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Resilience Through **Community Engagement** and **Technology**

Unmanned Aerial Vehicle (UAV) Flight Strategies for Post-Earthquake Inspections

J. Driscoll¹, E. Lo¹, T. Norton¹, R. Ji², T.C. Hutchinson³, N. Driscoll⁴ and F. Kuester³

ABSTRACT

The collection of structural health data is paramount to assuring public safety. Fortunately, the proliferation of small unmanned aerial vehicles (UAVs) is creating opportunities for rapid collection of time sensitive data before, after, and during extreme events such as earthquakes and fires. Careful UAV sensor platform selection and survey task planning as a function of the desired data products is needed, as it allows for strategic resource allocation. Often, low-cost consumer-level platforms are perfectly adequate in post-disaster reconnaissance, even when compared to high end enterprise-grade UAVs. Automated flight plans and autonomous flight executions anchored by real-time kinematic (RTK) positioning support repeatable large area surveys. Derivative data products such as point-based 3D models, backed by high resolution image collections with a ground sampling distance (GSD) of millimeters, allow for detailed damage assessment from individual structures to entire city blocks. This study offers a best practice strategy for collecting high resolution imagery of a single structure, while alluding to performance implications when deploying lower cost UAV-based sensor platforms. A full-scale 10-story cold-formed steel building tested in a laboratory setting under earthquake and fire scenarios was used as the testbed.

Introduction

Capturing damage data following natural hazards with a high level of detail is critical, as such data is inherently perishable. Advancements in unmanned aerial vehicles (UAVs) have allowed their utility as a powerful tool for post-hazard reconnaissance, enabling the collection of imagery and other data assets across large areas, or for detailed inspection of individual structures. Their autonomy allows access to sites where accessibility and safety concerns preclude traditional inspection methods. The resulting data products range from inspection photographs to detailed 3D reconstructions generated through photogrammetry. Notable examples include the collection of high-resolution and high-overlap post-earthquake imagery, which have enabled detailed reconstruction of damaged structures. Lo et al. [1] performed photogrammetric survey flights of a 10-story mass-timber building specimen during a shake table test program using an enterprise-grade UAV, achieving a ground sample distance (GSD) of 1 mm/pixel, sufficient to observe damage in a digital twin. Similarly, Yu et al. [2] demonstrates that at a 5-meter standoff distance with a consumer-level UAV achieves a 1.4 mm GSD and allows algorithmic detection of cracks in their 3D reconstruction. Collection of higher resolution data generally allows for detection of smaller scale damage when analyzing post-earthquake data but requires more

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flight time. Flight time can be minimized by optimizing the appropriate standoff distance to acquire a target GSD [3]. However, while studies thus far have focused on individual structures after real world events, a larger format survey is often required. At larger scales, UAV-based post-earthquake surveys are instrumental in preserving time-sensitive structural damage data over wide-reaching areas, where GSD becomes less important when compared to area surveyed. Calantropio et al. [4] proposed a lawnmower-style survey pattern to cover neighborhood-scale areas at an altitude of 100 meters with a GSD of 3-7 cm. Surveys with this methodology have also been operated in post-earthquake reconnaissance [5]. Ultimately, the resolution and quality of UAV surveys depend on both flight path and camera system performance [6]. This paper presents a case study of a suite of UAV-based surveys conducted during the shake table test program of a full-scale 10-story cold-formed steel (CFS) building conducted at the 6 Degree-of-Freedom Large High-Performance Outdoor Shake Table (LHPOST6) at UC San Diego [7]. The study highlights the efficiency of the implemented data collection strategies, the resolution of the photogrammetric reconstruction, and the high quality for the overall inspection.

Methodology

CFS10 Testbed Environment

UAV flight path planning strategies for post-earthquake inspection were developed and evaluated in the context of simulated earthquake tests on a full-scale 10-story cold-formed steel (CFS) building, coined CFS10 [8,9]. The CFS10 project explores modular CFS construction beyond current structural design code limits. The specimen was designed as a representative slice of a typical CFS framed residential structure, standing 31.6 m tall with a uniform floor plan dimensioned at 11.6 m $\times$ 6.9 m. In addition to the load bearing CFS studs and shear walls, the building was detailed with various nonstructural components including a stucco-based exterior insulation and finishing system (EIFS) on the north side of the building [8]. The specimen was subjected to 18 multi-directional earthquake tests scaled to various hazard levels [10], followed by two live fire compartment experiments [9]. The 18 earthquakes were conducted across seven active days of testing.

Platforms

Three quadrotor UAV models were used for these surveys, representing three categories of UAVs that could be used in post-hazard operations. Specifications for the UAVs are provided in Table 1. Both enterprise-grade UAVs feature real time kinematic (RTK) global navigation satellite systems (GNSS) allowing for centimeter level georeferencing of image data collected.

Table 1. UAV specifications.

UAV	Weight (grams)	Endurance (minutes)	Camera (megapixels)	Price (USD)
Mini consumer	249	34	48	<\$1,000
Small enterprise	915	45	20	<\$5,000
Medium enterprise	6300	55	45	~\$20,000

Each of these UAVs were employed throughout the CFS10 project to capture and aid in categorizing damage, while inspecting the specimen. The UAVs were selected for different flight tasks based on their capabilities. Table 2 below includes average flight statistics.

Table 2. Flight statistics.

Platform	Images	GSD	Collection Time	Region Covered
Small UAV	950	11.4 mm	21 minutes	243 $\times$ 278m (Entire site)
Medium UAV	2,400	0.9 mm	63 minutes	Entire CFS10 Structure
Medium UAV (close)	1,700	0.4 mm	60 minutes	North and east façade floors 6&7
Mini UAV	200	0.9 mm	60-90 minutes	North façade

Large Scale Area Survey

To capture imagery of the CFS10 building within the broader context of the entire test site, large area surveys were conducted after each day of testing. For these the small enterprise UAV was flown at an altitude of 40

meters in a double lawnmower pattern over the site, see Fig. 1A. Flights were planned using a “smart oblique” feature, which automatically flies a double lawnmower flight plan while actuating the gimbal between forward looking, nadir, and rear looking to provide oblique images. While flights for ortho-imagery only require nadir facing images, the addition of oblique images in the lawnmower pattern allow better reconstruction of building facades. This type of survey is applicable to gross damage detection over city block sized regions.

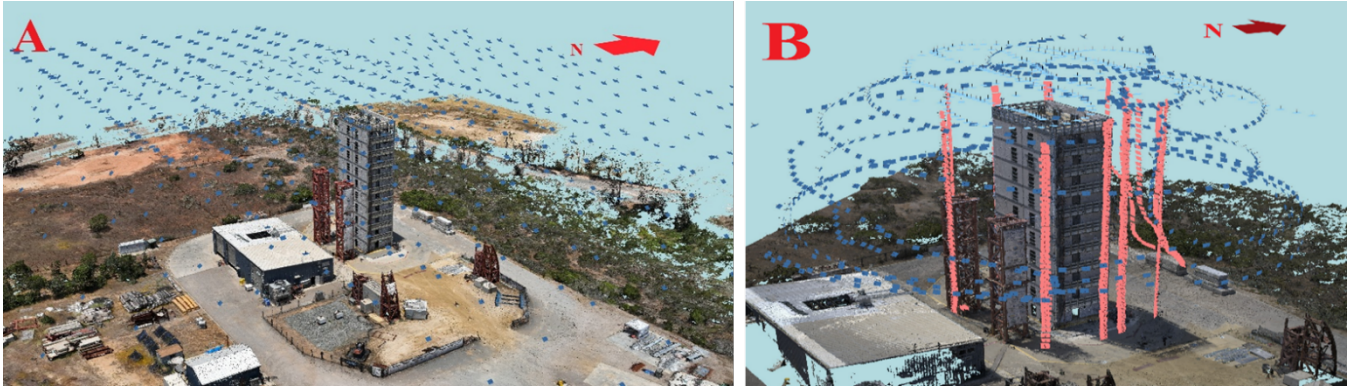


Figure 1. (A) Site-wide lawnmower flight pattern, blue squares represent instances of image capture. (B) High resolution single structure flight plan. Red squares represent the vertical lawnmower images, light blue squares the horizontal lawnmower images, and dark blue the oblique images.

High Resolution Single Structure Image Acquisition

To collect imagery for damage detection and photogrammetric reconstruction, a medium sized enterprise-grade UAV was used to collect thousands of high-resolution images. Due to the verticality of the structure, expected damage to the facades, and the desired 1 mm/pixel ground sample distance (GSD), manual flights were necessary. The flights included a traditional horizontal lawnmower to capture the roof and vertical lawnmowers 4-6 meters away from each façade targeting 80% along track and 70% cross track overlap. Following these patterns, circles were flown around the building to capture more oblique images improving 3D model reconstruction. Fig. 1B displays a projection of the flight plan surrounding the subsequently created 3D model. Additional flights with the medium UAV were conducted following fire testing as deformations were visible on the north facade of the structure within the exterior facade. These flights were conducted at a 2-meter standoff distance from the façade yielded a GSD of 0.4 mm. Acquisitions in this style are time intensive and in a real-world case would likely only be applied to highly important or culturally significant structures. Presumably image-based damage detection would be used to inspect potentially damaged areas of high value structures in order to improve efficiency.

Image Based Damage Inspection

To conduct inspection following earthquake tests on the CFS10 specimen, a mini UAV was used to collect close-up image data of specific areas where damage was deemed likely [11]. Surveys consisted of flying a lawnmower pattern at a standoff distance of 3-5 meters from the structure, acquiring a GSD of 0.9 mm. Each of these inspection flights required 60-90 minutes to complete.

Results

Fig. 2 shows a comparison of cropped image data from the 6th floor north façade from each UAV. For size reference, the black-and-white target on the right of each image is 20.3 cm (8 inches) square. The target and the surface texture allow for comparison of camera quality. The 45-megapixel image with a 2-meter standoff yields a theoretical GSD of 0.4 mm, see Fig. 2A. To collect this imagery, the obstacle avoidance on the UAV was turned to its minimum radius. Flying at such proximity to the structure increases risk and required pilot skill. Imagery from the 5-meter standoff flights provide a GSD of 0.9 mm, and the imagery from the mini UAV at a 5-meter standoff yields a GSD of 0.9 mm as shown in Figs. 2B and C. An oblique image from the small

UAV sitewide survey captures the same region at an angle, yielding a nominal GSD of 11.1 mm, see Fig. 2D.

In Fig. 2A, the texture detail of the stucco façade can be readily observed, as well as rippling in the caulking (gray) lines between panels. The slightly larger standoff in Fig. 2B leads to the loss of some of the details in the stucco due to image noise and reaching the limits of the lens optical quality. Most of the surface is still visualized, and the grout line ripples are still visible though not as clearly. By comparison, the imagery from the mini UAV shown in Fig. 2C lacks texture detail when compared to the enterprise grade UAV, despite the theoretical GSD of 0.9 mm of both. Only the largest texture features are still visible in the stucco, and the ripples in the grout are all but lost. Despite lower level of detail in the imagery data from the mini UAV, each of these platforms is sufficient to observe millimeter scale damage such as cracks in the façade, though some hairline cracks were missed. UAVs allowed for the remote inspection of the facades on the higher floors compared with the traditional inspection technique requiring structural engineers in a boom lift. The final image from the sitewide survey shown in Fig. 2D provides an example of lower resolution data products that can be expected from large scale area surveys. Texture on the stucco is unresolvable, but the grout lines (2-3 cm width) are still clearly visible, adequate for damage detection at the centimeter scale on a survey region the size of several city blocks.

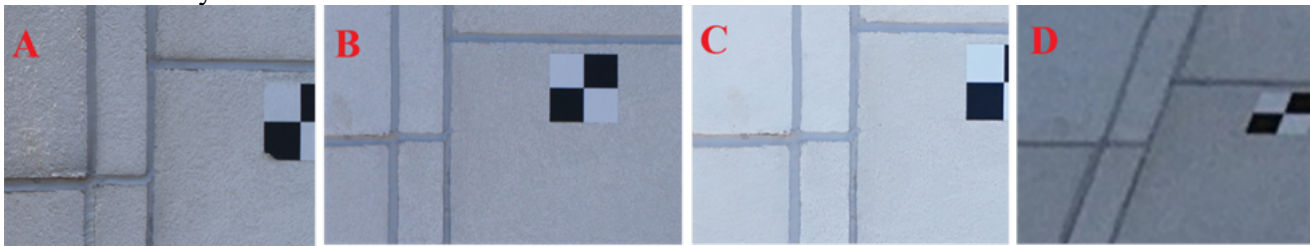


Figure 2. (A) Medium enterprise UAV with 45mp camera at 2-meter standoff, (B) Medium enterprise UAV with 45mp camera at 5-meter standoff, (C) Consumer UAV with 48mp camera at 5-meter standoff, and (D) Small enterprise UAV with 20mp camera from sitewide survey.

Conclusions

This paper presents a comparison of different post-earthquake UAV based survey strategies. Based on the desired GSD, flight plans prioritized proximity and complete capture of an earthquake and live-fire tested tall (10-story) building. Upon inspection of the imagery, it was found that despite matching theoretical GSD, the consumer UAV's images were of lower quality than those of the enterprise drone, likely due to sensor type (quad-bayer) and optical quality of the lens. Inspecting the resulting images to ensure adequate resolution for damage detection rather than relying solely on theoretical GSD is critical to capturing quality data. Due to the lack of significant improvement compared to the larger standoffs, it was found that despite producing the lowest GSD, the 2-meter standoff flights were not worth the increased risk as the superior resolution did not allow for improved damage detection. Ultimately, UAV selection and flight planning is based on the size of the area to survey and the desired image resolution. For use in imagery-based damage inspection consumer drones are comparable to enterprise drones, though the latter is required for precise georeferencing.

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