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Evaluation of Feasibility of UAV Technologies for Remote Surveying BART Rail Systems

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Record of Changes

Version Number	Date	Brief Description
1.0	4/12/2016	Initial base draft of the systems requirement
2.0	9/22/2016	Secondary draft, introducing outline elements
2.1	9/27/2016	Updating document to match format
2.2	11/10/2016	Added design chapter
2.3	12/05/2016	Major doc review and update sections
3.0	12/18/2016	Fix existing sessions
3.1	01/03/2017	Added recommendation session
4.0	01/03/2017	Revised
4.1	02/07/2017	Final revision

Executive summary

Routine inspection and monitoring of railway tracks and facilities is an important task to ensure operational safety. The existing standard manual and rail vehicle based investigation are substantially time consuming and inaccurate. UAV-based autonomous monitoring and inspection technology has shown great potential in many fields and industries but it has been rarely explored in railway transit systems.

UC Berkeley California Partners for Advanced Transportation Technologies (PATH) in partnership with Bay Area Rapid Transit (BART) investigated the application of unmanned aerial vehicles (UAV) and autonomous rail-based vehicles for autonomous routine inspection of the BART rail system, as well as rapid assessment of the BART system in case of emergency (train derailment, criminal events, earthquake, fire, and chemical leakage). The UAVs may also be utilized to monitor areas of interest, people or objects within BART's system and provide real-time visual and location information regarding where the events occur. The primary purpose of the UAV@BART application is to reduce human labors on routine maintenance tasks, and improve operational safety and personnel security by utilizing UAV technologies in BART system inspection and monitoring.

A Systems Engineering approach has been applied to this study, through which the following studies were conducted.

Concept of Operations: The stakeholder's needs that can be addressed by UAV@BART system were identified. The Concepts of Operations was developed and the UAV@BART functionalities were divided into three primary operational scenarios: maintenance scenarios, security scenarios, and emergency scenarios. Relevant regulations and concerns associated with its implementation were determined.

System requirement definition: The system requirements of the UAV@BART were specified based on the following categories: general requirements, functional requirements, data and interface requirements, performance requirements and administrative requirements.

System design: The UAV@BART system design was developed based on the operational scenarios and system requirements. The overall system architecture was defined, which consists of three primary subsystems: Centralized Ground Control and Monitoring Terminal (CGCMT), UAV and UAV Management Stations. Each subsystem design was further specified in terms of functional architecture, functional components and communication design.

Feasibility and Benefits: The study reveals that the UAV technology can support a wide range of scenarios for maintenance, operation and emergency responses, offering significant benefits over standard manual inspections. Through development of functional requirements and investigation of design options, the study shows that a low cost UAV-based architecture with various sensing payloads is capable of fulfilling the requirements of various operational scenarios of the BART system. The study concluded that the deployment of a UAV for routine inspection of the rail system as well as rapid assessment of the system conditions in the event of emergency applications for the BART system is achievable with reasonable cost. The implementation of UAVs for the BART system has the potential to reduce human labors in the inspection and monitoring tasks, improve operational efficiency and personnel life safety, and to facilitate quick emergency response and post disaster reconnaissance/recovery.

Deployment Plan and Recommendations: Based on the current state of the policy, regulations and technologies, a phased deployment approach is recommended.

- Phase 1: Field testing of prototype system. The field testing includes a series of testing that verifies the system functions, including the UAV, management stations and the centralized control and monitor server and sensing/detections functions that are necessary for completing operation scenarios. Through these tests, the system functional and performance requirements will also be verified.

- Phase 2: Deployment and demonstration in selected stations. The prototype system will be deployed in several selected stations (including underground stations, open-air stations, underground tracks and open-air tracks). A demonstration project will be conducted to verify the system functions in selected simulated operation scenarios (track inspection, infrastructure inspection, air quality monitoring etc.)
- Phase 3: Testing and evaluation of complete operational scenarios. The prototype will be tested in all prescribed operational scenarios including maintenance, security and emergency (The system can be tested in simulated security and emergency scenarios). The data generated by the testing and demonstration will be collected for further evaluation.
- A comprehensive evaluation will be conducted by an independent third-party. The system will be evaluated in terms of system performance measurements, operational safety and potential improvements in BART operational efficiency.
- Phase 4: Full deployment in the entire BART system. The UAV@BART system will be fully deployed in the entire BART after the system evaluation. A demonstration period may be included to further evaluate the system performance in actual BART operations.

This phased approach ensures the stakeholder to have a comprehensive understanding of the technical feasibilities, benefits and deployment constraints. The study also recommends that, as a first step in the deployment path, a prototype UAV system is to be developed, field tested and demonstrated. A comprehensive evaluation of the UAV@BART is to be conducted to assess system performance, safety, and cost-benefits. As FAA regulations require that the UAV shall be operated within the line-of-sight of certificated operators, a variance needs to be applied for testing out of line-of-sight. BART also needs to work with stakeholder cities where BART stations are located and rails passes to obtain consent and permits for UAV@BART.

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1. Introduction and Document Overview

BART operates 110 miles of electrified right of way. One third of tracks are at ground level, one third is on the elevated structure, and the other one third is underground. The entire right of way is barrier protected to prevent casual unauthorized entry into the hazardous environment of moving trains and electrified rail. However, there have been breaches of the safety perimeter from time to time, either by people or by things entering the right of way. Locating the intrusions is a time consuming task, during which trains are slowed or stopped. Furthermore, regular track inspection and maintenance is labor intensive. BART is interested in the potential application of aerial Unmanned Aerial Vehicle (UAV) to search for unauthorized people or things within BART's right of way and provide real-time visual and location information regarding where the intrusions occur for an expedite resolution and normal track service restoration. The aerial UAV may also be utilized for regular rail inspection and emergency response purposes.

UC Berkeley California Partners for Advanced Transportation Technologies (PATH) in partnership with BART is developing an application of aerial UAVs for routine inspection of the rail system as well as rapid assessment of the rail system in the event of emergency. The aerial UAV may also be utilized to search for unauthorized people or objects within BART's right of way and to provide real-time visual and location information regarding intrusions to expedite the restoration of normal track service. Through the six month study, the PATH research team investigated the concept of operations, system requirements, designs and implementation plan for implementation of UAV@BART.

The study uses the system engineering approach defined by the Institute of Electrical and Electronics Engineers (IEEE) and the US Department of Transportation. The inputs from meetings with BART staff were the primary foundation of this study, which establish the needs, operational scenarios and characteristics for the UAV@BART system. Based on the needs and operation scenarios, a set of functional requirements, system design options and a deployment plan were developed. This report summarizes the findings of the study, which intend to provide the BART with sufficient information for decision making and moving forward with deployment.

1.1 Development Process

The UAV@BART project began with a kickoff meeting with BART personnel to discuss and identify the needs to be addressed by UAVs, followed by the development the ConOps (concept of operations), system and performance requirements, system designs and a deployment plan. The development process is documented below.

Development of UAV concept of operations: A good understanding of the needs and characteristics of UAV@BART is essential for the assessment of feasibilities of UAVs for a variety of possible applications for BART. In developing the operation scenarios, the project team and BART staff discussed the current methods and procedures for operation, maintenance, security and emergency response, the needs for various applications, such as aerial intrusion detection using drones, and the operation environments and constraints including the characteristics and safety envelops about facility and trains, rules and regulations for the intended application. Based on the inputs from BART, the operation concepts were developed to include a set of operational scenarios for UAV@BART or for any general urban rail transit system.

Development of system requirements: Non-functional requirements were developed based on the needs of stakeholders and within the context and constraints of the existing BART infrastructure and activities. Following the systems engineering approach outlined in IEEE 1233, these scenarios are were to develop (a) general requirements, (b) functional requirements and (c) performance requirements.

Development of designs for UAV@BART: The entire drone operation and intrusion monitoring system was designed based on the ConOps and performance requirements. UAV system design was developed to meet the requirements of UAV operations. These include:, the system architecture, the vehicle, and the supporting infrastructure were.

Development of a deployment plan and Recommendations for UAV@BART: The project team developed a deployment plan for UAV@BART, which considers the deployment phases and scales, and addresses operational and maintenance needs... Costs for the various deployment options were also estimated. Recommendations regarding deployment of UAV@BART were made, including plans for technical development of the first prototype drone, analysis of potential risks and a technical feasibility demonstration.

1.2 Traceability Method

The UAV@BART functional and design requirements were developed based on a set of functional needs decomposed from stakeholders' needs. The requirements were defined based on the relationships among various functions identified through the functional requirement definition process. Accordingly, a traceability method was established to trace between functions, requirements, and design. MA, SC, EM, stand for Maintenance, Security and Emergency respectively. MA-01-01-01 is a representative example of how each function is developed from the scenarios. The first set of numbers represents the trigger event, a subcategory within each of the three main scenarios. The second set of numbers represent Mission Planning (01), Trajectory Planning (02), and Detection/Sensing, Controlling Maneuvering (03). The last set of numbers represents the function number within the second set. From these functions, we developed requirements (RQ) and design requirements (DN), and traced each of these back to specific functions.

1.3 Scope of Document

The content of this report are organized as follows:

Section 1: provides an introduction on the purpose and scope of this document.

Section 2: contains the overview of the UAV@BART system, system concepts, as well as operational scenarios.

Section 3: describes the system needs from the stakeholder's view and the operation scenarios of UAV@BART .

Section 4: provides the description on functional requirements, verification methods, as well as performance requirements.

Section 5: contains the information describing the design process.

Section 6: describes a deployment plan for UAV@BART, from field testing to full deployment, and cost estimates for two deployment options.

Section 7: includes summary and recommendations for the phased implementation of UAV@BART and recommendation for the next step to develop and test a prototype UAV@BART system.

1.4 Referenced Documents

The System Requirements are developed based on the following documents:

- UAV@ BART Concept of Operations Document
- UAV@BART System Concept Design Document
- IEEE Guide for Developing System Requirements Specifications, IEEE 1233, 1998 Edition

The development process of these System Requirements followed a number of standards and guidelines, listed in Table 1.1.

Table 1-1 Documents Referenced in the BART System Requirement

Title	Version
IEEE Guide for Developing System Requirements Specifications, IEEE 1233	1998 Edition
IEEE Standard 1362-1998, IEEE Guide for Information Technology – System Definition – Concept of Operations (ConOps) Document	1998 Edition
Systems Engineering Guidebook for Intelligent Transportation Systems	3.0

The operational scenarios to be implemented at UAV@BART covers all three dynamic operations, as summarized in Table 1.1.

1.5 Acronyms and Definitions

BART	San Francisco Bay Area Rapid Transit
COA	Certificates of Waiver or Authorization

ConOps	Concept of Operations
FAA	Federal Aviation Administration
FOT	Field Operational Test
FPV	First-Person View
FTA	Federal Transit Administration
GPS	Global Positioning System
LED	Light-Emitting Diode
LIDAR	Light Detection and Ranging
PATH	California Partners for Advanced Transportation Technology
SAC	Special Airworthiness Certificate
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle

2. Overview of the UAV@BART System

2.1 Overview of UAVs

Aerial UAVs are unmanned aerial vehicles (UAVs) that have various degrees of flight control, ranging from manual control from an operator to autonomous control from onboard computers. Initially, UAVs were known from their military applications; however, over the years, their utilization has expanded into personal entertainment, commercial industries, agriculture, power line inspection, environment exploration, etc.

In the oil industry, UAVs have been implemented to inspect the perimeter around oil rigs and detect oil leaks and slicks through an onboard infrared radar. Since 2003, the Aerostar Tactical UAVs have been patrolling offshore oil fields on a regular basis. Even at night, the Aerostar's FLIR camera reveals the presence of thieves and potential kidnappers, who often try to reach the rigs using small boats. Oil leaks and slicks also show up clearly in infrared, and by detecting them early,Aerostar has saved oil companies millions in fines, which are imposed automatically for such leaks. The Aerostar's flight profile, with its 12 hours of endurance, slow loitering speed and fully programmable flight path, make it ideal for this surveillance role. The UAVs have significantly improved the security, time efficiency, and safety of workers.

Similarly, UAVs have been used in the agriculture industry to record humidity, temperature, pressure and incident lights, andmonitor crops and livestock. Imaged-based data is transmitted and analyzed in real time. The PrecisionHawk, a fixed wing UAV, has been specifically developed for the agriculture business to maximize crop performance, optimize asset monitoring, and manage crops efficiently.

In the power transmission system, UAVs have been widely utilized for the power transmission line inspections. UAVs equipped with onboard cameras can fly along the power transmission line either autonomously or manually controlled by operators and capture real-time image data of the transmission line and towers. The data then can be transmitted to a ground-based station for analysis of the potential defects. The utilization of UAVs has improved the efficiency of power transmission inspection and reduced human labors in many applications of the power industry.

Therefore, UAVs have been exhibiting increasing potential in various industries, especially because of the exponentially growth of technology. UAVs are very versatile and can be customized for various purposes with different programs and devices.

As an example of UAV applications in the railway system, the BNSF Railway is using UAVs for the inspection of its railway networks. The BNSF's initial UAV fleet includes AirRobot models AR180 and AR200, and 3DRobotics Spektres equipped with onboard cameras to detect obstructions, crude oil spills, and trespassers. The utilization of UAVS is also intended to relieve rail inspectors from far-distance and dangerous manned inspections. In another instance, German national railway company, Deutsche Bahn, is using UAVs carrying infra-red cameras to collect evidence of vandals who paint graffiti on railway facilities at night.

2.2 UAV@BART Conceptual Architecture

The conceptual architecture and conceptual workflow of the UAV@BART system is depicted in Figure 1 and Figure 2, respectively. The conceptual architecture can be considered as a centralized UAV control/management scheme for environment/target data collection and analysis. The UAV@BART system consists of the following functional elements:

A Centralized Ground Control & Monitoring Terminal (CGCMT) that sets mission goals and assigns tasks to each vehicle in the system to achieve those overall mission goals. Additionally it generates flight trajectories/plans that are tobe carried out by the vehicles. The status and operational progress of each system component is monitored by the CGCMT and relayed to other functional. The CGCMT also evaluates the BART system and designated mission targets in real time while providing alerts to the BART agency in need for further actions. The data collected during the mission operation is available to be processed and stored in the forms of log/task records/mission reports.

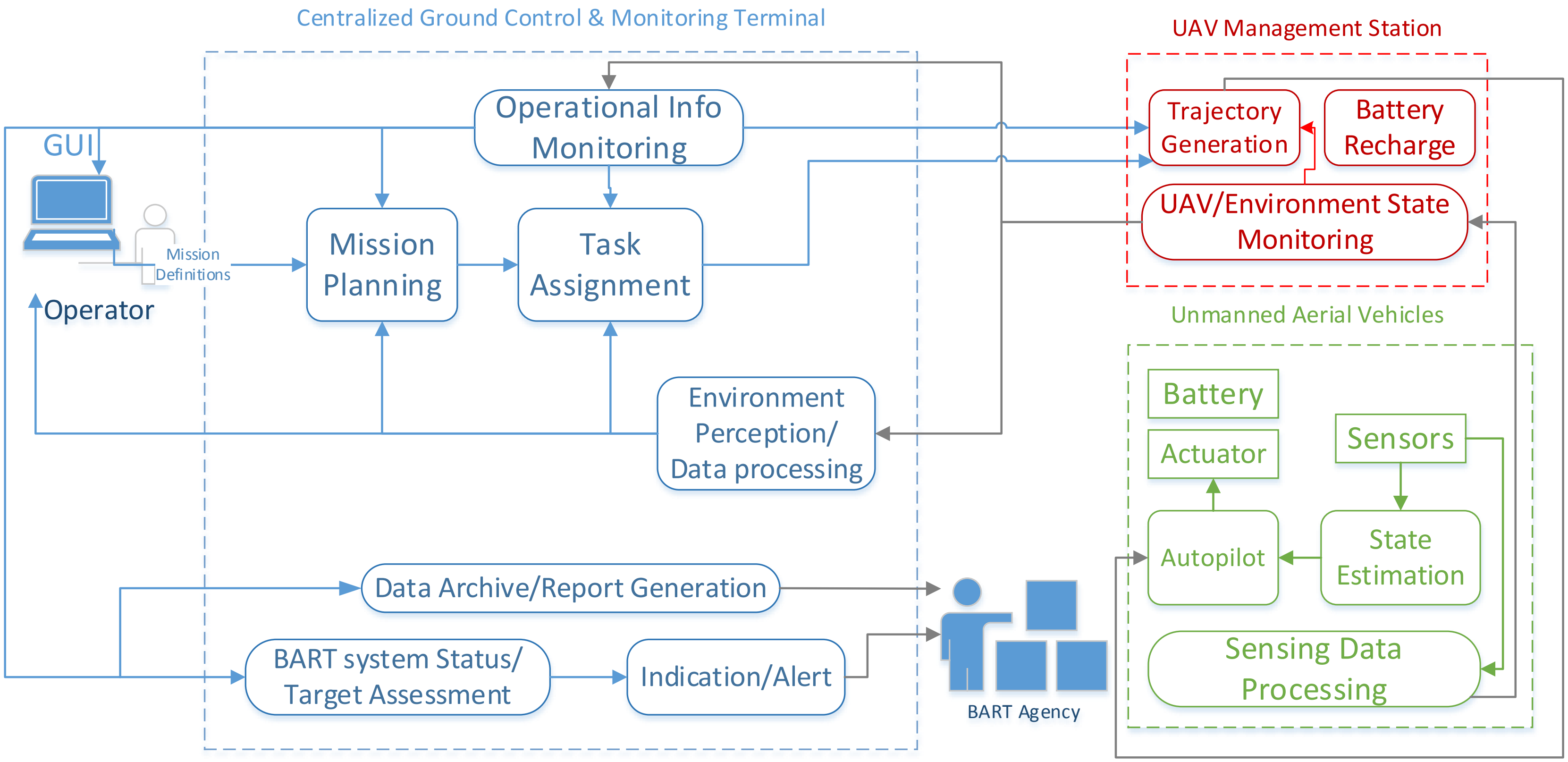


Figure 1Conceptual architecture of UAV@BART system

- Unmanned aerial vehicles (UAVs) that host onboard control, sensing and processing units and carry out the assigned tasks. The UAVs are used to perform most of the general environment/target data gathering and sensing data processing tasks. They can also transmit the collected data to the CGCMT via a UAV management station for further processing. The UAVs are designed for rapid surveying of tracks during both day-to-day maintenance operations and emergency situations. The UAV@BART system also includes rail-based autonomous vehicles designed to inspect the tracks for internal flaws. The systems complement one another in order to make maintenance, security, and emergency response safer and more efficient for BART personnel.
- UAV management stations that execute UAV management functional modules and handle task processing. Each UAV is paired with a dedicated management station which is installed at a specific location along the BART system. The real-time processing also aids the guidance of UAVs during takeoff and landing. Environment/target data collected by UAVs are first transmitted to the management stations, which uploads the data to the CGCMT. In addition, the management stations also monitor the UAV's status for maintenance and provide battery charging functionality.

The primary participants include BART operational/maintenance personnel, system operators and the police/fire department. They assume different roles in the UAV@BART system and interact with the system based on their roles.

- BART operational personnel are primary system users who schedule missions to the UAV@BART system and monitor the progress of the mission. They also review BART system/target data and information acquired by the vehicles, in order to evaluate the situation and determine if further action is necessary.
- System operators interact directly with the UAV@BART system. They input the mission information and performance controls of the system during the execution of the mission progress. UAV can also be controlled manually by system operators when it is necessary.
- Police/fire department are auxiliary agents who submit requests to the BART agency and system operators for deployment of UAVs in the cases of security and emergency events. They provide initial mission information and requirements before the deployment and issue commands directly to the system operators to cope with changes of the overall situation.

They also make decisions for further actions based on the environmental data provided by the UAVs.

The conceptual workflow of the UAV@BART system is depicted in Figure 2. The overall mission procedure is triggered by events (security or emergency events) or initialized according to schedules (routine maintenance schedules). Then mission goals and formatted descriptions are generated and the mission is decomposed into tasks that will be assigned to each UAV for execution. Trajectories/flight plans are calculated based on the tasks. The UAVs carry out the flight plans and execute the assigned tasks, which include track inspection, target surveillance and environment data collection. The UAV@BART system processes the data acquired by the UAVs and assesses the status of the BART system or targets. After the accomplishment of the mission, the UAVs land and upload the information of the mission. The collected data is utilized for further processing and report generation.

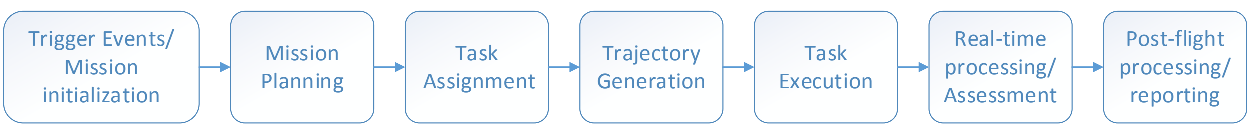


Figure 2 Conceptual workflow of UAV@BART system

2.3 Key Concepts for the UAV@BART System

2.2.1 Overview of BART system

The Bay Area is the fifth most populous metropolitan area in the United States, and BART is one of the main and most important forms of public transportation. There are approximately 37 miles of track through subways and tunnels, 23 miles of aerial track and 44 miles of surface track (four additional miles of doubletrack in subways and four underground stations for the S.F. Municipal Railway were constructed by BART as specified by the original 1962 plan).

There are 45 BART stations in total: 16 surface, 14 elevated and 15 subway. Four of these are a combination of BART and MUNI Metro stations in downtown San Francisco and one station is a combination of BART and Caltrain in Millbrae.

Tunnels and tracks are 5'6" wide compared to 4'8.5" for standard track gauge, and the trains operate at a speed of up to 80 mph and an average of 33 mph, including 20-second duration of station stops.

Rail safety is drawing heightened scrutiny as there is an increase in the number of accidents according to the reports of the Railroad Administration. A large portion of the accidents involving human fatalities and injuries were caused by defective tracks or track intrusions; therefore, it is of vital importance that the tracks and other BART facilities be inspected on a routine basis to ensure the operational safety and security. However, most of the track inspection tasks currently rely on human labor and manned inspections, which results higher risk of accidents and dangerous exposure for workers.

The UAV@BART system utilizes UAVs and autonomous vehicles to regularly inspect tracks in order to optimize maintenance efficiency. They implicitly serve as intrusion detectors and offer improved emergency capabilities, allowing police to monitor a standoff and maintenance to rapidly survey the tracks in case of natural or man-made disasters. Therefore, UAV@BART system would allow for more frequent and efficient inspections with lower labor costs, leading to increased operational safety and security.

For the implementation of the UAV system, management stations will be installed at specified maintenance zones and other secure areas on the BART system. These stations are strategically placed to allow rapid inspection of the entire system, with priority placed on known areas of interest such as tunnels. The UAVs can launch, land, and recharge autonomously from these stations. They will also be maintained and parked at these stations when they are not in operation. The system will operate under the guidelines of the Federal Aviation Administration (FAA) and in cooperation with local governments. The implementation of the UAV@BART system will also be based on the BART station designs and under the operational regulations of the BART system.

2.2.2 Autonomous Rail Vehicle-based Track Inspection

While UAVs would allow for efficient and fast inspection of external track defections and intrusions, the computer-vision approach based on airborne sensors is ineffective in detecting internal track flaws. Therefore, autonomous rail-based vehicles will be used as a supplement to UAVs for internal track defection/flaw inspections.

The rail vehicle will be equipped with onboard processing units and probe ultrasonic transducers that generate and receive ultrasonic pulses and echoes. The ultrasonic transducers will be installed perpendicular to the tracks in the vertical direction, and positioned in different angle to cover track areas. The embedded processing unit analyze the raw ultrasonic data reflected by the tracks, and recognize the track flaws in real time. The ultrasonic data-based flaw detection may involve multiple steps, such as data transformation, feature extraction, segmentation and alignment, as well as flaw pattern recognition. Once a potential flaw is recognized by the rail vehicle, the parameters of the flaw and its location will be stored in log file and transmitted to BART maintenance personnel for further actions. Using ultrasonic testing, the autonomous rail vehicle will be capable of inspecting the tracks for internal flaws (operating at a maximum speed of ~50 mph).

In addition, if the UAV detects a track defection that may involve potential internal flaw, a notification will be sent to the maintenance system which will deploy the rail vehicle to move to the marked location for internal detections. Rail-based vehicles will operate under current right-of-way regulations of the BART system.

2.3 Stakeholders Characteristics

The successful operation of UAV@BART involves the cooperation of multiple jurisdictions and agencies. The management and operations of the UAV system will be a joint effort involving all the stakeholders and users. For the effective operation and management of the UAV system, each user will have specific responsibilities.

Table 2-1 Stakeholders Characteristics

User/ Stakeholder	Responsibilities
BART Control Center operations personnel	Monitor overall conditions and performance measures of the UAV@BART system Ensure coordination between different stakeholders to provide accurate information
BART Maintenance Operations personnel	Monitor scheduling and mission data of the UAV maintenance system Review data and video footage and determine if further action is necessary
BART Police Department	Determine the severity of the emergency and deploy the UAV system to survey the area Alert officials if further action is necessary
Dispatchers of fire fighting agency	Respond to BART police and review UAV footage to determine proceeding actions
Dispatchers of city police department	Respond to BART police and review UAV footage to determine proceeding actions

2.4 Assumptions and Dependencies

The preliminary requirements developed in this document are to address all needs identified by the stakeholders. The requirements rely on the following assumptions:

(1) Stations shall be equipped with several UAV management stations to aid the landing and take-off, maintenance, and data downloads of the UAVs. Power supplies shall also be available to recharge the battery of the UAVs. The UAV management stations shall be connected to BART network for the transmission the collected data and flight log files.

(2) The UAVs shall fly with permission granted by the city where each station is located. The UAVs shall fly within a defined foot radius within the tracks, unless in the case of an emergency, and fly within the BART tunnels.

(3) UAVs shall be operated by certified pilots with FAA permissions for UAV operations, in the case when manual control is required by the mission, or system functional failures require emergency switch to manual control.
(4) Programming and hardware maintenance of the UAVs must be done periodically to ensure the operational effectiveness of the system. The software will need to be updated in regards to any future BART construction, as to update the UAVs' GPS for autonomous flight. Additionally, due to wear, hardware will be updated and replaced accordingly.
(5) All devices and facilities of the UAV@BART system shall be installed under the guidelines and regulations of the BART administrations, and the implementation and commissioning of the system will be performed during off-hours without interfering with BART operations.

2.5 UAV@BART Operational Scenarios

According to the decisions made during the initial kick-off meeting with BART, it was determined that the UAV system would provide support for three categories of operational categories: Security, Maintenance, and Emergency, with the concerns of safety and efficiency given priority. To define the functions and requirements of the system, the three categories were further divided into specific scenarios. Each scenario is listed and detailed, and further developed in regards to the necessities and suggestions from BART.

2.5.1 Security Scenarios

Security scenarios pertain to atypical events, specifically involving intrusions, emergency hostage situations, and unidentified objects. The main purpose of the UAV system is to monitor the situation at hand and inform the officials through video and audio alerts and indications. There will not be day to day surveillance, but if the UAV detects an abnormality during scheduled maintenance operations, then the situation will be reported in real-time to BART personnel. Additionally, if there is an emergency, the UAV may be manually deployed to assess the situation, which is practical for hostage situations.

2.5.1.1 Scenario 1: Intrusion detection on ground and underground level tracks

BART police need to prevent people from entering the tracks for the safety of the intruders themselves and passengers in BART trains. The prevention of intrusions guarantees the normal operation of BART. If a track intrusion of object or person occurs, a UAV can detect the event much faster than any human inspector and provide immediate real-time data on the situation.

1) UAVs and rail vehicles, deployed for scheduled maintenance, detect unauthorized trespassers or objects through analyzing images captured by onboard cameras.
2) Once intrusion is detected, the real-time image and the location of the intrusion is transmitted by the UAV to the BART operational office, and the BART operator personnel is immediately informed of the intrusion and will conduct a manual situation assessment to determine the next course of action.
3) The UAV can be switched to manual control mode to perform a closer check of the intrusion. The real-time video will be transmitted to the centralized control and monitor terminal for further assessment.

2.5.1.2 Scenario 2: Police standoff / active shooter

In the case of a hostage situation, the police may be unable to safely approach the armed criminal. A UAV rather than a person could be sent in to gather more information. (A UAV is relatively disposable compared to a human life).

1) An armed crime event occurs in which police forces are unable to advance into a station or train because of a lack of information. (e.g. a hostage situation occurs on a BART train)
2) The police issues a request for an inspection mission and provide preliminary information to the system operator, who will then manually deploy one or more UAVs, which are able to transmit a live video feedback of both the target of interest and the overall situation. The data will be provided in real time to the police for decision making.
3) UAVs determine and transmit the location/coordination of civilian(s) and criminal(s).
4) Police and other officials use this information to more safely and efficiently assess and resolve the situation.

2.5.1.3 Scenario 3: Unidentified package on tracks

Aside from regular debris that falls onto the tracks, suspicious packages may also appear along BART lines. These packages need to be examined as they may contain harmful chemicals or explosives. Instead of sending a human to inspect a possibly dangerous item, a UAV would be sent in instead.

1) An unidentified object is detected by a UAV during routine inspection, or the object is reported by passenger or operational personnel.
2) The UAV or the personnel notifies BART of the location of the object, and the system initializes manual controls of a UAV so BART personnel can obtain a detailed assessment of the object.
3) The UAV examines the object for chemicals or explosives using onboard sensors and transmits the information to BART operational personnel for further assessment and actions.

2.5.2 Maintenance Scenarios

In these maintenance scenarios, the objective of the UAVs is to perform autonomous day-to-day inspection of overall track integrity and safety, thereby improving the efficiency of maintenance work and increasing worker safety. The UAVs will detect track flaws as well as any intrusions, and alert the BART personnel if an on-site maintenance is required. Additionally, the UAVs can also be deployed manually to inspect construction projects to evaluate overall progress and provide topographic information.

2.5.2.1 Scenario 4: Track inspection using UAVs

In order to increase efficiency and reduce inspection time, a UAV fleet can be used to perform routine day-to-day track inspections.

1) Instead of sending a test rail vehicle prior to regular BART service to visually inspect the tracks, UAVs are deployed from management stations located throughout the rail system, and tasks are assigned to UAVs based on the overall inspection mission.

2) The UAVs follow predetermined flight plans, inspect the tracks for potential track [1]defections and intrusions using on-board sensors.
    a) Since different sensors provide different sensing capabilities, the potential exists to utilize a hybrid UAV fleet containing UAVs equipped with various sensors (e.g. some UAVs equipped with LIDAR sensors and other UAVs equipped with cameras to capture image and video data) to address different problems that arise.
3) The UAVs analyze the collected data to recognize the detected events (track defections, person intrusions, and debris intrusions), and assess the hazard level of the events.
    a) If all events are recognized to be low-hazard, the events will be marked and the data of events (location and images, etc.) and log file will be transmitted and stored. These data will be further analyzed and inspection reports will be generated. The BART maintenance personnel will use these data to determine further actions (e.g. whether a closer check is needed).
    b) If an event of high hazard level (large track flaw or track intrusion) is recognized, an alert will be sent immediately to the BART operational personnel, and the location of the event will also be provided. The security procedure described in 2.4.1 will be activated and the entire rail system is surveyed in under one hour.

2.5.2.2 Scenario 5: Track inspection using rail-based vehicles

Both UAVs and rail vehicles are used to inspect tracks in the UAV@BART system. However, the rail-based vehicles are primarily used for internal flaw inspections.

1) The entire rail system must be inspected multiple times per year for internal flaws that could lead to structural failures, track offset, debris on tracks, and damages to the right-of-way fences that line the rails.
    a) Inspections should be done based on FRA regulations.

Note: *Many of these scenarios are drawn from implementations currently being experimented with by other railways, including BNSF (US), Network Rail (UK), ProRail (Netherlands), and more.*

2) Rail-based vehicles are sent between stations during off-hours to prevent interfering withs normal operations.
3) Track alignment are inspected using on-board sensors to check for potential flaws.
   a) This would allow for maintenance workers to verify the need for them to travel out to the site of interest if a problem is found.
4) The rail-based vehicles store and analyze the data they collects, reports their findings to maintenance personnel, and transmit the data to the central processing terminal for more detailed analysis and record keeping.

2.5.2.3 Scenario 6: Air Quality Inspection

The UAVs can also be configured to inspect the air quality in order to generate an air quality map of the track network.

1) If it is required, UAV systems can include the capability to inspect air quality data by additional sensors or functionality. The air quality inspection mission is initialized by the centralized control and monitoring terminal, and tasks are assigned to UAVs along with flight plans.
2) UAVs take off autonomously from the management station and operate along the predefined flight plan. Then, and the collected air quality data is processed and analyzed to detect abnormal events.
3) The processed air quality data is transmitted to the control and monitor terminal, and the log file is stored in the server for further analysis.
4) If an abnormality of air quality (which may be caused by gas leaks in tunnels nearby or containing oil pipelines, such as in the Pittsburgh Line) is detected, an alert is immediately sent to BART maintenance personnel for further actions, and the location of the events will also be provided. The BART maintenance personnel will use these data to determine further actions (e.g. whether a closer check is needed)

2.5.2.4 Scenario 7: Analysis of Debris on Tracks

UAVs can be used to remotely inspect debris on a track, which will increase worker efficiency. If further inspection is needed, then a worker will go on site. The UAV system will result in more efficient and faster inspection.

1) UAVs can be integrated into the daily maintenance of tracks and trains by being employed as a tool for workers to use when they proceed to a potential track flaw.
2) Manual mode would be enabled, and a human pilot would be able to get a detailed visual of the debris, in addition to other potential needed information from rigged sensors, in order to more efficiently prepare a solution.
3) The data collected during the flight would be transferred to a server for further analysis, record keeping, and statistical studies.

2.5.2.5 Scenario 8: Project Progress Supervision

For the case of ongoing rail construction or large maintenance projects, UAVs can be used to regularly monitor and capture footage of day to day progress.

1) UAVs are deployed to fly to the construction sites of interest to capture data of the site, and ongoing BART and PD&C projects can be supervised and documented with aerial footage.
    a) Specifically, the desired data would be an accurate point cloud of existing field conditions (e.g., using LIDAR or other mapping software and hardware).
2) Alternatively, UAVs may be used to assist in generating status reports of progress monthly or weekly more effectively by capturing comprehensive images of the overall construction project quickly.
3) The image data and point cloud data are processed to evaluate the progress and the construction reports are generated according to the evaluation results.

2.5.2.6 Scenario 9: Worker Safety During Blanket

This scenario emphasizes the life-safety of workers, specifically to avoid accidents and injuries. Incidents of train collisions (with workers) are usually caused by invalid operations or mistakes made by human operators. An effort to find ways to prevent these incidents with UAVs is described below.

1) UAVs are deployed with a task to fly to an area of interest (pre-examine an area with low lighting or potential hazards) and capture the image data of the area.
2) The collected data are analyzed to identify potential hazard. The workers will be notified if a potential risk is detected.
3) UAVs (rigged with on-board sensors and strong lighting, etc.) may be manually piloted by maintenance operators, to capture and transmit the image of areas of interest and to expedite nightly maintenance procedures.
4) Additionally, UAVs can be used during the day to regulate single rail maintenance operations.

2.5.2.7 Scenario 10: Remote Inspection of Large Infrastructure

Besides the track, BART system includes bridges, stations and large structures that also need to be inspected and maintained. For larger infrastructure like bridges, on board sensors are used to acquire very accurate sensory data.

1) UAVs approach the target structures.
2) UAVs captures and transmit image and cloud point data of the structure and transmit the data to the control and maintenance terminal.
3) The status of the structure is evaluated based on the captured data.
4) Deployment in these situations would be manual, as described in Scenarios 7 and 9.

2.5.3 Emergency Scenarios

The UAV@BART system enables a rapid assessment of an emergency situation in order to facilitate a safe and efficient response by BART and emergency personnel.

For any emergency scenario that occurs, the possibility of utilizing throwaway rail-based vehicles is possible. These would travel along the rails, collect data, and be considered disposable should the situation deem these vehicles are unrecoverable; they would send keep-alive signals, allowing the system to detect under the harsh environment such as fires, derailment, etc. so as to assess the situation in more detail and with faster response.

2.5.3.1 Scenario 11: Earthquake

The Bay Area is known for its tectonically active geography, and has a history of such especially with the San Andreas Fault being so close. It is highly possible that large earthquakes occur in the future, therefore BART system requires a solution to be prepared to assess the damages when another significant earthquake hits the Bay Area.

1) A large magnitude earthquake occurs originating at the Hayward fault, causing damage even to well-designed structures throughout the Bay Area.
2) Under the guidelines of the UAV@BART emergency deployment procedure, the UAV network is activated and initiates a predetermined damage assessment flight plan.
3) UAVs are launched from strategically placed base stations throughout the rail system and fly at optimal altitude and speed in order to survey the entire system as quickly as possible.
4) Sites of immediate emergency are identified and the location information is sent to BART maintenance personnel, who are able to determine the best course of action.
5) Structural damage is identified and the location and image data are communicated to BART personnel in-flight. The entire rail system is surveyed and all UAVs identifiable damage accounted for.
    a) Furthermore, the best means of evacuation for civilians on BART lines is calculated based on this data and multiple pathways are generated and provided to BART personnel.
6) Nominally undamaged tracks are rapidly inspected for internal damage by rail-based UAVs with vehicle-borne sensors. (The procedure of these rail-based UAVs overlap with those specified in maintenance scenarios)
7) A complete map of the damage to the rail system is generated in under two hours.

2.5.3.2 Scenario 12: Train Derailment

In case of train derailment, a UAV can reach quickly the accident spot in order to provide live footage and the situation status to the emergency crew. A train derailment may occur because of an earthquake or a system operational failure. This scenario could also occur in a place that is dangerous for emergency personnel to reach, so a UAV could be sent in to assist in areas of high hazard.

1) An above-ground train derailment occurs near the Daly City Bart Station.
2) UAVs are deployed from the Daly City maintenance station within minutes of initial emergency notification.
    a) Fleet may include both aerial and rail-based vehicles, depending on the projected seriousness of the derailment.
3) Within minutes from time of derailment, the UAV fleet arrives to the area of event to survey situation and provide live feed to operators and data collection bank.
4) With multiple life feed aerial views available, the safest course of emergency action are readily planned.
5) Post-derailment surveillance data from UAVs and rail-based vehicles are uploaded and archived, allowing better insight into the causes of derailment and preventing future accidents.

2.5.3.3 Scenario 13: Fire in Tunnels

Fires pose some of the greatest threats to passengers and workers in tunnels due the limited ventilation. A fire can occur because of an earthquake, a train derailment, faulty electronics, and more. Before deploying the firefighters, a UAV can be used to get as close as possible from the fire to provide more information about the status. The UAV could also be manually piloted by operators so that the fire department may determine how best to handle the situation.

1) Smoke is detected in the Berkeley Hills tunnel, and an UAV is launched from a nearby base station to investigate the source.
2) The UAV sends a live feed of sensory data to BART personnel as it inspects the tunnel.
3) The UAV locates a fire in the tunnel and from the transmitted location, video and sensor data (including direction of airflow when ventilation is turned on), BART personnel are able to determine its extent and growth rate. BART personnel are also able to determine the best approach to extinguishing the fire.
4) The fire is safely and efficiently extinguished by personnel, and the damage is accurately surveyed by the UAVs in order to facilitate repairs

2.5.3.4 Scenario 14: Oil or Chemical Spills on Tracks

Besides debris and due to environmental factors, some old trains can leak oil and cause other chemicals to spill onto the track. The spills can be quickly and efficiently assessed by a UAV and can inform the maintenance or emergency crew.

1) An oil or chemical spill leakage on the BART track is reported.
2) A UAV may be deployed to inspect the damages using a combination of sensory and live video feed to inspect reported oil or chemical spills.
3) The UAV will assess the damage and promptly alert BART personnel.
4) For tunnels, a similar procedure may be implemented by rail-based vehicles, which can arrive to the spill site within minutes.

3 Function Decomposition

According to the above operational scenarios, the UAV@BART system functions that would be required for each scenario are developed. The system functions are further divided into two categories: The common functions and scenario-specific functions.

- Common functions: common system functions are those functions that the UAV@BART system shall exhibit in multiple scenarios. For example, if system functions are required in several scenarios such as mission planning, trajectory generation and image data transmission, these should be categorized as common functions. The UAV@BART system operates in the same routine of the function to fulfill the functional requirements in those scenarios. In addition, common functions can be further categorized based on the system components that are responsible for the associated functions (i.e. UAV functions, CGCMT functions and Ground Management Station functions).
- Scenario-specific functions: scenario-specific functions are those associated with one specific scenario, and these scenario-specific functions are not required in the missions described by other scenarios. If a function is only performed in some specific scenario, such as the air quality evaluation in Scenario 6, it should be listed as a scenario-specific function.

Each scenario was broken down into: mission planning, trajectory planning, and sensing and controlling. Mission planning refers to the tasks each UAV will execute, trajectory planning explains the route and location of the UAV, and sensing and controlling describe the necessary sensors and autonomy needed for the specific task. The UAV functions were then decomposed to a level where functional requirements were defined (Section 4.2).

3.1 Maintenance

Maintenance functions are mostly based on scheduled missions, where the UAV will fly over and collect data for post-flight analysis.

Table 3-1 Maintenance Function Decomposition

Maintenance (MA)
MA-01 Track Inspection Using Aerial UAVs MA-01-01 Mission Planning MA-01-01-01 Visual flaw inspections for major cracks, debris, loose coverboards MA-01-01-02 Survey entire rail system in less than one hour MA-01-01-03 Inspect internal flaws and/or intruders MA-01-02 Trajectory Planning MA-01-02-01: Follow predetermined flight plans along the tracks while avoiding no fly zones MA-01-02-02: Fly in the right of way and BART jurisdiction zones (a few feet above tracks) MA-01-03 Detection/Sensing, Controlling, Maneuvering MA-01-03-01: Detection: on-board sensors (video feed from cameras, basic LIDAR for surface flaws, headlights) MA-01-03-02: Control: pre-determined flight path, deployment from base stations, autonomous MA-01-03-03: Maneuvering: obstacle avoidance, announcement of flight MA-02: Track Inspection Using Rail-Based UAVs MA-02-01 Mission Planning MA-02-01-01: Visual and internal flaw inspection MA-02-01-02: Track alignment analysis MA-02-02 Trajectory Planning MA-02-02-01: Follow its own path line in respect with each BART line MA-02-03 Detection/Sensing, Controlling, Maneuvering MA-02-03-01: Detection: video feed to register disruptions/obstacles, ability to flag maintenance workers/control, headlights, optical sensors for fences, onboard computer to store and send data MA-02-03-02: Control: pre-determined path (on tracks), capable to match higher speeds

MA-02-03-03: Maneuvering: autonomous, on rails

MA-03: Air Quality

MA-03-01 Mission Planning

MA-03-01-01: Record air quality data

MA-03-01-02: Detect gas leaks and fires from oil pipelines

MA-03-02 Trajectory Planning

MA-03-02-01: Check components that may include: ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrous oxide

MA-03-02-02: Capable of remain stationary and direct airflow to detect contaminants

MA-03-03 Detection/Sensing, Controlling, Maneuvering

MA-03-03-01: Detection: air quality sensors (particulate detection), headlights

MA-03-03-02: Control/Maneuvering: obstacle avoidance, manual piloting

MA-04: Analysis of Debris on Track (Maintenance Efficiency and Capability)

MA-04-01 Mission Planning

MA-04-01-01: Integrate UAVs into daily maintenance of tracks and trains

MA-04-01-02: Deploy UAVs first to inspect the flaw before sending out maintenance workers

MA-04-01-03: Easy and fast deployment from stations designed to reduce the need for maintenance workers to travel to location (thereby increasing efficiency and reducing wasted hours of travel), where worker makes the decision of which UAV to bring or deploy based on the sensors rigged

MA-04-02 Trajectory Planning

MA-04-02-01: In the case of an unexpected flaw that causes delays during operating hours, workers will send out manually operated UAVs to assess the situation and plan accordingly

MA-04-02-02: Define speed to be slow enough to capture good quality video images and sensor data

MA-04-03 Detection/Sensing, Controlling, Maneuvering

MA-04-03-01: Detection: same as aerial-based UAV

MA-04-03-02: Maneuvering: manual piloting, LEDs to indicate flight

MA-05: Maintenance Progress Supervision

MA-05-01 Mission Planning

MA-05-01-01: Generate status reports of progress of construction projects

MA-05-01-02: Provide timelapse or overarching video capture of progress

MA-05-01-03: Map areas of interest to be shared between Maintenance and Engineering

MA-05-02 Trajectory Planning

MA-05-02-01: Use aerial UAVs to obtain an overall view and analysis of the construction project

MA-05-02-02: Define speed to be slow enough to capture good quality video images and sensor data

MA-05-03 Detection/Sensing, Controlling, Maneuvering

MA-05-03-01: Detection: video feed/capture, mapping sensors (LIDAR, etc.)

MA-05-03-02: Maneuvering: manual piloting, LEDs to indicate flight

MA-06: Worker Safety During Blanket

MA-06-01 Mission Planning

MA-06-01-01: Pre-examine an area with low lighting or potential hazards to notify maintenance workers of risks MA-06-01-02: Manually piloted UAVs to be employed by maintenance workers operating in particularly dangerous locations (or at times of night that historically have the most incidents) MA-06-02 Trajectory Planning MA-06-02-01: Pre-assess area to determine if a maintenance worker is needed MA-06-02-02: Define speed to be slow enough to capture good quality video images and sensor data MA-06-03 Detection/Sensing, Controlling, Maneuvering MA-06-03-01: Detection: same as aerial-based UAV MA-06-03-02: Control/Maneuvering: manual piloting, LEDs to indicate flight MA-07: Remote Inspection of Large Infrastructure MA-07-01 Mission Planning MA-07-01-01: Inspect larger infrastructure for cracks, erosion, debris, intrusions MA-07-01-02: Deployment of these UAVs will be independent of the aerial/rail-based track UAVs MA-07-02 Trajectory Planning MA-07-02-01: manually fly UAVs to inspect elevated rail systems, bridges, and stations MA-07-02-02: define speed to be slow enough to capture good quality video images and sensor data MA-07-03 Detection/Sensing, Controlling, Maneuvering MA-07-03-01: Detection: specific sensors for analyzing infrastructure, video feed/capture, headlights MA-07-03-02: Control: auto/manual piloting (i.e. assisted flight) MA-07-03-03: Maneuvering: obstacle avoidance from all angles, no fly zones

3.2 Security

The security functions are based on a mix of scheduled missions, like patrol, and on-demand missions in case of police standoffs.

Table 3-2 Security Function Decomposition

Security (SC)
SC-01: Intrusion Detection on Ground and Underground Level Tracks SC-01-01 Mission Planning SC-01-01-01: Detects unauthorized trespassers SC-01-01-02: Notifies BART operator of intruder on tracks SC-01-02 Trajectory Planning SC-01-02-01: BART worker will remotely observe the UAV's data and be flagged if the UAV indicates an intrusion SC-01-02-02: UAV will deploy from base station flying for ~30-40min until landing at the

next base station for maintenance, recharge, or data download

SC-01-02-03: Speed must be slow enough to capture good quality video images and sensor data

SC-01-03 Detection/Sensing, Controlling, Maneuvering

SC-01-03-01: Detection: on-board sensors (video feed from cameras, temperature/heat sensors)

SC-01-03-02: Control: pre-determined flight path, deployment from base stations, autonomous

SC-01-03-03: Maneuvering: obstacle avoidance, announcement of flight

SC-02: Police Standoff/Active Shooter

SC-02-01 Mission Planning

SC-02-01-01: Broadcasts a live feed of the train without placing any BART personnel in danger

SC-02-01-02: Locates (if any) hostages and people in immediate danger

SC-02-01-03: Locates the gunman without notifying the gunman

SC-02-02 Trajectory Planning

SC-02-02-01: When BART police is notified of a hostage or active shooter situation, they will send out a UAV manually to the specified location

SC-02-02-02: Speed must be slow enough to capture good quality video images and sensor data

SC-02-03 Detection/Sensing, Controlling, Maneuvering

SC-02-03-01: Detection: on-board sensors (video feed from cameras, temperature/heat sensors)

SC-02-03-02: Control: Manual

SC-03: Unidentified Package on Tracks

SC-03-01 Mission Planning

SC-03-01-01: UAV will notify BART and enable manual controls for further action

SC-03-01-02: Scan the object for chemicals

SC-03-01-03: Identify whether the package is hazardous

SC-03-01-04: Possibly notify bomb control immediately if the package is determined to be explosive

SC-03-02 Trajectory Planning

SC-03-02-01: BART worker will remotely observe the UAV's footage/sensor data and be flagged if the sensor on the UAV indicates an unidentified object

SC-03-02-02: UAV will deploy from base station flying for for ~30-40min until landing at the next base station for maintenance, recharge, or data download

SC-03-02-03: speed must be slow enough to capture good quality video images and sensor data

SC-03-03 Detection/Sensing, Controlling, Maneuvering

SC-03-03-01: Detection: on-board sensors (video feed from cameras, temperature/heat sensors,)

SC-03-03-02: Control: pre-determined flight path, deployment from base stations, autonomous

SC-03-03-03: Maneuvering: obstacle avoidance, announcement of flight

SC-03-03-04: Switch to manual control if unidentified object is detected

3.3 Emergency

Emergency functions are based on on-demand missions, and most of the missions involve manual control.

Table 3-3 Emergency Function Decomposition

Emergency (EM)
EM-01: Earthquake EM-01-01 Mission Planning EM-01-01-01: Deploy UAVs before sending in emergency personnel EM-01-01-02: Capture live feed of structural damages EM-01-01-03: Determine areas of immediate danger to human life EM-01-01-04: Identify other emergency scenarios (EM-02, EM-03, EM-04) resulting from EM-01 EM-01-02 Trajectory Planning EM-01-02-01: Follow predetermined flight plans along the tracks while avoiding no fly zones EM-01-03 Detection, Controlling, Maneuvering EM-01-03-01: Detection: On-board sensors (live video feed, thermal sensors) EM-01-03-02: Controls: Manual piloting along predetermined route EM-01-03-03: Maneuvering: Obstacle avoidance, no fly zones EM-02: Fire EM-02-01 Mission Planning EM-02-01-01: Capture live feed of reported blaze (to assist emergency personnel tackle blaze) EM-02-01-02: Determine areas of immediate danger to human life EM-02-01-03: Assess extent and potential spread of fire EM-02-02 Trajectory Planning EM-02-02-01: Autonomous UAV flying to reported site of blaze EM-02-02-02: Manual UAV flying for further inspection when at site EM-02-03 Detection, Controlling, Maneuvering EM-02-03-01: Detection: On-board sensors (live video feed, thermal sensors, air quality sensors) EM-02-03-02: Controls: Auto piloting to site of blaze, manual piloting available for further inspection of blaze EM-02-03-03: Maneuvering: Obstacle avoidance; data collection from safe distance when at site of blaze if on autopilot EM-03: Train Derailment EM-03-01 Mission Planning EM-03-01-01: Capture live feed of reported site (to assist emergency personnel) EM-03-01-02: Identify survivors EM-03-01-03: Identify other emergency scenarios (EM-02, EM-04) resulting from EM-02 EM-03-02 Trajectory Planning EM-03-02-01: Autonomous UAV flying to reported derailment site EM-03-02-02: Manual UAV flying for further inspection when at site EM-03-03 Detection, Controlling, Maneuvering EM-03-03-01: Detection: On-board sensors (live video feed, thermal sensors) EM-03-03-02: Controls: Auto piloting to site derailment, manual piloting available for further inspection of site

EM-03-03-03: Maneuvering: Obstacle avoidance; data collection from safe distance at best angle when at site if on autopilot

EM-04: Oil/Chemical Spill on Tracks

- EM-04-01 Mission Planning
  - EM-04-01-01: Inspect severity and scope of chemical spill
  - EM-04-01-02: Identify other emergency scenarios (EM-02) resulting from EM-04
  - EM-04-01-03: Report findings to hazard specialists
  - EM-04-01-04: Live feed of spill
- EM-04-02 Trajectory Planning
  - EM-04-02-01: Autonomous UAV flying to reported spill
  - EM-04-02-02: Manual UAV flying for further inspection when at site
- EM-04-03 Detection, Controlling, Maneuvering
  - EM-04-03-01: Detection: On-board sensors (live video feed, thermal sensors, air quality sensors)
  - EM-04-03-02: Controls: Auto piloting to site of spill, manual piloting available for further inspection
  - EM-04-03-03: Maneuvering: Obstacle avoidance; manual piloting to achieve best view of spill

4. UAV@BART Requirements

This section provides the functional and performance requirements of the system. These requirements are based on the scenarios document and the stakeholder's needs. The functional requirements serve as the foundation for further development of requirement specifications, and they may be reevaluated and updated during the system development and implementation stage to account for schedule and cost.

4.1 Requirement Number and Numbering scheme

The structure of the requirements is indicated by the numbering scheme which is listed in Table 4-1. The numbering scheme is used to uniquely define and identify a requirement.

Table 4-1Requirements Numbering

Requirement Numbering	Descriptions/Notes
A-$\#_1\#_2$-$\#_3\#_4$	Prototype system requirement
F-$\#_1\#_2$-$\#_3\#_4$	Future implementation requirement
C-$\#_1\#_2$-$\#_3\#_4$. $\#_5\#_6$	Children requirement, where $\#_1\#_2$-$\#_3\#_4$ are identical to that of their parents requirement, $\#_5\#_6$ is the consecutive children requirement number
$\#_1\#_2$	Requirement structure diagram: 00- General requirements 01- Common function requirements: CGCMT 02- Common function requirements: Management Station 03- Common function requirements: UAV 04- Scenario-specific function requirements: CGCMT 05- Scenario-specific function requirements: Management Station 06- Scenario-specific function requirements: UAV 07- Data requirements 08- Performance requirements
$\#_3\#_4$	Consecutive requirements number
$\#_5\#_6$	Consecutive requirements number

A requirement ID starting with an A represent requirements that must be implemented within the period of the development and deployment of the demonstrative UAV@BART prototype system, while requirement IDs beginning with letter F denote requirements that must be implemented within the period specified by the stakeholders after the demonstration period of the prototype system. An A or F requirement can be a single requirement or a parent requirement. A child requirement begins with letter C and it is attached with the same numerical specification $\#_1\#_2$-$\#_3\#_4$ as its parent requirement.

4.2 Requirement Traceability

Each requirement is accompanied by traceability information that corresponds the requirement with the final UAV@BART ConOps and/or specific stakeholder inputs of needs.

4.3 Requirement Verification Methods

The verification methods of requirements are specified in Table 4-2. For each requirement, one or several of the presented approaches may be utilized in the system demonstration and verification stage.

Table 4-2 Requirement Verification Methods

Abbreviation	Verification methods	Description
T	Test	External test equipment-based function verification
D	Demonstrate	Demonstration of characteristics without using any external test equipment
A	Analyze	Theoretical analysis and conclusion-based verification
I	Inspect	Visual inspection-based inspection

4.4 General Requirements

General functional requirements are those requirements that have a scope throughout the entire UAV@BART expanse and lifecycle. For example, if function requirements are imposed on every level, aspect or component of the UAV@BART such as software and hardware compatibility or power supply characteristic, these requirements would be listed as general functional requirements. The general functional requirements of the UAV@BART are listed in Table 4-3.

Table4-3 General Requirements

RQID.	Requirements	Traceability	Verification Methods
	UAV@BART Infrastructure Software Compatibility		
A00-01	The UAV@BART prototype software shall be compatible with the computers, processor or	**N/A**	T

	microcontrollers used in the current BART system.		
	UAV@BART Infrastructure Electrical Compatibility		
A00-02	The UAV@BART prototype (including centralized control and monitoring terminal and the UAV management stations) shall be compatible with the electrical infrastructure of the BART system	**N/A**	T
	UAV@BART Infrastructure Mechanical Compatibility		
A00-03	The UAV@BART prototype shall be compatible with the mechanical infrastructure of the BART system. (The UAV@BART system hardware including the equipment, cabinet or UAV station devices shall provide mechanical compatibility with the BART infrastructure)	**N/A**	T

4.5 Functional Requirements

The UAV@BART team used a systems engineering process is to gather, review, analyze, and transform stakeholder needs into functional requirements that define "what" the system will do. The functional requirements are specified as capabilities or functions of the UAV@BART system, and qualifying conditions and bounding constraints that are identified distinctly from capabilities.

Table 4-4 Common Functional Requirements

RQID.	Requirements	Traceability	Verification Methods
	Common Function requirements		
	CGCMT Function requirements		
A01-01	The centralized ground control and monitoring terminal (CGCMT) shall provide GUI interface and allow operators to define mission goals and input initial information including mission category, destination location, and target information.	MA-01-01 MA-02-01 MA-03-01 MA-04-01 MA-05-01 MA-06-01 MA-07-01 SC-01-01 SC-02-01	T
A01-02	The CGCMT GUI interface shall allow operates to modify and cancel missions.		T
A01-03	The CGCMT shall automatically assign the		T

	tasks to UAVs based on the mission definition.	SC-03-01 EM-01-01 EM-02-01 EM-03-01 EM-04-01	
C01-03.01	The CGCMT shall be capable of keeping a list of predefined missions.		D
C01-03.02	The CGCMT shall allow the operator to select, load and activate predefined missions.		D
C01-03.03	The CGMCT shall store the detailed task schedule of each predefined mission		D
A01-04	The CGCMT shall provide the task assignment information via the GUI		D
A01-05	The CGCMT GUI shall provide detailed status information (location, health status, battery duration, etc.) of the UAVs that are assigned with the tasks		T
A01-06	The CGCMT shall allow the operators to modify the task assignments, and replace, add, or remove UAVs		T
A01-07	The CGCMT shall allow the operators to confirm the task planning results.		T
A01-08	The CGCMT shall be connected to the computers of the UAV management stations, and communicate with the computers to send the task information to the management station.		T
A01-09	The CGCMT shall be connected to the computers of the UAV management stations, and communicate with the computers to obtain the health status information of the UAVs.		T
A01-10	The CGCMT shall monitor the progress of the overall mission and evaluate the performance of each component (UAV and management station), and provide feedback to the operator regarding its health status, progress and mission effectiveness.		T
F01-11	The CGCMT shall perform mission replanting if the mission effectiveness is affected by downgrade of system components or failure.		T
A01-12	The CGCMT shall communicate with the management stations to obtain the real-time alert of events detected by the UAVs during operation.		T
A01-13	The CGCMT shall communicate with the management stations and obtain the flight log, sensory data and information collected by the		T

	UAVs after the accomplishment of the mission. It shall also process and archive the data marked by time.		
A01-14	The CGCMT shall allow the operator to access and review the collected data and flight log via the GUI interface after the accomplishment of the mission.		D
A01-15	The CGCMT shall generate mission report files in predefined formats after the accomplishment of the mission.		D
	UAV Management Station Requirements		
A02-01	The management station shall be connected to the CGCMT and obtain the assigned tasks from the CGCMT.	MA-01-02 MA-02-02 MA-03-02 MA-04-02 MA-05-02 MA-06-02 MA-07-02 SC-01-02 SC-02-02 SC-03-02 EM-01-02 EM-02-02 EM-03-02 EM-04-02	T
A02-02	The management station shall autonomously generate trajectories/flight plans (containing waypoints, task commands, destination locations, takeoff and landing procedure and velocity profile) based on the assigned task.		T
C02-02.01	The management station shall maintain and update a detailed map and 3D model of the corresponding area.		D
C02-02.02	The flight plans shall consist of the following elements: ● Destination locations (Lat & Lon or coordinates) ● Takeoff and landing procedure ● Waypoints (position, altitude and commands) ● Velocity profile.		D
G02-02.03	Each waypoint of the flight plans shall be corresponded with a task command that belongs to the following command types: ● Navigation commands (e.g. hover for a period of time, loiter over an area) ● Action commands (e.g. taking pictures) ● Sensor commands (e.g. camera command) ● Condition commands (execute the action commands until some condition is met)		T
C02-02.04	The management station shall store a list of predefined trajectories/flight plans		D
C02-02.05	The management station shall be capable of autonomously loading and activating the predefined trajectories/flight plans associated		T

	with the task goal.		
C02-02.06	The management station shall allow the operator to select, load, modify (add/remove the waypoints, modify the task commands, modify takeoff/landing procedures) and activate predefined trajectories/flight plans via GUI-based interface.		T
C02-02.04	The management station shall allow the users to enter waypoints by clicking on the map or inputting the Lat&Lon/Coordinates.		T
A02-03	The management station shall evaluate the UAV's health status and battery status, and determine whether it is due for maintenance.		T
A02-04	The management station shall provide GUI-based interface to monitor the flight status of the UAV and task progress		T
C02-04.01	The management station GUI shall provide a HUD (Head-Up Display) area to provide the real-time flight status including attitude, height and velocity of the UAV.		D
C02-04.02	The management station GUI shall provide a map area to provide the real-time position of the UAV and the task progress		T
C02-04.03	The management station shall provide real-time health status information (system functions and battery status) of the UAV		T
A02-05	The management station shall be able to be configured to match the airframe of the UAV used in the task		T
A02-06	The management station shall show the real-time sensing data (video streaming, images, LIDAR point clouds and other sensing data) transmitted by the UAV during operation		T
A02-07	The management station shall allow the operator to interact with the UAV and send operation command directly via the GUI.		T
C02-07.01	The operation command send by the management station shall include but not limited to: • Engage/disengage • Takeoff • Travel to a given location • Change altitude • Chang velocity		T

	• Return to rally point		
F02-08	The management station will be capable of creating a list of rally points and navigating the UAV to the closest rally point to perform an automated landing, in the cases of system malfunctions and emergencies		T
A02-09	The management station shall allow for configuration and calibration of the onboard motion sensors		T
C02-09.01	The management station shall allow the onboard accelerometers to calibrate autonomously		T
C02-09.01	The management station shall allow the onboard compass to calibrate autonomously		T
A02-09	The management station shall contain a R/C transmitter that allows the operator to manually operate the UAV when necessary		D
A02-10	The management station shall allow the operator to switch the UAV between autonomous mode and manual mode		D
C02-10.1	The management station shall show the current operation mode of the UAV (autonomous or manual)		T
C02-10.1	The management station shall allow the calibration of the R/C transmitter		
A02-11	The management station shall allow the UAV to upload the collected data during the operation after landing		T
A02-12	The management station shall allow the UAV to upload the flight data (location, motion status, flight log) during the operation after landing		T
A02-13	The management station shall process the collected data with the flight log file (e.g. tag the captured image with the GPS location) and upload the data to the CGCMT server		T
A02-14	The management station shall provide battery recharge capability to the UAV		T
C02-14.01	The management station shall detect the battery status after the UAV lands		T
C02-14.02	The management station autonomously recharge the onboard battery if the power is below operation level		T

F02-15	There shall be mobile management stations that can move between different locations at certain BART stations		D
	UAV system requirements		
A03-01	The UAV shall be capable of taking off from a management station and fly to a defined altitude	MA-01-03 MA-02-03 MA-03-03 MA-04-03 MA-05-03 MA-06-03 MA-07-03 SC-01-03 SC-02-03 SC-03-03 EM-01-03 EM-02-03 EM-03-03 EM-04-03	T
A03-02	The UAV shall be capable of landing on the landing pad of the management station		T
A03-03	The UAV shall be capable of stabilizing its attitudes (roll, pitch, yaw) autonomously		T
A03-04	The UAV shall be capable of flying to a given location defined by location or coordinates		T
A03-05	The UAV shall be capable of hovering within a small vicinity of a given location		T
A03-06	The UAV shall be capable of maintaining its altitude at the required accuracy		T
A03-07	The UAV shall be capable of changing its flying speed		T
A03-08	The UAV shall be capable of following the given trajectory/flight plan.		T
A03-09	The UAV shall carry the required sensor devices		T
A03-10	The UAV shall be capable of transmitting collected data and flight status information to the ground management station in real time		T
C03-10.01	The UAV shall transmit the flight status: • Attitude (roll, pitch, yaw) • Altitude • Speed (ground speed) • GPS location (lateral, longitudinal)		T
C03-10.02	The UAV shall transmit the collected data (video streaming, point clouds target image, etc.) in real time		T
C03-10.03	The UAV shall transmit real-time alert data to the station		T
A03-11	The UAV shall be capable of receiving the operation command send by the ground station and acting accordingly		T
A03-12	The UAV shall allow manual control by operators		T
A03-13	The UAV shall be capable of avoiding obstacles during the flight.		T

Table 4-5 Scenario-specific Functional Requirements

RQID.	Requirements	Traceability [2]	Verification Methods
	Scenario-specific function requirements		
	CGCMT Scenario-specific function requirements		
A04-01	The CGCMT shall receive the track intrusion alert from the management station and get the location of the event	SC-S1-01	T
A04-02	The CGCMT shall receive the real-time report data of the criminal events	SC -S2-01	T
A04-03	The CGCMT shall receive the real-time assessment data of the unidentified package	SC -S3-01	T
A04-04	The CGCMT shall be capable of re-planning the track inspection mission based on the mission progress and task effectiveness of each vehicle	MA-S4-01	T
A04-05	The CGCMT shall receive the alert on the hazardous track situations	MA-S4-02	T
A04-06	The CGCMT shall obtain the location information of the hazardous track situations	MA-S4-03	T
F04-06	The CGCMT shall generate a map of the track status of the overall BART system after the accomplishment of the track inspection mission	MA-S4-04	T
F04-07	The CGCMT shall obtain the location information of the hazardous internal track flaws	MA-S5-01	T
F04-08	The CGCMT shall generate a map of the internal track status of the overall BART system after the accomplishment of the track inspection mission by the rail-based vehicles	MA-S5-02	T
F04-09	The CGCMT shall receive the alert on the hazardous air quality situations (potential gas leaks or oil spills)	MA-S6-01	T
F04-10	The CGCMT shall obtain the location information of the hazardous air quality	MA-S6-02	T

[2] The traceability numbering corresponds the requirements to the specific scenarios: SE- Security scenarios, MA-maintenance scenarios, EM- emergency scenarios; S#- Scenario number #

	situations.		
F04-11	The CGCMT shall generate a representative map of the air quality along the overall BART system after the accomplishment of the track inspection mission	MA-S6-03	T
A04-12	The CGCMT shall collect the image and point cloud data of the construction sites uploaded by the management station	MA-S8-01	T
F04-13	The CGCMT shall generate a model of the construction sites by matching and merging the point cloud data	MA-S8-02	T
F04-14	The CGCMT shall generate progress reports by comparing the models of different dates	MA-S7-04	D
A04-15	The CGCMT shall be capable of loading and activating an emergency flight mission based on the status of the UAV@BART system of each station	EM-S11-04	T
F04-16	The CGCMT shall generate evacuation plans for civilians based on the data transmitted by the UAV stations (emergency event and location, structural damage and location)	EM -S11-04	T
F04-17	The CGCMT shall transmit the evacuation plan to the BART personnel of the stations	EM -S11-05	T
F04-18	The CGCMT shall generate a complete map of the damage situations of the overall BART system based on the data uploaded by the UAV stations	EM -S11-05	T
F04-19	The CGCMT shall receive the real-time report data of the train derailment events	EM -S12-01	T
F04-20	The CGCMT shall generate the courses of emergency actions based on the data of the train derailment collected by the UAVs	EM -S12-02	T
F04-21	The CGCMT shall archive the collected data of the derailment events and generate reports on the events	EM -S12-03	T
F04-22	The CGCMT shall receive the real-time report data of the fire events.	EM -S13-01	T
	UAV Management Station Scenario-specific function requirements		
F05-01	The UAV management station shall estimate the location of criminals and civilians based on the video streaming and image transmitted by the UAVs	SC-S1-02	T

F05-02	The UAV management station shall process the data of unidentified package collected by the UAV and output the following information: • Location of the package • Size of the package • Whether it is explosive • Whether it contains hazardous chemicals	SC -S3-02	T
A05-03	The UAV management station shall tag the data (images) collected by the UAVs with geographical information	EM -S4-05	T
A05-04	The UAV management station shall provide the information of hazardous events on tracks via the GUI	EM -S4-06	T
C05-04.01	The information of hazardous events on tracks shall include the following items: • Location of the events • Image of the events • Category of the events (external flaws, intrusions, potential internal flaws) • Hazardous level of the events	EM -S4-07	T
A05-05	The UAV management station shall provide the information of potential internal track flaws via the GUI	EM -S5-03	T
A05-06	The UAV management station shall tag the air quality data collected by the UAVs with geographical information	MA-S6-04	T
A05-07	The UAV management station shall provide the information of hazardous air quality events on tracks via the GUI	MA-S6-05	T
C05-07.01	The information of hazardous air quality events on tracks shall include the following items: • Location of the events • Scope of the events • Category of the events (gas leaks, heavy smoke, oil spills) • Hazardous level of the events	MA-S6-06	T
A05-08	The UAV management station shall tag the image and point cloud data of the construction sites with geographical information	MA-S8-03	T
A05-09	The UAV management station shall process the image data collected by the UAVs during the worker safety evaluation tasks, and	MA-S9-01	T

	identify potential hazards		
C05-09.01	The UAV management station shall provide the following information on the potential hazards via the GUI: • Location • Hazard categories • Hazardous level	MA-S9-02	T
A05-10	The UAV management station shall generate a model of the infrastructure based on the images or laser point cloud data captured by the UAVs	MA-S10-01	T
C05-10.01	The model of the infrastructure shall be one of the flowing categories: • 3D structure model • 3D terrain model • Merged 2D image	MA-S10-02	T
A05-11	The UAV management station shall identify the damages of the structure including cracks, collapses, missing components and debris	MA-S10-03	T
A05-12	The UAV management station shall identify the damages of the BART system caused by earthquakes, using the data collected by the UAVs	EM-S11-04	T
C05-12.01	The UAV management station shall identify damages of infrastructures caused by earthquakes	EM -S11-05	T
C05-12.02	The UAV management station shall identify damages of tracks caused by earthquakes (slip sites, track deviations, track fractures)	EM -S11-06	T
A05-13	The UAV management station shall generate a map of damages on the corresponding portion of the BART system	EM -S11-07	T
F05-14	The UAV management station shall show the location of the fire and the scope of affected area via GUI	EM -S13-02	D
F05-15	The UAV management station shall show he location of the oil or chemical spills and the scope of affected area via GUI.	EM -S14-01	D
	UAV Scenario-specific function requirements		
A06-01	The UAV shall be capable of identifying unauthorized objects on the BART tracks	SC-S1-03	T
C06-01.01	The UAV shall send alert to the management station if unauthorized objects are identified	SC -S1-04	T

A06-02	The UAV shall be capable of identifying potential explosives or hazardous chemicals of unidentified packages	SC -S3-03	T
A06-03	The UAV shall be capable of identifying tracks and sleepers from the images	MA-S4-08	T
A06-04	The UAV shall be capable of identifying the following track defects: • Defecting cracks on the sleepers • Missing bolts • Bends on the rail tacks	MA-S4-09	T
A06-05	The UAV shall be capable of evaluating the hazard level of the track defects	MA-S4-10	T
C06-05.01	The UAV shall send alert to the management station if the track defects may harm the operations of the BART system	MA-S4-11	T
A06-06	The UAV shall be capable of identifying debris, objects or persons that enter the rail	MA-S4-12	T
C06-05.01	The UAV shall send alert to the management station if the track intrusions or debris may harm the operations of the BART system	MA-S4-13	T
A06-07	The rail-based vehicles shall be capable of identifying internal track flaws	MA-S5-01	T
A06-08	The rail-based vehicles shall send alert to the management station if the internal flaws may harm the operations of the BART system	MA-S5-02	T
F06-09	The UAV shall be capable of detecting the ammonia (NH_3), nitrogen oxides (NOx), benzene, smoke, CO_2 and other harmful or poisonous gases that impact air quality	MA-S6-07	T
C06-09.01	The UAV shall send alert to the management station if an air quality abnormality is detected	MA-S6-08	T
A06-10	The onboard camera of the UAV shall allow operators to manually control its orientation and set zoom, focus and shutter release if necessary	MA-S10-04	T
A06-11	The UAV shall provide lighting and adjust the lighting level if necessary	MA-S10-05	T
A06-12	The UAV shall be capable of identifying smoke in the BART system	EM-S13-03	T
A06-13	The UAV shall be capable of identifying oil and chemical spills along the BART system.	EM-S14-02	T

4.6 Data Requirements

The requirements listed in the table 4-6 include the UAV@BART data elements that are acquired, processed, shared, and used by the components of the UAV@BART system.

Table 4-6 Data Requirements

RQID.	Data Element Name	Data items	Data Source	Data Description	Verify method
UAV Data Requirements					
A07-01	Flight plans	Waypoints	Management Station	Waypoint position	D
A07-02	Flight plans	Takeoff procedure	Management Station	Take of waypoints	D
A07-03	Flight Plans	Control command	Management Station	Flight mode Sensor commands	D
A07-04	Manual Control commands	Control command	R/C Transmitter	Control command	D
A07-05	Telemetry	Flight Time (Battery)	UAV	Number (minutes)	D
A07-06	Telemetry	Position	UAV	Latitude, Longitude	D
A07-07	Telemetry	Ground Speed	UAV	Km/h, m/s	D
A07-08	Telemetry	Heading	UAV	Degree	D
A07-09	Telemetry	FPV Footage	UAV	H.264 compressed video	D
A07-10	Post flight data	Flight log	UAV	Time-stamped flight status	D
CGCMT Data Requirements					
A07-11	Mission definition data	Mission type	operator	Inspection, Maintenance, Security	D
A07-12	Mission definition data	Sensor configuration	operator	Sensor combination and configuration	D
A07-13	UAV status	UAV status	UAV Management Station	Unengaged/engaged , Battery life availability	D
A07-14	Landing Pad Status	Power status	UAV Management	Charged, Power connected or Battery	D

			Station	level	
A07-15	Landing Pad Status	Network status	UAV Management Station	Network connection on/off, rate	D
A07-16	Landing Pad Status	Occupation status	UAV Management Station	UAV parked UAV left	D
Management Data Requirements					
A07-17	Alert information	Track defects and intrusions	UAV	Event location Event category	D
A07-18	Sensing data	Camera data	UAV	Images, H.264 compressed video	D
A07-19	Sensing data	LIDAR data	UAV	3D point clouds	D
A07-20	Sensing data	Air quality data	UAV	Geo-referenced air quality data	D
A07-21	Mission assignment information	Mission definition	CGCMT	Mission category Mission goal Destination location	D

4.7 Performance Requirements

Performance requirements specify the quantity measures that UAV@BART estimates, controls, monitors, collects, calculates, communicates and archives in the process of functioning and operating the system. The performance requirements of the UAV@BART system are listed in Table 4.7.

Table 4-7 Performance Requirements

RQID.	Requirements	Verification Methods
	UAV Performance Requirements	
	UAV localization accuracy	
A08-01	The UAV shall achieve a localization accuracy of < 0.2m if visual-aided navigation or differential GPS (DGPS) is utilized	T
A08-02	The UAV shall achieve a localization accuracy of <5m if localization, either based on pure GPS or other means while GPS is not available	T
	UAV hovering accuracy	
A08-03	The UAV shall be capable of hovering with a range of 0.2m× 0.2m in the position holding mode	T

	UAV altitude holding accuracy	
A08-04	The UAV shall be capable of maintaining its altitude within a range of 0.1m in the position holding mode	T
	UAV wind stability	
A08-05	The UAV shall be capable of maintaining its position and altitude accuracy in winds up to 12m/s	T
	UAV carriage capability	
A08-06	The UAV shall have a take-off weight of up to 3 kg	T
A08-07	The UAV shall be capable of carrying a payload of up to 1.5kg	T
	UAV trajectory following accuracy	
A08-08	The UAV shall be capable of navigating to the defined waypoints at an accuracy of 0.2m×0.2m	T
	UAV Flight Endurance	
A08-09	The UAV shall be capable of flying for up to 20min at one battery charge	T
	UAV sensing requirements	
A08-10	The onboard camera shall have of resolution of >12 megapixel	D
A08-11	The image from the camera shall achieve a sub-millimeter spatial resolution	D
A08-12	The onboard camera shall be capable of providing full-HD video (1080/50p)	D
A08-13	The onboard lens shall have a focal length from 4.3 to 200mm	D
	UAV data transmission rate	
A08-14	The UAV shall transmit data to the management station at a maximum rate of 300Mbps	D
A08-15	The UAV shall transmit data to the management station at a maximum range of 2 km	D
	UAV remote control range	
A08-16	The UAV shall be manually controlled by the R/C transmitter at a maximum distance of 2km	D
	Track inspection efficiency	
A08-17	The UAV fleet shall complete inspection of the entire track rails within 1 hour	T
	Management Station Performance Requirements	
A08-18	The model of the infrastructure generated by the management station shall have a resolution of <1m	T
	CGCMT Performance Requirements	
A07-19	Environment models shall have a resolution of less than 1m	T

5. System Design

In this section, the overall system architecture design is specified, and the detailed subsystems design are provided in terms of functional components and communication design. All component designs are based on the requirements definitions for system function and performances. There are two main approaches to implement the system. One is to use small UAVs with very limited endurance but installed on all stations, and the other is to use big UAVs with high endurance, but only install them on few stations. Each approach has its own advantage and the Bart decision makers will have to choose which approach to go ahead in the deployment. Both as explained here in this section.

5.1 Policies, Regulations, and Liabilities

The actual UAV regulation is new and it is still undergoing several changes. The context of this report does not completely align with the current regulation. As of the writing of this report, the FAA does not allow UAVs to fly autonomously or without visual line-of-sight. These two characteristics are necessary to deploy this system without unnecessarily increasing the number of operators. However, since the industry pressure shapes, we believe that the FAA will evolve to allow this kind of operation in the near future. Below are the actual FAA rules for UAVs.

Civil Operation:

- Section 333 exemption here: Used with COA, to perform operations in low-risk controlled environments
- Special Airworthiness Certificate (SAC): The users must be able to describe the manufacture, design, engineering processes, software/control, configuration management and quality assurance measures-- along with where we intend to fly
- SAC in the experimental category: Primarily given to civil aircraft for research purposes
- Part 107: Rules for non-hobbyist uses for UAVs weighing less than 55 lbs. It covers commercial uses.

In 2015, FAA developed a framework of regulations that would allow ‘routine use’ of UAVs by commercial operators. The framework was initially limited to drones weighting less than 55 lb (25 kg), flying no more than 500 ft (153 m) in attitude and only during day light hours, with line-of-sight maintained at all times, among other criteria that effectively limit testing to all but most of operations. Before the above framework is finalized, the FAA granted an interim broad airspace authorization as long as they limit their flying to an altitude of 200ft (61m) and two nautical miles from airports and heliports. In May 2015, FAA also allows PrecisionHawk and DNSF railway to test UAVs beyond line-of-sight for surveying purposes. FAA also announced that it allows CNN to test UAVs in densely urban areas for news gathering. These developments show promises for broader applications of UAVs.

5.2 UAV@BART System Architecture

The research team conducted a preliminary system design in order to further investigate the feasibility of the UAV@BART that will fulfill the requirement concept of operations described in previous sections. The proposed system architecture of UAV@BART is defined and depicted in Figure 3. In this view of the system, the UAV@BART consists of three major subsystems: the Centralized Ground Control and Monitoring Terminal (CGCMT), the UAV Management Station and the UAV. 1) The CGCMT is designed to be deployed in the BART operational center and is responsible for setting the mission-level goals and monitoring the system progress. 2) The UAV@BART contains multiple UAV Management Stations that are deployed in each BART station and. Each Management Station manages one or more UAVs and generates trajectories/flight plans based on task level assignments, it also performs monitoring and data receiving/processing tasks. 3) The UAVs carry onboard sensing and navigation payloads and perform data collection and inspection tasks based on the flight plan or operators' commands.

5.3 Design Dependencies and Standards

The protocols, standards and software libraries used in the system design are listed in Table 5-1:

Table 5-1 System Design dependencies and Standards

Category	Item	Description
Network Communication Protocol	Extensible Markup Language (XML)	Extensible Markup Language is used to provide data feeds to external systems
	Hypertext Transfer Protocol (HTTP)	Networking protocol for distributed, collaborative, hypermedia information systems utilized by web based applications.
	File Transfer Protocol (FTP)	Standard network protocol used to transfer files from one host to another host over a Transmission Control

		Protocol (TCP) - based network, such as the Internet.
	Hypertext Transfer Protocol Secure (HTTPS)	HTTPS is a combination of the Hypertext Transfer Protocol (HTTP) with Secure Sockets Layer (SSL)/Transport Layer Security (TLS) protocol to provide encrypted communication and identification of a secure network web server.
	Real-time transport protocol (RTP)	It is a network protocol to allow video to be broadcast in realtime with little overhead.
Data Link Protocol	WiFi 802.11n	Wireless local area networking standards for data transmission.
	MavLink	A serial protocol used to communicate with the UAV autopilot
	R/C control	Radio control for the remote manual control of UAVs, consisting of a transmitter and an onboard receiver
Video/Image compression standard	MPEG-4 Part 14	A container standard to store video and audio
	H.264	A video compression standard
Operating systems and software libraries	Robotic operation system (ROS)	An operating system/library that allows the communication with several sensors, actuators, and to control a network of UAVs.
	OpenCV	A programming library of functions mainly aimed at real-time computer vision
	APM Planner	Open-source ground station application for MAVlink with mission planning and monitoring capabilities

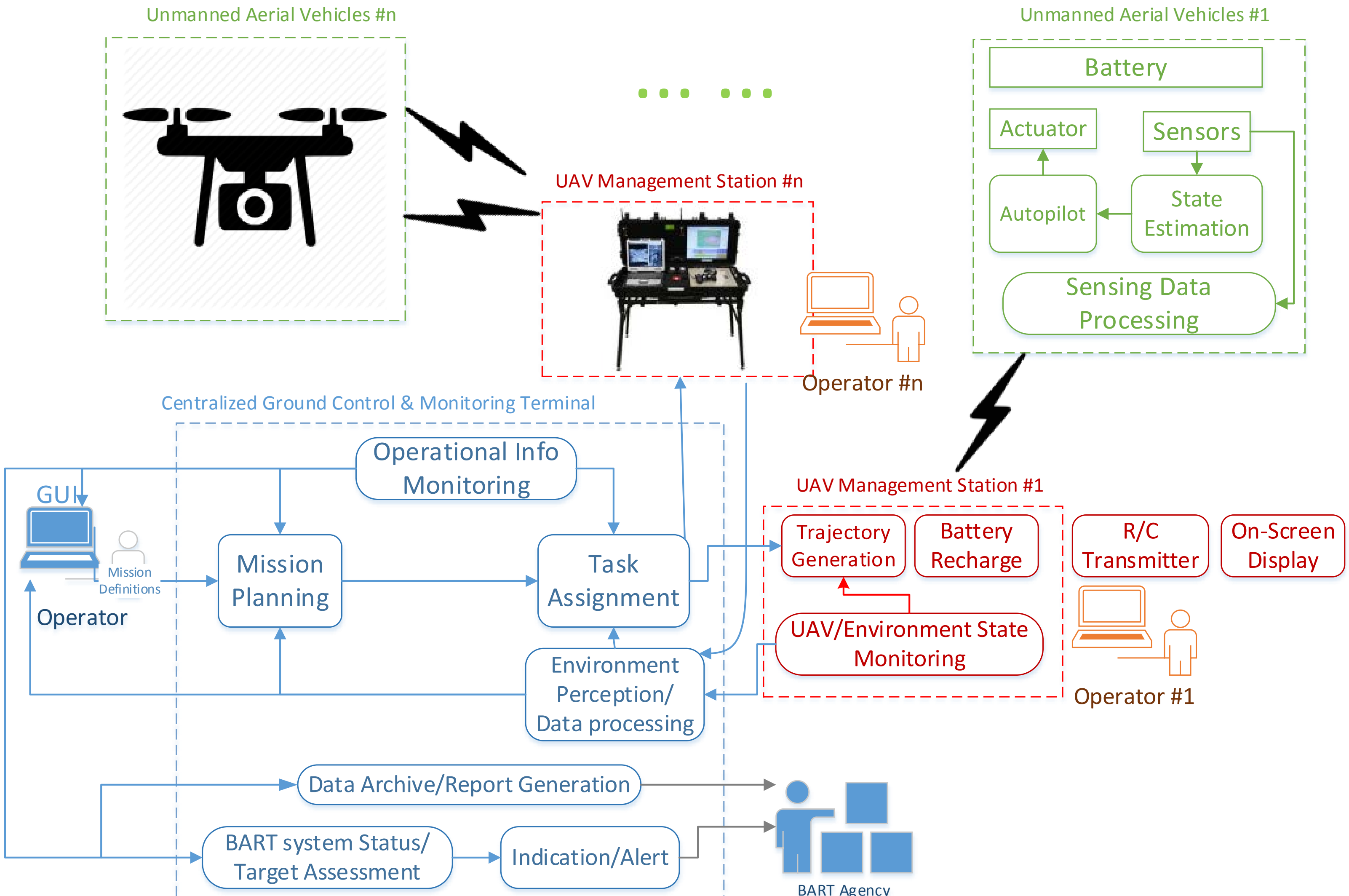


Figure 3 UAV@BART system architecture

5.4 UAV Subsystem Design

5.4.1 UAV Architecture Design

The proposed functional architecture of the UAV is depicted in Figure 4. The UAV subsystem contains all the subsystems that need to be equipped onboard the vehicle (Onboard computer, autopilot, onboard sensors, GPS, data link, actuators and R/C receiver).

- Onboard sensors. In order to implement the functionalities of application scenarios, the UAV carries various kinds of sensors that are connected to an onboard computer capable of real-time sensor measurement processing. The onboard sensors include: 1) cameras that capture images and video, 2) LIDAR that generate 3D point clouds, 3) air quality detector that detect compositions of air, 4) chemical detectors. Due to payload limitations of the UAV, each UAV will carry 1~2 kinds of sensors.
- Onboard computers. They are responsible for these onboard processing and estimation tasks: 1) measurement processing of images, LIDAR point clouds and air quality/chemical data, 2) detection of targets (rail track defects, objects, infrastructures and persons) based on sensor measurements, 3) position estimation by fusing the measurement of IMU, GPS, and other onboard sensors for detection and positioning (for tunnel operation).
- Autopilot. The flight plan from the management station and the control commands from operator will be processed by the autopilot for correctly adhering to the desired trajectory. It is also responsible for inner-loop attitude stabilization and control. The IMU units are also integrated in the autopilot.
- Data link. The short range high-speed WiFi connection are implemented between the UAV and the UAV management station to upload all collected data during the mission. Images, video streaming and point clouds will be transmitted to the ground in real-time for target monitoring manual control.
- R/C receiver. The standard R/C receiver will be equipped onboard the UAV to receive the flight commands from the ground management station or the R/C transmitter.

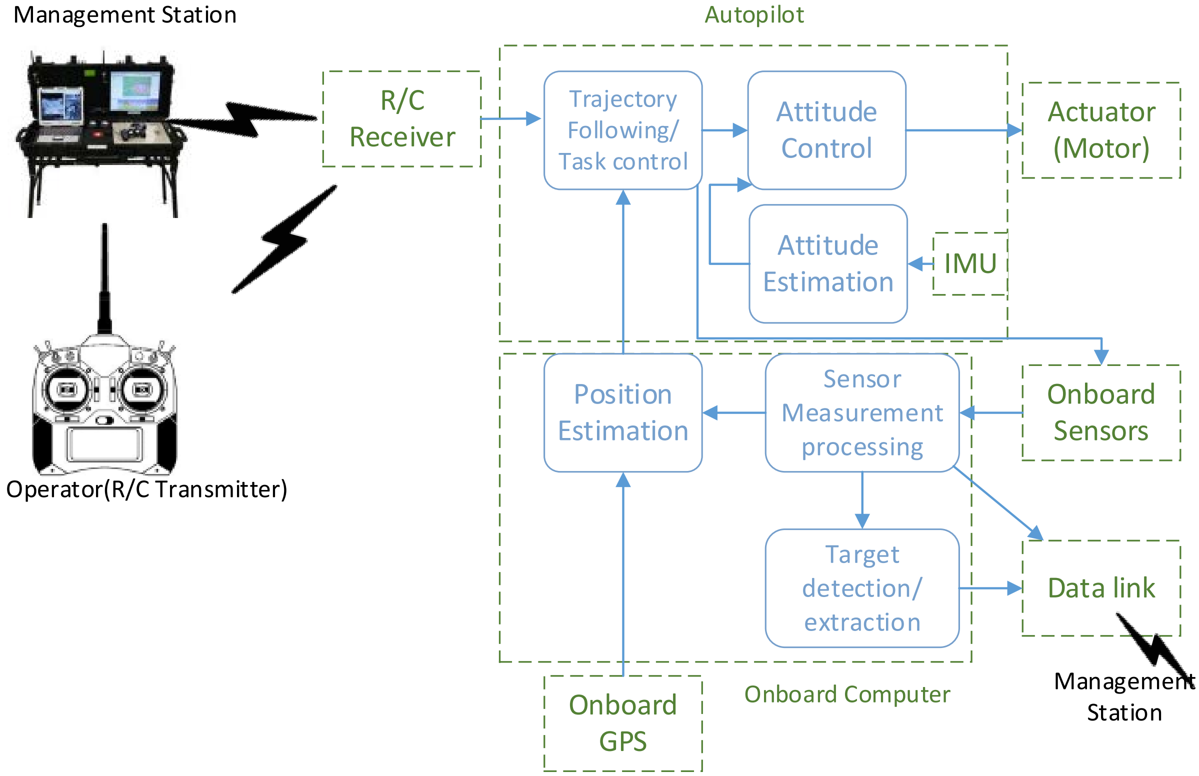


Figure 4 UAV architecture design

5.4.2 Communication Design

The details of the communication design of the UAV are listed in Table 5-2.

Table 5-2 Communication Design

No.	From End	To End	Communication Type
1	Management Station	R/C receiver	Standard R/C
2	R/C Transmitter	R/C receiver	Standard R/C
3	Onboard computer	Management Station	e.g., WiFi 802.11n or 915MHz radios

.

5.4.3 Functional Components Design

5.4.3.1 Functional Components

Below are the functional components listed that runs onboard the UAV:

- Flight/Plan Task processing - gets the information from GPS and the mission data to navigate the UAV to the specified waypoints
- Sensor measurements process - collects and process sensor measurements.

- Target detection - collects both images/point cloud data and detect targets/anomalies/event using computer vision and pattern recognition algorithms. Once an anomaly/event is detected, it will be registered with the position and marked as an anomaly/event, and an alert will be transmitted to the ground management station.

5.4.3.2 UAV Payloads

In order to perform the functions specified in the required scenarios, the onboard payload will include various sensing and communication units. Below is the list of components that are equipped on the UAV airframe:

- Air quality sensor
- Chemical sensor
- LIDAR
- Ultrasonic sensor array on the four sides and bottom to detect obstacles
- Bottom mounted 3-axis gimbaled camera
- First person view 1-axis gimbaled camera
- Onboard computer
- Wifi 802.11 ac radio
- 50 miles long range telemetry radio – Microhard n920
- HDMI transmitter

5.4.3.3 UAV Airframe

Considering the payloads required by the UAV@BART system and the operational limitations, only helicopters and multicopters are feasible for the applications of UAV@BART, since fix winds aircrafts requires much larger space for taking-off and landing. The potential candidate UAV airframes for the UAV@BART are shown in Figure 5:

a) DJI M600. The DJI M600 is an industrial specific UAV that allows for industrial applications and services. The M600 is capable of lifting up to 13 pounds and have a maximum flight duration (without payload) of 40 minutes. Its maximum speed can reach up to 40 mph.

b) Black Eagle 50. This vehicle made in Israel has a flying time of 3 hours, and a payload capacity of 6 pounds. Its dimensions are 2.3m in length, and a rotor of 2.15m in diameter.

c) Camcopter S-100. The Camcopter S-100, manufactured by an Austrian company Schiebel, is larger than the Black Eagle. It has 3.1m length and 3.4m rotor diameter. Its flight endurance can reach 10 hours with additional fuel tank and can lift up to 100 pounds of payload.


a) b)

c)

Figure 5 Candidate UAV airframes

While gas powered UAVs can fly for a longer period of time, they need to be refueled periodically. The electrical UAVs can be automatically charged wirelessly when landed, however they have very limited flight endurance. Therefore, if an electrical UAV is selected for implementation, multiple UAVs will have to be deployed throughout the system.

5.5 UAV Management Station design

5.5.1 UAV Management Station Architecture Design

The UAV Management Station is deployed in the BART station and acts as the primary interface between the operator, UAV and CGCMT. The functional architecture of the UAV management Station is depicted in Figure 6. The primary components of the management station include the management station computer, the landing pad and the manual control devices.

- Management station computer: The management station computer consists of GUI interface and functional modules. 1) The trajectories/flight plans are generated by the computer and sent to the UAVs before the activation of the tasks. 2) The GUI interface shows all the real-time information of status, a list of every anomaly/events detected by them, and the alerts send by the UAVs. This interface allows the operator to modify the flight plans and control the UAV flight modes. It also allows the operator to control the orientation and zoom of the onboard camera. 3) Several computation-consuming tasks are also performed on the management station computer, such tasks including environment/infrastructure modelling, mapping, and data geo-referencing. 4) This system is also responsible for generating and displaying flight mission reports. The reports are generated automatically after the mission, while the collected data and flight log is uploaded and processed.
- Landing pad: The landing pad is the component responsible for bridging the communication between the UAVs and BART network. It has a high-speed short-distance wireless connection with the UAVs for high bandwidth data transmissions, and also a long-range, low-bandwidth and low latency data link to get telemetry and navigation footage from the UAV. The landing pad is also responsible for recharging the onboard battery, and keep the management station computer updated with the actual UAV battery status (ready, recharging, maintenance required, etc.) For the same reason, the landing pad also has a LTE modem in case of connectivity loss with BART network. A small embedded computer keeps all the systems running and triggers an indication once a UAV is ready to take off or when it is landing.
- Manual Control devices: These devices include an R/C remote control transmitter and an on-screen display (OSD). The R/C remote control transmitter allows the operator to switch the flight mode from autonomous to manual, and transfer the manual operation into R/C commands that are sent to the autopilot. The OSD can show the real-time video streaming data transmitted by the UAV, which is required in certain operational scenarios.

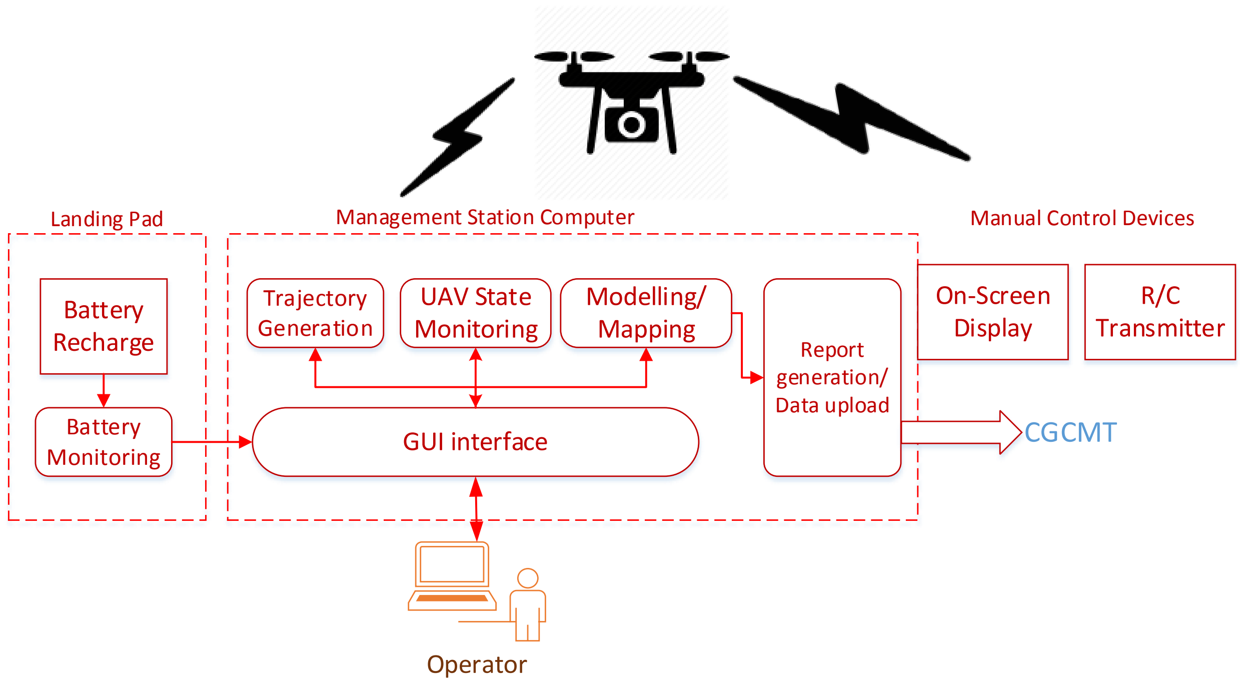


Figure 6 UAV Management Station Architecture Design

5.5.2 Communication Design

The details of the communication design of the UAV Management Station are listed in Table 5-3. The data transmission between the landing pads, the management station computer and the CGCMT are based on LAN networks. The data collected by the UAV are transmitted to the Management Station via WiFi or other communication types. In addition, The R/C remote control commands are sent via standard R/C and the video are transmitted to the OSD via video transmitter/receiver.

Table 5-3 Communication Design of UAV Management Stations

No.	From End	To End	Communication Type
1	UAV	Landing pad	WiFi 802.11n
2	Management station	CGCMT	LAN
3	Landing pad	Management station	LAN
4	UAV	OSD	5.8GHz video transmitter/receiver

5.5.3 Functional Components Design

1. UAV Management Station Processing Module Design

The management station computer consists of a series of functional modules for flight planning, data processing, environment modelling and mapping. The functional components of this subsystem are listed as follows:

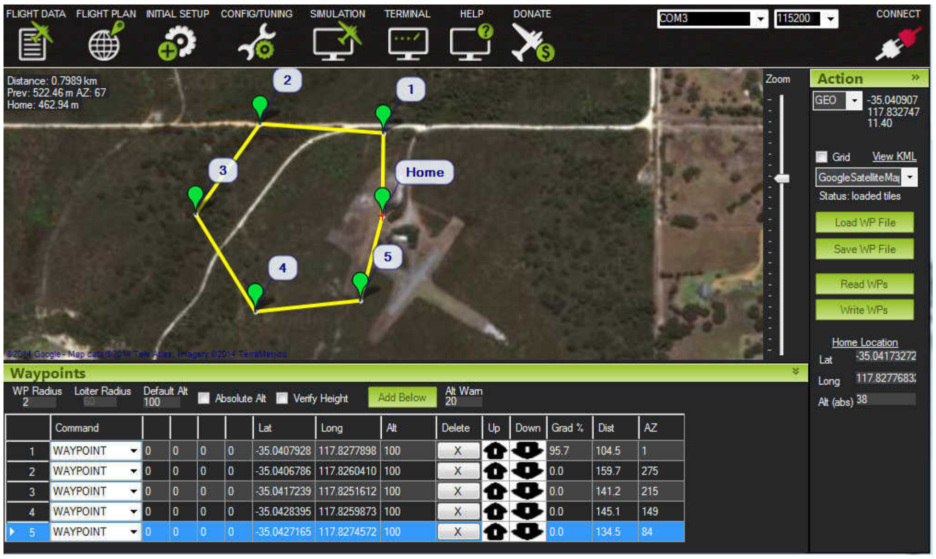
- Trajectories/flight plans generation – generates flight plans consisting of take-off, landing procedures, waypoints, and navigation commands
- Environment/infrastructure modelling, mapping, and data geo-referencing – generates 2D/3D models of the environments and track status/air quality maps based on the collected data
- Flight mission reports – generates reports based on flight log and collected sensing data.

2. Preliminary GUI design

The GUI of the UAV Management consists of the following elements:

- Flight plan lists that contain detailed information of waypoints and navigation commands
- Flight status display that shows the real-time attitude, speed, heading and altitude information of the UAV
- Alarms list showing all the system warnings, alerts and alarms
- UAV remote control showing live feed with telemetry data overlay of each UAV
- Map display showing UAVs and flight plan progress
- Report generator interface showing all anomalies detected

Examples of ground station GUI interfaces are shown in Figure 7.



a)

b)

Figure 7 Examples of Ground Station GUI

3. Landing Pad Design

The landing pad contains a mechanical structure to hold and support the UAV. LED lights and buzzer will be used for UAV status indication. In addition, the landing pad contains an embedded computer which receives data collected by the UAVs. The information is then forwarded to the management station computer. The components of the landing pad are listed as follows:

- 50 miles long range telemetry radio – Microhard n920
- Wifi router 802.11ac
- Local battery (UPS) for 4 hours of landing pad power
- 4g/LTE modem
- Single board computer – Odroid XU4 – Running the landing pad maintenance system with 128Gb of memory
- Wind and rain weather sensors
- UAV wireless charger
- Rigid platform
- Retractile hoof
- LED lights and buzzer

5.6 Centralized Ground Control and Monitoring Terminal Design

5.6.1 CGCMT Architecture Design

The functional architecture of the CGCMT subsystem is depicted in Figure 8. The CGCMT system is basically a central system running on a server which is accessible by BART operational agency. The operational agency can issue missions to be executed on demand or under a schedule. The CGCMT subsystem contains a mission database storing predefined missions for the operation scenarios, and a mission planning function module to allow new missions to be created. After a mission is selected, the CGCMT system selects available UAVs capable of executing the mission and assign the tasks to the associated management station. In addition, pre-defined missions can be loaded automatically from the mission database. The operational information monitoring model receives updated status of all UAVs and monitors the mission progress. If one or more UAVs are considered to be ineffective to accomplish the task, the CGCMT will re-plan the mission based on the evaluation of current system status.

This system is also responsible for generate and display reports. After the operator defines the mission, s/he selects the kinds of report s/he is expecting. The reports are generated automatically after the mission when the UAV data is upload and processed. The stakeholder can also decide to generate new reports based on the previous data received from management stations. In addition, operational alerts and response plan can be generated by the CGCMT in the cases of emergency (fire, earthquake and train derailment), and the complete map of system status can be generated for determine the evacuation plan.

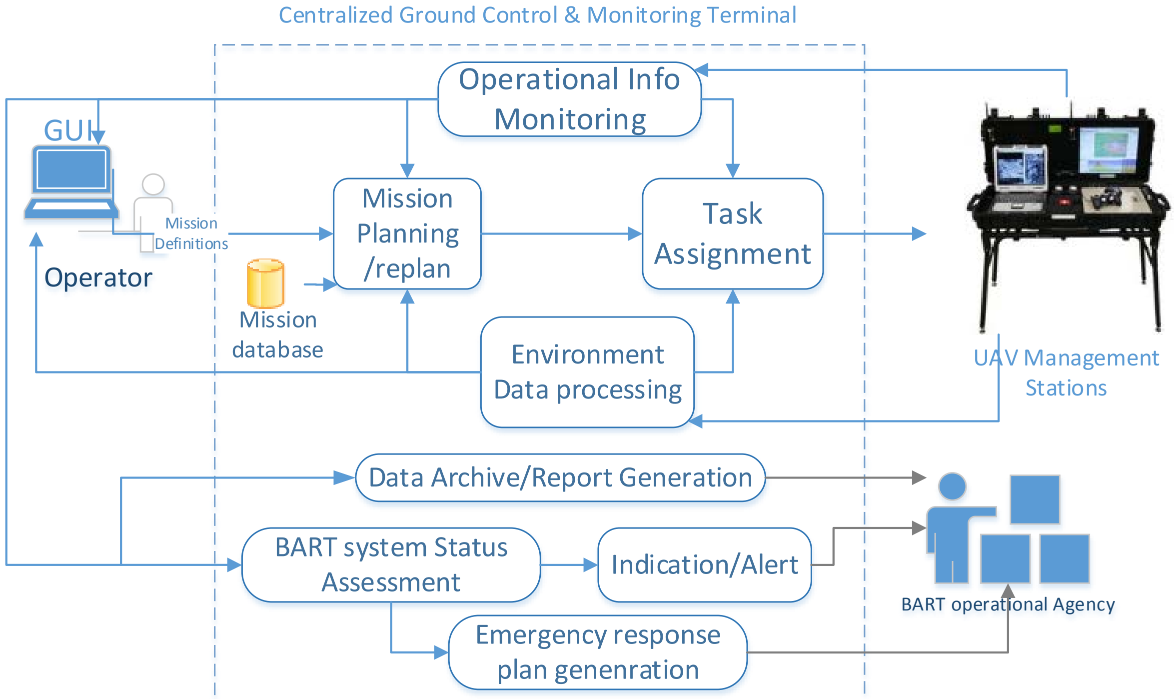


Figure 8 CGCMT architecture design

5.6.2 Communication Design

The CGCMT mainly communicates with the UAV management stations via dedicated LAN, as listed in Table 5-4.

Table 5-4 Communication Design of the CGCMT

No.	From End	To End	Communication Type
1	CGCMT	UAV management station	LAN
2	UAV management station	CGCMT	LAN

5.6.3 Functional Components Design

The primary components of the CGCMT subsystem are listed below:

- Mission database that stores pre-defined missions associated with operational scenarios
- Mission definition page/GUI which supports the creation of new missions
- Task assignment module that assign the tasks to feasible UAVs

- System operational information page that shows the current status of UAVs, mission progress and overall system status
- Alert/Indication display that shows alert when system defects (track defects, intrusions) and emergency events (train derailment, fire, air quality abnormality) are discovered
- System status evaluation that generates a complete system status map (track integrity map, air quality map, track internal status map)
- Emergency response plan generation that determines the optimal sequences of action in cases of emergency
- Report generation that creates and archives mission reports based on data collected during the mission.

Potential candidates for the CGCMT server include:

- Web Server cluster - 2x Dell PowerEdge R730
- Database server cluster - 2x Dell PowerEdge R730xd

5.7 System Operational Sequence Design

The operational flow for the UAV@BART architecture is designed to be as straightforward as possible. First, the operators (maintenance, emergency and security) should define the mission schedule using UAV CGCMT planning system. For example, track inspection first has the operators define the part of the track that needs to be inspected and the status information that needs to be collected (visual, thermal, debris, damage, etc). This definition will create a mission that will be saved for future reuse. After the mission is created, the operators should define the schedule and repeatability of the mission. This scheduling process is a similar process to a calendar event creation, where the operators chooses the day and time and the period of repetition. For instance, if the maintenance team wants a track segment to be inspected for debris every week on Sundays at midnight, the team can create a mission for this track segment, select the beginning and the end points of the track segment in question, and then choose which high definition camera to use from the onboard sensor check list. After that, the operators should define the execution time schedule, in this case Sundays at midnight weekly. In addition to scheduled events, a mission can be executed on demand. For instance, a mission can be carried out in case of emergency or if closer-look inspection is required after an inspection report.

The CGCMT analyzes the segment of the track contained in the mission and selects the UAVs available that can execute segment of the mission. Now the mission is broken down into tasks to be executed by each individual UAV. These tasks are further transformed into flight plans that contain the waypoints the UAV needs to flyover and the sensor to be used. They are transmitted to each selected UAV pad and loaded into the UAV. When the scheduled time is reached, the UAV takes off and flies towards the waypoints to collect the data. After completing all flight plans, the UAV goes back to its landing pad to land, recharges the battery and uploads all collected data. The UAV has onboard video and sensor processing capability that allows the UAV to perform basic signal and image processing to detect events in real-time and inform the ground station. More complex processing is executed offline in the management station server cluster after the UAV lands and uploads the data.

All data collected by the UAV is sent to CGCMT. The real-time information is displayed to an operator via the CGCMT interface, and the reports are generated after the accomplishment of the mission. The mission report contains the point-of-interest detected during the inspection for further action by the operator.

6. Deployment Plan

Through the analysis of needs and operation scenarios of UAV@BART, the development of functional requirements, and the investigation of system design options, the PATH study team has concluded that UAV@BART has significant application values and is feasible for deployment. BART can become an early adopter of UAV for routine inspection of the rail system. The study team outlines a five step deployment plan for UAV@BART. Given the state of policy, regulations and technologies, it is recommended that BART take an incremental approach to validate the feasibility of UAV@BART through a field testing and demonstration project. The more detailed work plan for the testing and demonstration project is also developed.

6.1 Deployment steps

The deployment of the UAV@BART system include the following steps:

- **Phase 1**: Field testing of prototype system. The field testing includes a series of testing that verifies the system functions, including the UAV, management stations and the centralized control and monitor server and sensing/detections functions that are necessary for completing operation scenarios. Through these tests, the system functional and performance requirements will also be verified.
- **Phase 2**: Deployment and demonstration in selected stations. The prototype system will be deployed in several selected stations (including underground stations, open-air stations, underground tracks and open-air tracks). A demonstration project will be conducted to verify the system functions in selected simulated operation scenarios (track inspection, infrastructure inspection, air quality monitoring etc.)
- **Phase 3**: Testing and evaluation of complete operational scenarios. The prototype will be tested in all prescribed operational scenarios including maintenance, security and emergency (The system can be tested in simulated security and emergency scenarios). The data generated by the testing and demonstration will be collected for further evaluation.
- A comprehensive evaluation will be conducted by an independent third-party. The system will be evaluated in terms of system performance measurements, operational safety and potential improvements in BART operational efficiency.

- **Phase 4**: Full deployment in the entire BART system. The UAV@BART system will be fully deployed in the entire BART after the system evaluation. A demonstration period may be included to further evaluate the system performance in actual BART operations.

6.2 Cost Analysis

In order to analyze the costs of the deployment of UAV@BART, two different implementation methods were analyzed. The first is implementing smaller UAVs at each BART station, and the second is implementing bigger UAVs at selected stations. The primary impact of changing the UAV's size is the cost and the physical specs of landing pads. For both methods, the management station facility costs are the same since the ground control station and CGCMT are the same.

- Ground-based servers and licenses: $500k

For the first method, we considered one UAV and one landing pad per station. The small UAV can take off and land in a small landing pad, and is driven by battery. So the power and structural requirements for this landing pad are a regular 110v 10a power connection and a hard 4 square meters square plate fixed in the station hoof. All the landing pad equipment (Wi-Fi router, telemetry radio, control board) will be installed in a weather resistant NEMA box, and the landing pad will have a retractable cover to protect the UAV from the rain. The cost of potential UAV prototype and facilities are as follows.

- Facilities on each station - UAV pad ~$5k, UAV ~$10k, installation service ~ $10k
- Approx. total costs (45 stations x $25k) + $500k ground-based servers and license = $1.625M
- Spare parts
- Staff labor - maintenance team (one van, 3 people), 2x pilots for 24/7 operation

For the second method, the UAV will need a bigger clearance area. Since it will be powered by gas, it will be heavier and it will require more maintenance and spare parts. Extra safety devices can be installed in the UAV to improve overall safety. The landing pad size needs to be 25 square meters to provide clearance of the propellers, and each landing pad needs a fuel container and a logistic procedure to refuel the vehicle and the fuel container after each flight. The estimated costs are listed as follows:

- Facilities on few station - UAV pad ~$40k, UAV ~$150k, installation service ~ $10k
- Approx. total costs (7 stations x 200k) + $500k IT servers and license = $1.9M
- Spare parts
- Human labor - maintenance team (one van, 3 people), pilots for 24/7 operation

In addition to the cost factors, the level of complexity for obtaining operational license for operating larger UAVs may be significantly higher than that for smaller drones.

6.3 A Field Testing and Demonstration Project

The PATH study team recommends that the deployment of the UAV@BART system be first started with a testing and demonstration project. The primary goal of the testing and demonstration project will focus on the proof of concepts, verification of functional designs and feasibilities of UAV for BART specific applications.

6.3.1 Scope of the project

The testing and demonstration project consists of the following tasks:

- Development and testing of prototype system. The major system components including the UAV, the management station and CGCMT the will be developed and tested separately. The basic functions of each subsystem and component will be implemented and tested.
- Deployment of UAV in selected BART stations. The prototype system with basic configurations (one UAV with one associated ground station) will be installed in selected stations.
- Field testing and demonstration of fundamental system functions. The prototype system will be tested in the BART stations and a series of basic testing will be conducted to verify the fundamental system functions such as the autonomous flight planning, autonomous taking off and landing of the UAVs, data collected and transmission, etc.
- Demonstration of selected operational scenarios. Several selected scenarios (track inspection, infrastructure inspection, manual-controlled monitoring) will be used for demonstrations.

6.3.2 Application of local operational permits and exemption/variance of FAA regulations

Since the deployment of the UAV-based system involves testing and operations of UAVs in urban areas, BART needs to apply for certificates and exemptions of regulations from FAA, as well as to obtain operational permits from local administrations. The required certificates/exemptions may include:

1) Certificates/exemptions of FAA regulations

- **Section 333 exemption**: Since UAV@BART system will be testing UAV's outside of direct visual contact with their operator, the 333 exemption is required (used with COA) to perform limited UAV operations in low-risk controlled environments
- **Special Airworthiness Certificate (SAC)**: It is required that the stakeholder shall provide detailed information on the UAV, including the manufacturer, UAV design, engineering processes, software/control, configurations, management and quality assurance measures, as well as the areas that the UAV will operate within.
- **SAC in the experimental category**: This SAC is granted to the utilization of civil aircraft for research purposes, and it will be used in the prototype development and initial testing phase.
- **Small UAS Regulations (Part 107)**: Part 107 contains regulations for non-hobbyist uses for UAVs weighing less than 55 lbs. and also covers commercial uses. Since flying a UAV under a covered structure or over a person are prohibited by the regulations, waivers should requested by the stakeholders and developers for the operations in certain scenarios (underground BART station inspection, criminal inspection, etc.). In addition, pilot certifications should be requested by the stakeholders for the UAV operators during initial testing, according to Part 107 regulations

2) Variance of regulations from state and local administrations

Local regulations on the use of UAVs in the SF Bay Area are listed as follows:

- Berkeley: PROCLAIM BERKELEY A NO DRONE ZONE AND ENACT AN ORDINANCE TO THAT EFFECT: "NOW THEREFORE BE IT RESOLVED by the Council of the City of Berkeley that the City of Berkeley, with this Resolution and by Proclamation proclaims Berkeley a No Drone Zone, and instructs the City Attorney to perform the necessary legal tasks to transform this declaration of a No Drone Zone into an Ordinance for the City of Berkeley wherein drones are hereby banned from airspace over the City of Berkeley, including drones in transit.

- Daly City: Daly City Code 12.36.050: “No person, group or organization in any park or recreational area shall . . . P. Use unmanned aircraft systems (drones) of any size.”

Therefore, waivers or variance of regulation may be needed for the testing and deployment of UAVs in the above cities as the UAV may be deployed at the BART stations and facilities locate at Berkeley and Daily City.

7. Summary and Recommendations

This study reveals that the UAV technology can support a wide range of scenarios for maintenance, operation and emergency responses, offering significant benefits over standard manual inspections. Through development of functional requirements and investigation of design options, the study shows that a low cost UAV-based architecture with various sensing payloads is capable of fulfilling the requirements of various operational scenarios of the BART system. The study concluded that the deployment of a UAV for routine inspection of the rail system as well as rapid assessment of the rail system in the event of emergency applications for the BART system is achievable with reasonable cost. The implementation of UAVs for the BART system has the potential to reduce human labors in the inspection and monitoring tasks, improve operational efficiency and personnel life safety, and to facilitate quick emergency response and post disaster reconnaissance/recovery.

Based on the current state of the policy, regulations and technologies, a phased deployment approach is recommended. This approach ensures the stakeholder to have a comprehensive understanding of the technical feasibilities, benefits and deployment constraints. The study team recommends to divide the deployment of UAV@BART into four phases, including (1) development and field testing of prototype system, (2) deployment of UAV at selected stations, (3) field testing and evaluation of complete operational scenarios, and (4) full deployment of UAV based inspection and monitoring technology. The study team further recommends, as the first step in the deployment path, a prototype UAV system is to be developed, proof-of-concept tested and demonstrated. While conducting field testing of UAV system, a comprehensive evaluation of the UAV@BART to assess system performance, safety, and cost-benefits. As FAA regulations require that the UAV shall be operated within the line-of-sight of certificated operators, a variance needs to be applied for testing out of line-of-sight. BART also needs to work with stakeholder cities where BART stations are located and rails passes to obtain consent and permits for UAV@BART.