flight envelope.
The SUAS is heading to an obstruction.	Major	Remote	Require RPIC and visual observers to inspect for obstructions prior to twilight. Improve flight operation planning.
The SUAS is heading to an object in air (air traffic).	Hazardous	Remote	Utilize a second visual observer for intruding air traffic monitoring. Provide sufficient operation maneuverability for evasive actions.
The SUAS collides with power lines, trees or vegetation.	Hazardous	Remote	Require RPIC and visual observers to inspect for obstructions prior to twilight. Improve flight operation planning. Provide sufficient operation maneuverability for evasive actions.
The RPIC and primary observer lose communication.	Major	Remote	Require RPIC and primary visual observers to be co-located.
The RPIC and secondary observer lose communication.	Minor	Probable	Utilize secondary means of communication. Acceptable risk.

The common themes of potential risks led to the development of a set of goals that a safe flight operations at night must achieve. A flight operations at night must:

- Define the visibility range of the lighting system for a RPIC to conduct manual/guided flight or autonomous flight.
- Define the visibility range of the lighting system for observability for VOs and others.
- Implement a lighting system that enables the RPIC to determine SUAS position and attitude.
- Implement communication protocols for multiple VOs.

- Develop additional protocols for ensuring proper lighting system functionality.
- Develop additional protocols to minimize the risk of collisions (intruding air traffic and obstacles).

In the following subsections, a detailed description of the SUAS lighting system and procedural updates is presented.

5.2.2.2 SUAS Lighting System

The SUAS is to be outfitted with a lighting system that ensures visibility to the RPIC and visual observers, and is sufficient to determine SUAS orientation and position. Following the convention of §23.1385, the SUAS lighting consists of wingtip lights, wing-strip lights, tail lights and launch mechanism lights (Figure 5.2).

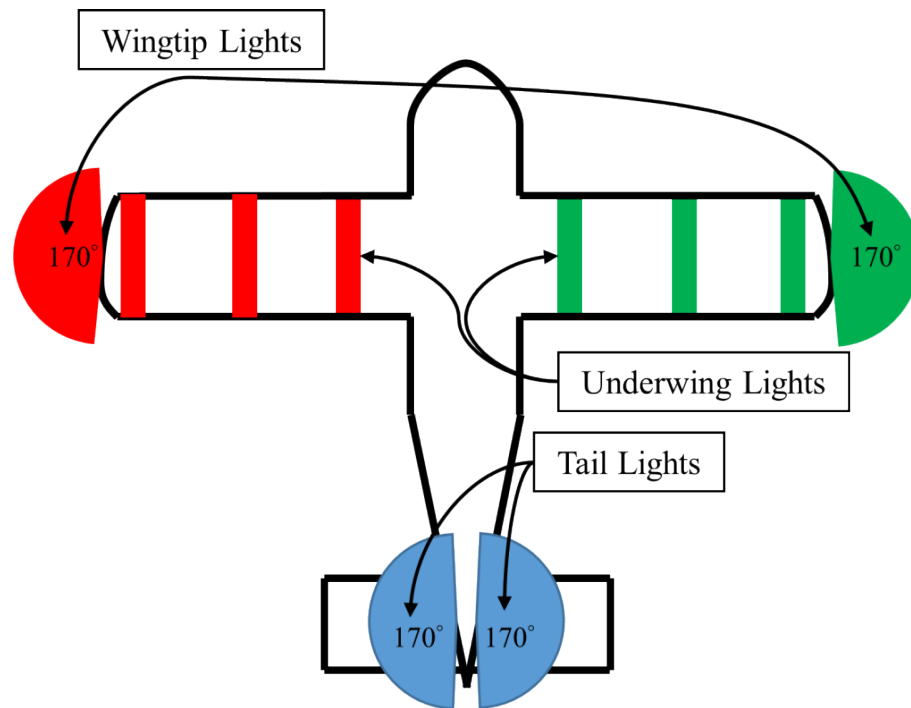


Figure 5.2: Wingtip lights, underwing lights and tail lights for SUAS.

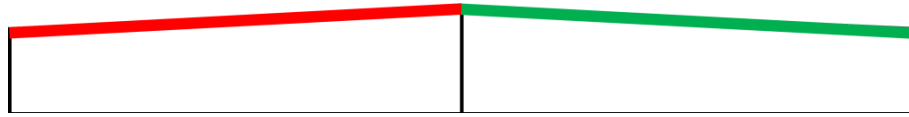


Figure 5.3: Underwing lights parallel with leading edge of wing.

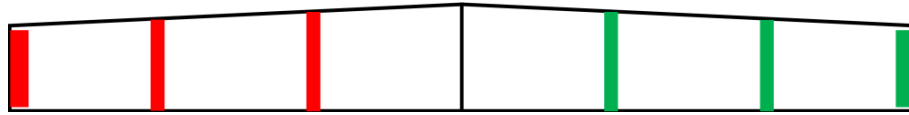


Figure 5.4: Underwing lights perpendicular with leading edge of wing.

Wingtip Lights

Wingtip lights, as previously described, are used for position and right-of-way determination in general aviation. While the proposed wingtip lights have a similar design, they have additional uses specific for SUAS use. With the RPIC on the ground, the ability of the RPIC to fly safely is dependent on the RPIC's situational awareness of the SUAS. At night, the normal visual cues of SUAS attitude (roll, pitch and yaw) and position (latitude, longitude and altitude) are not visible without illumination. The wingtip lighting is a simple mechanism for determining which wing is facing the RPIC, from which to infer flight direction and SUAS roll. At close range, it can be used for full pose estimation, however at long distances is only useful for roll and heading estimation by the RPIC. In contrast to §23.1387 requirements, nearly omni-directional lighting is preferred. The RPIC must be able to estimate SUAS orientation from any orientation in order to maintain an adequate level of safety. In the AggieAir system, the lighting used on each wing provided visibility up to 170 degrees. The use of red and green on the left and right wing respectively conformed to existing FAA regulations.

Underwing Lights

Ideally wingtip lights would be sufficient for RPIC and VOs; however, in practice they are insufficient on their own. Factors such as wing dihedral and narrow viewing angles at large roll angles necessitates the use of additional lighting. Underwing lighting was proposed to improve orientation estimation, especially at close distances. Two options were proposed: lighting strip parallel to the leading edge of the wing (Figure 5.3) and lighting strips perpendicular to the leading edge of the wing (Figure 5.4).

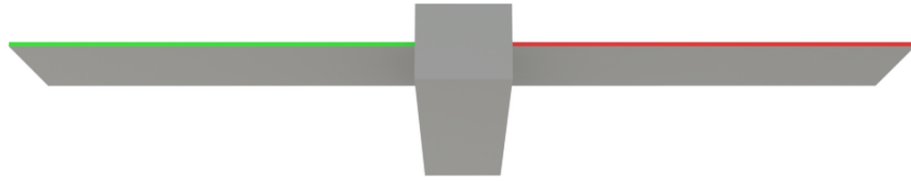


Figure 5.5: Perspective view of underwing lights parallel with leading edge of wing.



Figure 5.6: Perspective view of underwing lights perpendicular with leading edge of wing.

While underwing lights parallel to the leading edge of the wing initially seemed effective, it was found that arranging the lights perpendicular to the leading edge of the wing proved more effective. In this perpendicular orientation, the heading or yaw estimation was greatly improved, especially when directly facing the SUAS. As seen in Figures 5.5-5.8, the heading angle of the SUAS can be judged by the angle of the lights, whereas when parallel with the wing, the RPIC or VO must estimate the relative length and infer heading angle. In SUASs where recessing the lights within the wing is unfeasible, the use of strips of lighting additionally reduces the loss of airflow compared to arranging strips parallel with the leading edge of the wing.

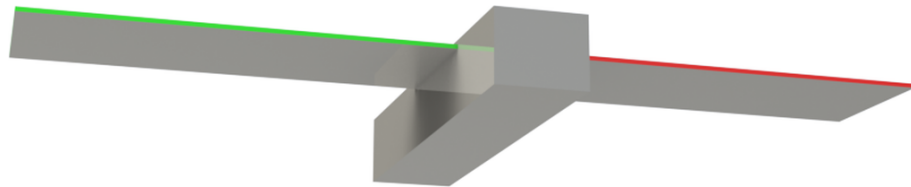


Figure 5.7: Perspective view of underwing lights parallel with leading edge of wing with SUAS at 20° yaw.

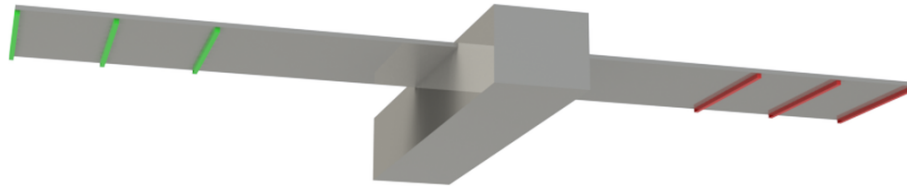


Figure 5.8: Perspective view of underwing lights perpendicular with leading edge of wing with SUAS at 20° yaw.

Tail Light

The use of the tail light on an SUAS is used both as a beacon and as an indicator of SUAS pitch. While a pulsing light on the tail is common for general aviation, it was found to be ineffective and potentially distracting for the RPIC. As the RPIC or VO must maintain constant visual with the SUAS at all times, the need to be ‘attention grabbing’ was not a priority over SUAS attitude estimation. The RPIC or VO would use the general relationship between the wingtip lights and the tail light to infer SUAS pitch. To prevent obscuring the tail light with the red or green light of the wings, white was chosen as the light color. At close distances, the light from the tail provided illumination of the SUAS registration number on the tail of the SUAS.

Launch and Recovery Lighting Systems

The launch and recovery of a fixed-wing SUAS is often the most sensitive and challenging aspect of SUAS operation. As such, extra precautions were developed to provide a sufficient level of situational awareness during these key phases. In the case of a catapult, slingshot or other assisted launch system, indicator lights are valuable to alert the RPIC and VOs of successful actions or the need for corrective actions. In the AggieAir system, a slingshot or bungee system is used to propel the SUAS with sufficient airspeed for lift. Two critical conditions exist for this setup: the successful release of the bungee cord and the SUAS has cleared the launch zone at an appropriate velocity. Due to the need for the RPIC and VOs to have adapted to the darkness, all phases of the SUAS mission must occur at the same illumination. This eliminates the ability to use a brightly lit runway for the visualization of these two critical conditions. Instead, two indicator LEDs are used: on the bungee cord and at the clearance point. The RPIC is able to use the bungee indicator LED to judge if the bungee cord has released from the SUAS. The clearance point marker provides the RPIC a reference point at which the RPIC may judge the airspeed of the SUAS (Figure 5.9)

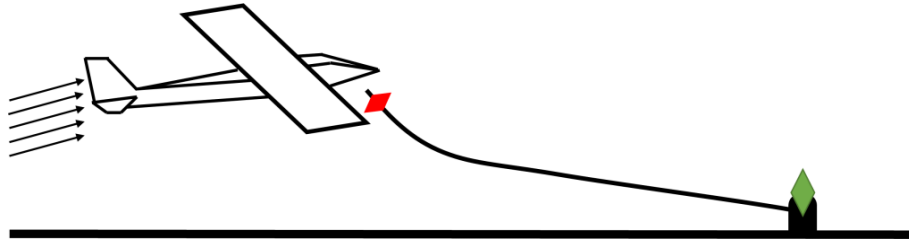


Figure 5.9: Diagram of lighting system for a mechanically assisted launch.

Recovery operations also may require modifications. In general aviation, landing lights are common to illuminate the terrain or runway during approach, however, these are most effective to the PIC within the SUAS. The same lights are of limited value to a RPIC or VOs outside of the SUAS. The major challenge of the recovery operation is in the accurate determination of SUAS altitude on approach and heading angle. In practice, RPICs found the addition of bright landing lights to be a distraction. Instead, the use of mild lights at an evenly space interval was found more conducive for a safe landing. These mild lights provided the necessary reference point for the RPIC to judge SUAS altitude, and the use of underwing lights provided the necessary information to infer SUAS heading.

5.2.2.3 Protocols for Flight Operations at Night

Supplemental operations are necessary for safe flight operations at night in addition to the implementation of an SUAS lighting system. In this section, additional operations for site inspection and training requirements are discussed to minimize risk.

Site Inspection

Site inspections are common for SUAS operations, however, the added difficulty of night operations necessitates several additional requirements and processes. The SUAS lighting system previously described addresses the visibility issues of night operations, but it does not adequately address the potential of air safety threats such as visual obstructions and potential collisions.

While visual obstructions are a common issue in all SUAS operations, the related issues are increased during night operations. Whereas during day operations, a visual obstruction is immediately apparent, at night with limited visibility, the complete loss of visual on the SUAS is sudden, without warning and introduces ambiguity where the RPIC or VOs must guess whether the loss of visual is an obstruction or an SUAS failure. To mitigate this potential risk, a site inspection is recommended during daylight hours to allow the RPIC and VOs an opportunity to scout out any and all risks. SUAS flight plans can be adjusted or alternatively,

potential obstructions can be marked with low-intensity illumination. Potential collision risks can be marked in a similar fashion during a daylight site inspection.

Additional Training Requirements

SUAS orientation is more difficult to determine when the number of visible cues are reduced. In the proposed system, the RPIC or VOs must be able to infer SUAS orientation solely on the installed lights. At short distances, this is relatively easy, as the individual lights are sufficiently spaced to be visible. However, as the distance increases, it becomes more and more difficult to discern the colors and shapes. In practice, for an 8 ft wingspan SUAS, full pose estimation was rendered impossible at distances greater than 1000 ft, however, roll and heading estimation was possible to 2.0 NM.

In order to sufficiently train the RPIC and VOs for night operations, an SUAS orientation training and testing system was developed. This training system uses a model aircraft outfitted with the SUAS lighting system and the trainee practices inferring the correct orientation from a distance greater than 700 ft. This training is described as follows. The testing team is composed of a crew of two: the test evaluator and an SUAS manipulator. The SUAS manipulator will be set up at a predefined location, greater than 700 ft from the test evaluator and testee. When the test begins the SUAS manipulator will activate the SUAS lighting system with the SUAS in a predefined orientation, such as level with right wing facing testee. The SUAS manipulator will rotate the SUAS slowly in a predefined pattern mimicking the motions of an SUAS in flight. At predefined test points, the SUAS manipulator will signal to the test evaluator to question the testee on the SUAS's orientation. This process is repeated for a minimum of 15 evaluations. The test evaluator will score the testee on the accuracy of their responses in coordination with the SUAS manipulator. A score is considered passing with an accuracy over 70%.

As flight operations at night poses an additional challenge, an additional concurrency requirement is added. RPICs and VOs must complete 3 night launch and recovery operations within the past 90 days to maintain their concurrency. It is recommended that VOs be able to substitute a successful SUAS orientation test in lieu of a flight operations at night.

Protocols

Additional adjustments to SUAS protocols are required for flight operations at night. These adjustments are small, but critical to maintain an equivalent level of safety as daylight flights.

- The use of a secondary, distant VO provides a secondary viewing point for obstacles and to monitor for intruding air traffic. This is particularly important as inferring position becomes more difficult at night with the reduction in visible cues.

- To ensure the RPIC and VOs have adapted their visibility to the dark, it is required that all participants be in place at least 30 minutes prior to UAS operations. This provides sufficient time for the RPIC and VOs to adapt to the dark such that they are able to see effectively during the night.
- Additional pre-flight checks are recommended to ensure that the SUAS lighting system is operational and that VOs are in place prior to SUAS operations.
- During long operations, the RPIC and VOs may begin to lose orientation as fatigue sets in. It is required that the Ground Control Station Operator or operator with access to the SUAS telemetry repeat heading, altitude, and general location every minute. This provides the RPIC and VO with a known SUAS status for them to infer future orientation and position.
- During night operations, it can be easier to overlook damage in the dark. An additional round of SUAS inspection is required immediately after a flight in order to ensure integrity is intact.
- The human factors of night operations also require addressing. During night operations, operator fatigue and prolonged exposure at night can contribute to operator complacency and potential unsafe acts. Operational requirements to mitigate these effects include reducing operation time compared to daylight flights and utilizing a rotating ground crew for inspections and critical flight elements.

5.2.3 Implementation and Regulatory Recommendations

While flight operations at night is allowed and performed regularly by AMA licensed persons for pleasure at AMA fields, the scale and scope of many SUAS operations require a different approach. It was noticed during development that the brightly lit model aircraft regularly flown by trained persons were ineffective at long distances. The sheer number of lights blend together at long distances, creating an indiscernible bright spot that disorients the RPIC. While the SUAS was plainly visible, the level of situational awareness was a significant safety risk, unsuitable for SUAS operations.

It was determined that rather than adding a fully illuminated SUAS, that optimally placed lights would prove to be a more efficient and safer solution. Initial developments utilized the regulations found in 14 CFR 23 to mimic the utility found in full-size aircraft. However, the drastic reduction in lighting also led to a different set of issues. The purpose of the lights found in 14 CFR 23 ultimately held a different purpose than the proposed operations. In an SUAS operation, constant visual observation of the SUAS is required, but this also includes the ability of the RPIC to retain a sufficient level of situational awareness to RPIC the SUAS

when necessary. This revelation caused a shift in approach and design to focus on the RPIC's ability to maintain correct orientation during flight, while maintaining the ability for air traffic to visually observe the SUAS from an adequate distance. Visibility of at least two of the three colors (red, green and white) on the SUAS was necessary at all times, and thus the need for nearly omni-directional lighting was realized.

Initial testing of the illumination system was performed on a half-sized foam SUAS, where orientation tests were performed on the ground with the RPIC observing orientation and assistant manipulating SUAS attitude at a series of set distances. The illumination system was then adjusted and retested until justifiable confidence in the system was achieved. The SUAS was then flown at night by trained persons to reassure the concluded system, as well as assess the effectiveness of the system and make necessary changes. Some conclusions drawn from this testing are:

RPIC Experience:

1. Too much ambient light results in disorientation;
2. Too much light on the SUAS is too distracting;
3. The RPIC needs a VO that can assist in radio communications between the RPIC and the GCS, transportation of the RPIC if need be and illumination of landing strip;
4. Red light must be used by anyone in close proximity to the RPIC prior to and during operation.

VO Experience:

1. Similar to RPIC, too much light on the SUAS is too distracting;
2. Ensure all necessary pre-flight preparations;
3. Ensure crew readiness prior to launch;
4. Difficult to confirm cord was detached from hook when using the catapult launcher;
5. VO needs to follow proper radio communication protocol, including repeating every message for clarification;
6. Constant scan for air traffic is needed to help RPIC.

As previously described, flight operations at night require some level of adherence to existing FAA regulations. A summary of existing relevant regulations and their applicability to SUAS operations is presented in Table 5.5.

Table 5.5: Relevant Federal aviation regulations.

Statute	Description	Notes
§23.1322	Cockpit Warning Lights	Not Applicable for SUAS operations
§23.1381	Instrument Lights	Not Applicable for SUAS operations
§23.1383	Taxi and Landing Lights	Could be considered applicable for SUAS operations, but was found that landing lights were distracting to RPIC, and thus a safety risk. Recommendation is to grant exemption for SUAS operations at night.
§23.1385	Position Light System Installation	Applicable for SUAS Operations.
§23.1387	Position Light System Dihedral Angles	Insufficient for SUAS operations. Recommendation is to expand dihedral angles R and L to 170°, and tail light should be visible 360°.
§23.1389	Position Light Distribution and Intensities	Difficult to meet intensity requirements on SUAS. Recommendation is to grant exemption and adopt a scale appropriate intensity requirement.
§23.1391	Minimum Intensities in the Horizontal Plane of Position Lights	Difficult to meet intensity requirements on SUAS. Recommendation is to grant exemption and adopt a scale appropriate intensity requirement.
§23.1393	Minimum Intensities in Any Vertical Plane of Position Lights	Difficult to meet intensity requirements on SUAS. Recommendation is to grant exemption and adopt a scale appropriate intensity requirement.
§23.1395	Maximum Intensities in Overlapping Beams of Position Lights	Overlapping beams of position lights is necessary for orientation estimation by the RPIC. Recommend exemption for SUAS operations.
§23.1397	Color Specifications	Applicable for SUAS Operations.
§23.1399	Riding Light	Not evaluated in this study
§23.1401	Anti-collision Light System	Anti-collision light proved distracting and detracted from the conspicuity of the position lights for RPIC and presented a safety risk. Exemption not necessary due to §91.209(b)
§61.57(b)	Recent Flight Experience	Applicable for SUAS Operations.
§61.109(a)(2)	Aeronautical Experience	Applicable for SUAS Operations, but recommend scale appropriate.
§91.209	Aircraft Lights	Applicable for SUAS operations. §91.209(b) provides exemption for lack of anti-collision light as its installation would pose a safety risk.

While many regulations are applicable for SUAS operations, several are recommended to require amending. Minimum intensities, as required, may be significantly excessive depending on the size of the SUAS and the scope of the operation. The lighting system intensity is recommended to be sufficient for the maximum proposed distance rather than regulated to a specific intensity level.

The use of anti-collision lights is recommended to be relieved for SUAS. In the development and testing of AggieAir’s system, the pulsing light proved to be a distraction and detracted from the conspicuity of the position lights. While a pulsing light greatly improves detectability, especially in the peripheral of a RPIC’s vision, it is unnecessary for an SUAS RPIC who is required to maintain constant visual contact. When the RPIC focused on the bright flashes of the anti-collision light, the RPIC’s eyes attempted to adapt to the elevated brightness and diminished the RPIC’s ability to discern the other dimmer position lights.

5.3 Optimal SUAS Swarm Safety Management

As discussed in Chapter 4, the optimization of data collection may require multiple SUAS working simultaneously or cooperatively to meet the application goal. In a cyber-physical system, a similar challenge exists if an SUAS is proposed for the actuation of control parameters [39]. This is especially true for the proposed use of SUAS for precision spraying of pesticides [137]. While SUASs have a number of advantages, such as portability and ease of use, they suffer from some disadvantages: limited flight duration, limited payload capacity, and fragility [26, 137]. The optimization of SUAS actuation can be deployed, as described in [137], but this only addresses limited flight time and limited payload capacity. The fragility of an SUAS often manifests itself as factors that impact performance; poor weather conditions that require additional fuel usage, damaged or ineffective propulsion elements, or even instantaneous hardware failures during flight. The fragility element of the SUAS can be measured as its ‘health,’ and in many cases, it is not limited to only the current flight operation. The damage or improper usage of an SUAS can have a significant effect on the future reliability and robustness of the SUAS. However, with a swarm configuration, there is an opportunity to compensate and balance usage. With an interconnected SUAS swarm, this balancing can be done in real-time. The balancing of ‘health’ then could be used for improving SUAS safety and could be a component moving forward on multiple SUAS management [4].

Typically, this issue has been addressed in literature for military applications or persistent surveillance operations where the objectives are simply to provide a presence at a location. In [138], a cooperative control architecture is implemented with stochastic risk models to add intelligence to the UASs to avoid risky behaviors or locations. Previous work by [139] incorporated fuel usage into the architecture to develop a ‘health-aware’ mission planner with a dynamic programming approach. This architecture is well-poised for the discrete mission task orientated approach

posed by those authors but is not well-suited for implementing diffusion process control such as found in agricultural applications. Other cooperative control approaches that include health management often appear in conjunction with enemy damage avoidance and balancing fuel consumption in those efforts, such as in [140] where Model Predictive Control (MPC) was developed with a particle swarm optimization to incorporate fuel consumption with the potential of enemy damage.

In a civilian setting, a different cooperative control and management is better suited. Cyber-physical systems, such as pesticide management can be better modeled as a partial differential equation (PDE) diffusion process [141]. In that work, the authors utilized Centroidal Voronoi Tessellations (CVT) to solve the optimal actuator placement for a diffusion process of a PDE. The optimality of the actuator placement provides the best use of control effort, reducing the use of spraying application and neutralizes the infection in the fastest time. This framework can be used in an agricultural application and provide a significant economic gain [39].

In [142], a CVT based framework was utilized for coverage control and introduced the use of multiplicatively weighted Voronoi partitioning for addressing non-identical health conditions for sensors. In this work, each SUAS was responsible for sensing and localizing some process. The use of the multiplicatively weighted regions allowed for region shaping depending on the health of each SUAS's sensor. This effort was focused on the sensing of a process, however, when the objective is to provide control (such as the spraying of a pesticide) to diffuse an infection, this approach would not improve performance.

In this section, a swarm of cooperative SUASs are set up within a cyber-physical framework to optimize spraying a neutralizing agent over a rapidly spreading diffusion process, while simultaneously balancing the health of the fleet to ensure the maximum life of the weakest SUAS using a Smart Health Balancing (SHB) system. In Section 5.3.1, the problem statement and the CVT framework is introduced. The control system of the SUAS and the SHB system is described in Section 5.3.2. In Section 5.3.3, the proposed SHB is evaluated through simulations. Finally, concluding remarks are found in Section 5.3.4.

5.3.1 Optimal Coverage

The problem of optimal coverage in the presence of degrading health can be framed in a cyber-physical system [54]. In a setting where real-time sensing of an area is possible, an optimal cooperative control system for the eradication of an invasive and volatile pathogen is possible [137].

Suppose Ω represents a convex polytope such that $\Omega \in R^2$, where a diffusion process can occur. Within this region, suppose there exists a group of n SUASs, denoted as the set $P = \{p_1, p_2, \dots, p_n\}$ where $p_i = (x_i, y_i)$, representing the coordinates of each SUASs.

The region with the pathogen within Ω can be described as $\rho(x, y) : \Omega \rightarrow R_+$. This diffusion process can be described by the following PDE:

$$\frac{\delta \rho}{\delta t} = k \left(\frac{\delta^2 \rho}{\delta x^2} + \frac{\delta^2 \rho}{\delta y^2} \right) + f_d(\rho, x, y, t) + f_c(\tilde{\rho}, x, y, t) \quad (5.1)$$

where k is some positive constant system parameter, $f_d(x, y, t)$ represents the pathogen source, $f_c(\tilde{\rho}, x, y, t)$ represents the control application for neutralizing the pathogen, and $\tilde{\rho}$ is the measured sensor data. For convenience, ρ is used to represent $\rho(x, y)$.

The group of SUASs behave as mobile actuators, each applying some application control force $f_c(t) = f_{c1} + f_{c2} + \dots + f_{cn}$.

The region Ω can be partitioned into n Voronoi diagram regions such that $\mathcal{V} = \{\mathcal{V}_1, \mathcal{V}_2, \dots, \mathcal{V}_n\}, p_i \in \mathcal{V}_i, \mathcal{V}_i \cap \mathcal{V}_j = \emptyset$ for $i \neq j$

$$\mathcal{V}_i = \{q \in \Omega \mid |q - z_i| < |q - z_j| \text{ for } j = 1, 2, \dots, n, j \neq i\} \quad (5.2)$$

where $|\cdot|$ is the Euclidean distance, z_i represents a set of points belonging to Ω and q is any arbitrary point. The members of the set $\{z_i\}_{i=1}^k$ are referred to as the generators of each cell $\mathcal{V}_i$.

Given a density function $\rho(\tilde{q}) \geq 0$ defined in Ω , then for each Voronoi cell, $\mathcal{V}_i$, the mass centroid z_i can be defined by:

$$z_i = \frac{\int_{\mathcal{V}_i} q \rho(q) dq}{\int_{\mathcal{V}_i} \rho(q) dq}. \quad (5.3)$$

For controlling a diffusion process, the following objectives are introduced:

- To control the diffusion of the pathogen
- To neutralize the pathogen as quickly as possible without over application of control force
- To balance the health and usage of the fleet

To meet the desired control objectives, the following evaluation equation is introduced:

$$\kappa(\rho, \mathcal{V}) = \sum_{i=1}^n \int_{\mathcal{V}_i} \rho(q) |q - p_i|^2 dq \text{ for } q \in \Omega \quad (5.4)$$

such that

$$|\dot{p}_i| < k_v, |\ddot{p}_i| < k_a, \sum_{i=1}^n \int u_{spray,i}(t)dt < k_s, |h_i - h^*| < k_h \quad (5.5)$$

where $\dot{p}_i$ and $\ddot{p}_i$ represent the first and second-order dynamics of the UAS, $u_{spray,i}$ represents the neutralizing control input of actuator i at time t , h_i is the health of the actuator, h^* is the average health of the all actuators, and constants k_v, k_a, k_s, k_h are strictly positive threshold constants.

5.3.2 Distributed Coverage Control with Smart Health Balancing

5.3.2.1 SUAS Vehicle Dynamics and Control

Throughout the section, the SUAS is assumed to be a highly mobile vehicle, capable of moving in any direction and capable of hovering in place, such as a rotary-wing vehicle or a blimp. In this assumption, each SUAS can be treated as a virtual particle with second order dynamics,

$$\ddot{p}_i = u_i, \quad (5.6)$$

where u_i is the control input of the i^{th} SUAS.

The neutralizing spraying actuation force $f_c(\tilde{\rho}, x, y, t)$ can be any arbitrary function. In this section, it is assumed to be in the form of a PDE, spraying an airborne neutralizing agent directly underneath the SUAS.

5.3.2.2 SUAS Health Management

The health for each SUAS, i , can be represented by $h_i(t)$ at time t . The health function $h_i(t)$ can be formulated as:

$$h_i(t) = h_i(0) - d_i(t), \quad (5.7)$$

$$d_i(t) = \int_0^t k_d u_i^2 dt + f_{d,i}(t), \quad (5.8)$$

such that

$$\dot{h}_i(t) \leq 0, \dot{f}_{d,i}(t) \geq 0, h_i(t), f_{d,i}(t) \in [0, 1], \quad (5.9)$$

where $h_i(0)$ is the starting health of SUAS i , k_d is a usage gain scalar, and $f_{d,i}(t)$ represents external negative effects on SUAS health, for example in the event of a mid-air collision. In this section, the health of each SUAS degrades over time as a function of its control effort and any external damage it may encounter. An SUAS directed to move quickly and change directions rapidly will encounter a faster health degradation than an SUAS that is largely stationary. Physically speaking,

this calculation can be a combination of remaining fuel and structural health, or amended to include SUAS spraying usage [4].

The nominal health $h^*(t)$ of the SUAS fleet is calculated as the current average health of all SUASs,

$$h^*(t) = \frac{1}{n} \sum_{i=1}^n h_i(t), \quad (5.10)$$

such that

$$\dot{h}^*(t) < 0, h^*(t) \in [0, 1]. \quad (5.11)$$

It is assumed that each SUAS can communicate globally with other SUASs in the region to calculate their respective Voronoi regions and have access to the global average health $h^*(t)$. The control of each SUAS is accomplished with a simple P controller modulated by the SHB system which utilizes a simple PD controller. The control $u_i(t)$ can be represented as:

$$u_i(t) = k_p \cdot [1 + k_{h,i}(t)] \cdot (p_i - z_i), \quad (5.12)$$

$$e_i(t) = h_i(t) - h^*(t), \quad (5.13)$$

$$k_{h,i}(t) = k_{h_p} e_i(t) + k_{h_d} \dot{e}_i(t), \quad (5.14)$$

where $k_{h,i}$ represents the SHB gain that changes the movement control of the UAS, e_i represents the health residual between SUAS i and the global health average $h^*(t)$ and k_{h_p} and k_{h_d} represent the SHB gains.

The desired observation of the SHB system is to maximize the lifetime t of the vehicle with the lowest health, h_i . At each time step, SUAS i calculates its Voronoi region and calculates its centroid z_i in order to construct its desired location. It then calculates its health and computes the residual to adjust its control input. The result is that the less healthy SUASs are commanded to move more conservatively to maximize flight endurance.

5.3.3 Simulation Results

The performance of the smart health balancing system can be demonstrated by maximizing the minimum time till an SUAS death for the swarm of SUASs [4]. With the implementation of the smart health balancing system, the goal is to keep all the SUASs as healthy as possible and to mitigate disproportional health degradation. In this section, four scenarios are presented and examined:

1. No abnormal health behavior for any SUAS in the swarm,
2. One SUAS suffers from an increase rate of health degradation,

3. One SUAS initializes at a lower health than the rest of the swarm,
4. One SUAS suffers from a sudden decrease in health.

These scenarios represent some common expected health issues. Scenario (1) represents the best case scenario where no SUAS suffers from abnormal health behavior and thus the SHB is utilized to balance the utilization of each SUAS. Scenario (2) may occur during an engine malfunction that lowers fuel efficiency. Scenario (3) could represent a battery that was not fully charged before being used. Scenario (4) could be a minor component malfunction such as a structural fracture. In these scenarios, the health degradation or malfunction does not require an immediate recovery, but continued operation may impact future health and performance.

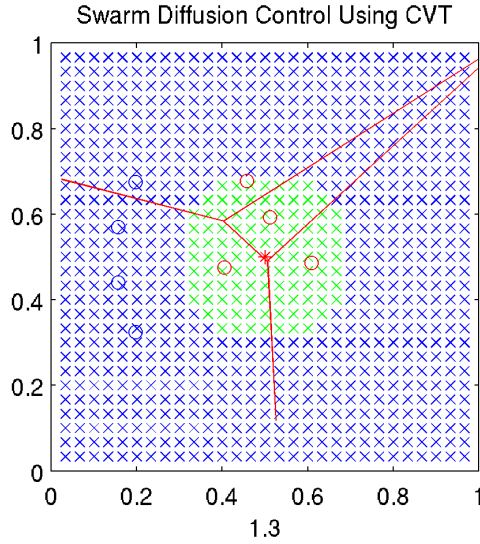


Figure 5.10: Diffusion control using four SUASs in a CVT framework.

Each of these four scenarios were run with a swarm of four SUASs sent to neutralize a diffusion process in the center of the region (Figure 5.10). For each scenario, two simulations were performed, one without the smart health balancing system (Nominal) and one with the SHB. The green region in the center represents the diffusion source. The red circles represent the centroids of the Voronoi regions and the desired SUAS positions. The red lines represent the boundaries between Voronoi regions. The blue circles represent the SUAS.

5.3.3.1 Scenario 1

Figures 5.11 - 5.14 depict results from the first scenario, where each SUAS initializes at the same health level and the health of each SUAS degrades normally

with its motion. Figure 5.11 plots the health of each SUAS during the neutralization swarm control without the smart health balancing. In this simulation, SUAS 4 drops faster than the rest and hits an arbitrary health threshold at $h_i(t) = 0.4$ at time step 300. In Figure 5.12 with smart health balancing, the same SUAS extends its life and does not reach the threshold until time step 347, representing a 15% increase in life.

It can be seen in Figure 5.13 that without the smart health balancing, the disparity in SUAS health diverges over time, whereas in Figure 5.14, the disparity is bounded and satisfies the $|h_i - h^*| < k_h$ requirement set in eq. 5.5. Even though there is nothing wrong with any of the SUASs, the addition of the smart health balancing extends the lifetime of the swarm.

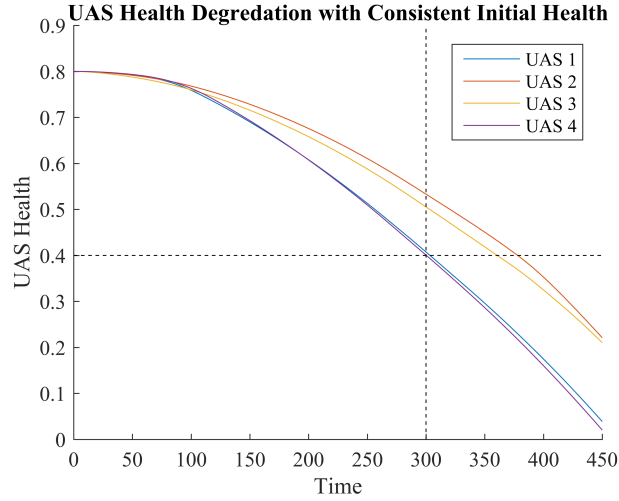


Figure 5.11: Plot of SUAS Health for four SUASs with an initial health of $h_i(0) = 0.80$ and normal degradation rate for Nominal.

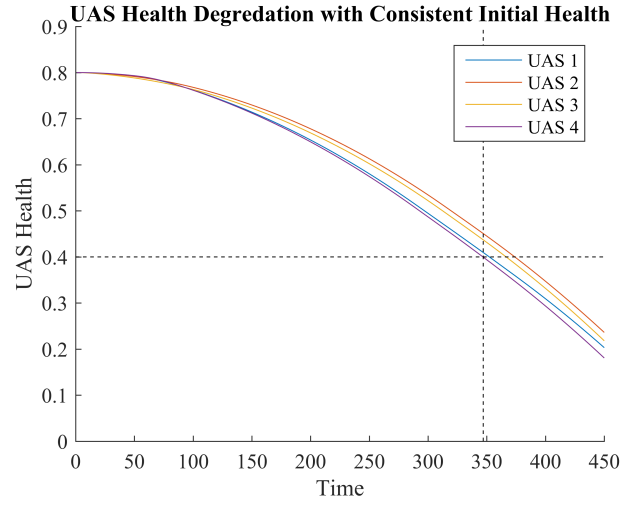


Figure 5.12: Plot of SUAS Health for four SUASs with an initial health of $h_i(0) = 0.80$ and normal degradation rate for SHB.

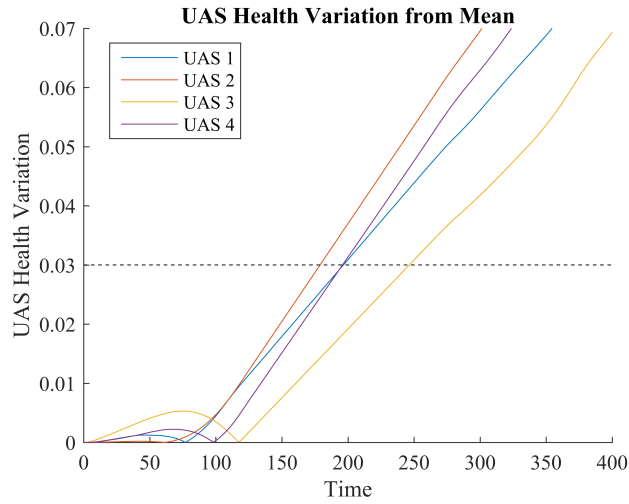


Figure 5.13: Plot of the difference between SUAS health and mean health for Nominal.

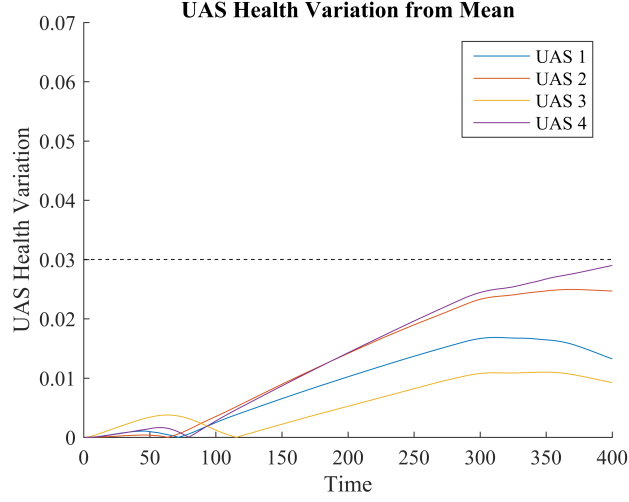


Figure 5.14: Plot of the difference between SUAS health and mean health for SHB.

5.3.3.2 Scenario 2

The results are further pronounced in the remaining three scenarios. Figures 5.15 and 5.16 show the health of each SUAS under consistent initial health with SUAS 4 having a degradation rate double that of the other SUAS. In the Nominal scenario, the first SUAS to degrade to $h_i(t) = 0.4$ health occurs after 204 time steps. After smart health balancing is applied the system requires 280 time steps. This represents a 37% increase in survival time for the mission.

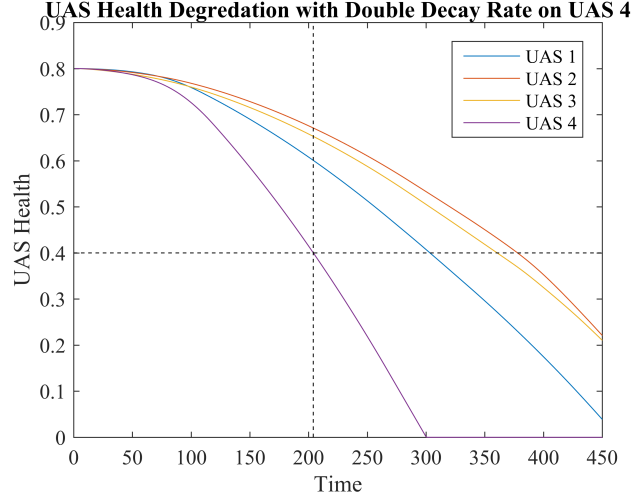


Figure 5.15: Plot of SUAS Health for four SUASs with an initial health of $h_i(0) = 0.80$ and double degradation rate for SUAS 4 for Nominal.

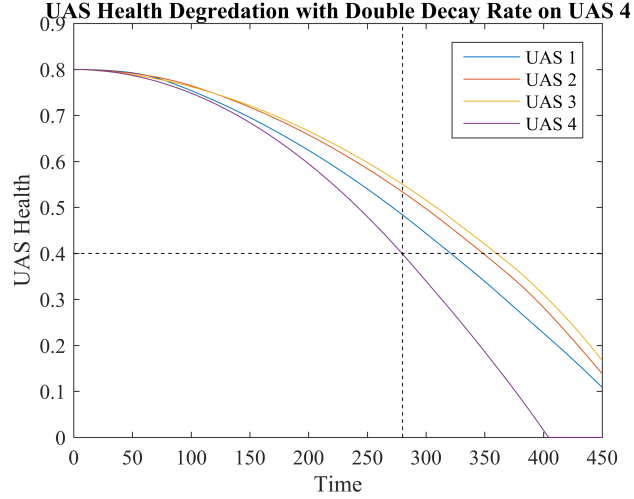


Figure 5.16: Plot of SUAS Health for four SUASs with an initial health of $h_i(0) = 0.80$ and double degradation rate for SUAS 4 for SHB.

5.3.3.3 Scenario 3

Figures 5.17 and 5.18 show the health of each SUAS for scenario (3). While SUASs 1-3 start at $h_i(0) = 0.8$, SUAS 4 initializes at $h_4(0) = 0.6$. In the Nominal simulation (Figure 5.17), SUAS 4 degrades to $h_i(t) = 0.4$ after 204 time steps. After

smart health balancing is applied the same system survives to 282 time steps before reaching the threshold (Figure 5.18).

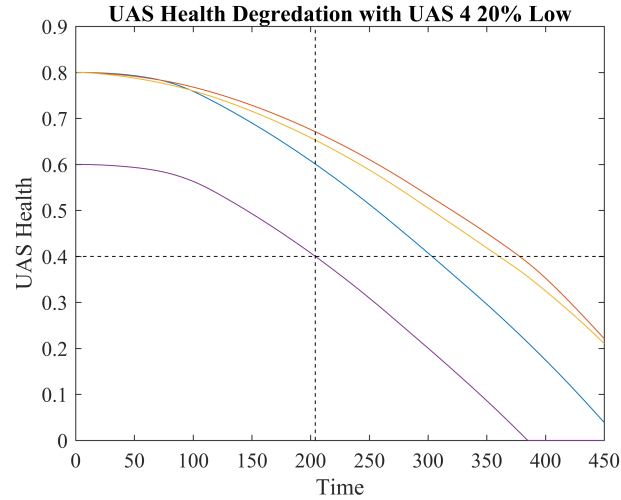


Figure 5.17: Plot of SUAS Health for three SUASs at $h_i(0) = 0.80$ and SUAS 4 at $h_4(0) = 0.60$ for Nominal.

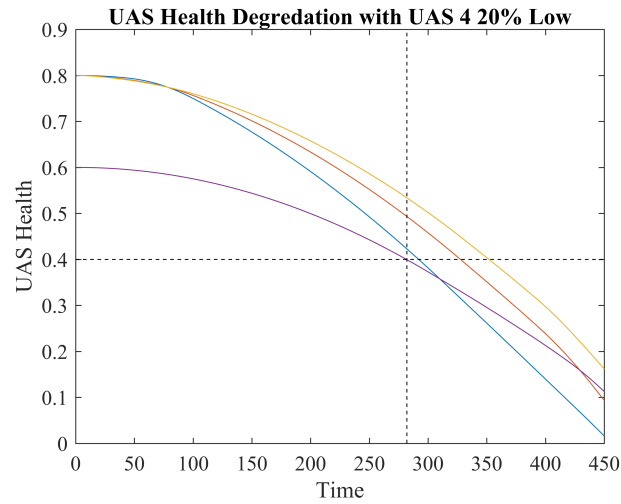


Figure 5.18: Plot of SUAS Health for three SUASs at $h_i(0) = 0.80$ and SUAS 4 at $h_4(0) = 0.60$ for SHB.

5.3.3.4 Scenario 4

Figures 5.19 and 5.20 show the health of each SUAS under equal initial health and health degradation rates under scenario (4). At time step 250, SUAS 4 simulates receiving damage mid-flight by applying $f_{d,i}(t) = 0.3$ at $t = 250$. In the Nominal simulation (Figure 5.19), SUAS 4 degrades to death ($h_i(t) = 0$) after 346 time steps. After smart health balancing is applied (Figure 5.20) the SUAS survives to 397 time steps.

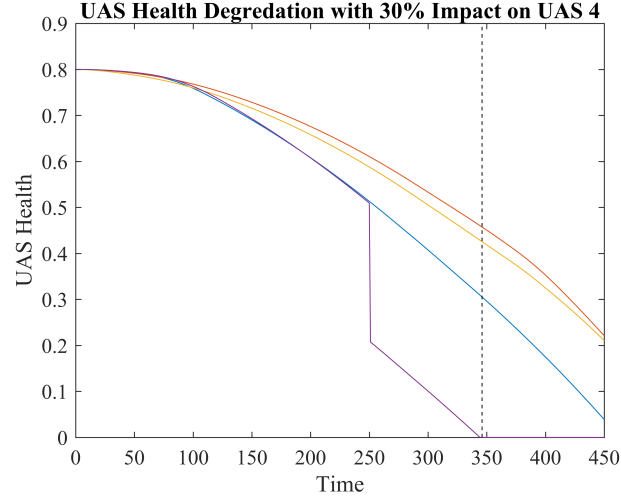


Figure 5.19: Plot of SUAS Health for four UASs with an initial health of $h_i(0) = 0.8$ and a 0.3 health impact for SUAS 4 for Nominal.

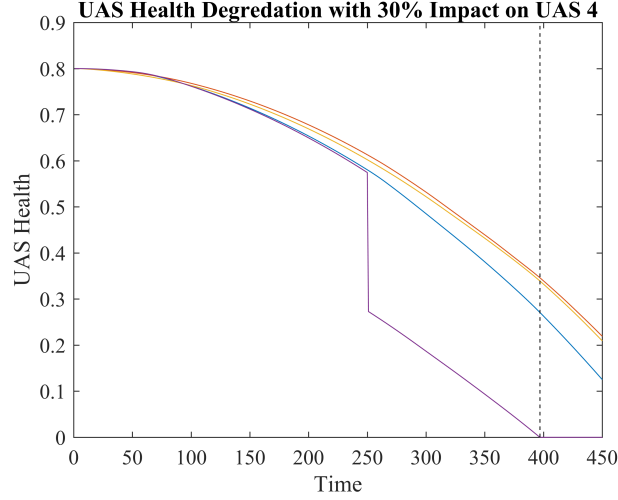


Figure 5.20: Plot of SUAS Health for four UASs with an initial health of $h_i(0) = 0.8$ and a 0.3 health impact for SUAS 4 for SHB.

The results from all four scenarios can be seen in Table 5.6. In all four scenarios, the addition of the smart health balancing increases the minimum time till death of the weakest SUAS by a significant margin with only minimal adjustments to the existing framework. The SHB ensures that the swarm is capable of operation for a longer period of time and prevents prolonged disproportional wear.

	Nominal	SHB
Scenario (1)	300	347
Scenario (2)	204	280
Scenario (3)	204	282
Scenario (4)	346*	397*

Table 5.6: Time for first SUAS to reach $h_i(t) = 0.4$. * denotes time till SUAS death, $h_i(t) = 0$.

5.3.4 Analysis

The concept of balancing health for operations such as coverage control addresses one of the aircraft safety challenges identified by the FAA as an impediment of SUAS integration into the NAS. Ensuring the reliability of SUAS in the field is vital to promoting SUAS as a viable option for autonomous diffusion control applications. In real-world applications, the SUASs are likely to experience a wide variety of environments and conditions that will negatively affect performance and

lifetime. In commercial operations, swarm robustness and reliability is a vital aspect, especially in agricultural environments where usage can be frequent in harsh conditions. It can be seen that through the application of smart health balancing to each SUAS, the entire SUAS swarm is more robust to variations in health, caused by any number of very plausible scenarios. The system can better react to unforeseen damage from collisions, mechanical failure, or insufficient maintenance. The method of team and individual health aware motion control can also be applied to systems of SUAS with different performance capabilities, that is, the heterogeneous drone team, which can be investigated in future research efforts.

5.4 The Implementation of ADS-B for SUAS

The safe integration of UASs into the NAS has been the subject of numerous exploratory reports and research. Of the many challenges identified, sense and avoid (SAA) is routinely singled out one of the major limiting factors in UAS to NAS integration [33, 129]. However, developing a single solution is counter to the FAA’s layered approach towards safety [33, 143]. As with the regulatory process, it is clear that there is no ‘one size fits all’ solution [36]. One of the proposed solutions is to require the deployment of ADS-B, a key piece of Next Generation Air Transportation System (NextGen), the FAA’s goal for a modern NAS. Within NextGen, ADS-B is proposed to help transform the US’s Air Traffic Control (ATC) system from a radar-based system to a Global Positioning System (GPS)-based system [144]. As the rapid growth of UASs have coincided with the development of ADS-B, it has been proposed to utilize this technology for SAA [145].

On the topic of SAA, current regulations and proposals have addressed UASs, but have largely explicitly excluded SUASs in many discussions [145]. While larger UASs perform similarly to other manned aircraft and have similar requirements and characteristics, SUASs have a very distinct set of challenges that warrant special consideration [90]. Within specific discussions for SUAS, the FAA has been reluctant to set safety standards due to lack of research [35]. In this section, the integration of ADS-B in future Sense and Avoid Systems (SAASs) is addressed, specifically for SUASs. The implementation challenges and regulatory issues are outlined and addressed. The rest of this section is organized as follows. In Section 5.4.1, Conflict Detection and Resolution Strategies, strategies associated with safety, sensing and conflict resolution is introduced. In Section 5.4.2, Sense and Avoid Systems, a survey of existing SAAS and their implementations is presented with an emphasis on ADS-B. Regulations regarding SUASs, SAAS and ADS-B are discussed in Section 5.4.3, Regulations and Limitations. Implementation strategies for the use of ADS-B in future SAAS is presented in Section 5.4.4, Integration of ADS-B in SUASs. Final remarks are presented in Section 5.4.5.

5.4.1 Conflict Detection and Resolution Principles

The goal of a SAAS is to deliver an analogous capability to ‘see and avoid’ requirements of manned aircraft. This capability has been identified by the FAA as being comprised of two major aspects: collision avoidance and self-separation [33]. In the following section, the existing strategies and approaches towards air safety, sensing and conflict resolution are introduced.

5.4.1.1 Air Safety Strategies

The FAA relies on the eyesight of its human PICs as the primary method of collision avoidance, utilizing other systems such as ADS-B as secondary systems. These responsibilities are defined within Title 14 of the CFR and the Aeronautic Information Manual (AIM) [146]. However, even with experienced PICs, seeing and avoiding is often a challenging task when coupled with other PIC responsibilities. Most mid-air collisions, in fact, occur not in dangerous weather conditions, but rather in daylight hours, in satisfactory weather conditions and on warm weekend afternoons. Studies have identified that the majority of in-flight collisions are the result of a faster aircraft overtaking and striking a slower one [147]. According to the FAA, the failure of the PIC to see other aircraft is the leading cause of mid-air collisions. Recent technology has significantly aided in air safety, but the exponential increase in air traffic has made the problem more difficult. To address air safety concerns, the FAA utilizes a layered approach for collision avoidance (Figure 5.21) [32,33].

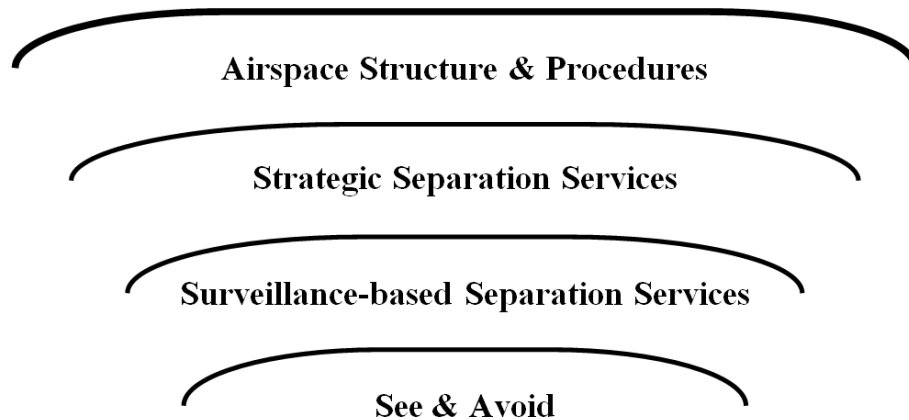


Figure 5.21: Layered approach for collision avoidance. Adapted from [32,33].

Airspace structure and the proper operating procedures provide the first layer of protection. Through the use of regulations and standard operation procedures, the FAA attempts to keep the airspace segregated to limit encounters of disparate flight characteristics, especially airspeed differences. Airspace classification acts

as a significant mechanism for defining operations and flight rules, depending on flight altitude, and airport size and location. Other mechanisms, such as altitude levels and approach and departure procedures, provide additional levels of built-in separation [148].

The next two layers of separation services refer to ATC management of the NAS. The management of separation done in these layers is dependent on the airspace and the flight plan specific operating rules. Strategic separation services include additional management aids to balance air traffic controller workload [33] while the surveillance-based separation services rely on surveillance data and decision support tools.

The final layer of collision avoidance relies on the ability to ‘see and avoid’ other aircraft as defined by the FAA to remain all clear from other aircraft [134]. Accomplishment of this is done primarily with visual observation and confirmation. Under current regulations, ADS-B traffic information is not sufficient justification for avoidance maneuvers and are intended only to assist in visual acquisition of other aircraft [146].

5.4.1.2 Sensing and Awareness Strategies for Manned Aircraft

While the first three layers of the collision avoidance approach requires coordination with ground support, the final level of ‘see and avoid’ relies solely on the PICs. PICs of manned aircrafts are required to rely on visual acquisition for avoidance maneuvers, with an exception to ATC instructions. This places the responsibilities of the final layer of collision avoidance sensing fully upon the human PIC. The FAA, through their education agency, teaches the use of various visual scanning techniques to keep PICs constantly alert of their surroundings. Scan patterns based on the ‘block’ system have been proven effective in covering the necessary scan range of $\pm 60^\circ$ to the left and right, and 10° up and down (Figure 5.22) with occasional glances to either side beyond the $\pm 60^\circ$.

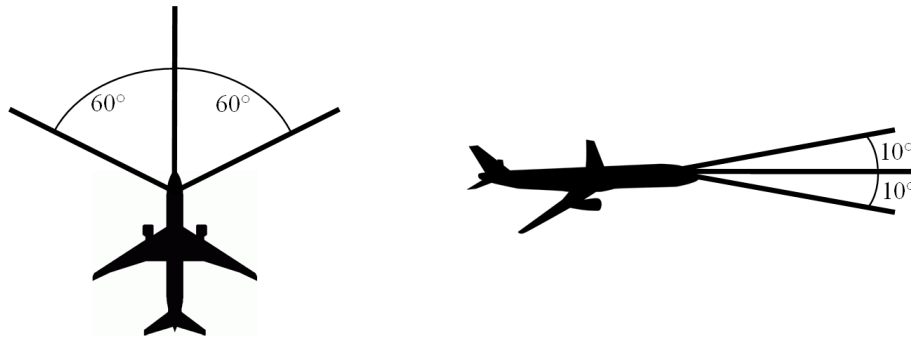


Figure 5.22: Recommended minimum see and avoid scanning range for PICs.

The entire scan is completed in 10-15 seconds, allowing the PIC the estimated 12 seconds needed for collision avoidance [147]. Weather additionally plays a significant role in sensing. The minimum visibility requirements for visual flight rules (VFR) flying in Class E airspace is 3 statute miles and 1 statute mile in Class G airspace [146]. Despite all of the technological improvements in recent years, the human factors still play the primary role in ‘See and Avoid’ collision detection and resolution strategies as the standard model of performance. The challenge for SUASs integration is the development of a system capable of meeting these requirements of sensing and procedures to enhance being sensed by other aircraft.

5.4.1.3 Conflict Detection and Resolution Strategies

For a PIC, the process for Conflict Detection and Resolution (CDR) consumes valuable time. The process may take on average 10-15 seconds from aircraft detection to the correct avoidance maneuver. AC 90-48C, an advisory circular first published by the FAA in 1983, lists the process in the following manner with each stage’s respective average time (Table 5.7) [149].

Table 5.7: Recognition and reaction times for PICs. Adapted from [149].

Stage	Time (s)
See Object	0.1
Recognize A/C	1.0
Become Aware of Collision Course	5.0
Decision to Turn Left or Right	4.0
Muscular Reaction	0.4
Aircraft Lag Time	2.0
Total	12.5

More recently, a panel of experts from the FAA and the Department of Defence (DoD) described the eight stages of CDR that are expected to be required for SUAS SAAS [150] and follows similarly to the stages of AC 90-48C.

1. **Detect** - The first stage is to detect any obstacle or hazard to initiate the CDR process.
2. **Track** - The motion of the detected object must next be tracked. This involves the confirmation of the existence of an object and the determination of accurate position and trajectory information.
3. **Evaluate** - The evaluate stage of CDR evaluates the confidence of the previous two stages and the necessity of an avoidance maneuver. The confidence level

of the previous stages are highly affected by uncertainties, such as the object has changed trajectories or has just been detected. This stage is analogous to the recognition of an aircraft and becoming aware of a collision course in Table 5.7, but more generalized to include the evaluation of non-aircraft conflicts.

4. **Prioritize** - This stage prioritizes the tracked objects based on their evaluated parameters from the previous stage, including distance or hazard type. This may be utilized as a method for handling multiple conflicts or utilizing more advanced autonomy in SUASs.
5. **Declare** - The point at which a prioritized conflict is determined to need resolution occurs at the declaration stage. Separate declarations may be utilized for different levels of conflicts depending on the evaluated parameters.
6. **Determine** - The determination of the correct conflict resolution maneuver is calculated at this stage. This may take into account a myriad of conditions include the specific geometry of the encounter, type of hazard, other air traffic, and the limitations of the aircraft.
7. **Command** - Once an appropriate maneuver has been determined, the aircraft can be commanded to perform it. In manned aircraft systems, this is analogous to the muscular reaction stage in Table 5.7, however extra challenges are presented in SUASs depending on the aircrafts capabilities and communication networks.
8. **Execute** - Finally, the commanded maneuver is executed.

The eight stages illuminate specific challenges necessary for CDR. The timeliness of the process adds a level of complexity when the detecting component and the analysis component are not co-located; data transmission lag from stage to stage can be significantly detrimental.

However, in an ideal case, this level of CDR would not be time-critical. As collision threats are detected further and further away, different and more optimal approaches could be accomplished. The distances and thresholds can be visualized as threat shells as in Figure 5.23 [150].

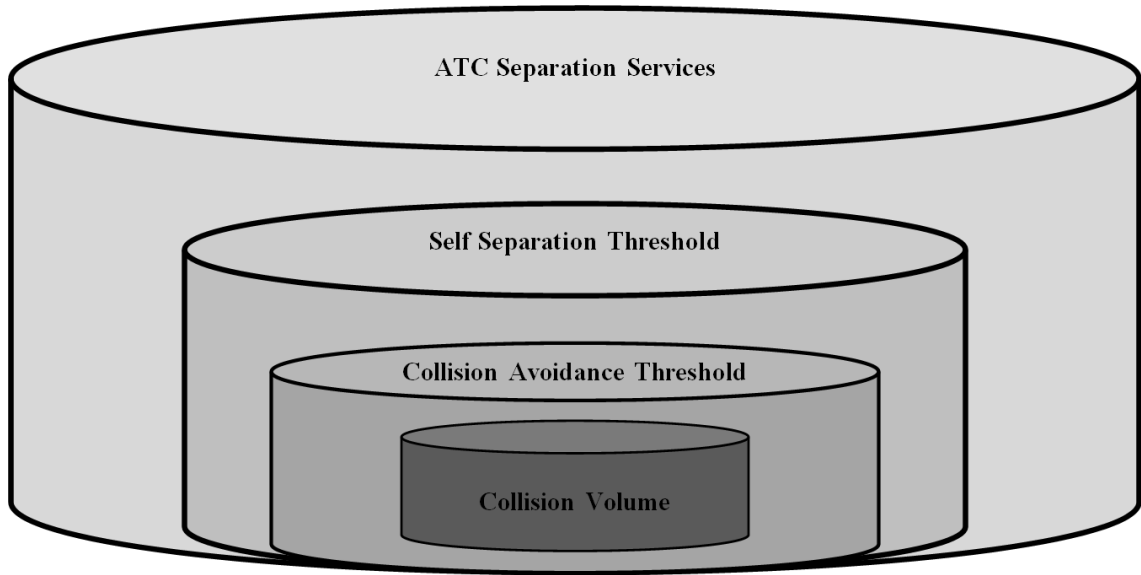


Figure 5.23: Visualization of UAS ATC separation, self-separation and collision avoidance shells. Adapted from [150].

Figure 5.23 depicts the different danger zones and the threat classification thresholds. In the outermost layer is the ATC separation volume, where other aircraft may exist but are not currently regarded as a threat. The ATC has sufficient time and situational awareness to manage and prevent encounters, satisfying the first three layers of the layered approach in Figure 5.21.

Entry into the second volume indicates that the invading aircraft may be a threat. However, there is sufficient time for the aircraft to engage in self-separation maneuvers, without ATC management, to avoid last-moment avoidance maneuvers.

The final volume represents the estimated volume of the aircraft to be avoided. The typical definition of this volume aligns with the ‘critical near-midair collision’ definition as outlined by Traffic Collision Avoidance System (TCAS) II 7.1 [151], a mandatory collision avoidance system for passenger aircraft. This definition equates the volume to a truncated cylinder of ± 100 ft. in height and a radius of 500 ft. The volume is considerably larger than the actual size of the aircraft to account for the uncertainties in the aircraft’s position and the invading hazards uncertainty. It may vary in size depending on these issues of uncertainty and measurement latency. Any conflict resolution maneuver must be sufficient to overcome these variations and sources of error.

5.4.2 Sense and Avoid Systems

Sense and avoid systems have been a significant target for improvement and development in recent years as technology has advanced and matured. In an attempt

to replace or augment the human vision, numerous approaches and techniques have been developed. In this section, some of the common approaches are presented.

5.4.2.1 Sense and Avoid System Classifications and Metrics

Within SAAS, sensing functionalities vary widely across approaches. They can be divided into two major classifications: cooperative and non-cooperative systems. Cooperative systems, such as ADS-B and other air traffic transponder based systems rely on all other aircraft to operate openly and transmit their information freely. The range and capabilities of these systems typically make them ideal for self-separation conflict resolution with other aircraft. Non-cooperative technologies such as radar and vision systems are capable of monitoring the sky for other air traffic and hazards, but suffer from difficult implementations and limited capabilities.

A second major classification of sense and avoid systems is based on the installation location of the sensing technology [152]. Ground Based Sense and Avoid Systems (GBSAASs) seek to satisfy the necessary air traffic management and conflict resolution requirements without burdening the aircraft with an extra subsystem. These systems are common on testing and proving grounds and can serve as a valuable role in establishing UAS requirements, collecting data and airworthiness appraisals. Airborne Based Sense and Avoid Systems (ABSAASs) are intended for deployment on an aircraft for the most accurate and up-to-date information to ensure appropriate level of air safety. These are the systems that are designed to completely replace the human PIC's vision ability in situations outside of the range of GBSAASs and ATC management.

More technical metrics include the total effective detection range, field of view, latency and resolution. The necessary requirements for these technical metrics depend on the type of sensor and its overall utilization. All of these technical qualities have strong implications on performance. Detection ranges must be sufficient for avoidance maneuvers. Field of view must meet the requirements to be equitable to a manned aircraft PIC (Figure 5.22) or greater. Latency and update rate must also be sufficient to provide accurate information to allow for avoidance maneuvers while taking into account sensor uncertainty. Resolution, an important metric in optical and radar systems must be sufficient to detect an appropriate percentage of hazards. Weight classifications are critical in ABSAASs, especially in considering the applicability of its integration into an SUAS.

5.4.2.2 Automatic Dependent Surveillance - Broadcast

ADS-B is a surveillance tracking system that can be split into two subsystems, ADS-B In and ADS-B Out. Currently, only the ADS-B out portion of the system has been mandated by the FAA to be installed in most general aviation aircraft by 2020 [144].

ADS-B Out is a transmitter that broadcasts the positional location and directional velocity of the ADS-B equipped vehicle as well as being capable of transmitting additional data such as the vehicle's planned route and identity [153]. The output broadcasts sent by the ADS-B system are transmitted periodically without any required external action. Currently the FAA has approved both the universal access transceiver (UAT) and 1090 MHz extended squitter (1090ES) as transmitters for ADS-B out [144]. The UAT is approved for flight up to 17,999 ft mean sea level (MSL) and the 1090ES is approved for operating higher than 18,000 ft MSL [144].

Though the ADS-B In portion of the system has not yet been mandated by the FAA, it provides a method to display the information of nearby ADS-B Out equipped vehicles to the PIC or ATC. This provides real time information to PICs about all nearby ADS-B equipped aircraft as being capable of receiving Traffic Information Service - Broadcast (TIS-B) from ground stations when using the UAT [146]. Aircraft that can receive and display data can also receive Flight Information Service - Broadcast (FIS-B), a similar data broadcasting service for weather alerts and airport information.

ADS-B standards mandate a minimum range of 40 NM air-to-air even in poor environmental conditions, and the capacity of above 200 NM in clear skies. This allows for PICs to be aware of other aircraft even in environments where visibility and radar would not prevail [154]. This long-range detection of aircraft would allow PICs equipped with ADS-B In to engage in self-separation maneuvers far before see and avoid techniques would take place and would help to reduce air-to-air collisions caused by low visibility conditions.

5.4.3 Relevant ADS-B Regulations

In order to integrate ADS-B effectively, considerations into existing regulations are as necessary as technical challenges.

5.4.3.1 Summary of SUAS Regulations

With the enactment of 14 CFR 48 and 14 CFR 107, SUAS have a legal mechanism for regular flight activity. While the introduction of 14 CFR 48 was designed to simplify the SUAS registration process, it is not on the same legal standing as the existing aircraft registration under 14 CFR 47 [155]. Registration under the new process is not internationally recognized or equivalent to any International Civil Aviation Organization (ICAO) registration. For many UAS operations, this is not typically a significant issue, however it has ramifications for ADS-B requirements as to be discussed.

Under the new regulations, as discussed previously, the operator must have a RPIC certificate with SUAS rating and operate in Class G airspace, unless granted an airspace waiver. The 1SUAS must not interfere with and give way to all manned aviation, and may not be operated in a manner that interferes with operations and

traffic patterns at any airport, heliport or seaplane base [35]. The aircraft must always be within visual line of sight (VLOS) and not operated at night. Primarily, the FAA expects that the majority of SUAS operations will still rely on the human operator to satisfy all sense and avoid requirements. The limitations imposed by the regulations provide the first layer of procedural safety. The final layer of safety relies on the RPIC for collision avoidance. If an RPIC desires to operate in Class C, D, or surface E airspace, they may request an airspace authorization from the FAA. Within the permission of the airspace waiver, ATC communication may be required, meeting one of the middle layers of safety.

However, in a case where an RPIC desires to fly where they are unable to act as the final layer of collision avoidance (eg. beyond visual line of sight (BVLOS)), they may apply for a waiver from the FAA by providing a safety case. Currently, ADS-B has not been deemed as sufficient for satisfying this layer of safety, and with the absence of other layers of safety, such operations would be difficult to justify [132].

5.4.3.2 Regulations on ADS-B

The operation of the ADS-B system is defined in §91.225 of 14 CFR 91 [134]. At the 1090 MHz band, the equipment minimum performance standard is defined by TSO 166b, whereas the 978MHz band equipment is regulated by TSO-C154c. Additional guidance for the operation of ADS-B systems was provided by the FAA in AC 90-114 [156].

Additional minimum performance standards for ADS-B systems are specified in TSO-116b and TSO-C195a. These systems must meet functionality conditions such as upholding the reception of FIS-B and TIS-B. UAT subsystems must also uphold various classes of failure conditions, including providing applications with faulty reports no more than once in 10^3 flight hours [157, 158].

Important equipment needs to be marked as outlined in TSO C154a. An outline for the process for airworthiness approval of ADS-B Out is laid out in AC 20-165 [159]. ADS-B Out is currently only available for registered aircraft under Part 47 [146], which many SUASs are currently not. ADS-B In receivers may be purchased and used, but will not receive the full spectrum of information without an ADS-B Out transmitter as TIS-B information is only available to registered aircraft. Ground-based ADS-B In systems are commercially available as well, but they are not subjected to existing standards which limits the FAA ability to sanction their use.

5.4.4 Integration of ADS-B into SUASs

The possibility of integration of an ADS-B system into a UAS has been proposed on several occasions, however, these discussions have been focused on the capabilities and challenges of full-size UASs [145].

The approaches for these integration plans are not always applicable or appropriate for SUASs which face several unique challenges. In this section, a specific look into the challenges and operations of ADS-B integration into SUASs are presented.

5.4.4.1 SUAS Specific Remarks and Observations

Based on the previous sections of SAAS solutions, ADS-B operations, SUAS standard operating procedures and regulations, the following set of observations can be made [2].

- SUAS operations are a moderate risk to air traffic.
- SUASs typically operate at low airspeed and are more likely to be hit rather than to hit other air traffic.
- SUASs missions are atypical of manned aircraft operations.
- SUASs are typically several magnitudes smaller than manned aircraft.
- Limited endurance of SUAS (<1 hr.) and range of operations can be used to define collision thresholds.
- Limited airspeed of SUAS results in insufficient lateral avoidance maneuvers.
- SUAS regulations recommend vertical avoidance maneuvers.
- Current regulations limit SUAS operations to VLOS, low flight altitudes and short lateral distances.
- Current regulations require the use of visual observation as the primary method of sense and avoid.
- Visual observers have limited detection and recognition range.
- Visual observers provide limited situational awareness due to lack of distance ranging and limited field of view (FOV).
- All aircraft flying in Class G airspace must operate under VFR, ensuring operation only under visual meteorological conditions (VMC) with specific requirements for visibility.
- Manned aircraft flying in Class E airspace may operate under either VFR or instrument flight rules (IFR).

- VFR operations in Class E requires greater visibility range than Class G, but must remain below cloud cover due to potential for collision with aircraft flying under IFR.
- FAA currently does not authorize ADS-B In as a suitable collision avoidance system, but is intended for future use.
- Stringent requirements of DO-317A ensures performance, but adds complexity to integration.
- Standards for visual integration of ADS-B In data into ground control stations must be consistent with existing standards.

5.4.4.2 ADS-B Implementation Capabilities for SUAS

Implementing SAAS for SUASs poses a significant challenge. The strict size and weight constraints limit the airborne capabilities, and maintaining the low cost of entry constrains the use of GBSAASs. The common practice of maintaining visual contact with an observer has limitations on operating environments and unsatisfactory results for all but the closest SUAS missions. Cooperative technologies, such as ADS-B provide significant advantages to range, but will not be commonly adopted in the expected SUAS operational airspace. Visual and other optical systems can be utilized for an approximation of a manned PICs point of view, but pixel resolutions and bandwidth issues limit hazard identification range.

While not all aspects of a SAAS can be addressed with current technology, the use of ADS-B in SUAS can be part of a capable solution. The range, resolution, accuracy and update rate are all superior from other existing technology. The challenges to overcome with an ADS-B based system are not negligible however. Cooperative technology suffers from a reliance on widespread adoption and implementation costs. While ADS-B Out is currently scheduled for adoption by 2020 through legislative mandates, its adoption is not currently widespread and not required for aircraft flying at the low altitudes expected for SUAS operations. However, as the technology improves and the integration of ADS-B into NextGen is completed, the adoption of ADS-B based SAAS will improve an SUAS operator's situational awareness in regard to other air traffic. Specifically, it addresses a current weakness in the proposed operating procedures for SUAS operation.

Visual observers are the current primary source of situational awareness in the proposed standard operating procedures for SUAS operations. While satisfactory for many operations, it has significant blind spots in its deployment. An SUAS operating in Class G airspace is subject to the same VFR as manned aircraft. Manned aircraft flying in this airspace and these low altitudes are typically slow moving. Combined with the limited altitude of Class G airspace (under 700 ft or 1250 ft), an SUAS is capable of diving to a safer altitude in a sufficient time to complete a

self-separation or collision avoidance maneuver. However, this arrangement is only sufficient if the visual observer is able to detect, track and evaluate invading aircraft as per the eight stages of CDR. This requirement significantly affects the operational bounds which is limited by the capability of the visual observer. The overall performance can be further improved with on-board visual or optical systems, either autonomous or human-in-the-loop, for terrain and structure hazards. The addition of ADS-B into this setup would enable an SUAS operator to detect cooperative aircraft before they reach visual range.

However, a greater benefit of the addition of ADS-B is found in larger operations and at higher altitudes [2]. Increased range and endurance introduces additional dangers, but may be necessary for many SUAS missions. Aircraft flying under VFR are still subject to favorable conditions for visual observations and the use of visual optical SAAS. However, class E airspace also permits the use of IFR for aircraft. The combination of VFR and IFR aircraft increases the danger of mid-air collisions. An aircraft flying IFR may descend through a cloud layer only to find themselves in a collision course with an aircraft flying in VFR below the clouds. Neither the visual observer or the use of vision or optical SAAS is capable of detecting the invading aircraft in this situation. The situation may be further worsened by the mismatch of airspeed of the two aircraft. The implementation of an ADS-B SAAS would enable the first three stages of CDR to be accomplished sooner and would allow an SUAS operator sufficient time to complete a self-separation or conflict avoidance maneuver.

In some cases, an SUAS may be tasked to operate in a more congested airspace class, with permission of a local ATC. In these situations, ADS-B integration may be necessary to gain sufficient situational awareness. SUAS operation in high air traffic areas requires a heightened attention to air space management and control. This can be achieved by addressing all levels of conflict resolution strategies. By utilizing ADS-B as required by FAA laws, the outer levels of ATC management and self-separation layers are addressed.

Additional discussion is warranted to the topic of the effects of introducing a new and likely heavily utilized class of aircraft to the ADS-B frequencies. The increased utilization of the two ADS-B frequency bands may result in an overly crowded system, especially in airspace segments where ADS-B information is most critical. Additional management from ATC would be required for the oversight of these operations as well. The FAA has remarked that these are significant issues that factored into their decision to not require ADS-B for SUAS operations under 14 CFR 107 [132].

5.4.4.3 Potential Implementations

There are five configurations for implementing an ADS-B SAAS for an SUAS and its corresponding ground control station (GCS) (Figures 5.24 - 5.28). Each

implementation has its advantages and challenges, but each may be a preferred implementation for a specific architecture depending on the technical challenges [2].

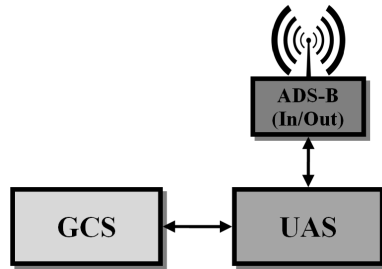


Figure 5.24: Representation of SUAS with ADS-B (In/Out).

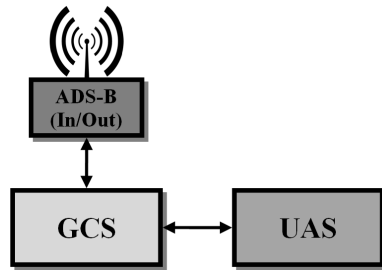


Figure 5.25: Representation of GCS with ADS-B (In/Out).

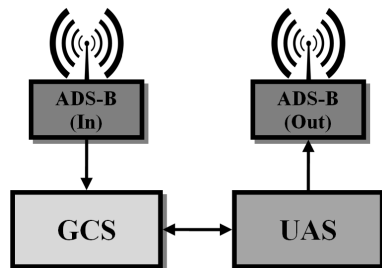


Figure 5.26: Representation of SUAS with ADS-B Out, GCS with ADS-B In.

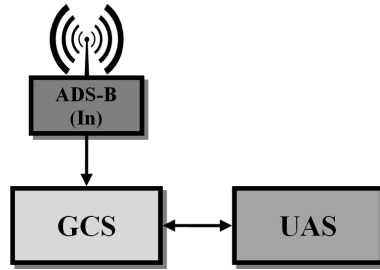


Figure 5.27: Representation of GCS with ADS-B In Only.

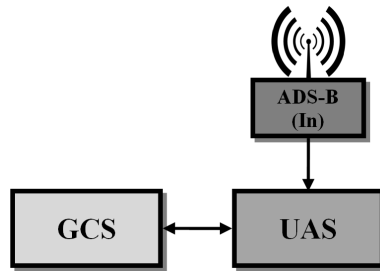


Figure 5.28: Representation of SUAS with ADS-B In Only.

In Figure 5.24 an implementation that is most similar to a manned aircraft implementation is depicted, placing a full system ADS-B In/Out system on the SUAS. This implementation would require the least technical challenges, requiring only that the ADS-B In situational awareness information is passed down from the SUAS in the air to the ground station. However, this setup places the additional weight cost airborne, a limitation that may be too costly for many of the lighter SUASs. The advantage of this setup is that it allows for autonomous self-separation algorithms to be conducted autonomously, a potentially valuable capability in lost-link situations. Situational awareness relaying may additionally increase system latency, however, with the long-range capabilities of ADS-B, it may be tolerable for all but the closest calls.

Alternatively, the entire ADS-B SAAS may be attached to the GCS (Figure 5.25). This removes the weight of the ADS-B system off the SUAS, and onto the ground where weight and size are not significant constraints. ADS-B Out messages can be constructed from the real-time telemetry link from the SUAS to the GCS. However, this implementation may be incompatible with ADS-B standards regarding message accuracy and message latency. In this situation, the implementation acceptance would be autopilot system specific and may be too challenging to regulate by the FAA. Another alternative using this same setup would have the ADS-B

Out message broadcast an uncertain range of the aircraft's position, trajectory and velocity. Given the relatively small size of an SUAS compared to most manned aircraft, a sufficient uncertain bound could be broadcast without affecting safety.

A more complex setup places the ADS-B Out transmission on the SUAS while collecting ADS-B In messages on the GCS (Figure 5.26). The necessary ADS-B Out message accuracy can be obtained without concern for latency on the SUAS, enhancing the ability for self-separation for other air traffic. ADS-B In messages for situational awareness can be directly viewed on the GCS display. Low latency ensures a better experience for the SUAS operator and allows for a quicker human response to air traffic hazards. However, in the prescience of telemetry disruptions and interference, the activation of self-separation or collision avoidance maneuvers may be delayed or lost.

The final two implementations utilize only ADS-B In on either the GCS (Figure 5.27) or the unmanned aircraft (Figure 5.28). In consideration of the increased usage of the ADS-B frequencies, it may be prudent to consider using ADS-B for only increasing the SUAS operator's situational awareness. In many situations, while a manned aircraft may be capable of spotting the SUAS, it may lack the maneuverability to conduct self-separation maneuvers. In these situations, the SUAS should always yield right of way to larger aircraft and is expected to get out of the way rather than conducting a cooperative self-separation. In the case where immediate action is necessary, the SUAS may be tasked to perform beyond its safe operational bounds. While the loss of an SUAS may be unfortunate, the loss of a human life would be unacceptable. Additionally, in an ADS-B In only implementation, manned aircraft can be alerted to an SUAS operation through other means such as Notices to Airmen (NOTAMs) or through the ATC. Current regulations prevent ADS-B Out systems to be installed on unregistered systems, a category that currently includes the vast majority of SUASs. This makes the use of an ADS-B In system currently more feasible legally and addressing the concerns of frequency crowding.

Utilizing only ADS-B Out is not a viable option as it removes the ability for the SUAS operator to gain situational awareness and places the burden of avoidance using ADS-B on the manned aircraft.

5.4.5 Analysis

There is no single solution for sense and avoid for SUASs; the most effective solutions are the ones that address each and every level of threats from multiple approaches. It is foreseeable that SUAS operations will become common place and the augmenting of visual observers and optical sensors with ADS-B SAAS will keep the air safe for all who wish to utilize it.

There remains several challenges left to overcome before its use becomes common. Several of these remain legislative and regulatory prohibitions that will likely be adjusted as the technology matures. Current implementations should focus on

ADS-B In integration, a setup that currently has less regulatory issues and standards requirements. However, if ADS-B In is to be utilized for SUAS operations, standards must be developed specifically for this new application. Regulations also currently prohibit the use of ADS-B as a primary self-separation and collision avoidance system for manned aircraft. The FAA is expected to address these issues, and potentially as the technology continues to mature, these prohibitions will subside.

The role of aircraft registration has implications for the use of ADS-B Out. Under 14 CFR 48, the FAA has required that all SUASs are to be registered, with a special case if SUAS is to be used exclusively as a model aircraft (i.e. recreationally or for specific education programs). Prior to 14 CFR 48, SUAS operated between November 2014 and April 2016 were required to be registered through the existing aircraft registration processed referenced within this work and thus would be eligible for ADS-In/Out functionality. Since April 2016, when the new registration requirements were finalized for all users, the majority of SUAS operators have chosen to use 14 CFR 48, and as previously discussed, this does not satisfy the registration requirement for ADS-B In/Out functionality. However, SUAS operators may choose to register under 14 CFR 47, and be eligible for ADS-B functionality.

The discussion regarding the use of ADS-B for SUAS air traffic deconfliction is still on-going, even with the finalized regulations for the operation of SUAS [35]. Due in part to the lack of a proven ABSAAS, the regulations prohibit BVLOS operations for SUAS. ADS-B is still considered a potential solution, but as with manned aircraft, the FAA has stopped short of suggesting that it can be more than a secondary solution [132].

5.5 Human-SUAS Interaction Model

Despite removing the human from the aircraft, SUASs still have a significant level of human interaction at multiple points throughout development and implementation. In the discussion of the integration of SUASs into the NAS, there remains still a sizable amount of work quantifying these human factors. There have been a handful of studies evaluating the human factor involved in military UAS accidents [160–162]. These reports document many of the areas where the human plays a role in system performance, but also documents the need to develop sufficient human systems to ensure a resilient system. Ultimately, the human role in any system is to enhance the system resilience by providing an abstract sense of safety. This sense of safety is a complex abstraction of a multitude of human factors, including many factors that may not appear to be directly involved.

Within the closed-loop system that is an SUAS, the human-automation interaction is a key element. While this interaction has been extensively studied in a variety of manners, it rarely plays a role within the development of a UAS. Within the literature, many publications have studied the human interaction with robotics in terms of human-automation challenges [53,163–169] or interface designs [170,171].

The evaluation of the situational awareness of an operator is also a common theme when evaluating human-automation interaction [53, 163, 168, 172–174]. The study of the cognitive load and its implications on performance has also been researched with respect to human-automation interaction [166, 175–178]. A similar approach to the human-automation interaction, human-in-the-loop research has attempted to quantify the human operator as a mathematical model [179, 180]. It is with this knowledge base that the development of a holistic human factors study of an SUAS is accomplished.

The framework in this section was developed to organize a unified model that incorporates several aspects in a cohesive manner so that the human factor of an SUAS can be fully understood. This is especially critical as the FAA has moved more and more safety responsibilities to the RPIC for SUAS flights. This model attempts to provide a framework to give researchers and developers a more complete understanding in order to improve the resiliency of SUASs. The rest of the discussion is organized as follows. In Section 5.5.1, the existing models of human factors and human-automation interaction are presented. The performance metrics used to serve as the quantitative analysis of the framework is presented in Section 5.5.2. In the following section, Section 5.5.3 the holistic framework is presented and analyzed. The discussion concludes with some thoughts on how this framework can be utilized to improve the design of an SUAS in Section 5.5.4.

5.5.1 Human Factor Models

In order to develop a framework for human-SUAS interaction, a thorough examination of human interaction with the system is needed. A simplistic approach would be to only consider the human operator, but a more holistic approach is given in this section. The human factor extends beyond the human operator to the situation the human is placed in and going up the supervisory chain of command all the way to the organization. In this section, an introduction to the models that are utilized within the framework is presented, starting with a top-down approach.

5.5.1.1 Human Factor Analysis and Classification System

The Human Factors Analysis and Classification System (HFACS) [162] was designed to support accident reporting systems for aviation accidents. It is intended to provide a data-driven strategy for identifying underlying human factors to lead to improvements in training and intervention programs [162]. It uses a ‘Swiss Cheese’ approach to identifying faults by forcing accident investigators to evaluate latent failures that allowed the final doomed act. HFACS describes four levels of factors in accidents (Figure 5.29): Organizational Factors, Unsafe Supervision, Preconditions for Unsafe Acts and Unsafe Acts. These categories are briefly described.

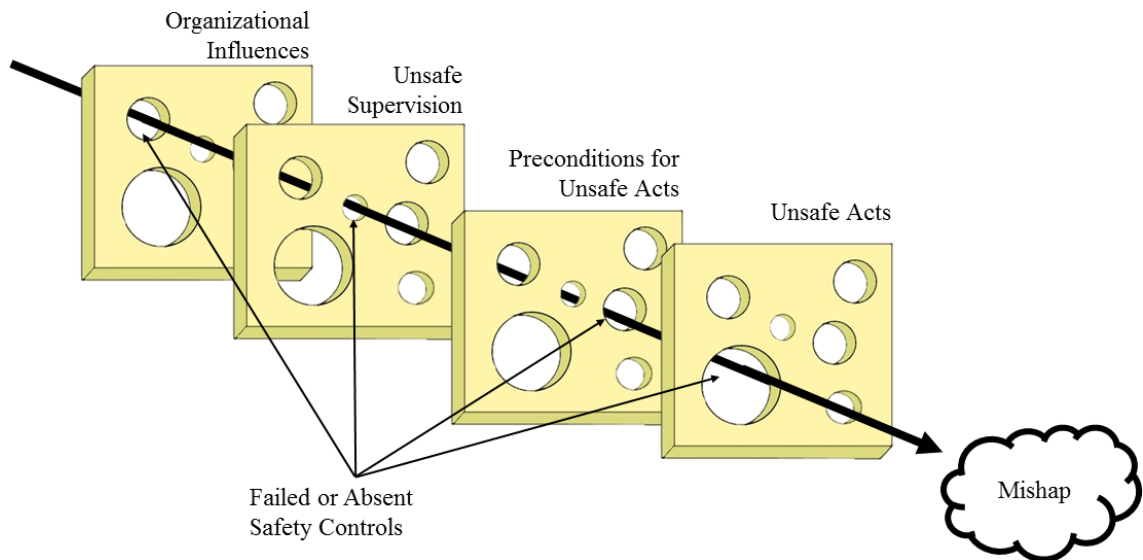


Figure 5.29: The ‘Swiss Cheese’ model of accident causation. Adapted from [162].

Organizational Influences

While distant from the inner workings of a system, the organizational factors play a significant role in latent failures. These include almost innocuous factors such as a substandard resource management, a lack of a clear chain of command, organizational policies and operational pressure and standards.

Unsafe Supervision

Closer to the action, unsafe supervision can play a factor in accidents. This category includes inadequate supervision by a supervisor, planned inappropriate operations, failing to correct a known problem, supervisory violations. These factors may not directly cause an issue, but may contribute to a future error by the operator.

Preconditions for Unsafe Acts

This level of factors involves the state of the human directly involved with the system. These factors are often the underlying factors for affecting the behavior of the human involved in the system. They include adverse mental and physiological states, physical or mental limitations as well as the general substandard practices of operators.

Unsafe Acts

The final level of human factors is the unsafe acts of the human directly involved in the system. It is these errors that are the most direct causes of incidents. Factors that fall into this level can be described as errors (decision, skill-based or

perceptual) or violations (routine or exceptional).

The HFACS is a sufficient method for categorizing many of the human factors, especially the overlooked ones in the upper levels of the ‘Swiss Cheese’ model. However, in the case of an SUAS, it particularly overlooks the human factor when interacting with automation. The framework developed in Section 5.5.3 will allow these factors to be included in a holistic approach to human factors to identify how these factors influence the various aspects of the human-SUAS interaction.

5.5.1.2 Four Stage Model of Human Information Processing

At every instance, the human involved within the system undergoes some method of information processing to decide on response. A simple four stage model is presented in [166] and has been adopted in many human-automation interaction studies. In this model, the human information processing is broken down to the following four stages: Sensory Processing, Perception/Working Memory, Decision Making, and Response Selection. In the first stage, sensory data is collected and preprocessed, including selective reception. The second stage refers to the human recognition of the value of the data and may include the fusion of other sources such as experience or inference. Decision-making occurs within the third stage, where the cognitive processing is done. Finally, the fourth stage refers to the effort involved in the implementation of the decision reached in the third stage.

This model can be abstracted to be applied to a human-automation system (Figure 5.30). The processing that occurs at each stage can now be thought of as a combination of human processing and automation [166]. The individual stages are more accurately described as:

1. Information Acquisition
2. Information Analysis
3. Decision and Action Selection
4. Action Implementation

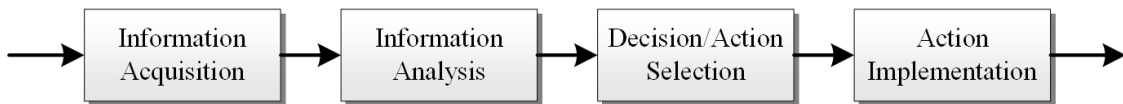


Figure 5.30: Block diagram of four stage model of information processing [167].

The level of human or automation control at each stage can be designed into the system, but this requires the identification of the optimal balance of human or automation control. To this effect, the human-automation relationship with human performance must be investigated further.

5.5.1.3 Automation Model

Several quantifications of the different levels of automation have been published over the years, however in this section, a 10-point scale is used (Table 5.8) [167].

Table 5.8: Automation levels. Adapted from [167].

Rating	Level	Description
High	10	The computer decides everything, acts autonomously, ignoring the human
	9	Informs the human only if the computer decides
	8	Informs the human only if asked
	7	Executes automatically, then necessarily informs the human
	6	Allows the human a restricted time to veto before automatic execution
	5	Executes the suggestion if the human approves
	4	Suggests one alternative
	3	Narrows the selection down to a few
	2	The computer offers a complete set of decision/action alternatives
	1	The computer offers no assistance, human must take all decisions and actions
Low		

This scale provides a simple quantitative metric for measuring the automation of a system. In practice, a system is often comprised of varying levels of automation, in which case, this scale can be applied to each stage of a system [167]. The combination of the stages of processing and the levels of automation can be utilized to create a visual representation of the levels of automation in a system. An analysis of an SUAS navigation mission automation can be viewed in Figure 5.31. The visualization shows that the SUAS automation is completely dominant in the acquisition of data and in the implementation of control strategy, while the human has complete authority over the actions.

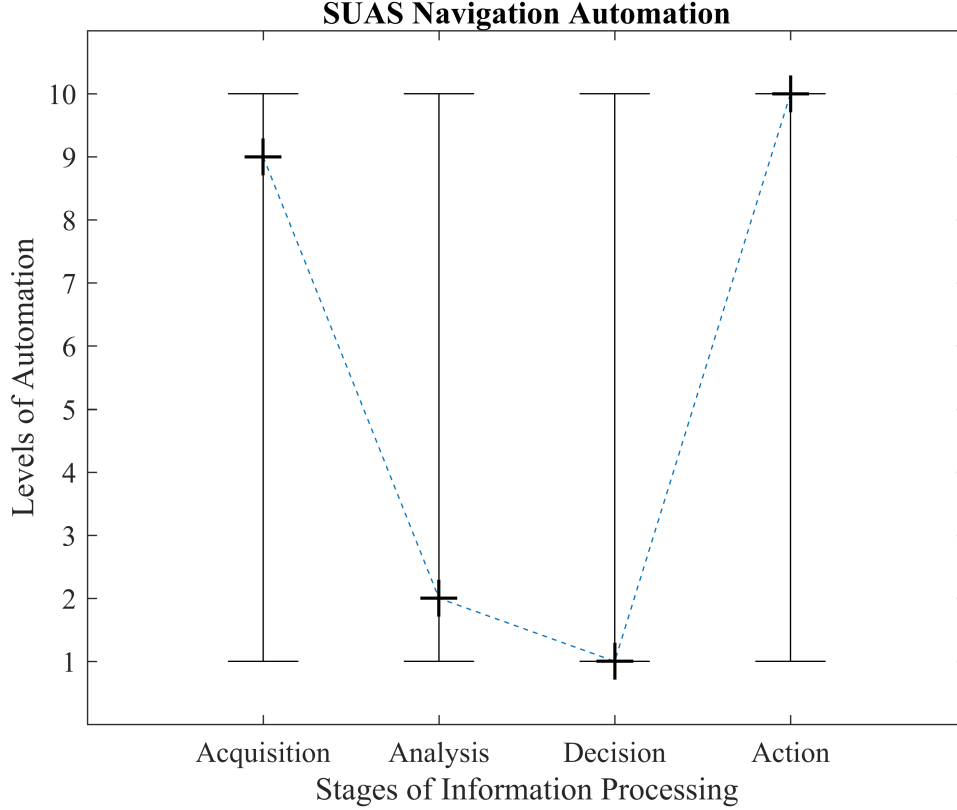


Figure 5.31: Levels of automation for stages of information acquisition, information analysis, decision selection and action implementation for a SUAS ground control system operator.

5.5.2 Human Performance Metrics

The human is a complex and largely unpredictable aspect of any system. In this section, some common metrics are presented for use in quantifying the components of the proposed framework. There are three major human performance metrics: cognitive workload, situational awareness and complacency/skill degradation.

5.5.2.1 Cognitive Workload Factors

The mental workload of a pilot or operator is perceived to be a major contributor to the level of system safety [162]. For example, an overworked pilot may not have the situational awareness required to maintain an acceptable level of safety. The Cognitive Load Theory (CLT) framework can be applied to demonstrate the relationship between mental workload factors and overall human performance [181].

CLT is a powerful tool to aid in the development of many systems, including educational instructions [182]. This framework can be further applied within the human-automation model. According to this framework, cognitive workload is defined as the additive combination of three major load factors: the ‘necessary’ intrinsic load, the ‘bad’ extraneous load and the ‘good’ germane load [182]. The total cognitive load is a summation of these three factors. Intrinsic cognitive load is defined as the innate difficulty of the given task while extraneous cognitive load is defined as the external pressures such as time or performance pressures. Germane load is defined as the conscious application of learned strategies. A summarization of CLT is shown in Table 5.9. In the following subsection, these load factors are utilized within the holistic human-UAS framework to quantify the factors that affect system performance.

Table 5.9: Summarization of Cognitive Load Theory. Derived from [182].

Aspect	Factors
Intrinsic Load	Due to the intrinsic aspects of a task Fixed for a given task, expertise and education, but variable for design
Extraneous Load	Due to interactivity of relevant information at limits of user memory Due to maintaining relevant information Due to interactivity of irrelevant information Due to waste of time and effort
Germane Load	Due to the conscious application of learned strategies Due to restructuring of problem representations in order to solve a task more easily Constrained by working memory capacity Constrained by intrinsic load Constrained by motivation
Design Principles	Reduce extraneous load as far as possible Adapt intrinsic load to user’s expertise Reduce intrinsic load if task difficulty is too high Increase intrinsic load if task difficulty is too low Adapt germane load to the intrinsic load

5.5.2.2 Cognitive Workload

Subjective workload assessment is a critical tool in measuring the cognitive workload of an operator. One such tool, the NASA Task Load Index (NASA-TLX) has been utilized as an estimate of mental workload [183]. It is a well-known standard for measuring workload and has been implemented significantly in a variety

of different situations, especially with automation and/or decision aids and visual and/or audio interface displays [184]. It has been demonstrated to be sensitive to even small workload changes [181]. When conducting a NASA-TLX survey, each participant is asked to rate their experience with the given task in 6 categories: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration Level and its relative importance.

A typical resulting analysis can be seen in Figure 5.32. In this figure, the cognitive workload of an SUAS GCS operator is shown. The workload is primarily derived from the mental demand on the operator as well as the temporal pressure. The weighting of the task depicts that the mental and effort aspects were considered to be the most important as well. The overall weighted workload index is roughly just above 50%.

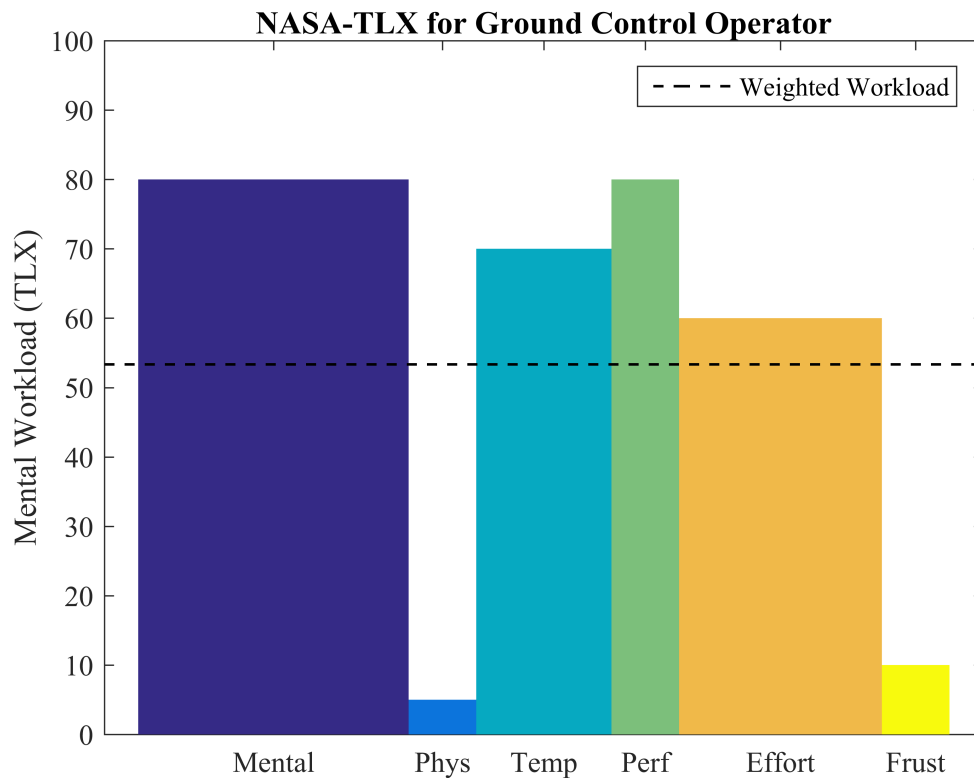


Figure 5.32: Cognitive workload profile of an SUAS ground control system operator.

5.5.2.3 Situational Awareness

An important aspect of any human in the loop system is the situational awareness of the operator. This not only affects the decision-making process but also its

level of automation has an effect on the mental workload of the operator. In order for the situational awareness of an operator to be analyzed, it must be measurable in some capacity. The Situation Awareness Global Assessment Technique (SAGAT) is a comprehensive tool to assess the situational awareness of an operator based on an objective quantitative analysis [174]. This method implements online situational awareness data ‘snapshots’ of the operator’s immediate perception, limiting the influence of other behaviors. Situational awareness can be broken down into three distinct levels, each of which can be measured by SAGAT.

Level 1

Perception of data. In this level of situational awareness, the operator has perceived the relevant data such as an output or sensor measurement. This can be used for simple recognition or actions, but lacks further understanding or the ability to predict future measurements. In a UAS example, the operational state of a particular module would be level 1 Situational Awareness.

Level 2

Comprehension of meaning. This level is concerned with the interpretation of key features of data rather than the data. Level 2 Situational Awareness indicates a level of comprehension of the data and the system and its interaction. In an UAS example, level 2 Situational Awareness is the recognition of the performance of an attitude controller in the presence of unfavorable environment.

Level 3

Projection of the near future. The final level of Situational Awareness describes the ability to predict future performance of the system based on the previous levels of Situational Awareness and the operator’s a priori knowledge. In the same SUAS example, an operator with level 3 Situational Awareness of the remaining fuel would be able to predict the remaining flight time thereby being able to adjust the flight plan accordingly.

5.5.2.4 Complacency

While automation has the ability to improve efficiency, it also may cause negative effects as well. One such effect is the over-trust of the automation that leads operators to become complacent during operation [167]. This can cause significant issues if the automation fails or the environment system changes. A complacent operator may be unable to respond to an emergency in adequate time or the operator may no longer remember the skills necessary to complete the action. One proposed model of complacency was proposed in [185]. In this model, complacency is modeled as a feedback loop based on situational awareness and operator behavioral state. This aspect in particular has an important relationship to system resiliency. In the

event of an automation failure, in order for the system to be resilient, the human operator must be able to maintain safety.

5.5.3 Human-SUAS Interaction Framework

With the individual components of the framework in place, a holistic framework can be implemented for human-SUAS interaction [1]. In this section, the human factor models from Section 5.5.1 is combined with the human performance metrics from Section 5.5.2 to develop the overall human-SUAS interaction framework. An overview of the human-SUAS interaction framework is presented in Figure 5.33.

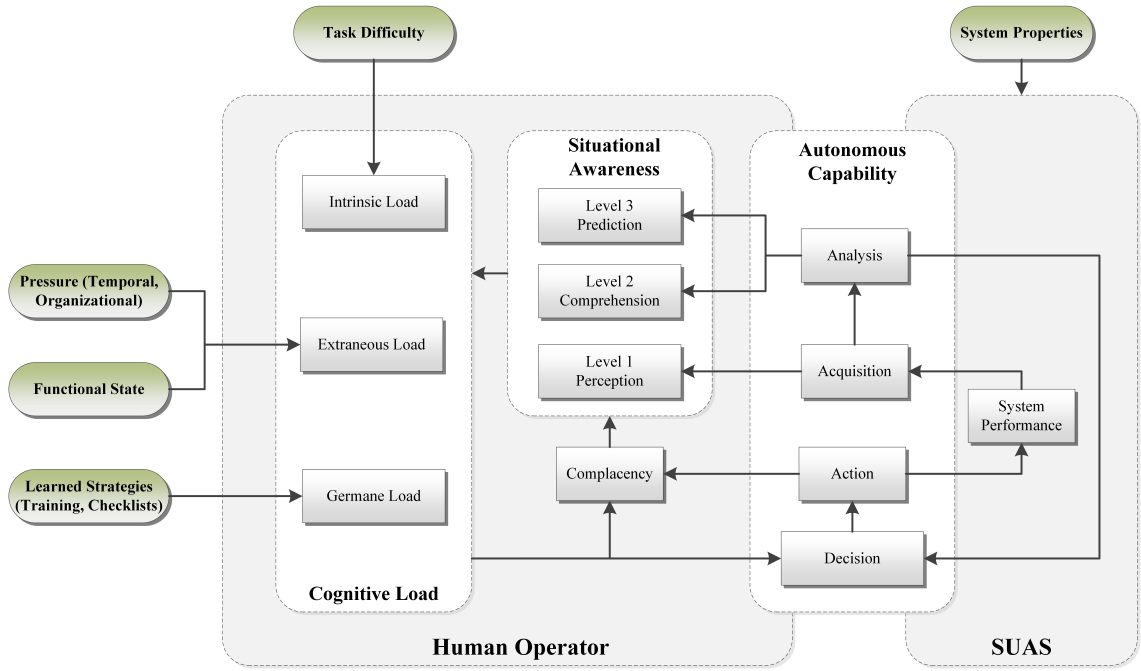


Figure 5.33: Human-SUAS interaction framework.

The framework incorporates a large variety of human factors as inputs into the system. Some of the aspects of HFACS can be found within the pressures input; at the organizational level, poor resource management and unreasonable expectations increase the external cognitive load of the operator. Unsafe supervision often manifests as lack of motivation or complacency which are constraints affecting the germane cognitive load.

The manifestation of situational awareness is a function of the system properties of the autonomous level of the information acquisition and analysis. A well-designed system will provide an operator with sufficiently high levels of situational awareness. Within this framework, the SAGAT survey described in Section

5.5.2 can be utilized to provide a measure of situational awareness that can provide valuable information for an SUAS designer. However, while improvements to the situational awareness of an operator can improve system efficiency, it is apparent that a failure to improve other factors such as learned strategies and external pressures may saturate the performance of the overall system.

The influence of the autonomous level of the decision selection and action implementation of the human operator is a result of the cognitive load and has an effect on complacency as well. In addition, the attribute of complacency also manifests in the human operator's situational awareness. Both of these factors play a role in user motivation, a constraining factor in germane cognitive load. In this framework, the total cognitive load can be measured through the use of the NASA-TLX survey.

5.5.4 Application of the Framework

Though the work here was developed for SUAS, it may still be applicable for UAS in general. The cohesive, comprehensive framework presented here can be utilized for understanding the effects of human factors on SUASs operations. The multiple roles of humans in such a system is quantified, and the human factors in the system have been identified. Factors such as cognitive workload, situational awareness, complacency and skill degradation have been taken into account. This framework integrates much of the previous research such as NASA-TLX and HFACS, allowing proven inputs to the system to provide reliable data, with the goal of optimal balance between cognitive workload of human operators, and division of labor to autonomous behaviors of the unmanned system. With this framework, the ability to judge the effectiveness of training and autonomy is improved, allowing feedback to improve the design of safer and more reliable SUASs.

The utilization of this framework is in the evaluation of advanced human interface devices and the various levels of autonomy provided by the SUAS. In addition, future work with this framework can incorporate describing functions of human operators so that other performance metrics such as bandwidth, saturation limits of human performance and operator state can be analyzed in more detail. This framework also enables a focus to break down input abstractions so that individual components can be evaluated on their effect on operator efficiency and performance. While currently under-utilized, the analysis of the human-SUAS interaction will be an invaluable tool for designing SUASs and improving SUAS operator training.

5.6 Chapter Summary

The challenges for bringing SUASs into the NAS has been extraordinary. In this chapter, only four of the multitude of identified challenges were addresses, and still much more work could be done on each of those four. The safety challenges

presented are an eclectic mix of engineering, legal, safety and human factor domains that exemplify the diverse range of issues that this new technology introduces. However, with each investigation, solutions become clearer and continue to provide guidance for new investigations. Over the course of the four years of work presented in this chapter, significant advances in technology and the regulatory environment have led to an even more pronounced increase in SUAS usage, culminating in the introduction of a formalized FAA RPIC certificate with SUAS Rating. Though this is a promising step in UAS integration, much more work remains.

In the following chapter, many aspects of these works will be revisited in the formation of the UAS Safety Management System (SMS), a novel implementation of a relatively new safety framework introduced by the FAA and adopted towards UAS oversight and management in the University of California system.

Chapter 6

SAFETY MANAGEMENT SYSTEMS FOR UNMANNED AIRCRAFT SYSTEMS

6.1 Introduction

As the use of Unmanned Aircraft System (UAS) has risen dramatically over the past several years, there has been an increased focus on the safety and management of their operations. In the previous chapter, the safety challenges of UAS integration into the National Airspace System (NAS) was discussed in terms of aircraft safety, procedures, technical challenges and training. However, there are many challenges in the UAS industry beyond NAS integration. One such challenge is the management of UAS safety and risk for large agencies and companies that deploy UAS and have UASs operated on their property. While individuals and smaller agencies can be more agile and adaptive in UAS use, larger agencies struggle to balance between acceptance and prohibition of UAS, understanding their liabilities and exposures, managing UAS inventory and establishing a culture of safety. This has introduced a new domain and specialty, the ‘UAS safety professional.’ Similar to the growth of other disciplines in safety engineering, UAS safety has grown into a necessity as a specialty to address the unique challenges of managing UAS risk and safety by identifying hazards, mitigating risks, preventing unsafe behavior and implementing effective safety controls. In a large agency setting, the scope of these goals is not on the technical aspects of the UAS or on UAS operation in the NAS but rather on the management of UAS activities. Within the aviation industry, there has been a recent push towards the adoption of a safety framework known simply as a Safety Management System (SMS). Within the U.S., SMS is a relatively new approach to safety oversight. It was only in 2006 that the Federal Aviation Administration (FAA) issued its first guidance on implementing a SMS in Advisory Circular (AC) 120-92 *Introduction to Safety Management Systems for Air Operators* [186]. The new oversight system quickly gained traction within aviation safety due to its robust and scalable performance [187]. It is these characteristics that make SMS attractive for implementation in the nascent new discipline of UAS safety and management.

In this chapter, the development of a UAS safety management system, as implemented in the University of California system, is presented. Section 6.2 introduces the concepts of the FAA’s SMS. The processes of identifying hazards and

managing UAS risk is addressed in Section 6.3. Safety assurance and other oversight processes are discussed in Section 6.4. In Section 6.5, the utility of safety policies are discussed to tie the frameworks of managing UAS risk and safety assurance. Safety promotion, an oft-overlooked concept is discussed in Section 6.6. The chapter concludes with preliminary analysis of the University of California’s implementation of the UAS SMS.

6.2 Safety Management Systems

The FAA describes SMS as a decision-making system built around four components of safety policy, safety risk management, safety assurance and safety promotion [186]. An alternative description by [187] refers to SMS as a dynamic risk management system based on quality management system (QMS) principles in a structure scaled appropriately to the operational risk and applied in a safety culture. Both definitions hold significant merit and at their core, refer to SMS as a system. This is one of the defining characteristics of SMS over previous approaches to aviation safety. An SMS is designed for continuous improvement with active participation in safety, incorporating feedback rather than relying on static linear processes. A graphical diagram shown in Figure 6.1 depicts the connectivity of an SMS. Each component plays a critical role in the wholistic approach of an SMS.

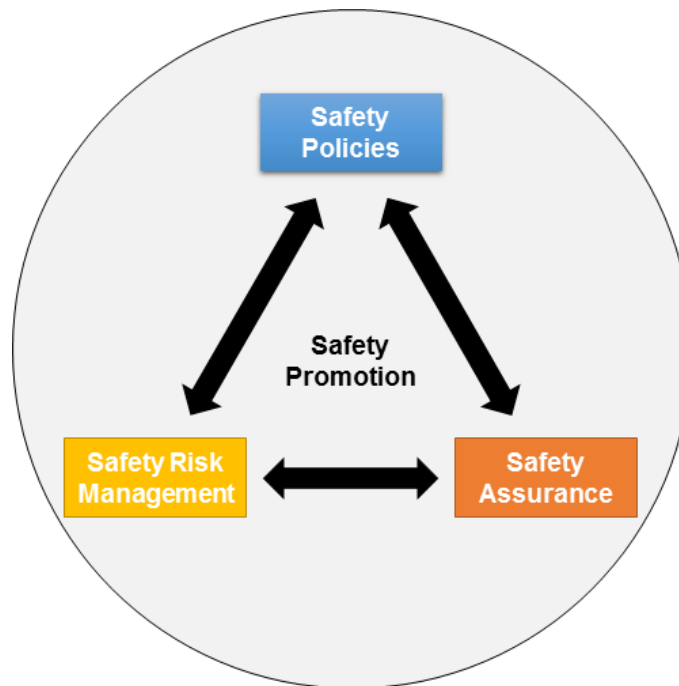


Figure 6.1: Safety management system.

Safety Policy

The organization's safety policy is an important component that establishes a top-down commitment to continually improve safety, defines safety objectives and outlines the processes and responsibilities to reach those objectives [188].

Safety Risk Management

Safety risk management (SRM) is an active framework for initial and continued hazard identification, risk analysis, and safety controls.

Safety Assurance

Safety assurance is the process in which the controls established by safety risk management are reviewed in a continuous and active manner. This component includes aspects such as data acquisition, monitoring systems, audits and regular reviews.

Safety Promotion

A positive safety culture is an important component to foster at all levels in an organization. This includes the promotion of sufficient safety knowledge, training programs and suitable mechanisms for information sharing for improved decision making and accountability.

All four of these components form a wholistic approach to safety. Taken individually, these components contain familiar processes. However, when working in concert, these components can be used to drive the QMS principles that make SMS an effective system. Continual improvement and dynamic management are key aspects that are enabled by this approach. This is a critical feature when applied to UAS safety management. While traditional aviation safety tends to follow a 'fly-crash-fix' cycle or utilize significant historical testing to derive risk probabilities, these two cycles are ineffective in the UAS industry. Unlike traditional aviation, UAS has no historical data to draw upon and technological developments far outpace data collection effectiveness. Simply put, by the time the characteristics of a UAS model has been determined, the technology may be obsolete and previous iterations have limited relations to current iterations. Understanding UAS operations is similarly fraught with difficulties. Low sample sizes, significant coupled risks and heavy reliance on experience have proven challenging for quantifying risk factors. Given the diverse user base and their experience, it comes difficult to devise effective policies and training. The value of the feedback driven model of a SMS becomes easily apparent in this new and ever-changing field of UAS safety. In the following sections, the specific challenges of deploying an SMS and the novel approaches for UAS management is described.

6.3 Safety Risk Management

Safety can be a difficult word to define. Safety could be described as the ‘condition of being safe from undergoing or causing hurt, injury or loss’ [187]. But the common definition is left vague as to how ‘safe’ is defined. One may consider staying home to be ‘safe,’ but according to the U.S. National Safety Council, over 20,400 people died from falls at home in 2014 [189]. But can safety be understood from this single statistic? How many people were in homes in 2014? Are there relations or patterns within? Safety is a difficult concept to apply a static definition; ‘safety’ is largely defined by context and relations where the goal is to reduce the potential of harm to an acceptable level. As such, safety is an active process, one that requires definitions of the context of the issue, the definition of an acceptable level and a process to reach it. In improving the safety of a system, the risk is reduced or mitigated to a ‘safe’ level.

This introduces the need to discuss risk and its relationship with safety. As alluded to, risk is a complex topic that addresses both the severity and the probability of an accident or incident. The process in which safety is ensured by reducing risk (either by reducing severity, chance of occurrence, or both) is known as risk management. However, the risk management process can encompass a larger scope than safety risks. Risks in a system may also include financial losses due to personal injury, damage to property or reputation, or fines from regulatory agencies. While not directly related to safety, these risks may be influenced by safety issues. This connection has led to the development of the field of Enterprise Risk Management, where a whole portfolio of risks are addressed to reduce the chance of loss, create greater financial stability and protect an agency’s resources (Figure 6.2).

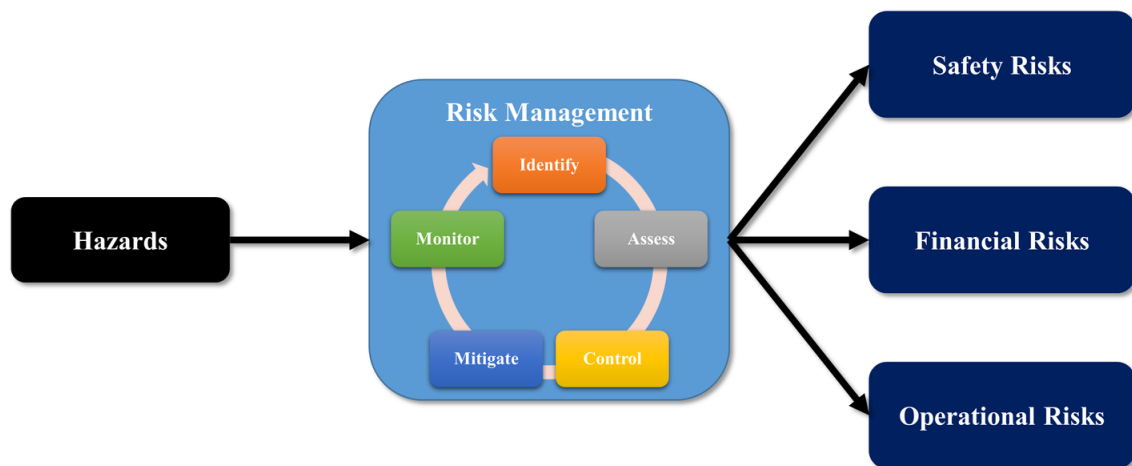


Figure 6.2: Enterprise risk management and the risk management process.

Within the SMS framework, the safety risk management (SRM) process starts with identifying the root causes of the risks, described as hazards (Figure 6.2). A risk is what happens should a hazard manifest itself, whereas a hazard can be any potential or existing condition. As an example, a hazard may be a pole in the middle of a flight field. The risk is that a Small Unmanned Aircraft System (SUAS) may crash into it. Once hazards are identified, potential risks can be identified with careful analysis of the system of interest and the interconnections between other hazards. Only once risks can be measured can they be controlled or mitigated. This process was utilized in the previous chapter when studying the safety impact of flight operations at night (Section 5.2.2.1). In this section, the SRM is detailed with the processes of identifying hazards, understanding risks and controlling risks and are presented in a more general sense as they pertain to the unique challenge of managing UAS operations.

6.3.1 Identifying Hazards

In order to understand risks within a system of interest, an accurate and consistent method of hazard identification is critical. The FAA defines a hazard as ‘any existing or potential condition that can lead to injury, illness, or death to people; damage to or loss of a system, equipment, or property; or damage to the environment. A hazard is a condition that is a prerequisite of an accident or incident. A hazard might or might not result in a situation of high risk’ [190]. By contrast, a risk is defined as ‘the composite of predicted severity and likelihood of the potential effect of a hazard’ [190]. Hazards are potential issues, risks are the chances and consequences of a hazard.

The challenge of identifying hazards is not trivial. Best practices across all domains of safety have developed a multitude of different methodologies, from formal processes to collaborative user sessions, to identify hazards [191]. Within the UAS domain, specific processes have only begun to be developed. In its publication of the final rule for SUAS, the FAA proposed a modification of one of its preferred models, known as the Personal Minimums (PAVE) Checklist [192]. The PAVE Checklist categorizes risk into four groups: **P**ersonal, **A**ircraft, **E**nvironment, **E**xternal Pressures. This granular categorization has been known to be effective as it focuses hazard assessments to ‘fill bins’ [191]. However, in a complex industry such as aviation, the length and complexity of a hazard list can be unwieldy to manage [187].

An alternative proposed for SUAS operations is an adaptation of the SHELL model (Figure 6.3) [193]. Similar to single-pilot manned aviation, SUAS operations are individual driven. Rather than SUAS operations being part of a ‘clockwork system,’ they are often considered discreet operations revolving around the pilot in command (PIC), as established in the final rule for SUAS [35]. In the SHELL model, hazards are categorized in the individual components (**S**oftware, **H**ardware,

Environment, Liveware) and in the connection between the components (Software $\leftrightarrow$ Liveware, Hardware $\leftrightarrow$ Liveware, Environment $\leftrightarrow$ Liveware, Liveware $\leftrightarrow$ Liveware). This breakdown adds additional focus on how the user in the center of the system interacts with all of the components as potential hazards. This approach is more in line with analysis of human factors as it identifies that the human in the center has significant responsibilities and that task complexity may affect performance, as described in Section 5.5.

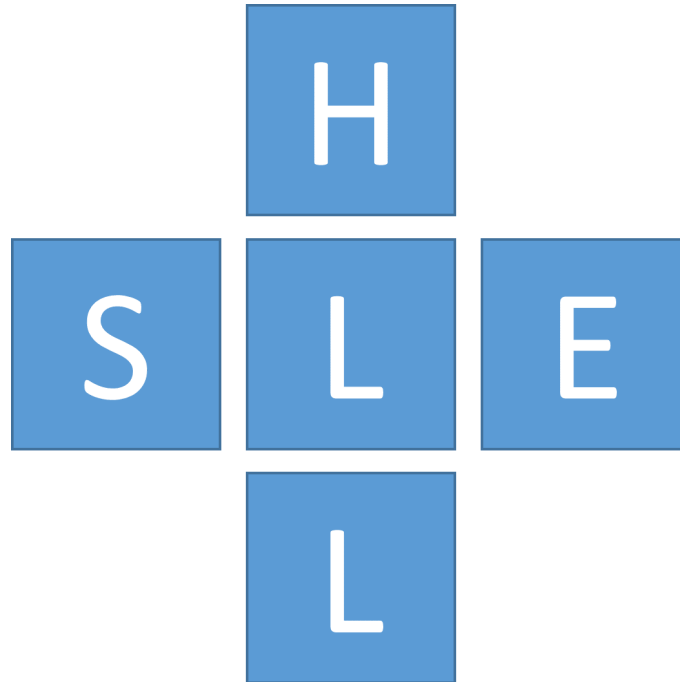


Figure 6.3: The SHELL hazard model.

The components of the SHELL model are similar to those found in the PAVE model. The aircraft is replaced by separating the hardware components with the ‘software’ components. However, in this context, software includes any other non-physical aspects of the operation, such as instructions, checklists, standard operating procedures, or documentation. The environment component includes the totality of the context in which the operation is taking place, including weather, airspace and regulatory or other sociopolitical conditions. The external liveware refers to other humans in the operation, including ground crew, management or administrative personnel.

However, the largest contrast of the SHELL model is in specifying the importance of identifying hazards in the interconnections between the components. This captures hazards such as ‘miscommunication between pilot and visual observer,’

‘inadequate protective equipment,’ or ‘misinterpretation of instructions.’ These interconnections may not always be apparent when looking for hazards in individual components or when conducted by the UAS operator. An example hazard identification sheet utilized by the University of California can be found in Appendix C.1.

By breaking down a hazard identification process into components and the interconnections between components, a more complete analysis is possible. In the next section, the hazards identified are used to understand risks.

6.3.2 Analyzing and Controlling Risks

In many domains, risk analysis is often a forensic approach, where various safety databases would be utilized to determine the severity and occurrence of a risk, based on historical data and aggregate reports. From this, a final ‘risk index’ could be determined from a risk matrix as shown in Figure 6.4. Risk matrices are a simple means for quantifying acceptable risk. In Figure 6.4, the resulting risks are color coded; acceptable (green), unacceptable (red) and acceptable with mitigation (yellow).

Risk Probability	Risk Severity				
	Negligible A	Minor B	Major C	Hazardous D	Catastrophic E
Frequent 5	5A	5B	5C	5D	5E
Occasional 4	4A	4B	4C	4D	4E
Remote 3	3A	3B	3C	3D	3E
Improbable 2	2A	2B	2C	2D	2E
Extremely Improbable 1	1A	1B	1C	1D	1E

Figure 6.4: Safety risk matrix example (adapted from [192]).

In simple scenarios, these risk matrices enable operational managers to visually identify high risk scenarios. In practice, this scoring system is difficult to implement on dynamic risk situations. The definitions of risk severity or risk probability can be assigned to metrics, such as a remote frequency is defined as 1 incident per 10,000 flight hours [187]. But the metrics used are context dependent, and the context can be subjective. Should a UAS rotor failure be considered remote if it occurs once per 10 flight hours? Is 10 flight hours considered a significant number?

If the average flight is 45 minutes and flown daily, rotor failure could be considered frequent. If the average flight is 5 minutes and flown once a week, rotor failure could be considered rare. For the PIC, what determines a suitable level of experience, 5 flight hours or 20 launches and recoveries? In essence, the risk matrix can be used for risk management, but the assignment of the levels and frequency requires data and experience, both of which are in limited supply in UAS operation management. The ramifications of this will be discussed in Section 6.4.

However it is clear that even with a limited data set to work with, there are a multitude of risks that can be assessed. A full analysis of all identifiable hazards can be problematic for any given operational case. If a risk matrix was to be made for each one, it could involve a significant amount of work for minimal improvement. As described by the FAA in [192], the focus should be on those hazards that pose the greatest risk. Examples of some key indicators are found in Table 6.1. To balance the need to manage risk while enabling analysis, a more efficient approach was developed. Based on experience, the top eight risks were identified: Pilot, Aircraft, Airspace, Weather, Ground Crew, Location Risks, and Organizational Risks. A risk assessment survey (found in Appendix C.1) was developed to capture specific key information regarding potential hazards. Static information is combined with survey questions to provide a snapshot assessment.

Table 6.1: Example key indicators in risk survey for hazard identification and risk analysis.

Category	Parameter	Hazard	Example Risks
Aircraft	Registration Make/Model	FAA Requirement Weight, Size, Weather To- lerance	FAA Violation Flight region too small, too windy, aircraft overlo- aded
Pilot	Certificate Experience	FAA Requirement Limited experience, unfam- iliarity with vehicle	FAA violation Incorrect flight maneu- vers, Failure to follow pro- tocols
Airspace	Airspace Class Proximity to air- port	FAA Auth. Required Frequent air traffic	FAA violation Interfere with manned avi- ation, FAA violation
Weather	Wind Conditions	High wind conditions	Wind levels outside accep- table parameters
	Visibility	Low visibility, visibility Requirement	Lose sight of aircraft, FAA violation
Flight Ope- rations	Flight Altitude	FAA Auth. Required	FAA violation
	Flight Plan	Acrobatic routines	Aircraft operated outside flight envelope
Ground Crew	Visual Observer	No visual observer, fre- quent air traffic	Interfere with manned avi- ation, FAA violation

	Experience	Limited experience, unfamiliarity with vehicle	Failure to follow protocols, Miscommunication with PIC
Location	Ground risks	Powerline pole	Aircraft crashes into powerline pole
	Spectators	Uncontrolled flight area, Loud discussions	FAA violation, PIC distraction
Organization	Training Program Readiness to cancel flight	Insufficient training External pressure	PIC unprepared Operational mistakes, operate beyond acceptable 'safe' limits

Based on the results of the survey (Appendix C.2), a risk assessment can be assembled and visually depicted in a radar graph as in Figure 6.5. The scoring of the risk assessments can be processed as in a risk matrix or through appropriate weighting of the survey responses. Some factors such as weather conditions and airspace can be automatically derived when a flight site location, date and flight time are selected.

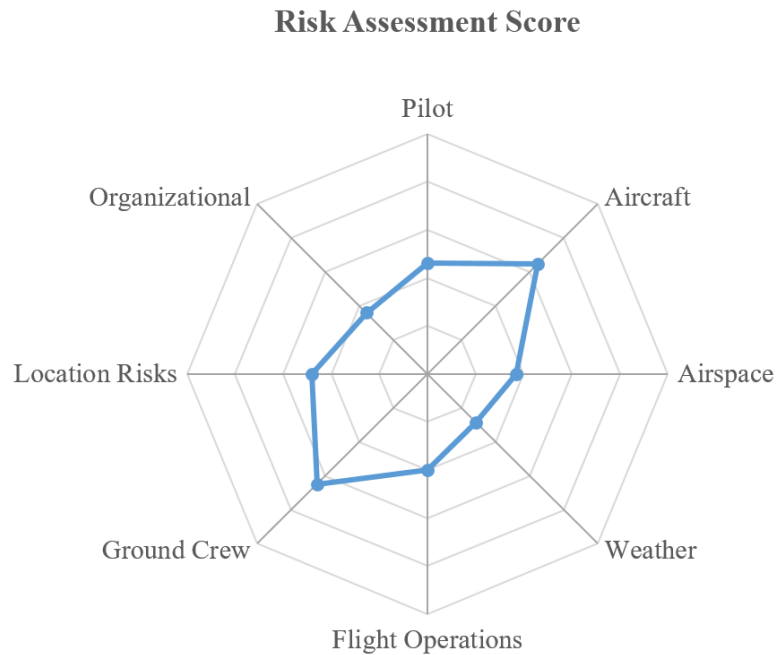


Figure 6.5: Example risk analysis from leading indicators.

The use of a visual depiction of a variety of risks, such as a heat map, is an effective means of communicating risks to a wider audience. While Figure 6.4

communicates the risk index of a single risk, Figure 6.5 communicates aggregate relative risk. A user or administrator could utilize the radar graph to identify that the risks associated with the aircraft could be reduced. Whether the risks are at an acceptable level is dependent on context. For example, if the location and airspace risks are low, it is possible a higher pilot or aircraft risks could be tolerated. Once risks are identified and measured, controls can be implemented to mitigate any unacceptable risks. This cycle can be iterated until all risks have been reduced to an acceptable level.

6.4 Safety Assurance

The SRM fulfills one aspect of a SMS. While it iterates to mitigate risks, as described in the previous section, it struggles to adapt to changes in the system due to lack of historical data and the fast-moving pace of the industry. The safety assurance aspect provides the complementary process that enables continual feedback into the SRM process. The relationship between the two processes can be best depicted as in Figure 6.6.

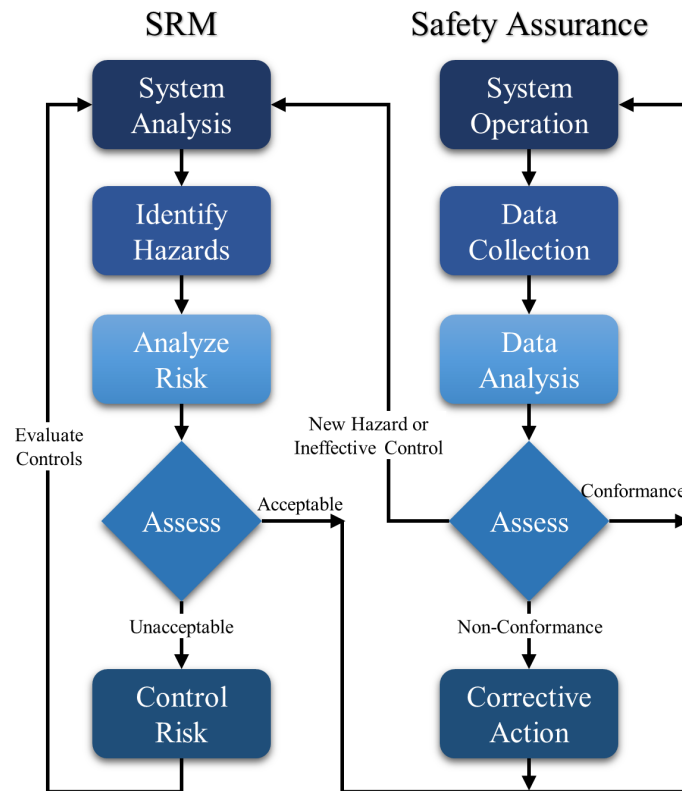


Figure 6.6: Safety risk management and safety assurance processes.

The safety assurance process provides active monitoring of the system, in this case the large-scale operation of multiple UAS across a variety of users and locations. Each UAS flight operation represents a new set of risks to be mitigated. With each flight operation, the data of the success of the risk mitigation strategies and additional information can be utilized within the safety assurance process for continual improvement.

6.4.1 Performance Monitoring

The key aspect towards performance monitoring is ensuring that the correct data is collected for each UAS flight operation. In this section, several key performance indicators (KPIs) are identified.

As defined in Section 6.3.2, the top eight risk categories were defined as Pilot, Aircraft, Airspace, Weather, Ground Crew, Location and Organizational risks. The risk assessment survey (Appendix C.2) was developed to capture some of the KPI utilized for risk assessment, but additional information is necessary to track the risk control strategy success and effectiveness. The total KPI can be described as separated into two categories: leading indicators and lagging indicators. Leading indicators are the indicators used to identify hazards and predict risks. Lagging indicators, such as accident rate and flight hours, enable the tracking of trends and compliance. Table 6.2 lists several examples of leading and lagging indicators that provide valuable information for managing UAS activity.

Table 6.2: Example UAS leading and lagging indicators.

Leading Indicators	Lagging Indicators
Pilot experience	Pilot flight time
Pilot familiarity with aircraft	Pilot launches and recoveries
Aircraft condition	Aircraft damage rates
Airspace class	Near misses with air traffic
Weather conditions	Reschedules due to weather
Flight operations	Abnormal flight performance
Flight altitude	Lost-link rates

6.4.2 UAS Management Process

It is easy to identify data to be collected, harder though is ensuring effective data collection, especially when reliant on self-reporting. Research in the safety domain has often remarked on the variety of strategies to enable effective self-reporting [187, 191], but in the context of the management of large scale UAS operations, it is one of the few solutions available. To influence compliance, a formalized process for managing UAS operations was developed (Figure 6.7).

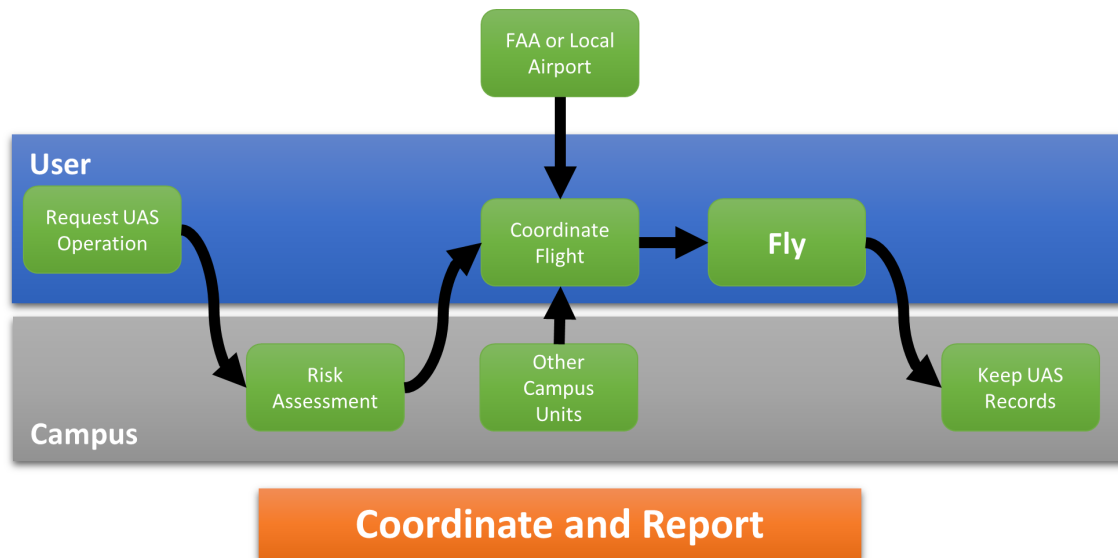


Figure 6.7: UAS flight operations process.

This process, following the strategy seen in Figure 6.6, funnels all UAS activity through a standardized process that enables risk analysis, coordination with various constituencies including the FAA, and post-flight reporting to capture all of the KPIs necessary for UAS operation oversight. To aid in this process, an online web app was designed and deployed. Screenshots of the flight request and flight reporting process can be found in Appendix C.3. The flight reporting form captures the majority of the necessary KPI for an initial risk analysis. If additional risk analysis is necessary, the risk survey found in Appendix C.2 can be utilized. In the backend, the data of the aircraft, pilot and flight operations are managed in a database to enable the tracking of lagging KPIs.

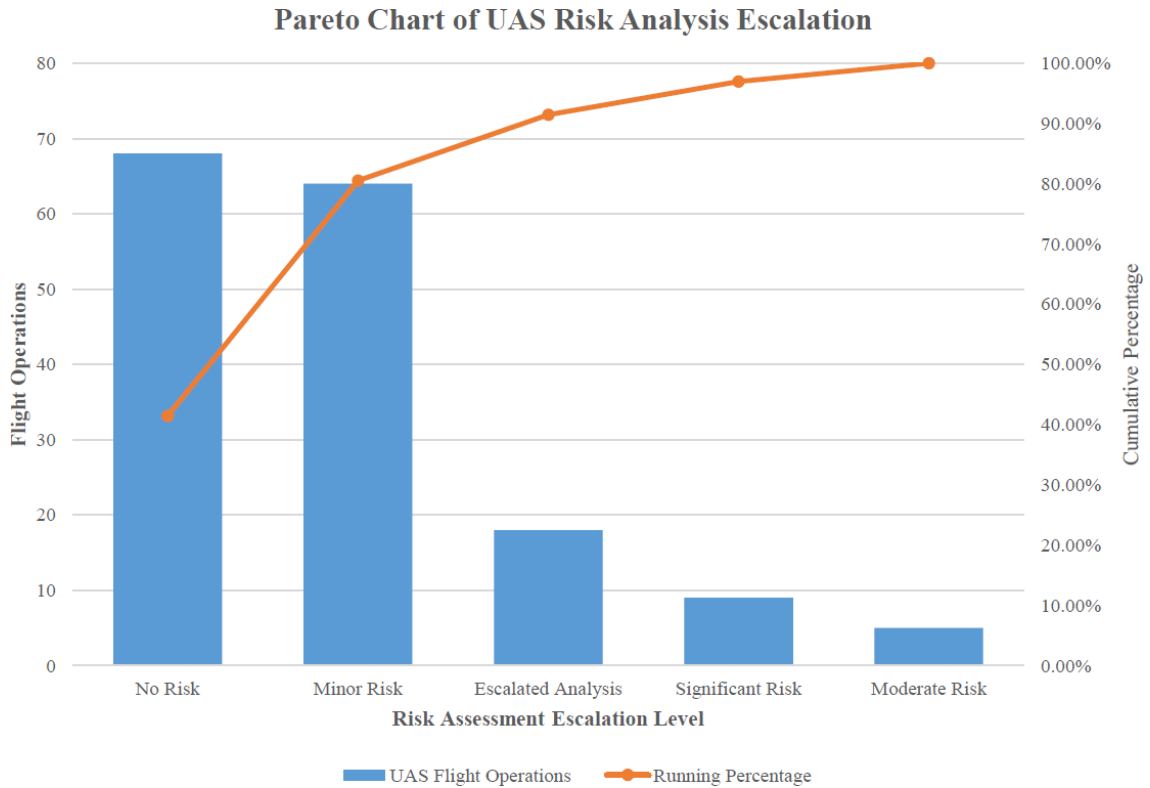


Figure 6.8: Pareto chart depicting the occurrence of UAS risk analysis escalation.

The majority of UAS activity can be effectively enabled with no or minor risk without the need for further risk analysis, based on the limited KPIs collected in the flight request form (Appendix C.3). Figure 6.8 depicts the levels of risk and risk analysis escalation of UAS flight activity in the UC system between October 1, 2016 and December 31, 2016. The majority of flight activity required no risk analysis escalation as they had no or minor risk. The definitions of the escalation columns are found in Table 6.3. UAS flights that required an escalated risk analysis and had moderate residual risk were primarily on-campus filming where the flight location, time and date were inflexible and other mitigation strategies were necessary.

Table 6.3: Escalation definitions.

Escalation Level	Escalation Definition
No Risk	Proposed UAS flight operation had acceptable levels of aircraft, pilot, and location risks. Example: SUAS flight in remote field location with experience pilot.
Minor Risk	Proposed UAS flight operation had an acceptable level of aircraft, pilot, or location risk. Example: Training SUAS flight in remote field location with a new pilot.

Escalated Analysis	Proposed UAS flight operation requires additional information before an analysis can be completed. Additional risk mitigation strategies, such as crowd control or additional visual observers necessary. Example: Proposed SUAS demonstration flight for a remote sensing course at a campus recreational field.
Moderate Risk	Proposed UAS flight operation requires additional information for a risk analysis and residual risks remain. Example: Proposed SUAS flight to film a campus event, requiring additional mitigation strategies to address most, but not all risks.
Significant Risk	Proposed UAS flight operation requires additional information for risk analysis and coordination with FAA. Example: Proposed UAS flight requires a Part 107 airspace waiver, ATC authorization and additional mitigation strategies due to proximity to airport.

One of the challenges of UAS management is that while there is overlap between regulatory requirements and safety considerations, they are not equivalent. This is visualized with the Venn diagram in Figure 6.9. The overall SMS must ensure both regulatory compliance and safety to adequately manage all risks. This can lead to unwieldy collecting of KPIs in order to analyze risk, both regulatory compliance risk and safety risk. As the regulatory environment for UAS is ever changing, it is important that these legal requirements are continued to be collected rather than assumed. Misunderstandings of federal regulations regarding UAS has been a common challenge over the entire history of commercial UAS usage.

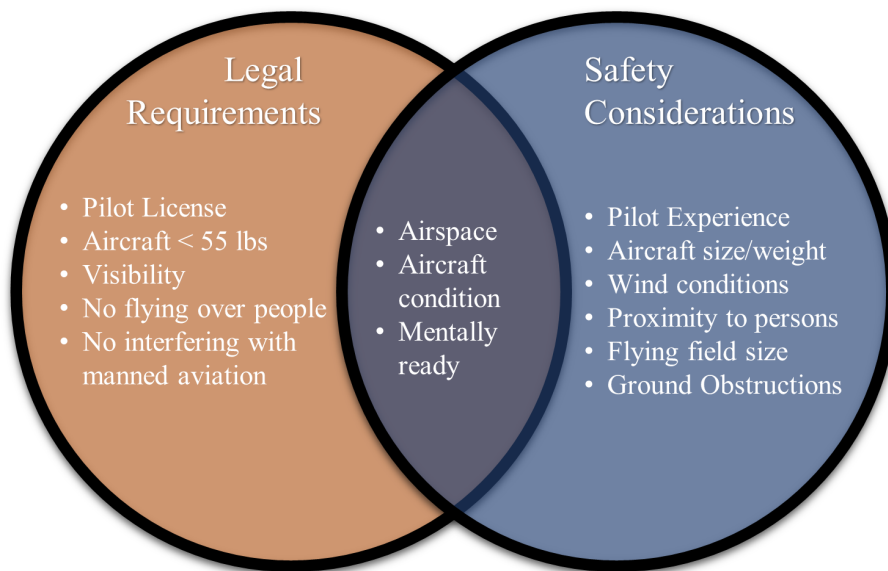


Figure 6.9: Venn Diagram of legal requirements and safety considerations for UAS operations.

6.5 Safety Policies and Privacy Considerations

The third major component of an SMS is the safety policy that establishes and organizes the roles and responsibilities of the organization and ensuring that the processes of SRM and safety assurance are implemented. From a policy perspective, one of the greatest challenges has been the pace of UAS regulations and technology. Policy development tends to be a linear process; one group develops a draft, passes it along to different subgroups for comment, iterates from the comments and then finalizes it. Technology, however tends to move at an exponential rate. The result is a policy that can only approximately follow the pace of technology with frequent revisions, though this challenge is not unique to UASs.

In the end, it was chosen for the UC system that the UAS policy framework should focus on the safety process (as described in the previous sections) rather than technical or regulatory requirements. For example, instead of establishing in policy that UASs should not be flown over 400 ft (as is a current regulatory limit), an effective policy establishes that UAS operations must follow the law (which may change over time) and that the flight must be done safely (which technology may make safer over time). These ‘checks’ are built into the SRM and safety assurance processes.

The policy establishes the roles of both centralized management and delegation for UAS management. While this is a function of some regulatory requirements, it enables the standardized process for UAS operations as shown in Figure 6.7.

One of the challenges in policy is the balance between academic freedom, safety and privacy. It is clear that the capture and use of photographs and videos from a UAS platform raises new concerns on the rights, privacies, and permissions that involve both the operators of UAS and individuals that are uninvolved in the operation. The right to privacy is an active component and should be considered as fluid as the technological or regulatory environment. Similar to safety being considered a process, privacy is not statically defined. Within the UC system, privacy best practices are presented with the expectation that it will lead to further discussion and iterations. A current document can be found in Appendix C.4.

6.6 Safety Promotion

The final component to an SMS is the overarching goal of safety promotion. Unlike the interconnection of the SRM, safety assurance and policy, safety promotion exists in all facets in a variety of forms. In this section, two specific challenges of developing a safety culture and the value of training and workshops are presented.

6.6.1 Safety Culture

Given the wide diversity of UAS operations in the UC system, it is a significant challenge to develop a unified process in any level of detail beyond that presented in Figure 6.7. The use of automated tracking systems may not interface

well with the wide diversity of UAS platforms and the wide range of applications all have substantially different risk associations. Rather than focusing the entirety of risk management on the aircraft and environment, a significant component is related to the human in the loop (as described with the use of the software, hardware, environment, liveware and liveware (SHELL) model for hazard identification, Figure 6.3). The focus of this approach can be exemplified by the following human-centric goals:

- Enable communication
- Provide responsiveness
- Build trust
- Promote and share understanding
- Provide processes that are useful rather than necessary

In the framework of flight requests and reporting, adding another layer of bureaucracy can be an unnecessary barrier to entry. This can be countered through following through with the goals of safety promotion. Developing processes that enable communication and can enable responsiveness builds trust. It is important that the communication that does occur promotes and shares understanding. Short documents such as ‘Top 10’ lists help provide useful tips while being easy to read (Examples in Appendix C.5, C.6, and C.7). Ultimately, the most successful SMS maximizes performance while minimizing risk. It then is important that the safety and risk processes that are implemented are useful to all; this helps build a reporting culture and a just culture. The structure enables processes where reporting is convenient and that safety is owned by all, not just the ‘UAS safety management.’

6.6.2 Training and Workshops

One of the common fallacies in safety is the over reliance on safety training, especially online training modules. It is understandable that they are deployed; they can provide an efficient means to disperse uniform or standardized knowledge and metrics such as attendance rates are easily calculated and can be compared to incident rates [187]. It is not to say that they cannot be made useful, but there are specific challenges. Training sessions can be poorly designed or rendered ineffective. This is especially apparent in the glut of SUAS training programs, workshops and certificate programs peddled in the wake of the rise of the SUAS industry. Some of the programs can charge thousands of dollars to teach participants how to pass the remote pilot in command (RPIC) certificate exam, participate in an SUAS ‘flight school’ or learn the ‘secrets’ of aerial photography. Some have erroneously claimed

to be ‘FAA’-approved or other such standard. This is a challenge for the nascent SUAS industry to gain legitimacy.

An effective training program for SUAS is possible, but more study is necessary. This aspect is left unanswered for now. In general, the steps for developing an effective program is as follows:

- Identify the audience
- Specify the goals
- Teach principles with practice
- Show the whole flow then the details
- Ensure participation
- Contingency situations are necessary training

To the larger question of what is important for the human operator, there still remains significant questions. In the risk analysis, one of the leading indicators is pilot experience, but its definition is left vague. Is a PIC considered experienced after 5 hours of flight experience? Or 20 launch and recovery actions? A combination of both? What sets the arbitrary limit between inexperienced and experienced? The extreme cases are easy to define, but the quantization is currently subjective. Why does experience act as a leading indicator? Literature has depicted that more experienced pilots were more consistent in identifying hazards and classifying risk severity [187]. In this depiction, experience had the advantage of improving the safety risk management processes. It remains to be seen how this will play out over the next several years as SUAS operations mature.

6.7 Chapter Summary

The development of a UAS SMS is a novel implementation to address an upcoming challenge of organizational management of UAS operations. Similar to the development of the field of safety engineering, the UAS safety specialist may become a necessary component of organizations, such as the University of California, as UAS activity continues to grow. With the UC system, UAS are primarily used in a research setting, though other usage such as instructional and campus media is growing (Figure 6.10).

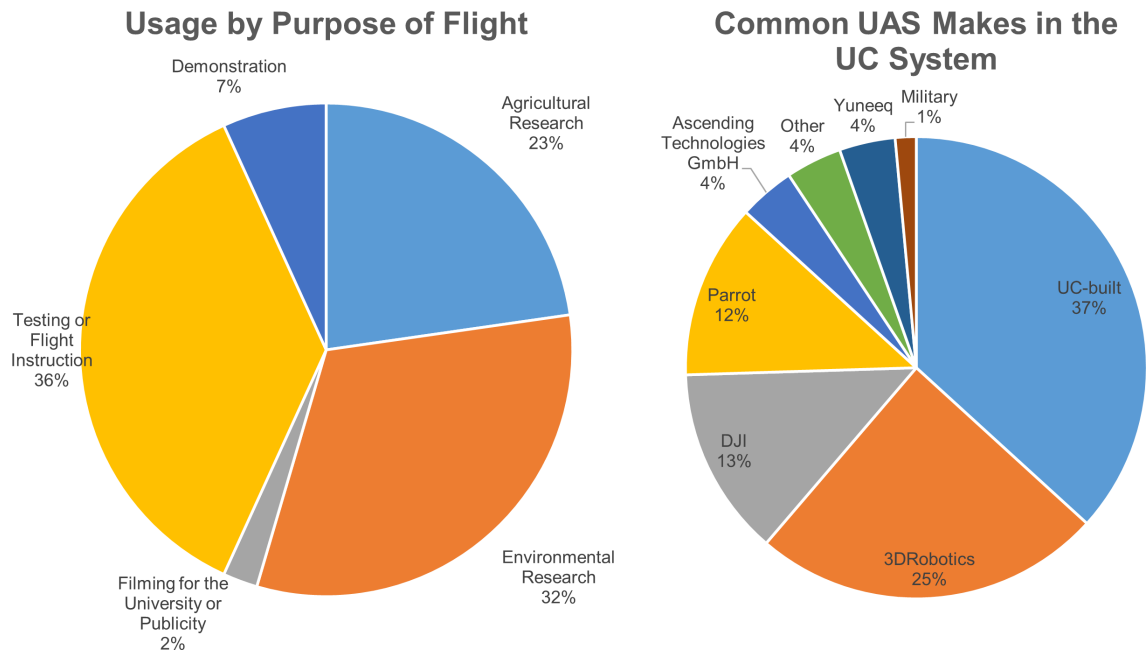


Figure 6.10: UC UAS usage and common aircraft.

However, it is important to note that the SMS is not a static system. It is a dynamic system, designed to adapt to changes in regulations and technology and scale appropriate to the wide range of risks. In this form, it can be effective, but there is still plenty of room for improvement. In particular, the understanding of the human factors of UAS operations and training requirements still remains unanswered.

Chapter 7

SUMMARY AND FUTURE WORK

7.1 Concluding Remarks

The rapid ascent of Unmanned Aircraft Systems (UASs) has coincided with a movement towards intense data collection, enabled by low-cost sensors and mobile devices, and it has been a dramatic explosion. A decade ago, the first iPhones were released, Android OS was released by Google, hard drives finally hit 1TB capacity, Facebook just started to redefine the social network and DIYDrones, one of the first UAS networks had just formed. Ten years later, each of these are parts of the engine that is driving a rapid change in technology and society. Though the ‘drone revolution’ is only one part of it, it has made its mark and has entered the commercial mainstream. But this journey was only made possible by the legions of researchers and developers slowly tackling and chipping away at the barriers, technological, operational and regulatory, to give shape to the potential of this new platform. In 10 years, 5 years, or even a single year, the advances discussed in this dissertation may be considered as quaint as the advancement from 64 MB flash drives to 256 MB flash drives, but at the time of their work they were new and innovative. Though the efforts discussed may be washed away by future advances, their development has set the stage for the next rounds. In Chapter 2, the challenge of Small Unmanned Aircraft System (SUAS) remote sensing methodology is introduced for the first time to guide the future uses of SUAS-based remote sensing applications. Chapter 3 chips away at one of the many unique sources of error that must be addressed for data accuracy analysis. In Chapter 4, the challenge of methodology and the unique advantages and challenges of SUASs are tweaked to reveal a framework for optimizing data collection with respect to spatial, spectral and temporal factors in a means never before realizable. Chapter 5 addresses four different investigations into improving the integration of SUAS into the National Airspace System (NAS), developing operations for flights at night, simulating multi-aircraft safety scenarios, questioning the use of Automatic Dependent Surveillance-Broadcast (ADS-B) for SUAS traffic management and developing a model for studying human-factors in SUAS operations. And finally in Chapter 6, the rise of the UAS has necessitated the development a new UAS Safety Management System to monitor and provide oversight for a large organization’s diverse UAS usage.

7.2 Future Challenges

The masterpiece of UAS is still far from being completed. In this nascent field, every development only uncovers more research challenges and questions. This dissertation concludes with the introductions to the next rounds of research.

7.2.1 The Sources of Error and the Challenges of Cross-Sensor Comparability

The nonstandardization of UASs and their payloads has driven technology, but it led to a worsening of an existing challenge: How to compare measurements across different sensors, across different data collection strategies and across the wide range of spatial/temporal challenges? The capture of aerial imagery is highly complex and highly coupled with spatial and temporal factors. Some of these variables are fixed, some are controllable, others may be adjustable, a handful can be mitigated, and the rest are unknown. This challenge is inherently rooted in the study of the sources of error, for one cannot control what one cannot measure. While Chapter 3 investigates the effect of the bidirectional reflectance distribution function (BRDF) on the wide field of view (FOV) cameras commonly employed on many SUAS and on the duration of SUAS flights, this is only one of many issues. The issues of unknown spectral sensitivity, unverifiable calibrations and inconsistent illumination can make it difficult to be confident in data accuracy within a single data set let alone across several data sets, even over the same site. In what regard could this data be comparable to satellite imagery or other SUAS imagery? What needs to be done to ensure that the work done yesterday can still provide meaningful information in five years? These are not easy questions to answer, but are critically important if the field of SUAS-based remote sensing is to mature.

7.2.2 Multi-Aircraft Solutions for Optimal Multispectral Remote Sensing

As mentioned in Chapter 4, the ‘optimal’ result for multispectral remote sensing for a single SUAS may not be able to provide a suitable solution. In this example of optimizing bird counts with a Thermal Infrared (TIR) imager, it was clear that the UAS platform would not be able to cover the 1200 ha as desired in a single night of operation. The balancing of flight altitude and resolution to provide the max coverage was unable to meet the end needs. It wasn’t necessarily the platform’s deficiency, but rather the sensor’s resolution. Given the state of TIR imagers, it may not be possible for single aircraft to accomplish the mission. While federal regulations limit operations to only a single SUAS in operation at a time, in the future, a fleet of SUAS may be able to accomplish the mission. The next aspect in remote sensing optimization is to extend the framework to multi-aircraft systems, such as described in [54]. This approach could merge the framework discussed in Chapter 4 with the diffusion control Centroidal Voronoi Tessellations (CVT)

framework discussed in [54] and Chapter 5.3. In this scenario, the aircrafts may be carrying different payloads with different goals, spatially, spectrally and temporally. How will the future of remote sensing look when the dynamic capabilities of UAS are finally realized?

7.2.3 Unmanned Traffic Management

The rise of drones has added a new wrinkle to an existing challenge: the US is running out of airspace and spectrum frequencies. Some predictions of the SUAS industry have estimated that there may be as many as half a million SUAS flying by 2020. And of course, most SUAS are flown where people live, in densely populated urban environments where major airports also exist. In recent years, NASA and the FAA have partnered to lead an effort to develop a solution for Unmanned Traffic Management (UTM). This is no small challenge and there are multiple gaps in policy and technology to enable such a system. Chapter 5.4 investigated one such gap, on the applicability of ADS-B on SUAS and how it may be used as a means for SUAS operators to announce their position or read the other air traffic. While ADS-B may be a solution, the overcrowdedness of the frequency spectrums and the high noise to signal ratio, suggests that it may not be an efficient solution where it is needed the most. Other solutions have also been proposed such as voluntary flight submissions or automated management over the internet or other such network. But it remains to see how effective these systems would be in the hands of the end-users who may be forgetful or not have network access. The possibility of other solutions opens the door to a multitude of research questions. Will the state of technology ever be reliable enough to ensure safety? In addition to the technical challenge, the regulatory and policy challenges are not trivial to address. Who gets to make the decision to fly? Will it be the pilot or an Air Traffic Control (ATC) agent? As SUAS do not have single access points to enter the airspace, will flight location play a role in decision priority? What about commercial or public agency priorities? There will be a solution to UTM to arise in the near future, and only the future knows how it will play out.

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Appendix A

LIST OF ABBREVIATIONS

4SAIL	Scattering by Arbitrary Inclined Leaves
ABSAAS	Airborne Based Sense and Avoid System
AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	above ground level
AIM	Aeronautic Information Manual
AMA	Academy of Model Aeronautics
AMOC	Alternate Means of Compliance
ARC	aviation rulemaking committee
ATC	Air Traffic Control
AUVSI	Association of Unmanned Vehicle Systems International
AVHRR	Advanced Very High Resolution Radiometer
BRDF	bidirectional reflectance distribution function
BVLOS	beyond visual line of sight
CDR	Conflict Detection and Resolution
CFR	Code of Federal Regulations
C_{ab}	Chlorophyll Content
CLT	Cognitive Load Theory
COA	Certificate of Waiver or Authorization

CONOPS Concept of Operations

CVT Centroidal Voronoi Tessellations

CWSI Crop Water Stress Index

DEM digital elevation model

DoD Department of Defence

EL electroluminescence

FAA Federal Aviation Administration

FIS-B Flight Information Service - Broadcast

FOV field of view

GBSAAS Ground Based Sense and Avoid System

GCP ground control point

GCS ground control station

GPS Global Positioning System

GSD ground sampling distance

HD high definition

HFACS Human Factors Analysis and Classification System

ICAO International Civil Aviation Organization

IFR instrument flight rules

IMU Inertial Measurement Unit

InGaAs Indium Gallium Arsenide

KPI key performance indicator

LAI leaf area index

LIDAR light detection and ranging

MPC Model Predictive Control

MSL mean sea level

MVPGR Merced Vernal Pool and Grassland Reserve

NANIF Normalized Nadir Anistrophy Factor

NAS National Airspace System

NASA-TLX NASA Task Load Index

NBR Normalized Burn Ratio

NDII Normalized Difference Infrared Index

NDVI Normalized Difference Vegetation Index

NDWI Normalized Difference Water Index

NextGen Next Generation Air Transportation System

NIR Near Infrared

NIST National Institute of Standards and Technology

NOTAM Notice to Airmen

NPRM Notice of Proposed Rule Making

PAVE Personal Minimums

PDE partial differential equation

PIC pilot in command

PRI Photochemical Reflectance Index

QMS quality management system

RPIC remote pilot in command

RTM radiative transfer model

SAA sense and avoid

SAAS Sense and Avoid System

SAGAT Situation Awareness Global Assessment Technique

SfM Structure from Motion

SHB Smart Health Balancing

SHELL software, hardware, environment, liveware and liveware

SMARTS Simple Model of the Atmospheric Radiative Transfer of Sunshine

SMS Safety Management System

SRM safety risk management

SUAS Small Unmanned Aircraft System

SWIR Short Wave Infrared

TCAS Traffic Collision Avoidance System

TIR Thermal Infrared

TIS-B Traffic Information Service - Broadcast

UAS Unmanned Aircraft System

UAT universal access transceiver

UTM Unmanned Traffic Management

VFR visual flight rules

VI vegetation index

VLOS visual line of sight

VMC visual meteorological conditions

VO Visual Observer

Appendix B
FLIGHT OPERATIONS AT NIGHT

Safety Case for UAS Night Operations

UNIVERSITY OF CALIFORNIA, MERCED
BRANDON STARK

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1 SYSTEM DESCRIPTION SCOPE

The system under consideration is limited in scope to enabling a UAS to conduct night missions. The change between night flights and daytime flights is assumed to be only within the change in visibility, both to the ground observer and pilots, and to other air traffic.

The elements in this system are directly related to the visibility of the system, including external aircraft navigational lights, external aircraft landing lights, modifications to pilot operations, modification to ground observer operations and modifications of ground control station operations.

The lighting system on the aircraft includes three sets of lights: Right-of-Way lights along the leading edge of the wings and wing tips, fuselage lights to indicate nose/tail, landing lights to illuminate the ground upon landing.

2 UAS NIGHT OPERATIONS OVERVIEW

In order to maintain a high level of safety during night operations, the following modifications to the existing mission plan is proposed.

2.1 MODIFICATIONS TO PRE-FLIGHT PROCEDURES

The modifications to the pre-flight procedures include updates for the pilot and observer placement and responsibilities, additional training requirements as well as the installation of a UAS lighting system.

2.1.1 Pilot and Observer Procedures

The pilot and observers must be in place a minimum of 30 minutes prior to night operations to ensure dark adaptation. Additionally, the pilot and observers must be on site prior to the end of evening civil twilight to inspect for a suitable landing location and potential obstacles, including those that might have been altered since the last operation. No vision aids, such as binoculars or night vision devices may be used as the primary means of visual contact.

2.1.2 UAS Pilot and Ground Crew Training

The UAS pilot must demonstrate proficiency in night flying with flights with a similarly outfitted model RC aircraft. A concurrency of 3 night launch and landing events per 90 days will be required as well. The ground crew must also demonstrate proficiency in night flying operation including demonstrating the ability to determine aircraft attitude and position based on the navigation lights outfitted on the aircraft.

2.1.3 Description of UAS Lighting System

The UAS is to be outfitted with lighting to ensure both the pilot and the observers are able to determine aircraft attitude. The navigation lights will conform to existing standards for aircraft lighting. (See Fig. 1)

- Right-of-way lights – Red lights will be installed on the left side of the aircraft and along the wings while green lights are to be installed on the right side of the aircraft and along the wings.
- Strobe lights – Strobe lights along the fuselage and tail will flash periodically to provide additional visibility.

- Landing lights – Directional high-power lights installed at the bottom of the fuselage will be available for the pilot to turn on during landing approach to illuminate an undeveloped landing strip.

The installation of the lighting system is recessed as to not change the aerodynamics of the wing profile or fuselage.

An additional pre-flight checklist item is to be added to check the operation of the UAS lighting system, including the pilot controllable landing lights.

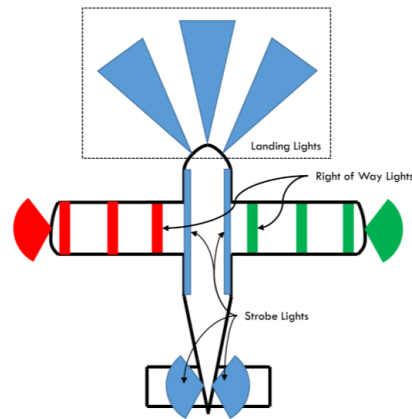


Figure 1: UAS Lighting System

2.2 MODIFICATIONS TO UAS OPERATION PROCEDURES

The operation of the UAS during night operations has been modified to improve visibility during operations, additional requirements for collision avoidance and provide additional illumination during the critical flight phases of launch and recovery.

2.2.1 UAS Mission Planning and Operation

The UAS will remain line-of-sight of the pilot and co-located observer at all times. An additional observer will be installed at a separate location, towards the opposite boundary of the proposed flight mission, and will remain in communication via a two-way radio system. The purpose of this observer is to scan for air traffic and monitor for the UAS. In the event that the pilot loses directional heading of the aircraft, the distant observer will provide verbal heading reports.

The UAS flight mission shall be designed with respect to the reduced visibility of night operations. The maximum safe viewing distance will be determined prior to flight and in accordance to the airworthiness criteria developed by the proponent.

The ground control station of the UAS will additionally be lighted sufficiently to reduce the strain on the ground control operator as well as any payload operators.

2.2.2 Collision avoidance

The proposed area is free of the majority of common obstacles that would challenge visibility and cause issues. However, both the pilot and the observers will make a site inspection prior to civil twilight to

examine for any obstacles. If an obstacle is found, a portable light will be used to illuminate it for the duration of the proposed mission.

In the event of other air traffic, it is the responsibility of the observers to alert the pilot and advise a corrective course. The addition of a distant, non-co-located observer will enable a better situational awareness of other air traffic and will provide sufficient warning to the pilot.

2.2.3 Launch and Recovery for Night Operations

In addition to the existing launch and recovery operations, an additional checklist item on the verification of the lighting system will be added prior to giving the final 'Go Ahead.' In addition to the aircrafts lighting system, to ensure visibility during the launch operation, a ground crew will additionally use a high-power flashlight to illuminate the aircraft during the launch process. In the proponent's launch system, an elastic bungee is used to generate the initial lift. A small LED light and reflector will be added to the clip that connects the elastic bungee to the aircraft (See Fig 2). This additional clip will enhance the visibility of the elastic bungee to make visible the separation of the clip from the aircraft as necessary for a safe launch.



Figure 2: LED and Reflector on launch clip

The recovery of the UAS will require two modifications: the addition of the pilot operated landing light system to illuminate the landing strip at an undeveloped location and a site selection with a minimum of 300 meters of available runway. The site of a recovery operation will be determined by the pilot prior to the end of civil twilight and the ground crew will maintain its operability as a landing site until the recovery operation is complete.

2.3 MODIFICATION TO POST FLIGHT PROCEDURES

Upon successful completion of a UAS night operation, the UAS will be taken to the lighted ground control station for post-flight inspection. If further night operations are requested, a detailed inspection is necessary. However, no more than two sequential flights will occur in a single night. A full system check, more detailed than a pre-flight check will be initiated to ensure continued safe operation.

The total duration of a UAS night operation shall not exceed 3 hours, from initial site inspection to the end of the final flight.

3 HAZARD IDENTIFICATION

The following Initial hazard identification is analyzed by flight phase.

The definitions for hazard severity and probability are described below:

1. Hazard Severity
 - a. Catastrophic – Failure conditions which could result in a fatality to UAV crew or ground staff
 - b. Hazardous – Failure conditions which could potentially result in serious injury to UAV crew or ground staff
 - c. Major – Failure conditions which could potentially result in injury to UAV crew or ground staff
 - d. Minor – Failure conditions what do not significantly reduce UAV system safety and involve UAV crew actions that are well within their capabilities.
 - e. No Safety Effect – Failure conditions that have no effect on safety
2. Probability Level
 - a. Extremely Improbable: Occurrence less than 10^{-6} per flight hour
 - b. Extremely Remote: Occurrence between 10^{-5} and 10^{-6} per flight hour
 - c. Remote: Occurrence between 10^{-4} and 10^{-5} per flight hour
 - d. Probable: Occurrence between 10^{-3} and 10^{-4} per flight hour
 - e. Frequent: Occurrence more than 10^{-3} per flight hour

3.1 PRE-FLIGHT PROCEDURES

Potential Hazard	Hazard Severity	Probability	Resolutions	Updated Severity / Probability
The pilot is not trained sufficiently	Precondition - N/A	Precondition - N/A	Require sufficient proficiency in night flying prior to UAS operation.	Extremely Remote - Acceptable risk
The ground crew is not trained sufficiently	Precondition - N/A	Precondition - N/A	Require sufficient proficiency in night operations prior to UAS operation	Extremely Remote - Acceptable risk
The ground crew is unable to view ground equipment	Precondition - N/A	Precondition - N/A	Provide additional illumination	Extremely Remote - Acceptable risk
The ground control station operator is unable to satisfactory view control station	Precondition - N/A	Precondition - N/A	Provide additional illumination	Extremely Remote - Acceptable risk
The pilot and ground crew are distracted and forget critical safety checks.	Precondition - N/A	Precondition - N/A	See further root cause analysis	Extremely Remote - Acceptable risk
Root Cause	Precondition for unsafe acts		Multiple preconditions exist	

Organization pressure			Allow for multiple flights per UAS operation. Require sufficient training.	Extremely Remote - Acceptable risk
Prolonged exposure to cold weather			Limit exposure by imposing a time limit for night operations	Extremely Remote - Acceptable risk
Fatigue			Limit operations to prevent excessive operations outside of normal hours.	Extremely Remote - Acceptable risk
The UAS lighting system is inoperable.	Precondition - N/A	Precondition - N/A	Add UAS lighting system operation to pre-flight checklist	Extremely Remote - Acceptable risk

3.2 LAUNCH PHASE

Potential Hazard	Hazard Severity	Probability	Resolutions	Updated Severity / Probability
The pilot encounters difficult control of the aircraft during launch	Minor		See further root cause analysis	
Root Cause Aircraft launch may be subject to environmental factors		Probable	Acceptable risk	
Pilot may be unable to see aircraft performance issues		Probable	Supply further illumination to improve visibility	Remote - Acceptable risk
The aircraft does not disengage from the elastic bungee	Major		See further root cause analysis	
Root Cause Aircraft launch is too shallow		Probable	Acceptable risk, provide sufficient training	
Pilot is unable to see disengagement		Frequent	Supply further illumination on bungee hook to improve visibility	Remote - Acceptable risk

3.3 STANDARD MISSION OPERATIONS

Potential Hazard	Hazard Severity	Probability	Resolutions	Updated Severity / Probability
The pilot lost visual sight of the aircraft	Precondition – N/A	Probable	Ensure UAS lighting system provides sufficient visibility. Reduce flight operations.	
Root Cause The aircraft is farther away than the lighting system is visible		Probable	Improve flight planning operations. Establish clear visibility limits.	Extremely Remote - Acceptable risk
The aircraft is behind an obstruction		Probable	Improve flight planning operations. Require pilot and observers to inspect for obstructions prior to twilight and adjust flight plan accordingly.	Extremely Remote - Acceptable risk
The aircraft lighting system has failed	Precondition – N/A	Extremely Remote	Acceptable Risk	
The pilot is unable to determine the orientation of the aircraft	Precondition – N/A	Probable	Require sufficient training. Ensure UAS lighting system provides sufficient visibility.	Remote - Acceptable risk
The pilot is confused by a perceived change in orientation due to changes in unidentified objects or lighting.	Minor	Remote	Utilize extra observers at a different location than the pilot to confirm orientations. Require sufficient training.	Remote - Acceptable risk
Aircraft Flight Performance has changed	Major	Remote	Recess the lighting system into the wing and the fuselage to avoid changing the aerodynamics of the aircraft.	Extremely Remote - Acceptable risk

3.4 FLIGHT MISSION PHASE TRANSITION

Potential Hazard	Hazard Severity	Probability	Potential Resolutions	Updated Severity / Probability
The aircraft is on a collision course with a stationary object	Hazardous	Probable	Require pilot and observers to inspect for obstructions prior	Extremely Remote - Acceptable risk

			to twilight. Adjust flight operations accordingly.	
The aircraft is on a collision course with an object in air	Hazardous	Remote	Utilize a second observer, not at the same location as the pilot to provide a secondary viewpoint for monitoring for intruding air traffic.	Extremely Remote - Acceptable risk
The aircraft collides with power lines	Hazardous	Remote	Require pilot and observers to inspect for obstructions prior to twilight. Adjust flight operations accordingly.	Extremely Remote - Acceptable risk
The aircraft collides with trees or vegetation	Hazardous	Remote	Require pilot and observers to inspect for obstructions prior to twilight. Adjust flight operations accordingly.	Extremely Remote - Acceptable risk
The pilot and non-co-located observer lose communication	Minor	Probable	Acceptable risk.	Extremely Remote - Acceptable risk

3.5 RECOVERY PHASE

Potential Hazard	Hazard Severity	Probability	Potential Resolutions	Updated Severity / Probability
The pilot is unable to determine the aircraft altitude as it descends for landing	Hazardous	Probable	Ensure UAS lighting system provides sufficient visibility during the recovery phase.	Extremely Remote - Acceptable risk
The pilot does not have sufficient length for landing	Minor	Probable	Ensure UAS lighting system provides sufficient visibility during the recovery phase. Require additional runway length	Remote – Acceptable risk
The aircraft collides with ground crew upon landing approach	Hazardous	Extremely Remote	Require sufficient proficiency in night operations prior to UAS operation	Acceptable Risk

3.6 POST-FLIGHT PROCEDURES

Potential Hazard	Hazard Severity	Probability	Potential Resolutions	Updated Severity / Probability
The aircraft, after returning from a flight mission, has suffered damage that requires repair before the next flight	Hazardous	Probable	Increase flight status inspection rigor for night operations. Limit UAS operations at night.	Extremely Remote - Acceptable risk
The pilot and ground crew are distracted and forget critical safety checks.	Precondition - N/A	Precondition - N/A	See further root cause analysis	Extremely Remote - Acceptable risk
Root Cause	Precondition for unsafe acts		Multiple preconditions exist	
	Organization pressure		Allow for multiple flights per UAS operation. Require sufficient training.	Extremely Remote - Acceptable risk
	Prolonged exposure to cold weather		Limit exposure by imposing a time limit for night operations	Extremely Remote - Acceptable risk
	Fatigue		Limit operations to prevent excessive operations outside of normal hours.	Extremely Remote - Acceptable risk

4 VALIDATION AND SYSTEM CHECKS

In order to demonstrate that the proposed modifications for UAS night operations are sufficient for safe operation, the following systematic checks will be added to the airworthiness self-certification and pre-flight operations.

4.1 UAS LIGHTING SYSTEM AIRWORTHINESS VALIDATION

The following list demonstrates the systematic process of validating the correct installation of the UAS lighting system and validates the performance of the system.

- Initialization
 - Correct location installation of lighting system
 - Lights receive correct voltage (12V)
 - Red lights active
 - Green lights active
 - Strobe lights active
 - Strobe lights pulse at correct frequency (2Hz)
 - Landing lights active
 - Landing lights user controllable
 - Correct power consumption of lighting system (< 12 Watts)
 - Bungee light active

- Aircraft Visibility Analysis

The visibility of the aircraft will be experimentally validated through ground testing prior to any flights.

- Aircraft orientation visible at dark at 100 ft.
- Aircraft orientation visible at dark at 250 ft.
- Aircraft orientation visible at dark at 500 ft.
- Aircraft orientation visible at dark at 1000 ft. (0.16 nm)
- Aircraft orientation visible at dark at 1500 ft. (0.25 nm)
- Aircraft orientation visible at dark at 2000 ft. (0.33 nm)

The testing will be conducted as follows. A ground crew operator will turn on the lighting system on the aircraft and carry the aircraft to a marked location. A separate operator will act as the testing personnel and will be co-located with the aircraft. The aircraft pilot will move to a marked location at the specified distance. Communicating using a two way radio, the ground crew operator will initiate the test and proceed to slowly move the aircraft to a total of 25 different orientation. The pilot is instructed to call out the orientation using the specified terminology. The testing personnel will score the accuracy of the pilot's statement. A test is considered successful if the accuracy rate is above 85%.

In the event that the pilot is unable to determine the orientation of the aircraft at a specified distance, several options are available. It is anticipated that the addition of brighter lights is a probable necessity. Less desirable, but also probable, is that the maximum distance of operations may be reduced.

- Obstacle Visibility Analysis

Prior to operations, the following three items will be evaluated. The testing will be accomplished in a similar manner as the aircraft orientation visibility analysis.

- Obstacles are illuminated sufficiently
- Ground crew personal illumination sufficient
- Launch and Recovery operation systems are sufficiently illuminated

4.2 PRE-FLIGHT OPERATIONS

The following list demonstrates the systematic process of preparing for UAS night operations immediately prior to operations.

- Mission Preparation upon arrival to site
 - Ground crew and pilot are on site prior to civil twilight
 - Ground crew and pilot identify potential obstacles
 - Obstacles marked with portable lighting systems
 - Ground crew installs portable runway illumination on designated landing site.
 - Ground crew installs illumination for ground control system operations
- Pre-flight Operations
 - Ground crew activates bungee light
 - Pilot checks for proper UAS lighting system operation
 - Secondary observer has signaled he/she is at the designated location and is ready to commence the mission.

5 FINAL REMARKS

The challenge of ensuring flight safety for night operations is not trivial. The drastic change in visibility challenges many aspects of a successful UAS mission. Simply installing lights onto the UAS will aid operations, but fails to ensure safety, especially in regards to collision avoidance. The proposed mission modifications have addressed the issues and has reduced the risks to an acceptable level.

The undersigned below acknowledges the modifications and certifies that the proposed modifications deems the aircraft and operations safe for night operations in accordance with the University of California, Merced.

Brandon Stark, Lab Manager
 MESA Lab
 University of California, Merced

B.2 COA 2014-WSA-193

FAA FORM 7711-1 UAS COA Attachment
2014-WSA-193-COA

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DEPARTMENT OF TRANSPORTATION FEDERAL AVIATION ADMINISTRATION	
CERTIFICATE OF WAIVER OR AUTHORIZATION	
ISSUED TO	University of California, Merced
MESA Lab 5200 N. Lake Rd Merced, CA 95343	
This certificate is issued for the operations specifically described hereinafter. No person shall conduct any operation pursuant to the authority of this certificate except in accordance with the standard and special provisions contained in this certificate, and such other requirements of the Federal Aviation Regulations not specifically waived by this certificate.	
OPERATIONS AUTHORIZED	Operation of the AggieAir Unmanned Aircraft System (UAS) in Class G airspace, up to but not including 700 feet Above Ground Level (AGL) in the vicinity of Isleton, CA as depicted in Attachment 1, under the jurisdiction of Northern California Terminal Radar Approach Control (TRACON). See Special Provisions.
LIST OF WAIVED REGULATIONS BY SECTION AND TITLE	N/A
STANDARD PROVISIONS	
1. A copy of the application made for this certificate shall be attached and become a part hereof. 2. This certificate shall be presented for inspection upon the request of any authorized representative of the Federal Aviation Administration, or of any State or municipal official charged with the duty of enforcing local laws or regulations. 3. The holder of this certificate shall be responsible for the strict observance of the terms and provisions contained herein. 4. This certificate is nontransferable.	
Note-This certificate constitutes a waiver of those Federal rules or regulations specifically referred to above. It does not constitute a waiver of any State law or local ordinance.	
SPECIAL PROVISIONS	
Special Provisions are set forth and attached.	
The certificate 2014-WSA-193 is effective from March 16, 2015 to March 15, 2017 and is subject to cancellation at any time upon notice by the Administrator or his/her authorized representative.	
BY DIRECTION OF THE ADMINISTRATOR	
FAA Headquarters, AJV-115 (Region)	 Jacqueline R. Jackson (Signature)
March 16, 2015 (Date)	Manager, UAS Tactical Operations Section (Title)

Version 2.1: June 2012

COA Number: 2014-WSA-193

Issued To: University of California, Merced, referred herein as the “proponent”

Address: MESA Lab
5200 N. Lake Rd
Merced, CA 95343

Activity: Operation of the AggieAir Unmanned Aircraft System (UAS) in Class G airspace, up to but not including 700 feet Above Ground Level (AGL) in the vicinity of Isleton, CA as depicted in Attachment 1, under the jurisdiction of Northern California Terminal Radar Approach Control (TRACON). See Special Provisions.

Purpose: To prescribe UAS operating requirements in the National Airspace System (NAS) for the purpose of aeronautical research relating to the development of UASs for environmental, biological and geological research applications.

Dates of Use: This COA is valid from March 16, 2015 through March 15, 2017. Should a renewal become necessary, the proponent shall advise the Federal Aviation Administration (FAA), in writing, no later than 45 business days prior to the requested effective date.

Public Aircraft

1. A public aircraft operation is determined by statute, 49 USC §40102(a)(41) and §40125.
2. All public aircraft flights conducted under a COA must comply with the terms of the statute.
3. All flights must be conducted per the declarations submitted on COA on-line.

STANDARD PROVISIONS

A. General.

The review of this activity is based upon current understanding of UAS operations and their impact in the NAS. This COA will not be considered a precedent for future operations. (As changes in or understanding of the UAS industry occur, limitations and conditions for operations will be adjusted.)

All personnel connected with the UAS operation must read and comply with the contents of this authorization and its provisions.

A copy of the COA including the special limitations must be immediately available to all operational personnel at each operating location whenever UAS operations are being conducted.

This authorization may be canceled at any time by the Administrator, the person authorized to grant the authorization, or the representative designated to monitor a specific operation. As a general rule, this authorization may be canceled when it is no longer required, there is an abuse of its provisions, or when unforeseen safety factors develop. Failure to comply with the authorization is cause for cancellation. The proponent will receive written notice of cancellation.

During the time this COA is approved and active, a site safety evaluation/visit may be accomplished to ensure COA compliance, assess any adverse impact on ATC or airspace, and ensure this COA is not burdensome or ineffective. Deviations, accidents/incidents/mishaps, complaints, etc. will prompt a COA review or site visit to address the issue. Refusal to allow a site safety evaluation/visit may result in cancellation of the COA. Note: This section does not pertain to agencies that have other existing agreements in place with the FAA.

B. Airworthiness Certification.

The unmanned aircraft must be shown to be airworthy to conduct flight operations in the NAS. must be operated in strict compliance with all provisions University of California, Merced, MESA Lab has made its own determination that the AggieAir unmanned aircraft is airworthy. The AggieAir and conditions contained in the Airworthiness Safety Release, including all documents and provisions referenced in the COA application.

1. A configuration control program must be in place for hardware and/or software changes made to the UAS to ensure continued airworthiness. If a new or revised Airworthiness Release is generated as a result of changes in the hardware or software affecting the operating characteristics of the UAS, notify the UAS Integration Office of the changes as soon as practical.

- a. Software and hardware changes should be documented as part of the normal maintenance procedures. Software changes to the aircraft and control station as well as hardware system changes are classified as major changes unless the agency has a formal process, accepted by the FAA. These changes should be provided to the UAS Integration office in summary form at the time of incorporation.
 - b. Major modifications or changes, performed under the COA, or other authorizations that could potentially affect the safe operation of the system must be documented and provided to the FAA in the form of a new AWR, unless the agency has a formal process, accepted by the FAA.
 - c. All previously flight proven systems to include payloads, may be installed or removed as required, and that activity recorded in the unmanned aircraft and ground control stations logbooks by persons authorized to conduct UAS maintenance. Describe any payload equipment configurations in the UAS logbook that will result in a weight and balance change, electrical loads, and or flight dynamics, unless the agency has a formal process, accepted by the FAA.
 - d. For unmanned aircraft system discrepancies, a record entry should be made by an appropriately rated person to document the finding in the logbook. No flights may be conducted following major changes, modifications or new installations unless the party responsible for certifying airworthiness has determined the system is safe to operate in the NAS and a new AWR is generated, unless the agency has a formal process, accepted by the FAA. The successful completion of these tests must be recorded in the appropriate logbook, unless the agency has a formal process, accepted by the FAA.
2. The AggieAir must be operated in strict compliance with all provisions and conditions contained within the spectrum analysis assigned and authorized for use within the defined operations area.
 3. All items contained in the application for equipment frequency allocation must be adhered to, including the assigned frequencies and antenna equipment characteristics. A ground operational check to verify the control station can communicate with the aircraft (frequency integration check) must be conducted prior to the launch of the unmanned aircraft to ensure any electromagnetic interference does not adversely affect control of the aircraft.
 4. The use of a Traffic Collision Avoidance System (TCAS) in any mode while operating an unmanned aircraft is prohibited.

C. Operations.

1. Unless otherwise authorized as a special provision, a maximum of one unmanned aircraft will be controlled:
 - a. In any defined operating area,

- b. From a single control station, and
 - c. By one pilot at a time.
2. A Pilot-in-Command (PIC) is the person who has final authority and responsibility for the operation and safety of flight, has been designated as PIC before or during the flight, and holds the appropriate category, class, and type rating, if appropriate, for the conduct of the flight. The responsibility and authority of the PIC as described by 14 CFR 91.3, Responsibility and Authority of the Pilot-in-Command, apply to the unmanned aircraft PIC. The PIC position may rotate duties as necessary with equally qualified pilots. The individual designated as PIC may change during flight. **Note:** The PIC can only be the PIC for one aircraft at a time. For Optionally Piloted Aircraft (OPA), PIC must meet UAS guidance requirements for training, pilot licensing, and medical requirements when operating OPA as a UAS.
3. The PIC must conduct a pre-takeoff briefing as applicable prior to each launch. The briefing should include but is not limited to the:
- a. Contents of the COA,
 - b. Altitudes to be flown,
 - c. Mission overview including handoff procedures,
 - d. Frequencies to be used,
 - e. Flight time, including reserve fuel requirements,
 - f. Contingency procedures to include lost link, divert, and flight termination, and
 - g. Hazards unique to the flight being flown.

Note: Flight Crew Member (UAS). In addition to the flight crew members identified in 14 CFR Part 1, Definitions and Abbreviations, an Unmanned Aircraft System flight crew members include pilots, sensor/payload operators, and visual observers and may include other persons as appropriate or required to ensure safe operation of the aircraft.

4. All operations will be conducted in compliance with Title 14 CFR Part 91. Special attention should be given to:
- a. § 91.3 Responsibility and authority of the pilot in command
 - b. § 91.13 Careless or reckless operation
 - c. § 91.17 Alcohol or drugs
 - d. § 91.103 Preflight Actions
 - e. § 91.111 Operating near other aircraft.
 - f. § 91.113 Right-of-way rules: Except water operations
 - g. § 91.115 Right-of-way rules: Water operations
 - h. § 91.119 Minimum safe altitudes: General

- i. § 91.123 Compliance with ATC clearances and instructions.
 - j. § 91.133 Restricted and prohibited areas
 - k. § 91.137 Temporary flight restrictions in the vicinity of disaster/hazard areas
 - l. § 91.145 Management of aircraft operations in the vicinity of aerial demonstrations and major sporting events
 - m. § 91.151 Fuel requirements for flight in VFR conditions
 - n. § 91.155 Basic VFR weather minimums
 - o. § 91.159 VFR cruising altitude or flight level
 - p. § 91.209 Aircraft Lights
 - q. § 91.213 Inoperative instruments and equipment
 - r. § 91.215 ATC transponder and altitude reporting equipment and use
 - s. Appendix D to Part 91—Airports/Locations: Special Operating Restrictions
5. Unless otherwise authorized as a special provision, all operations must be conducted in visual meteorological conditions (VMC) during daylight hours in compliance with Title 14 of the Code of Federal Regulations (CFR) Part 91 §91.155 and the following:
6. Special Visual Flight Rules (VFR) operations are not authorized.
- a. VFR cloud clearances specified in 14 CFR Part 91 §91.155, must be maintained, except in Class G airspace where Class E airspace visibility requirements must be applied, but not less than 3 statute miles (SM) flight visibility and 1000' ceiling.
 - b. Flights conducted under Instrument Flight Rules (IFR) in Class A airspace shall remain clear of clouds. NOTE: Deviations from IFR clearance necessary to comply with this provision must have prior ATC approval.
 - c. Chase aircraft must maintain 5 NM flight visibility.
7. Night operations are prohibited unless otherwise authorized as a special provision.
8. Operations (including lost link procedures) must not be conducted over populated areas, heavily trafficked roads, or an open-air assembly of people.

D. Air Traffic Control (ATC) Communications.

- 1. The pilot and/or PIC will maintain direct, two-way communication with ATC and have the ability to maneuver the unmanned aircraft in response to ATC instructions, unless addressed in the Special Provision Section.

- a. When required, ATC will assign a radio frequency for air traffic control during flight. The use of land-line and/or cellular telephones is prohibited as the primary means for in-flight communication with ATC.
2. The PIC must not accept an ATC clearance requiring the use of visual separation, sequencing, or visual approach.
3. When necessary, transit of airways and routes must be conducted as expeditiously as possible. The unmanned aircraft must not loiter on Victor airways, jet routes, Q and T routes, IR routes, or VR routes.
4. For flights operating on an IFR clearance at or above 18,000 feet mean sea level (MSL), the PIC must ensure positional information in reference to established National Airspace System (NAS) fixes, NAVAIDs, and/or waypoints is provided to ATC. The use of latitude/longitude positions is not authorized, except oceanic flight operations.
5. If equipped, the unmanned aircraft must operate with:
 - a. An operational mode 3/A transponder with altitude encoding, or mode S transponder (preferred) set to an ATC assigned squawk.
 - b. Position/navigation and anti-collision lights on at all times during flight unless stipulated in the special provisions or the proponent has a specific exemption from 14 CFR Part 91.209.
6. Operations that use a Global Positioning System (GPS) for navigation must check Receiver Autonomous Integrity Monitoring (RAIM) notices prior to flight operations. Flight into a GPS test area or degraded RAIM is prohibited for those aircraft that use GPS as their sole means for navigation.

E. Safety of Flight.

1. The proponent or delegated representative is responsible for halting or canceling activity in the COA area if, at any time, the safety of persons or property on the ground or in the air is in jeopardy, or if there is a failure to comply with the terms or conditions of this authorization.
2. ATC must be immediately notified in the event of any emergency, loss and subsequent restoration of command link, loss of PIC or observer visual contact, or any other malfunction or occurrence that would impact safety or operations.
3. Sterile Cockpit Procedures:
 - a. Critical phases of flight include all ground operations involving:
 - (1) Taxi (movement of an aircraft under its own power on the surface of an airport).
 - (2) Take-off and landing (launch or recovery).

- (3) All other flight operations in which safety or mission accomplishment might be compromised by distractions.
- b. No crewmember may perform any duties during a critical phase of flight not required for the safe operation of the aircraft.
 - c. No crewmember may engage in, nor may any PIC permit, any activity during a critical phase of flight which could:
 - (1) Distract any crewmember from the performance of his/her duties, or
 - (2) Interfere in any way with the proper conduct of those duties.
 - d. The pilot and/or the PIC must not engage in any activity not directly related to the operation of the aircraft. Activities include, but are not limited to, operating UAS sensors or other payload systems.
 - e. The use of cell phones or other electronic devices is restricted to communications pertinent to the operational control of the unmanned aircraft and any required communications with Air Traffic Control.
4. See-and-Avoid.

Unmanned aircraft have no on-board pilot to perform see-and-avoid responsibilities; therefore, when operating outside of active restricted and warning areas approved for aviation activities, provisions must be made to ensure an equivalent level of safety exists for unmanned operations. Adherence to 14 CFR Part 91 §91.111, §91.113 and §91.115, is required.

- a. The proponent and/or delegated representatives are responsible at all times for collision avoidance with all aviation activities and the safety of persons or property on the surface with respect to the UAS.
- b. UAS pilots will ensure there is a safe operating distance between aviation activities and unmanned aircraft at all times.
- c. Any crew member responsible for performing see-and-avoid requirements for the UA must have and maintain instantaneous communication with the PIC.
- d. UA operations will only be conducted within Reduced Vertical Separation Minimum (RVSM) altitudes, when appropriately equipped or having received a clearance under an FAA deviation. **NOTE:** UA operations should not plan on an en-route clearance in RVSM altitudes, without being RVSM equipped.
- e. Visual observers must be used at all times except in Class A, airspace, active Restricted Areas, and Warning areas designated for aviation activities.
 - (1) Observers may either be ground-based or in a chase plane.

- (2) If the chase aircraft is operating more than 100 feet above/below and/or more than $\frac{1}{2}$ NM laterally of the unmanned aircraft, the chase aircraft PIC will advise the controlling ATC facility.
- f. The PIC is responsible to ensure visual observers are:
 - (1) Able to see the aircraft and the surrounding airspace throughout the entire flight, and
 - (2) Able to provide the PIC with the UA's flight path, and proximity to all aviation activities and other hazards (e.g., terrain, weather, structures) sufficiently to exercise effective control of the UA to:
 - (a) Comply with CFR Parts 91.111, 91.113 and 91.115, and
 - (b) Prevent the UA from creating a collision hazard.
5. Observers must be able to communicate clearly to the pilot any instructions required to remain clear of conflicting traffic, using standard phraseology as listed in the Aeronautical Information Manual when practical.
6. A PIC may rotate duties as necessary to fulfill operational requirements; a PIC must be designated at all times.
7. Pilots flying chase aircraft must not concurrently perform observer or UA pilot duties.
8. Pilot and observers must not assume concurrent duties as both pilot and observer.
9. The required number of ground observers will be in place during flight operations.
10. The use of multiple successive observers (daisy chaining) is prohibited unless otherwise authorized as a special provision.
11. The dropping or spraying of aircraft stores, or carrying of hazardous materials (including ordnance) outside of active Restricted, Prohibited, or Warning Areas approved for aviation activities is prohibited unless specifically authorized as a special provision.

F. Crewmember Requirements.

1. All crewmembers associated with the operation of the unmanned aircraft, including chase operations, must be qualified or must be receiving formal training under the direct supervision of a qualified instructor, who has at all times, responsibility for the operation of the unmanned aircraft.
2. Pilots and observers must have an understanding of, and comply with, Title 14 Code of Federal Regulations, and/or agency directives and regulations, applicable to the airspace where the unmanned aircraft will operate.

3. Pilots, supplemental pilots, and observers must maintain a current second class (or higher) airman medical certificate that has been issued under 14 CFR Part 67, or an FAA accepted agency equivalent based on the application.
4. At a minimum, the use of alcohol and/or drugs in violation of 14 CFR Part 91 §91.17 applies to UA pilots and observers.
5. At a minimum, observers must receive training on rules and responsibilities described in 14 CFR Part 91 §91.111, §91.113 and §91.115, regarding cloud clearance, flight visibility, and the pilot controller glossary, including standard ATC phraseology and communication.
6. Recent Pilot Experience (Currency). The proponent must provide documentation, upon request, showing the pilot/supplemental pilot/PIC maintains an appropriate level of recent pilot experience in either the UAS being operated or in a certified simulator. At a minimum, he/she must conduct three takeoffs (launch) and three landings (recovery) in the specific UAS within the previous 90 days (excluding pilots who do not conduct launch/recovery during normal/emergency operations). If a supplemental pilot assumes the role of PIC, he/she must comply with PIC rating requirements.
7. A PIC and/or supplemental pilot have the ability to assume the duties of an internal or an external UAS pilot at any point during the flight.
8. A PIC may be augmented by supplemental pilots.
9. PIC Ratings.

Rating requirements for the UAS PIC depend on the type of operation conducted. The requirement for the PIC to hold, at a minimum, a current FAA private pilot certificate or the FAA accepted agency equivalent, based on the application of 14 CFR Part 61, is predicated on various factors including the location of the planned operations, mission profile, size of the unmanned aircraft, and whether or not the operation is conducted within or beyond visual line-of-sight.

 - a. The PIC must hold, at a minimum, a current FAA private pilot certificate or the FAA accepted agency equivalent, based on the application or 14 CFR Part 61, under all operations:
 - (1) Approved for flight in Class A, B, C, D, E, and G (more than 400 feet above ground level (AGL)) airspace.
 - (2) Conducted under IFR (FAA instrument rating required, or the FAA accepted agency equivalent, based on the application or 14 CFR Part 61.
 - (3) Approved for night operations.
 - (4) Conducted at or within 5 NM of a joint use or public airfields.
 - (5) Requiring a chase aircraft.

- (6) At any time the FAA has determined the need based on the UAS characteristics, mission profile, or other operational parameters.
 - b. Operations without a pilot certificate may be allowed when all of the following conditions are met:
 - (1) The PIC has successfully completed, at a minimum, FAA private pilot ground instruction and passed the written examination, or the FAA accepted agency equivalent, based on the application. Airman Test reports are valid for the 24-calendar month period preceding the month the exam was completed, at which time the instruction and written examination must be repeated.
 - (2) Operations are during daylight hours.
 - (3) The operation is conducted in a sparsely populated location.
 - (4) The operation is conducted from a privately owned airfield, military installation, or off-airport location.
 - (5) Operations are approved and conducted solely within visual line-of-sight in Class G airspace.
 - (6) Visual line-of-sight operations are conducted at an altitude of no more than 400 feet Above Ground Level (AGL) in class G airspace at all times.
 - c. The FAA may require specific aircraft category and class ratings in manned aircraft depending on the UAS seeking approval and the characteristics of its flight controls interface.
10. PIC Recent Flight Experience (Currency).
- a. For those operations that require a certificated pilot or FAA accepted agency equivalent, based on the application, the PIC must have flight reviews 14 CFR Part 61.56, and if the pilot conducts takeoff, launch, landing or recovery the PIC must maintain recent pilot experience in manned aircraft per 14 CFR Part 61.57.; Recent Flight Experience: Pilot in Command.
 - b. For operations approved for night or IFR through special provisions, the PIC must maintain minimum recent pilot experience per 14 CFR Part 61.57, Recent Flight Experience: Pilot in Command, as applicable.
11. Supplemental pilots must have, at a minimum, successfully completed private pilot ground school and passed the written test or the FAA accepted agency equivalent, based on the application. The ground school written test results are valid for two years from the date of completion, at which time the instruction and written examination must be repeated. If a supplemental pilot assumes the role of PIC, he/she must comply with PIC rating, currency, medical, and training requirements listed in this document.
12. Ancillary personnel such as systems operators or mission specialists must be thoroughly familiar with and possess operational experience of the equipment being used. If the systems being used are for observation and detection of other aircraft for collision

avoidance purposes, personnel must be thoroughly trained on collision avoidance procedures and techniques and have direct communication with the UAS pilot, observer, and other crewmembers.

13. The Agency will ensure that Crew Resource Management (CRM) training is current for all crew members before flying operational or training missions. The CRM program must consist of initial training, as well as CRM recurrent training during every recurrent training cycle, not to exceed a 12 month interval between initial training and recurrent training or between subsequent recurrent training sessions.

G. Notice to Airmen (NOTAM).

1. A distant (D) NOTAM must be issued when unmanned aircraft operations are being conducted. This requirement may be accomplished:
 - a. Through the proponent's local base operations or NOTAM issuing authority, or
 - b. By contacting the NOTAM Flight Service Station at 1-877-4-US-NTMS (1-877-487-6867) not more than 72 hours in advance, but not less than 48 hours prior to the operation, unless otherwise authorized as a special provision. The issuing agency will require the:
 - (1) Name and address of the pilot filing the NOTAM request
 - (2) Location, altitude, or operating area
 - (3) Time and nature of the activity.
2. For proponents filing their NOTAM with the Department of Defense: The requirement to file with an Automated Flight Service Station (AFSS) is in addition to any local procedures/requirements for filing through the Defense Internet NOTAM Service (DINS).

H. Data Reporting.

1. Documentation of all operations associated with UAS activities is required regardless of the airspace in which the UAS operates. This requirement includes COA operations within Special Use airspace. NOTE: Negative (zero flights) reports are required.
2. The proponent must submit the following information through UAS COA On-Line on a monthly basis:
 - a. The number of flights conducted under this COA. (A flight during which any portion is conducted in the NAS must be counted only once, regardless of how many times it may enter and leave Special Use airspace between takeoff and landing)
 - b. Aircraft operational hours per flight
 - c. Ground control station operational hours in support of each flight, to include Launch and Recovery Element (LRE) operations

- d. Pilot duty time per flight
- e. Equipment malfunctions (hardware/software) affecting either the aircraft or ground control station
- f. Deviations from ATC instructions and/or Letters of Agreement/Procedures
- g. Operational/coordination issues
- h. The number and duration of lost link events (control, vehicle performance and health monitoring, or communications) per aircraft per flight.

I. Incident/Accident/Mishap Reporting.

Immediately after an incident or accident, and before additional flight under this COA, the proponent must provide initial notification of the following to the FAA via the UAS COA On-Line forms (Incident/Accident).

1. All accidents/mishaps involving UAS operations where any of the following occurs:
 - a. Fatal injury, where the operation of a UAS results in a death occurring within 30 days of the accident/mishap
 - b. Serious injury, where the operation of a UAS results in a hospitalization of more than 48 hours, the fracture of any bone (except for simple fractures of fingers, toes, or nose), severe hemorrhage or tissue damage, internal injuries, or second or third-degree burns
 - c. Total unmanned aircraft loss
 - d. Substantial damage to the unmanned aircraft system where there is damage to the airframe, power plant, or onboard systems that must be repaired prior to further flight
 - e. Damage to property, other than the unmanned aircraft.
2. Any incident/mishap that results in an unsafe/abnormal operation including but not limited to:
 - a. A malfunction or failure of the unmanned aircraft's on-board flight control system (including navigation)
 - b. A malfunction or failure of ground control station flight control hardware or software (other than loss of control link)
 - c. A power plant failure or malfunction
 - d. An in-flight fire
 - e. An aircraft collision
 - f. Any in-flight failure of the unmanned aircraft's electrical system requiring use of alternate or emergency power to complete the flight
 - g. A deviation from any provision contained in the COA

- h. A deviation from an ATC clearance and/or Letter(s) of Agreement/Procedures
- i. A lost control link event resulting in
 - (1) Fly-away, or
 - (2) Execution of a pre-planned/unplanned lost link procedure.
- 3. Initial reports must contain the information identified in the COA On-Line Accident/Incident Report.
- 4. Follow-on reports describing the accident/incident/mishap(s) must be submitted by providing copies of proponent aviation accident/incident reports upon completion of safety investigations. Such reports must be limited to factual information only where privileged safety or law enforcement information is included in the final report.
- 5. Public-use agencies other than those which are part of the Department of Defense are advised that the above procedures are not a substitute for separate accident/incident reporting required by the National Transportation Safety Board under 49 CFR Part 830 §830.5.
- 6. This COA is issued with the provision that the FAA be permitted involvement in the proponent's incident/accident/mishap investigation as prescribed by FAA Order 8020.11, Aircraft Accident and Incident Notification, Investigation, and Reporting.

FLIGHT STANDARDS SPECIAL PROVISIONS

A. Contingency Planning

- 1. **Point Identification.** The proponent must submit contingency plans that address emergency recovery or flight termination of the unmanned aircraft (UA) in the event of unrecoverable system failure. These procedures will normally include Lost Link Points (LLP), Divert/Contingency Points (DCP) and Flight Termination Points (FTP) for each operation. LLPs and DCPs must be submitted in latitude/longitude (Lat/Long) format along with a graphic representation plotted on an aviation sectional chart (or similar format). FTPs or other accepted contingency planning measures must also be submitted in latitude/longitude (Lat/Long) format along with a graphic representation plotted on an aviation sectional chart, or other graphic representation acceptable to the FAA. The FAA accepts the LLPs, DCPs, FTPs, and other contingency planning measures, submitted by the proponent but does not approve them. When conditions preclude the use of FTPs, the proponent must submit other contingency planning options for consideration and approval. At least one LLP, DCP, and FTP (or an acceptable alternative contingency planning measure) is required for each operation. The proponent must furnish this data with the initial COA application. Any subsequent changes or modifications to this data must be provided to AJV-13 for review and consideration no later than 30 days prior to proposed flight operations.

2. **Risk Mitigation Plans.** For all operations, the proponent must develop detailed plans to mitigate the risk of collision with other aircraft and the risk posed to persons and property on the ground in the event the UAS encounters a lost link, needs to divert, or the flight needs to be terminated. The proponent must take into consideration all airspace constructs and minimize risk to other aircraft by avoiding published airways, military training routes, NAVAIDs, and congested areas. In the event of a contingency divert or flight termination, the use of a chase aircraft is preferred when the UAS is operated outside of Restricted or Warning Areas. If time permits, the proponent should make every attempt to utilize a chase aircraft to monitor the aircraft to a DCP or to the FTP. In the event of a contingency divert or flight termination, the proponent will operate in Class A airspace and Special Use airspace to the maximum extent possible to reduce the risk of collision with non-participating air traffic.
- a. **LLP Procedures.**
- (1) LLPs are defined as a point, or sequence of points where the aircraft will proceed and hold at a specified altitude, for a specified period of time, in the event the command and control link to the aircraft is lost. The aircraft will autonomously hold, or loiter, at the LLP until the communication link with the aircraft is restored or the specified time elapses. If the time period elapses, the aircraft may autoland, proceed to another LLP in an attempt to regain the communication link, or proceed to an FTP for flight termination. LLPs may be used as FTPs. In this case, the aircraft may loiter at the LLP/FTP until link is re-established or fuel exhaustion occurs.
 - (2) For areas where multiple or concurrent UAS operations are authorized in the same operational area, a segregation plan must be in place in the event of a simultaneous lost link scenario. The segregation plan may include altitude offsets and horizontal separation by using independent LLPs whenever possible.
- b. **DCP Procedures.**
- (1) A DCP is defined as an alternate landing/recovery site to be used in the event of an abnormal condition that requires a precautionary landing. Each DCP must incorporate the means of communication with ATC throughout the descent and landing (unless otherwise specified in the Special Provisions) as well as a plan for ground operations and securing/parking the aircraft on the ground. This includes the availability of ground control stations capable of launch/recovery, communication equipment, and an adequate power source to operate all required equipment.
 - (2) For local operations, the DCP specified will normally be the airport/facility used for launch and recovery; however, the proponent may specify additional DCPs as alternates.
 - (3) For transit and/or mission operations that are being conducted in Class A airspace or Class E airspace above flight level (FL)-600, DCPs will be identified during the flight to be no further than one hour of flight time at any given time, taking into consideration altitude, winds, fuel consumption, and other factors. If it is not

possible to define DCPs along the entire flight plan route, the proponent must identify qualified FTPs along the entire route and be prepared to execute flight termination at one of the specified FTPs if a return to base (RTB) is not possible.

- (4) It is preferred that specified DCPs are non-joint use military airfields, other government-owned airfields, or private-use airfields. However, the proponent may designate any suitable airfield for review and consideration.

c. Flight Termination Procedures.

- (1) Flight termination is the intentional and deliberate process of performing controlled flight into terrain (CFIT). Flight termination must be executed in the event that all contingencies have been exhausted and further flight of the aircraft cannot be safely achieved or other potential hazards exist that require immediate discontinuation of flight. FTPs or alternative contingency planning measures must be located within power off glide distance of the aircraft during all phases of flight and must be submitted for review and acceptance. The proponent must ensure sufficient FTPs or other contingency plan measures are defined to accommodate flight termination at any given point along the route of flight. The location of these points is based on the assumption of an unrecoverable system failure and must take into consideration altitude, winds, and other factors.
- (2) Unless otherwise authorized, FTPs must be located in sparsely populated areas. Except for on- or near-airport operations, FTPs will be located no closer than five nautical miles from any airport, heliport, airfield, NAVAID, airway, populated area, major roadway, oil rig, power plant, or any other infrastructure. For offshore locations, the proponent must refer to appropriate United States Coast Guard (USCG) charts and other publications to avoid maritime obstructions, shipping lanes, and other hazards. Populated areas are defined as those areas depicted in yellow on a VFR sectional chart or as determined from other sources.
 - (a) It is preferred that flight termination occurs in Restricted or Warning Areas, government-owned land, or offshore locations that are restricted from routine civil use. However, the proponent may designate any suitable location for review and consideration.
 - (b) The proponent is required to survey all designated areas prior to their use as an FTP. All FTPs will be reviewed for suitability on a routine and periodic basis, not to exceed six months. The proponent assumes full risk and all liability associated with the selection and use of any designated FTP.
 - (c) It is desirable that the proponent receive prior permission from the land owner or using agency prior to the use of this area as an FTP. The proponent should clearly communicate the purpose and intent of the FTP.
 - (d) For each FTP, plans must incorporate the means of communication with ATC throughout the descent as well as a plan for retrieval/recovery of the aircraft.
 - (e) Contingency planning must take into consideration all airspace constructs and minimize risk to other aircraft by avoiding published airways, military

training routes, NAVAIDs, and congested areas to the maximum extent possible.

- (f) In the event of a contingency divert or flight termination, if time permits, the use of a chase aircraft is preferred when the UA is operated outside of Restricted or Warning Areas.
- (g) In the event of a contingency divert or flight termination or other approved contingency measures, the proponent will operate in Class A airspace and Special Use airspace to the maximum extent possible to reduce the risk of collision with non-participating air traffic.

B. Night Operation Limitations.

The following measures are considered adequate to ensure an acceptable level of safety for UAS night operations.

1. Night operations are authorized provided the proponent's airworthiness criteria includes a performance analysis of the light emitting diode (LED) position lights installed to comply with 14 CFR section 91.209. This performance analysis must ensure the position lights are of sufficient intensity, placement, and coverage to allow pilots of other aircraft to determine the orientation and direction of flight of the proponent's aircraft.
2. UAS night operations are those operations that occur between the end of evening civil twilight and the beginning of morning civil twilight, as published in the American Air Almanac, converted to local time. (Note: this is equal to approximately 30 minutes after sunset until 30 minutes before sunrise).
3. External pilots and UAS ground observer(s) must be in place 30 minutes prior to night operations to ensure dark adaptation.
4. Ground observers will undergo additional training on the lighting configuration of the UAS to ensure proper recognition during flight at night.

C. Operation Limitations.

The proponent must comply with the aircraft registration requirements set forth in Title 14 Code of Federal Regulations (14 CFR) section 47.3 and the nationality and registration marks prescribed by 14 CFR sections 45.21 through 45.33. Title 49 United States Code (49 USC) sections 44101 through 44110 contain the laws requiring aircraft registration in the United States.

AIR TRAFFIC CONTROL SPECIAL PROVISIONS

A. Communication Requirements.

Direct, two-way communication with ATC is not required.

B. Emergency/Contingency Procedures.

1. Lost Link Procedures:

In the event of a lost link, the UAS pilot will immediately notify Northern California TRACON at (916) 366-4080, state pilot intentions, and comply with the following provisions:

- a. The UA is programmed to fly back to the GCS Location and circle above at 400' AGL if communication is lost for more than 30 seconds.
- b. The GCS Location will be located near the pilot. If communication is reestablished while flying towards the GCS Location, the pilot can change the flight plan to stay within communication range and resume the flight. The pilot could also land the UA using the landing area indicated by the flight operations.
- c. If communication is not reestablished, the pilot will take manual control and land the UA in the landing area when it comes into visual line-of-sight.
- d. If the pilot is not able to take manual control of the UA and communication has not been reestablished with the GCS, the UA will continue circling around GCS Location for 2 minutes or until the battery voltage falls below 14v. At this point, the motor will shut off, the autopilot will stop holding altitude, and the UA will safely descend to the ground in the same pattern around GCS Location.
- e. If lost link occurs within a restricted or warning area, or the lost link procedure above takes the UA into the restricted or warning area – the aircraft will not exit the restricted or warning areas until the link is re-established.
- f. The unmanned aircraft lost link mission will not transit or orbit over populated areas.
- g. Lost link programmed procedures will avoid unexpected turn-around and/or altitude changes and will provide sufficient time to communicate and coordinate with ATC.
- h. Lost link orbit points shall not coincide with the centerline of Victor airways.

2. Lost Communications:

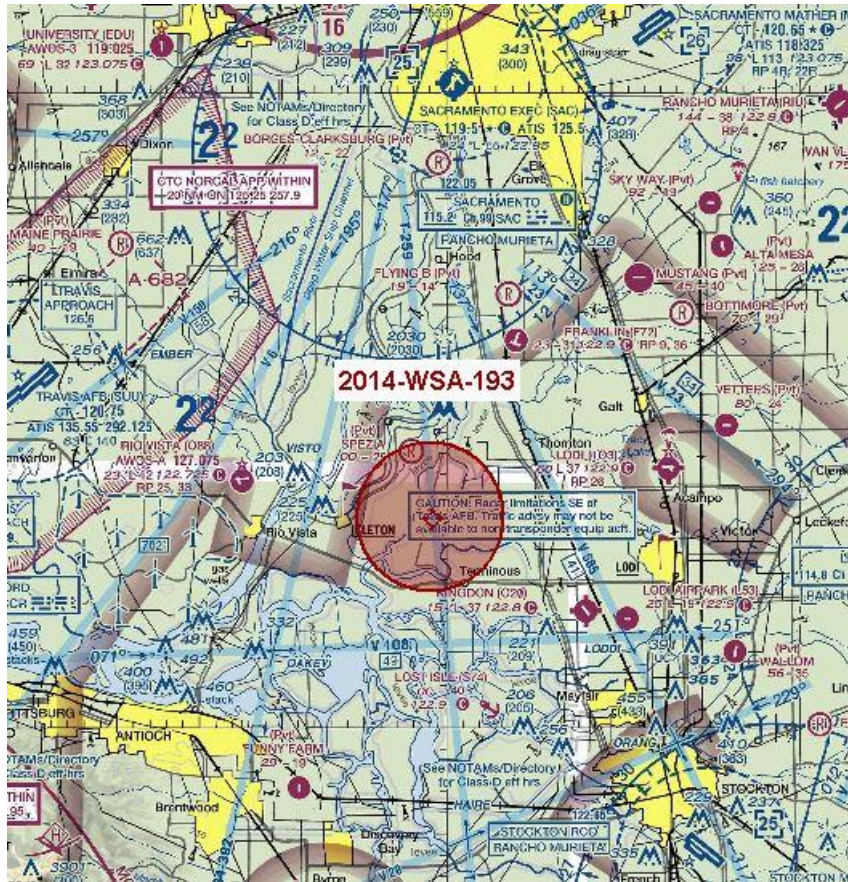
PIC must immediately land the UAS if communication with Visual Observer is lost.

C. Operations Area. See Attachment 1.

AUTHORIZATION

This Certificate of Waiver or Authorization does not, in itself, waive any Title 14 Code of Federal Regulations, nor any state law or local ordinance. Should the proposed operation conflict with any state law or local ordinance, or require permission of local authorities or property owners, it is the responsibility of University of California, Merced, MESA Lab to resolve the matter. This COA does not authorize flight within Special Use Airspace (SUA) without approval from the using agency. University of California, Merced, MESA Lab is hereby authorized to operate the AggieAir Unmanned Aircraft System in the operations area depicted in the Activity section of this attachment.

2014-WSA-193 Operating Area



Within 3.5 Nautical Mile (nm) radius of 38°09'59.26" N, 121°30'59.73" W

Altitude: Up to but not including 700 feet Above Ground Level (AGL)

Appendix C

UAS SAFETY MANAGEMENT SYSTEM DOCUMENTS

C.1 Hazard Identification Questionnaire



Hazard Identification Questionnaire

OVERVIEW

This questionnaire is designed to help identify potential risks and help identify areas of risk exposure. It is not an exhaustive list. This questionnaire is best utilized early in the mission operation planning stages, prior to any flight readiness reviews or pre-departure operations. Boxes shaded in gray may be pre-populated from a flight planning software.

Two models are implemented: Man, Machine & the Environment, and SHELL.

MAN, MACHINE & THE ENVIRONMENT MODEL

The man, machine & the environment model looks at the hazards and risks associated with the three major components of air safety. Each section contains asks to describe details of the component in question and pose questions related to risk.



MACHINE

The aircraft and all related components (attached or separate) that form the Unmaned Aircraft System

Hardware

Aircraft type	
Aircraft Make	
Aircraft Model	



UNMANNED AIRCRAFT SYSTEM
SAFETY

Aircraft Registration Number	
Aircraft Size	
Aircraft weight	
Aircraft flight endurance	
Aircraft wind tolerances	
Aircraft visibility limit	
Aircraft telemetry range (list for different systems)	
Expected range of flight altitudes	
Number of motors or propulsion elements	
Are there propulsion element safeguards?	
Does the aircraft airframe have sufficient safety factors?	
Fixed-wing: Have the wings undergone a wing load test?	
Rotary-wing: Is the total aggregate propulsion thrust > 2x total aircraft weight?	
Describe all non-aircraft components of the system	



UNMANNED AIRCRAFT SYSTEM
SAFETY

Are there Maintenances check prior to departure?	
Are there Maintenances check prior to each flight?	
Are there Maintenances check after each flight?	
Is there Airframe maintenance control?	
Is there Avionics maintenance control?	
Is the vehicle properly protected while in storage?	

Other Notes



UNMANNED AIRCRAFT SYSTEM
SAFETY

Software

Is the system equipped with an autopilot system? (include make/model)	
Is the system equipped with an attitude stabilization system or mode?	
Is the system equipped with GPS positioning?	
Is the system capable of waypoint flight planning	
Can a pilot interrupt a flight plan with manual controls?	
Can the system be programmed with new coordinates while in flight?	
Can the system be programmed with new flight patterns while in flight?	
Are there software system testing procedures?	
Are there automated failsafe system testing procedures?	
Is there live or real-time data telemetry	
Is there live or real-time video telemetry	
What is the resolution of the video telemetry?	
What is the data telemetry update rate?	
List telemetry information and update rate	



UNMANNED AIRCRAFT SYSTEM
SAFETY

Is there a Software version control?	
Are there avionics system checks on the preflight checklists?	
What are the testing procedures for failsafe systems?	
How are software systems tested prior to flight?	
Can the aircraft be operated without payload?	
If the payload system fails in flight, is airworthiness compromised?	

Other Notes



THE ENVIRONMENT

The environment includes the airspace, the weather, the flight terrain, and non-participants

Flight Location coordinates	
Airspace Class	
Proximity to Airports	
Proximity to runway approaches	
Proximity to heliports or emergency response	
Proximity to buildings	
Proximity to trees, powerlines or other obstructions (Please describe)	
Is the flight location near a VFR marker or other area where general aviation is common?	
Describe the flight location	
Is the flight location access controlled?	
How are non-participants kept safe (please describe)	
What is the ground elevation of the flight location?	
Are there nearby hills?	



UNMANNED AIRCRAFT SYSTEM
SAFETY

Are there areas of significant concrete or asphalt nearby?	
Are there concerns of thermals or downdrafts	
Describe the weather conditions	
What is the predicted wind speed and direction?	
Precipitation	
Lightning or storm warnings	
Fog warnings	
Visibility distance	

Other Notes



THE HUMAN

The human includes the operator, ground crew and any management or organizational procedures and oversight.

Operator and Ground Crew

Pilot Certificate	
Pilot Experience	
Ground Crew Experience	
How is experience validated?	
What are the preflight procedures for the pilot?	
What are the preflight procedures for the ground crew?	
What are part of the pre-flight briefings?	



**UNMANNED AIRCRAFT SYSTEM
SAFETY**

Management

What training procedures are in place?	
How are accidents or incidents handled?	
Is there a 3 rd party verification process for any process (please describe)	
Is there organization pressure on completing on time?	
Is there a strong safety culture?	

Other Notes



SHELL MODEL

The SHELL model addresses the interconnection of several components of the system. Whereas the Man, Machine & the Environment Model address inherent risks, the SHELL model address system risks that may arise from the connections between the components.



Software ↔ Liveware

How does the pilot check the software configurations?	
How does the pilot monitor correct software performance?	
How does the pilot use preflight checklist?	
Is there a procedure for software validation?	
Is there a procedure for monitoring payload software performance?	
Describe the attention needs of the software system at different phases of flight	
Are there processes to keep attention at the appropriate levels?	



UNMANNED AIRCRAFT SYSTEM
SAFETY

Hardware ↔ Liveware

How does the the pilot control the aircraft	
How does the ground crew interact with the aircraft?	
Are there launching procedures for ground crew members?	
Are there landing procedures for ground crew members?	
Does the pilot have the ability to override automated controls?	
Does the autopilot have the ability to override pilot commands?	
Describe the attention needs of the hardware system at different phases of flight	
Are there processes to keep attention at the appropriate levels?	
Does the flight path lead directly to any participants at any time?	



UNMANNED AIRCRAFT SYSTEM
SAFETY

Environment ↔ Liveware

Do the weather conditions require additional provisions for the pilot and ground crew?	
Is there communication protocols for alerting ground crew and pilot for changes in environment	
Is the pilot able to see potential obstructions during the flight path?	
Are visual observers positioned to see intruding air traffic?	
Are provisions provided for the comfort of the pilot and ground crew?	
Describe the attention needs of monitoring the environmental conditions at different phases of flight	
Are there processes to keep attention at the appropriate levels?	



UNMANNED AIRCRAFT SYSTEM
SAFETY

Liveware ↔ Liveware

Is there a standard nomenclature or phrasing system in place?	
Are communication equipment tested prior to use?	
What management oversight is provided?	
Is there a process to validate safety checks?	
Is there a flight readiness review process?	
Is the flight readiness review process validated by a 3 rd party or safety personnel?	
How does the pilot communicate to ATC?	
How does the pilot communicate risks to the flight crew?	
How does the pilot communicate risks to non-participants?	
How does the ground crew communicate risks to the pilot?	
Is there a 'sterile cockpit' rule in place?	
How are spectators managed?	



UNMANNED AIRCRAFT SYSTEM
SAFETY

Other Notes

C.2 Risk Survey



Risk Assessment Survey

Mission Name: _____ Mission Date: _____

Flight Details

Aircraft

Reg #	Make	Model	Size/Weight

Crew

Crew Member	Hours			Qualifications					Certifications			
	Total	Last 90 Days	In Type	RPIC	VO	GCS	Other	None or Trainee	SUAS	Pvt	GS	None

Location

GPS Coordinates	
Address (or Nearest City)	
Airspace Class	
Distance to nearest airport	
Distance to nearest helipad	
Elevation	

Weather Conditions

Temperature	
Wind Direction	
Wind Speed	
Precipitation Chance	
Visibility	
Weather Alerts	

Flight Plan

Expected number of flights						
Expected max flight altitude (Circle one)	< 50 ft	50 – 100 ft	100-200 ft	200-400 ft	400-1000 ft	> 1000 ft
Expected max flight speed (Circle one)	< 5 mph	5-10 mph	10-25 mph	25-50 mph	50-100 mph	> 100 mph
Type of Flight Plan	No plan or only basic maneuvers	Straight Up/Down	Surveying patterns	Specific Flight paths	Automated Flight (No user defined flight pattern)	Acrobatic routines
Payload Type (circle all relevant)	None	Real-Time Video	Imaging System	Non-Optical Sensor(s)	Cargo for Carriage	



Safety Survey

Pilot

Rate your physical and mental readiness to fly	<i>Not ready</i> 1	2	3	4	<i>Fully Ready</i> 5
Rate your experience with SUAS Operations	<i>Novice</i> 1	2	3	4	<i>Experienced</i> 5
Rate your familiarity with the aircraft	<i>Never flown it before</i> 1	2	3	4	<i>Flown it regularly</i> 5
Rate your familiarity with the rest of the flight crew	<i>Never worked together</i> 1	2	3	4	<i>Worked together regularly</i> 5

Aircraft

Rate the aircraft's last flight performance	<i>Had Issues</i> 1	2	3	4	<i>Flawless</i> 5
Rate the aircraft's last maintenance severity	<i>Needed immediate work</i> 1	2	3	4	<i>Cosmetic work</i> 5

Location

Rate the level of General Aviation traffic	<i>Rare</i> 1	2	3	4	<i>Very Common</i> 5
Rate the spaciousness of the location	<i>Urban</i> 1	2	3	4	<i>Wide-Open</i> 5
Rate the level of ground risks (Buildings, Trees, Powerlines)	<i>No Ground Risks</i> 1	2	3	4	<i>Many potential risks</i> 5
Rate the proximity to non-participating persons (include road traffic and spectators)	<i>None</i> 1	2	3	4	<i>Crowded or urban</i> 5

Ground Crew

Visual Observer	Yes			No	
Control or Payload Operator	Yes			No	
Other Ground Crew	Yes			No	
Rate their experience with SUAS Operations	<i>Novice</i> 1	2	3	4	<i>Experienced</i> 5
Rate their familiarity with their role	<i>Novice</i> 1	2	3	4	<i>Experienced</i> 5
Rate their familiarity with the rest of the flight crew	<i>Never worked together</i> 1	2	3	4	<i>Worked together regularly</i> 5

Organization

Readiness to cancel flights	<i>Flight is critically important</i> 1	2	3	4	<i>Flight can be canceled</i> 5
Rate your organization's safety culture	<i>Non Existent</i> 1	2	3	4	<i>Effective</i> 5
Rate your organization's training program	<i>Non Existent</i> 1	2	3	4	<i>Effective</i> 5
Rate the proximity to non-participating persons (include road traffic and spectators)	<i>None</i> 1	2	3	4	<i>Crowded or urban</i> 5

C.3 Excerpt from UC Drones Web App

UC DRONES WEB APP

Managing your UAS Flights (Flight Request and Reports)

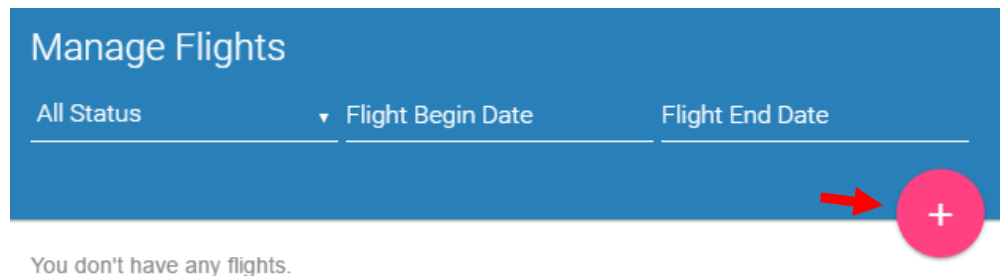
The Manage Flights/ Manage Aircraft section will allow the user to request a flight with the UC Center of Excellence on UAS Safety.



Manage Flights

Create a new Flight (Flight Request)

By selecting “Manage Flights” the user will be presented with a list of flights. New users will see a similar screen as shown on the following page:



To add a flight to the management page, select the + icon located to the right of the page.

Existing flight requests or reports can be found on this page and are searchable by status and can be filtered by date (Flight Begin Date and Flight End Date).

Flight Request Form

The Flight Request Form is broken up into 4 categories:

- A. Aircraft – The Aircraft to be used
- B. Pilot – The person who will be serving as the Pilot in Command
- C. Contact – The person responsible for ensuring the safety of the flight
- D. Flight Request.

Aircrafts and Pilots that have not been registered in the system can be added in the “Manage Aircrafts” and “Pilot” sections of the website. Please refer to the “Manage Aircrafts” and “Pilot” Sections of this guide to learn more.

The Aircraft, Pilot and Contact categories are all listed in one bar, as shown below.

Aircraft Search by registration #	Pilot Search by pilot name	Contact University of California, Davis ▼ Search by last name, first name
--	---	---

A. Aircrafts

Aircrafts that are already registered into the system will be searchable in the aircraft section. **The user must enter the aircraft’s FAA registration number.**

B. Pilot

Pilots that have also been registered into the system will be searchable in the Pilot section. **The user must enter the pilot’s last name first.**

C. Point of Contact

Under the Contact Section, the user will be prompted to select a point of contact for the operation. The point of contact is the person who will be ensuring the safety of the operation. This may or may not be the same person as the pilot, and does not have to be registered as a pilot in the UC Drone Web App.

Both the Pilot and the Point of Contact will receive emails regarding the status of the Flight Request and will be able to view any documents or communication.

By selecting the appropriate campus, the user can search for the UC affiliated contact by last, first name. From there, click on the UC affiliated contact to confirm the selection.

For example,

- By selecting the user, the prompt will change to finalized view, as shown.

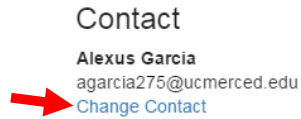
Contact

University of California, Merced ▼

Garcia, Alexus|

Garcia, Alexus(agarcia275@ucmerced.edu)

The aircraft, pilot and/or point of contact can always be changed by selecting the “Change Aircraft”, “Change Pilot” or “Change Contact” text.



D. Flight Request

The “Flight Request” category will prompt the user for information regarding the specifics of the proposed flight. The Information subcategories will be:

a. Flight Purpose

Clicking on the dropdown menu under Flight Purpose will reveal various categories of flights, such as environmental research, filming, and so on. Select the category closest to the intent of the flight.

Flight Purpose

Aerospace Research
Agricultural Research
Building Inspection or Surveying
Coursework
Club activity or Recreation
Environmental Research
Filming for the University or Publicity
Testing or Flight Instruction
Other

b. Flight Date

Flight Date refers to the date on which the proposed flight will be occurring. **Format will follow mm/dd/yyyy.**

c. Flight Time

Flight Time refers to the time at which the operation will begin. **Format will follow hr-minute-second -AM/PM.**

d. Expected Field time (*minutes*)

Expected Field time refers to how long the operation will last from arriving to location to the leave time.

e. Number of Flights

Number of flights refers to the number of flights that will occur during the field time.

f. Latitude & Longitude

Latitude and longitude can be entered manually or by utilizing the map shown underneath the Latitude & Longitude text. By scrolling to location of the operation on the map, the user can then click the position. The click will update the Latitude and Longitude text fields.

Updating the text boxes does not update the map. The text in the text boxes is saved, not the icon on the map.

g. Max Distance (ft)

The max distance will be the farthest distance from the ground control station position that the UAS will travel.

h. Max Altitude (ft)

The maximum altitude will be the maximum height during the flight that the UAS will reach.

i. Are you flying over people? Y/N

The User will be prompted to select either yes or no regarding this question.

j. Are you flying near buildings? Y/N

The user will be prompted to select either yes or no regarding this question. Flying near the proximity of a building may pose a risk for the operation and those not part of the operation.

k. Comments

The comment section will be used to give a brief description of the flight, or comment on the general operation. **Additional documents, such as flight path diagrams or safety mitigation plans can be added after the draft has been saved.**

Once the user has finished completing each section, their request will look similar to the example shown on the following page:

Flight Information

Aircraft

Parrot - Beebop 2

Registration Number: FA3YEFCLKT
 Storage Location: Campus & Public
 Safety
[Change Aircraft](#)

Pilot

Alexus Garcia

agarcia275@ucmerced.edu
 SUAS: 3908188
[Change Pilot](#)

Contact

Alexus Garcia

agarcia275@ucmerced.edu
[Change Contact](#)

Flight Request

a Flight Purpose
 Environmental Research

b Flight Date
 11/18/2016

c Flight Time
 12:00 PM

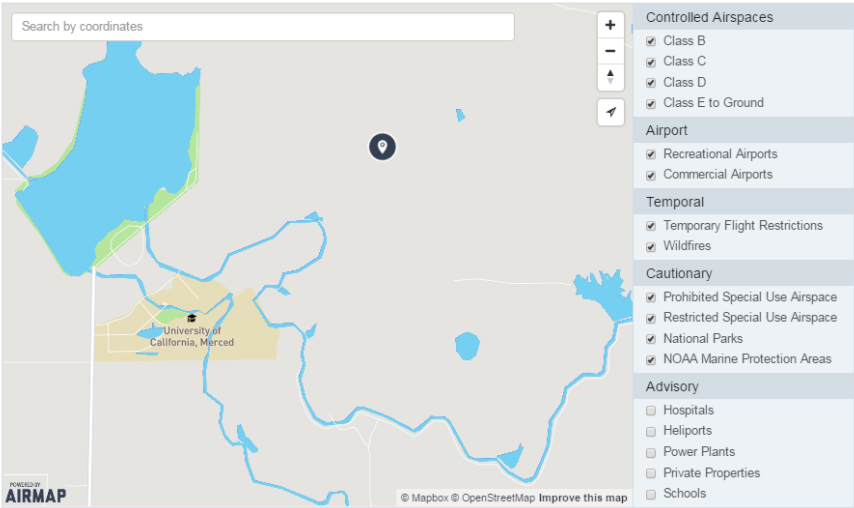
d Expected Field Time (minutes)
 60

e Number of Flights
 2

f Latitude
 37.37843487113416

f Longitude
 -120.40285478895335

Search by coordinates



Controlled Airspaces

- ☒ Class B
- ☒ Class C
- ☒ Class D
- ☒ Class E to Ground

Airport

- ☒ Recreational Airports
- ☒ Commercial Airports

Temporal

- ☒ Temporary Flight Restrictions
- ☒ Wildfires

Cautionary

- ☒ Prohibited Special Use Airspace
- ☒ Restricted Special Use Airspace
- ☒ National Parks
- ☒ NOAA Marine Protection Areas

Advisory

- ☐ Hospitals
- ☐ Heliports
- ☐ Power Plants
- ☐ Private Properties
- ☐ Schools

g Max Distance (ft)
 450

h Flight Altitude (ft)
 100

i Are you flying over people?
☒ No ☐ Yes

j Are you flying near buildings?
☒ No ☐ Yes

k Comments
 Flight to map vernal pools.

[Save](#) [Cancel](#)

By selecting save, the user will be prompted to a Flight Request Draft page with all the previous entered information. The page has three sections:

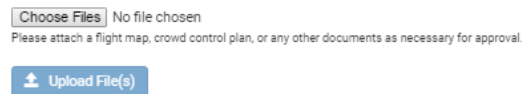
a) *Flight Request*

The Flight Request section will be a summary of the information entered on the previous page. **The user can go back and edit any incorrect information using the Edit button at the bottom of the page.**

b) *Attachments*

The Attachments section is for the user to enter in flight plans, crowd control plans, and any other documents that may be necessary to obtain approval.

Attachments



By selecting the “Choose Files” icon, the user can browse their computer files and select those relevant to the mission.

Once the files have been chosen, the user must select the “Upload File(s)” icon to attach the documents to the draft.

c) *Edit/ Submit*



At the bottom of the page, the user will be presented two options. Edit Request, and Submit Request. If all the information is correct and appropriate documents have been attached, the user can select “Submit Request.”

If there are issues with entered information, the user may go back to the previous screen and fix any issues by selecting “Edit Request.”

UC DRONES WEB APP

Below is an example of a completed draft with a flight plan:

Flight Information		Draft
Aircraft Parot - Beebop 2 Registration Number: FA3YEFCLKT Storage Location: Campus & Public Safety	Pilot Alexus Garcia agarcia275@ucmerced.edu SUAS: 3908188	Contact Alexus Garcia agarcia275@ucmerced.edu

a Flight Request

Flight Purpose	Environmental Research
Date Time	Nov 18, 2016 12:00 PM
Field Time	60
Number of flights	2
Location	37.37843487113416, -120.40285478895335
Max Distance	450 ft.
Flight Altitude	100 ft.
Flying over people	false
Flying near building	false
Comments	Flight to map vernal pools.

b Attachments

No file chosen
Please attach a flight map, crowd control plan, or any other documents as necessary for approval.

Document List

 flightplan.jpg



UC DRONES WEB APP

After submission of a Flight Request, the user will be able to again see a summary of their flight request, with a "Pending Review" text in the top right corner.

Flight Information

Aircraft Parot - Beebop 2 Registration Number: FA3YEFCLKT Storage Location: Campus & Public Safety	Pilot Alexus Garcia agarcia275@ucmerced.edu SUAS: 3908188	Contact Alexus Garcia agarcia275@ucmerced.edu
--	---	--

Pending Review

Flight Request

Flight Purpose	Environmental Research
Date Time	Nov 18, 2016 12:00 PM
Field Time	60
Number of flights	2
Location	37.37843487113416, -120.40285478895335
Max Distance	450 ft.
Flight Altitude	100 ft.
Flying over people	false
Flying near building	false
Comments	Flight to map vernal pools.

Attachments

Document List

 flightplan.jpg



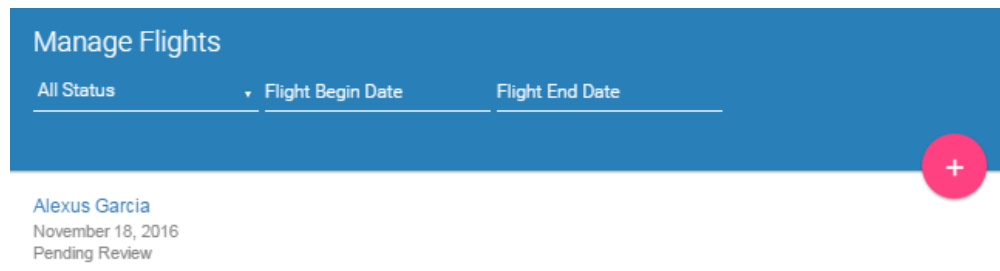
The user can click on "Drones" or the "Home" menu to return to the Home Page.



Flight Review Process

All flights must be reviewed for federal compliance and UAS safety before they can be approved. The review process validates that all federally required documentation is correct, including but not limited to aircraft registration, pilot certifications, airspace class, time of day, flights over people or other extended operations, and that appropriate safety procedures are in place. If the proposed flight occurs on UC property, the appropriate campus safety personnel may also review for campus safety.

The Flight Management page will inform the user if their flight is still pending, is approved, or denied. **Users will also receive an email regarding the approval or denial of flight requests.**



By clicking on the Name associated with the flight, the user will then be able to see the summary regarding the flight.

If denied, the user will be given commentary regarding the rejection. **The user may edit the flight request and resubmit after making appropriate changes.**

The reviewer, either a staff member from the Center of Excellence on UAS Safety, or a local campus safety coordinator, may attach additional comments or documents to the flight request. **The user should review any attached documents prior to operation.**

Flight Reporting

After submitting a flight request, if the request is approved, the user can report the flight for documentation purposes. On a flight information for an approved request, the user will see a “Create Report” icon at the bottom of the summary.

An example image is shown below:

Flight Information

Request Approved

Aircraft Parrot - Beebop 2 Registration Number: FA3YEFCLKT Storage Location: Campus & Public Safety	Pilot Alexus Garcia agarcia275@ucmerced.edu SUAS: 3908188	Contact Alexus Garcia agarcia275@ucmerced.edu
---	---	--

Flight Request

Flight Purpose	Environmental Research
Date Time	Nov 18, 2016 12:00 PM
Field Time	60
Number of flights	2
Location	37.37843487113416, -120.40285478895335
Max Distance	450 ft.
Flight Altitude	100 ft.
Flying over people	false
Flying near building	false
Comments	Flight to map vernal pools.

Attachments

Document List

 flightplan.jpg

Admin Comments

You should request flights at least 24 hours in advanced
Flight Approved

Create Report

After selecting the Create Report icon, a similar page to the flight request form will appear.

All information from the flight request will be automatically entered into the created report.

Information regarding the date, time and location may be edited to reflect any changes due to weather or ground hazards.

The new features for the user to enter are:

a) *Duration (minutes) per flight*

Input the flight duration in minutes per flight. **Click on the '+' sign to add additional flights to the report.**

b) *Takeoff and Landing Damages*

Report any damages that occurred to the UAS upon takeoff and landing, including failed takeoffs or landings. **If no damages occurred, write N/A into the text box to acknowledge that the aircraft suffered no physical damage.**

c) *Equipment Malfunctions*

Equipment malfunction lists various issues that may cause the drone to malfunction. If the issue is not listed, select "other." A dialog will pop up for the user to enter specifics about the malfunction. **Multiple may be selected.**

d) *Lost Link Events*

Lost link events refer to the events that cause loss of connection between the UAS and various other controls and systems. . If the issue is not listed, select "other." A dialog will pop up for the user to enter specifics about the malfunction. **Multiple may be selected.**

e) *Accidents/Mishaps*

Accidents and Mishaps will allow the user to enter any information regarding any incidents that may have occurred in the field. Damages to persons, property, and equipment will be recorded here. If the issue is not listed, select "other." A dialog will pop up for the user to enter specifics about the malfunction. **Multiple may be selected.**

When completed with the report, the user may select save.

UC DRONES WEB APP

An example is shown below:

Flight Information

Aircraft

Parot - Beebop 2
Registration Number: FA3YEFCLKT
Storage Location: Campus & Public Safety

Pilot

Alexus Garcia
agarcia275@ucmerced.edu
SUAS: 3908188

Contact

Alexus Garcia
agarcia275@ucmerced.edu

Flight Report

Flight Purpose

Environmental Research

Flight Date

11/18/2018

Flight Time

12:00 PM

Expected Field Time (minutes)

60

a

Duration (minutes) per flight

5

Latitude

37.37843487113416

Longitude

-120.40285478895335

Search by coordinates

+

-

↑

↓

Controlled Airspaces

☒ Class B
 ☒ Class C
 ☒ Class D
 ☒ Class E to Ground

Airport

☒ Recreational Airports
 ☒ Commercial Airports

Temporal

☒ Temporary Flight Restrictions
 ☒ Wildfires

Cautionary

☒ Prohibited Special Use Airspace
 ☒ Restricted Special Use Airspace
 ☒ National Parks
 ☒ NOAA Marine Protection Areas

Advisory

☐ Hospitals
 ☐ Heliports
 ☐ Power Plants
 ☐ Private Properties
 ☐ Schools

Max Distance (ft)

450

Flight Altitude (ft)

100

Are you flying over people?

☒ No
 ☐ Yes

Are you flying near buildings?

☒ No
 ☐ Yes

Comments

Flight to map vernal pools.

b Takeoff and Landing Damages

Required to report damages. If none occurred, please write: N/A

N/A

c Equipment Malfunctions

- ☒ None
- ☐ On-board flight control system
- ☐ Navigation system
- ☐ Powerplant failure in flight
- ☐ Fuel system failure
- ☐ Electrical system failure
- ☐ Control station Failure
- ☐ In Flight Fire
- ☐ Aircraft collision involving another aircraft
- ☐ Any in-flight failure of the unmanned aircraft electrical system requiring the use of alternate or emergency power to complete the flight
- ☐ A deviation from any provision contained in the COA
- ☐ A deviation from an ATC clearance and/or Letter(s) of Agreement/Procedures
- ☐ Other

d Lost Link Events

- ☒ None
- ☐ Lost link of pilot control
- ☐ Lost link of ground telemetry system
- ☐ Lost link of payload telemetry system
- ☐ Fly-away resulting in flight termination
- ☐ Execution of a pre-planned lost link procedure
- ☐ Execution of a unplanned lost link procedure
- ☐ Other

e Accidents/Mishaps

- ☒ None
- ☐ Damage to property other than the unmanned aircraft
- ☐ Substantial damage to the unmanned aircraft system where there is damage to the aircraft that must be repaired prior to further flight
- ☐ Total aircraft loss
- ☐ Serious injury
- ☐ Fatal injury
- ☐ Other

Save

Cancel

After selecting Save, the user will be prompted to a draft page similar to the flight request page. From the page, the user can review entered information, and either select the “Edit Report” option or “Submit Report” option. When the user feels that they have accurately completed the report, they should select “Submit Report.” Their summary page will update “Request Approved to “Report submitted.”

UC DRONES WEB APP

Flight Information

Request Approved

Aircraft

Parrot - Beebop 2
Registration Number: FA3YEFCLKT
Storage Location: Campus & Public Safety

Pilot

Alexus Garcia
agarcia275@ucmerced.edu
SUAS: 3908188

Contact

Alexus Garcia
agarcia275@ucmerced.edu

Flight Request

Flight Purpose	Environmental Research
Date Time	Nov 18, 2016 12:00 PM
Field Time	60
Number of flights	2
Location	37.37843487113416, -120.40285478895335
Max Distance	450 ft.
Flight Altitude	100 ft.
Flying over people	false
Flying near building	false
Comments	Flight to map vernal pools.

Flight Report

Flight Purpose	Environmental Research
Date Time	Nov 18, 2016 12:00 PM
Field Time	60
Location	37.37843487113416, -120.40285478895335
Max Distance	450 ft.
Flight Altitude	100 ft.
Flying over people	false
Flying near building	false
Comments	Flight to map vernal pools.
Flight Durations	5 minutes
Takeoff and Landing Damages	N/A
Equipment Malfunctions	- None
Lost Link Events	- None
Accidents/Mishaps	- None

Attachments

Document List

 flightplan.jpg



Admin Comments

You should request flights at least 24 hours in advanced
Flight Approved

[Edit Report](#)

[Submit Report](#)



The flight is considered complete after a follow-up review by the Center of Excellence on UAS Safety.

C.4 Best Practices for Privacy



Best Practices for UAS Privacy, Transparency and Accountability

Overview

In the United States today, the use of Unmanned Aircraft Systems (UAS) for both recreation and commercial use are becoming ever more prominent. UAS may be used for a variety of applications, including photography and videography. The capture and use of photographs and videos from a UAS platform raises new concerns on the rights, privacies, and permissions that involve both the operators of UAS and individuals that are uninvolved in the operation. The University of California recognizes the important value of privacy and strives to achieve an appropriate balance ensuring an appropriate level of privacy, nurturing an environment of openness, honoring its obligation as a public institution to remain transparent while safe guarding information about individuals.

Best Practices

- **Do not** use a UAS to monitor or record activities where there is a reasonable expectation of privacy.
- **Do not** use a UAS for unapproved recordings of any campus event or performance or for any unlawful purpose.
- **Do not** fly a UAS over private property without prior approval.
- **Do not** use a UAS to harass or otherwise intentionally cause harm.
- **Do not** use a UAS for the specific purpose of persistent and continuous collection of identifiable data about individuals without the consent of the data subjects.
- **Do not** retain identifiable data longer than reasonably necessary to fulfill a purpose.
- **Do not** knowingly publically disclosing data collected via UAS without undertaking a reasonable effort to obfuscate or de-identify identifiable data unless the data subjects provide specific consent to the disclosure.
- **Do** make a reasonable effort to provide prior notice to individuals of the general timeframe and area that they may anticipate a UAS intentionally collecting identifiable data.
- **Do** establish and make available a Privacy Policy for UAS Data if the UAS may intentionally or unintentionally collect identifiable data. The policy should be appropriate to the size and complexity of the data collected.
- **Do** be considerate of other people's concerns over privacy, security or safety.
- **Do** contact the Office of Research Compliance and Integrity if identifiable data is to be used for human-subject research.
- **Do** take steps to ensure the security of any identifiable data.

A Privacy Policy for UAS Data should include:

- The purposes for which the UAS will collect identifiable data
- The kinds of identifiable data the UAS will collect.
- Information regarding any data retention and de-identification practices.
- Examples of the types of any entities with who identifiable data will be shared
- Information on how to submit privacy and security complaints or concerns.
- Information describing practices in responding to law enforcement requests.

C.5 Top 10 Hazards



Top 10 Hazards to Look out for when Flying

Just got a new drone, gave it a couple of flights and now you're ready to use it for your work or research? Here are some of the top safety risk that you should look out for.

- 1) **People.** Flights near people pose a risk to not only the crew involved in the operation, but all people near the flight zone. Ensuring that the general public is aware of the operations can help prevent risk of injury.
- 2) **Poor Maintenance.** Many new drone enthusiasts aren't utilizing the user manuals and maintenance manuals for their drones. Maintaining a maintenance routine prior to flights will aid in identifying potential issues with your drone before it poses an in-flight issue.
- 3) **Location.** Many drone pilots want to capture footage over parks, buildings and so on. Although it may get some cool shots, flights around buildings and people pose a damage risk. Novice pilots should avoid densely populated areas and flights near buildings to reduce risk of crashes and damage.
- 4) **Weather Assessments.** New pilots may disregard the importance of weather assessments. Weather assessments allow pilots to note the wind speed and direction, humidity, temperature, cloud coverage, change of rain, and so on. As temperature and humidity increase, drone performance decreases. Wind speed and direction can also lower drone battery life and performance.
- 5) **Attitude and Health.** Pilots should assess their wellbeing and attitude prior to conducting any operation. Prescription medicine, alcohol, and drugs can greatly impede the cognitive processes of the pilot. If you wouldn't take something and drive, don't do it and fly!
- 6) **Lack of Crew Management.** Many operations require extra batteries, a computer, controllers, and various other materials. Organizing a crew to help carry materials, operate ground control station, and have a visual observer check for air traffic
- 7) **Air Traffic.** Monitoring air traffic is important to ensure the safety of the drone, manned aircrafts, and general public surrounding the operation. Having a Visual Observer scan for oncoming air traffic can greatly reduce the risk of impact and damage.
- 8) **Insufficient Documentation and Licenses.** Many new drone operators lack the proper licenses for their activity. Understanding the required licenses and documentation required will aid pilots in conducting flights both legally and safely.
- 9) **Local Airport Information.** Many novice operators may not know the local airport contract information and airspace classification. Assessing the airspace and knowing when to contact air traffic control is vital for both unmanned and manned aviation.
- 10) **Payloads.** It may be tempting to take your eyes off your drone to line up your great shot, but accidents can happen in the blink of an eye. Treat piloting your drone as your primary goal and operating your payload as secondary. Better yet, bring a friend to help guide you.

C.6 Top 10 Safety Tips



Top 10 Tips for Safe UAS Flying

Just got a new drone, gave it a couple of flights and now you're ready to use it for your work or research? Here are some tips to help keep you flying safely.

- 1) **Practice.** There is no substitute for experience. Gain experience by practicing flying your drone, conducting data collection missions, and flight planning. Get familiar with your equipment and processes.
- 2) **Write Everything Down.** Not only are many records federally required such as flight logs, they can help you maintain your equipment, monitor for unsafe practices and keep you on track. Things to track: battery usage, weather conditions, equipment use/damage, software versions.
- 3) **Make Checklists and Use Them.** Nothing derails a flight mission like forgetting an item or a step. Make a checklist for planning a mission, make a checklist for packing your equipment, make a checklist for preflight inspections and any other process you may have.
- 4) **Always Keep an Eye on the Weather.** Experienced field researchers know that weather reports are only a suggestion. Conditions in the field may change dramatically and can turn a good flying day to a disaster.
- 5) **Bring a friend or two.** Between juggling a flight controller, operating a payload, monitoring weather conditions and scanning for intruding air traffic, it can be taxing to try to do it all at an appropriate level. Bring some help to make sure everything goes smoothly.
- 6) **Bring backups or replacement parts.** Many operators will bring spare propellers or batteries to their flight missions, but don't forget about other supporting equipment such as cables, landing gear, radios or antennas. Make sure backup parts are on your pre-departure checklist.
- 7) **Choose appropriate flight locations.** When you choose a location to fly at, make sure you're aware of all the hazards. Look for indicators of hidden hazards like rolling hills or high tree lines that create turbulence, or low visibility hazards such as power-lines or towers that interfere with radio systems. Be aware that you as the pilot are responsible of ensuring the safety of all persons on the ground, whether you can see them or not.
- 8) **Set boundaries for go/no-go situations and stick to them.** Deciding when to fly and when not to fly should not be an ambiguous decision. Don't let external pressures push you to make unsafe decisions.
- 9) **If something isn't right, stop immediately.** Nothing fixes itself in the air. If something doesn't sound right on the ground during pre-flight checks, don't fly. If the weather changes to an unsafe condition, land as soon as it is safe.
- 10) **Pause and consider all the risks before you fly.** Damage to your aircraft is only one of many aspects to consider. Consider the payload, consider potential damage to other's property, consider secondary effects such as causing an auto accident when your aircraft crashes in the middle of a road.

C.7 Myths About Drones



10 Myths about Drones

1. A Model Aircraft is not a Drone or Unmanned Aircraft

Congress legally defined a model aircraft as a type of Unmanned Aircraft under [Section 336 of Public Law 112-95](#). Therefore, a Model Aircraft **is a drone**. In addition, there are many names for 'drones' such as quadcopter, quadrotor, hexirotor, model aircraft, and many more. Although there are different names, the FAA nomenclature for 'drone' is **UAS**. UAS stands for Unmanned Aircraft System. Although many believe that a 'drone' is fully autonomous while a model aircraft is pilot operated, a model aircraft can have autonomous and manual control modes. The legal difference between a model aircraft and a UAS is that a model aircraft is flown within visual line of sight of the person operating the aircraft and flown for hobby or recreational purposes. If a person is operating a 'model aircraft' for a business, then it is legally a UAS and the operator must have the proper FAA authorization.

2. I'm a hobbyist and registered my drone, I can go outside and fly everywhere now!

Wrong. Just because someone has registered their aircraft, there are still laws that need to be abided by. The FAA "**Know Before you Fly**" campaign covers the many safety guidelines you must follow. These include proper registration, flying at or below 400 ft, flying within your ability to see the aircraft, and never flying near other aircraft, over people, over stadiums or sporting events or under the influence. You should be aware of the airspace that you are flying in and whether you have permission to fly at a particular location. Some municipalities have adopted their own laws regarding land use or even the prohibition of flying model aircraft. Privacy and trespass laws extend out to the UC System and each UC has rules specific to their campus. Be sure to check with your campus and local community laws, such as the Academy of Model Aeronautics ([AMA](#)) before you operate your UAS.

3. I'm a hobbyist taking videos for a friend's commercial event and not getting paid. Therefore, I do not need a private pilot's license to cover the event.

Although you are not being paid, you are still flying for a commercial purpose because your flight purpose (photography) benefits the commercial activity. Therefore, you will need to follow the commercial laws and have the appropriate certification. A recent lawsuit case regarding an unpaid hobbyist flying for a commercial event has cost him a \$55,000 fine from the FAA. Refer to <https://www.faa.gov/uas/faqs/> for more information about safe operations to avoid fines.

4. I can wear First Person View goggles and fly my drone unaided by a visual observer.

First Person View (FPV) goggles do not satisfy the Line of Sight requirement of Unmanned Aircraft System (UAS) operations. Therefore, if the pilot is wearing any goggles obstructing their Line of Sight View, the Visual Observer must also have ability of taking control in the event of the goggles losing ability to live stream. A person with FPV goggles must form a buddy system with a visual observer to legally operate if you are operating for fun under the [AMA Safety Rule 2b](#) and [Part 107.107.31 and 107.33](#).

5. The FAA doesn't control all the airspace all the way to the ground.

Wrong. The FAA controls all navigable airspace, which does extend all the way to the ground. This is codified in 14 C.F.R. 91.119 (a) and (c), in which the FAA declares that the FAA is responsible for the safety during the operation of an aircraft during takeoff or landing, or in an in-flight emergency situation requiring immediate action, both of which preclude that the FAA controls airspace all the way to the ground.



6. The UAS Registration is meaningless.

Having a registered vehicle and displaying the proper license number allows the FAA to provide some oversight over UAS operations to better ensure the safety of all parties. By having a number visible, the FAA can hold people accountable for damages and reckless endangerment. To register your UAS with the FAA, go to registermyuas.faa.gov. The Academy of Model Aeronautics similarly requires that all AMA members display their AMA number on the inside or affixed to the outside of the model aircraft. Unfortunately, at this time, neither the AMA or the FAA registration numbers may be used interchangeably.

7. Drones are easy to operate.

Many of the advanced drones may be easy to operate, but not all drones have intelligent or automated safety features. These drones may require extra practice to get used to finicky or non-intuitive control schemes.

8. Flying a drone is expensive and requires a Private Pilot's license

Under the new FAA regulations, 14 CFR 107, or Part 107, UAS operators can receive a Remote Pilot's Certificate with a Small UAS rating for civil use of an UAS. This new certificate requires the operator to pass an aviation knowledge test at an FAA-approved testing center. More information on the new certificate can be found on the FAA's website https://www.faa.gov/uas/getting_started/fly_for_work_business/becoming_a_pilot/

9. I can fly over people if I'm flying for fun or recreational purposes.

No. You cannot operate a UAS over any people, even if you are a hobbyist. While recreational flights are protected from further legislation from the FAA, they must be done in accordance with a community-based set of safety guidelines and within the programming of a nationwide community-based organization (). All of these organizations, including the Academy of Model Aeronautics specifically state that flying over people, cars and buildings is prohibited under their safety code ([AMA Safety Code B1](#)). Failure to operate under those guidelines categorically changes the nature of your model aircraft flight and you would then be subject to the FAA regulations, namely Part 107.

10. I can legally arm a drone, it's just a paintball gun.

No. As either a model aircraft, or as a unmanned aircraft this is specifically forbidden. The AMA safety code specifically prohibits arming a model aircraft. For commercial UAS flights, arming a UAS can be considered careless or reckless operation and endangering the life or property of another ([Part 107.23a and Part 107.23b](#)). In addition to these rules, under Part 107.36, the carrying of hazardous materials is also prohibited. Based on [49 CFR 171.8](#) that Part 107 enforces, items such as explosives, compressed gas, and flammable gas are prohibited. Therefore, guns, flamethrowers, and paintball or airsoft guns cannot be equipped to a UAS.