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Final Research Report

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Project Title: Evaluation of Terrestrial Laser Scanning and Aerial Remote Sensing with small Unmanned Aircraft Systems for Forensic Crime-Scene Reconstruction

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List of Acronyms

Acronym	Definition
AARC	Applied Aviation Research Center
AGL	Above Ground Level
AOI	Area of Interest
CCTC	Crisis City Training Center
FOV	Field of View
GPS	Global Positioning System
GSD	Ground Sample Distance
IMU	Inertial Measurement Unit
KBI	Kansas Bureau of Investigation
LED	Light Emitting Diode
LIDAR	Light Detection and Ranging
NIJ	National Institute of Justice
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
SfM	Structure from Motion
sUAS	Small Unmanned Aircraft System
TLS	Terrestrial Laser Scanner

1. Summary of the Project

1.1 Major Goals and Objectives

Applications involving the use of small unmanned aircraft systems (sUAS), also referred to as drones, promote safety and efficiencies in multiple public use sectors, including law enforcement. Pragmatic use of sUAS for law enforcement applications may include: (1) search and rescue missions, (2) damage assessment, (3) disaster response and recovery, (4) explosive ordinance disposal, (5) response and assessment of hazardous materials (HAZMAT), (6) aerial surveillance, and (7) and crime scene data collection and reconstruction. The goal of this project was to evaluate sUAS remote sensing technologies for crime scene data collection, reconstruction, and visualization. The primary objectives of this project were to:

1. Compare the efficiency and quality of sUAS airborne based electro-optical sensor to ground-based methods (i.e. Terrestrial Laser Scanning) for crime scene reconstruction.
2. Compare the efficiency and quality of sUAS airborne based LIDAR sensor to ground-based methods (i.e. Terrestrial Laser Scanning) for crime-scene reconstruction.

Crime-scene reconstruction is the forensic scientific discipline dedicated to the sequential understanding of events that surround a criminal event. Crime scene data collection and evidence reconstruction of a crime scene using visual imagery aids contributes to the historic preservation of information and could assist investigators in understanding the totality of the circumstances, identifying the cause, and could potentially provide valuable information for law enforcement to apprehend the potential offender(s). Data collected at a crime scene during an investigation is a time-sensitive and meticulous task that requires a level of high fidelity and integrity in the data captured to ensure accurate collection of evidence, all while avoiding evidence contamination.

Currently, there are a variety of terrestrial remote sensing aids used by crime scene investigators and forensic scientists to gather evidence and details of a scene. Technologies include hand-held cameras, terrestrial laser scanners, and other measurement devices. In 2018, The National Institute of Justice (NIJ) Forensic Science Technology Working Group identified the inherent need to improve technologies and capabilities for crime scene data collection, reconstruction, and visualization (NIJ, 2018). This research sought to address this need by providing crime-scene investigators and forensic scientists with a thorough understanding of the effectiveness, efficiency, and reliability achieved with sUAS airborne remote sensing for crime scene data collection, reconstruction, and visualization. To accomplish this initiative, the research team established an exploratory applied research method and case study approach to evaluate three remote sensing modalities for crime scene data collection, visualization, and reconstruction. The three remote sensing modalities were: (1) aerial structure from motion (SfM) photogrammetry, (2) aerial light detection and ranging (LIDAR), and (3) terrestrial laser scanning (TLS). Both quantitative and qualitative data were collected across three simulated crime scenarios. The three crime scenarios included:

1. An urban scene established to resemble a carjacking/shooting.
2. A forested area scenario involving a suicide situation.
3. A clandestine grave in an open field.

A major goal of this project was to demonstrate the effective use of sUAS airborne-based remote sensing in crime scene data collection and reconstruction. Remote sensing with sUAS may serve as an advantageous utility that offers a unique vantage point (i.e., aerial perspective) in a cost-affordable, efficient, and safe manner. There is an inherent need across the law enforcement community to streamline data analysis by enhancing automation and computer system interfaces as a mechanism to minimize post-processing work while enhancing data preservation and distribution. The use of digital data captured from an aerial perspective using sUAS as a primary data gathering tool could aid in reducing contamination and streamline data collection and analysis for crime scene preservation tasks.

1.2 Research Questions

The following research questions were investigated as part of this study on the advantages and limitations of implementing sUAS airborne remote sensing in law enforcement applications:

1. What is the level of error for the models generated with each reconstruction method?
2. How complete is each model?
3. How do environmental factors such as sun, clouds, wind, night, day, precipitation affect the quality of the digital model? What are the environmental limitations of each method?
4. What is the appropriate selection of sensing technology based on crime scene variables?

1.3 Research Design, Methods, and Data Analysis Techniques

1.3.1 Methods

This research implemented an exploratory applied research method and case study approach. For each simulated crime scene, the data was collected under both day and night conditions. Scan measurement error and point cloud density served as the primary quantitative dependent variables. Qualitative variables included: (1) ease of data acquisition, (2) completeness of the model, and (3) environmental effects. Table 1 provides a visual depiction of the data evaluation matrix as established for this research.

Table 1.

Data Evaluation Matrix

Method/ Sensor	Ambient Light	Metrics	
		Quantitative	**Qualitative**
TLS	Day	• Measurement error • Point cloud density • Time to collect data • Cost	• Ease of data acquisition • Environment effects • Completeness of model
	Night		
SfM	Day		
	Night		
LIDAR	Day		
	Night		

Artifacts, essentially pseudo-evidence, were inventoried for each simulated crime scene by physical description, quantity, and location (i.e., latitude and longitude) and distributed across the three simulated scenes on one acre of the Crisis City Training Center (CCTC) facility. A general assumption established by the research team regarding the placement of evidence was that each scene should be located outdoors and be accessible from any direction. Figure 1 depicts crime scene marking tools, evidence, and the Major Incident Response Command Center provided and utilized by the Kansas Bureau of Investigation (KBI).

(A)  (B)

(C)  (D)

Figure 1. Evidence: (A) Firearm Casing; (B) Shovel; (C) Broken Glass; (D) Major Incident Response Command Center

1.3.2 Materials and Apparatus

The following section describes the materials and apparatus used for this research. The research team had access to a variety of sUAS and two TLS systems. Although a high level of variability exists across sUAS platforms, the research team elected to use the DJI Inspire 2 and the DJI M600 as their selected platforms. These systems are commercially available, reasonably priced, and a popular option when performing activities with sUAS in the commercial and public use sector. Appendix A, B, and C illustrate the technical specifications for all equipment used as part of this study.

Structure from Motion

The DJI Inspire 2 was equipped with a DJI Zenmuse X4S sensing payload and the AirGon Loki Direct Geopositioning System was used for SfM data collection. The Inspire 2 was selected due to its simple user interface, vertical take-off and landing capability, and ability to integrate seamlessly with sUAS remote sensing and mapping applications. The X4S sensor was selected as the payload of choice because of advantageous design features such as a 1-inch imager and a 3-axis gimbal. The 1-inch imager has become an industry standard because of its robust balance between pixel size and density. The 3-axis gimbal was used to stabilize the sensor and added the functionality to maneuver the camera independently of the sUAS. The seamless integration of the X4S payload with the Inspire 2 decreased the workload on the end user. The Loki direct geopositioning system was also integrated to ensure a high level of accuracy in terms of global positioning within each image captured. Information such as Global Positioning System (GPS) coordinates served as metadata within the SfM models and omits the need for land survey measurements to establish control points on the ground. Last, the researcher team integrated a 100-watt 12-volt spotlight containing light emitting diodes (LED) on the Inspire 2 for the night operations. Figure 2 depicts the equipment used for SfM data collection.

Figure 2. (Left) DJI Inspire 2 with X4S; (Middle) AirGon Loki Direct Geopositioning System; (Right) Inspire 2 at night

Light Detection and Ranging

A DJI M600 was selected to serve as the airframe for LIDAR data collection. Compared to the DJI Inspire 2, the M600 has a higher payload carrying capacity and therefore was selected for LIDAR data collection. Additionally, the M600 has become a popular platform within the law enforcement community as it is highly capable, affordable, and easy to use. Therefore, the M600 provided a suitable system configuration that closely aligns with law enforcement use and practice. Regarding the LIDAR data collection, the research team integrated the USA Snoopy A-Series 60

LiDAR system. It is also important to note that this LIDAR scanner was not equipped with a visual imager. The DJI M600 and LIDAR equipment is depicted in Figure 3.

Figure 3. (Left) Installing the A-Series 60 on the M600; (Right) M600 in flight

Terrestrial Laser Scanning (TLS)

Through a research partnership with the KBI, the research team had access to two models of TLS (i.e., Leica C10 and BLK 360) used by law enforcement in crime scene investigations today. When compared to the BLK360, the C10 is a cumbersome system to operate as it requires manual leveling before each scan. Yet it remains in use because of its superior scanning distance. When a far detection range is not required, the newer and easier to operate BLK360 is almost exclusively selected by the KBI.

Post-Processing Software

The integration of three different types of payload sensors used for this study necessitated the use of multiple software packages to post-process the data. Each software package was chosen specifically for the technology used for data collection and its independent format. For instance, Agisoft Metashape was the software selected for SfM photogrammetry. Agisoft Metashape is an industry standard stand-alone software application that performs photogrammetric processing of digital imagery and affords users with the ability to generate three-dimensional spatial models for various applications. The automated computer vision processing method imparts a high level of resolution accuracy for various types of data. Once post-processed, both direct and indirect measurements can be achieved through the digital image captures.

The Leica Cyclone three-dimensional point cloud processing software was used to post-process the TLS data captured from the C10 and BLK 360. The Leica Cyclone software suite boasts a family of software modules to accommodate various workflows in three-dimensional laser scanning projects such as engineering, surveying, and law enforcement applications. The Cyclone software is an industry standard software application for TLS post-processing and affords users the ability to generate deliverables such as reports, maps, and three-dimensional models using data formats that support a wide range of industry applications.

The research team elected to use Global Mapper with the LIDAR Module for data post-processing; this software suite continues to serve as the industry standard for geospatial LIDAR applications. At present, Global Mapper supports more than 300 spatial data formats; offers a complete suite of post-processing tools, image rectification and vectorization; and includes attributes that enhance thematic mapping capabilities.

Scale Bars

Last, the research team constructed and used scale bars to evaluate the measurement accuracy of each model. These scale bars measured 1 ft x 4 ft and were constructed of ¼ in thick plywood. The research team painted a checkered pattern with black and light grey paint on these panels. A unique code was also adhered to each scale bar to discriminate various scale bars in the captured imagery. An example of a scale bar is shown in Figure 4.

Figure 4. Vertical Scale Bar in the Urban Scenario

1.3.3 Environment, Setting, and Staging

The Crisis City Training Center (CCTC), a disaster training center for emergency response personnel, located eight miles southwest of Salina, Kansas, served as the testbed for this research. The CCTC is operated by the Kansas Division of Emergency Management and boasts acres of simulated urban, wooded and grassy terrain. Local, state, and federal responders; emergency managers; and public and private safety professionals utilize this fully functioning training complex for safety awareness and disaster response training. Overall, CCTC is a multi-agency and multi-disciplinary training environment. Access to the CCTC was available for use through a collaborative relationship with Kansas State University. At CCTC, three mock crime scenes were simulated as depicted in Figure 5 to include:

1. An urban scene established to resemble a carjacking/shooting. The urban scene included broken glass, bullet casings of various calibers, pseudo-blood trails/pools, and firearms.
2. A forest area scenario involving a hanging/suicide. This scene contained multiple pieces of clothing, empty alcohol containers, simulated narcotics representations, and rope.

3. A clandestine grave in an open field. This scene included a shovel, cell phone, clothing in plain sight and partially buried, and restraints.

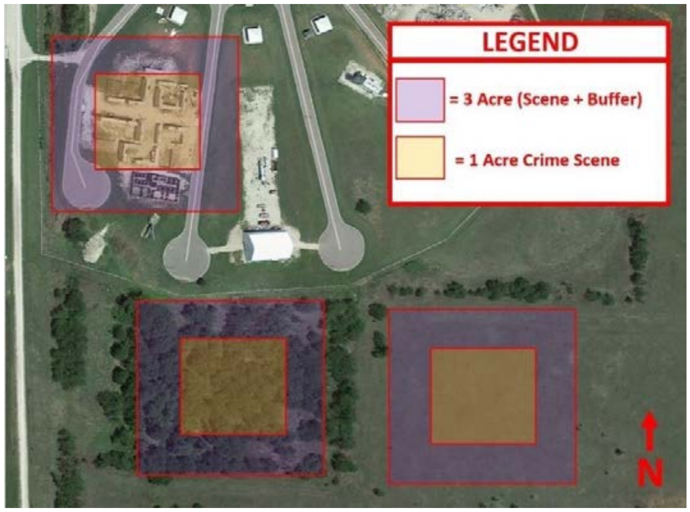

Figure 5. Sites for mock crime scenes at CCTC (Map data ©2014 Google)

1.3.4 Evaluation Procedures

Data Collection

On April 1st, the research team worked with law enforcement project partners to stage the simulated crime scenarios described above.

On April 2nd and 3rd, the research team scanned each simulated scenario with the identified technologies as presented in this work. The TLS equipment was operated by law enforcement experts at KBI. The sUAS flights were planned and operated by a two-person Kansas State University crew certified by the Federal Aviation Administration (FAA) as 14 CFR Part 107 sUAS commercial pilots.

Terrestrial Laser Scanning (TLS)

Four KBI agents collected TLS data using two C10 and three BLK360 scanners. These scanners were placed strategically in multiple locations throughout each of the scenes based upon the KBI team's expertise and accepted procedures for crime scene evidence capture. To improve scanning efficiency, multiple scanners were implemented simultaneously.

Light Detection and Ranging (LIDAR)

Using the UgCS, a ground station mission planning software, the LIDAR flight plan was designed to accommodate a raster pattern at 18 meters (i.e. urban scenario and clandestine scenario only) and 36 meters (i.e. urban, forest, and clandestine scenario) above ground level (AGL). Transects extended past the area of interest (AOI) by approximately 15 meters to ensure sufficient data capture beyond the AOI and to minimize gyroscope tumbling in the onboard inertial measurement unit (IMU). The LIDAR transect spacing was established at 30 meters with a LIDAR field of view (FOV) established at 90 degrees. The resultant output was a swath overlap of 17% at 18 meters and 60% at 36 meters AGL. The velocity of the sUAS in flight was 4.5 meters per second with a LIDAR head speed of 1200 RPM configured to capture dual returns.

Structure from Motion (SfM) Photogrammetry

Photographs for the SfM photogrammetry were collected using both a single-grid and double-grid flight plan. Similar to the LIDAR flight plans, the goal was to extend past the AOI to ensure adequate coverage of the AOI. For the day and night missions, the single-grid method was flown at 18 meters AGL, except for the forest scene where efforts were made to avoid natural obstacles (i.e. trees). There was an 80% forward and 60% side overlap and the camera was positioned 90 degrees perpendicular to the Earth's surface (nadir). Exposure settings were adjusted to shutter priority as this technique afforded researchers the ability to minimize motion blur in the imagery. Screen captures from the DJI Ground Station Pro mission planning software application are provided in Figure 6.

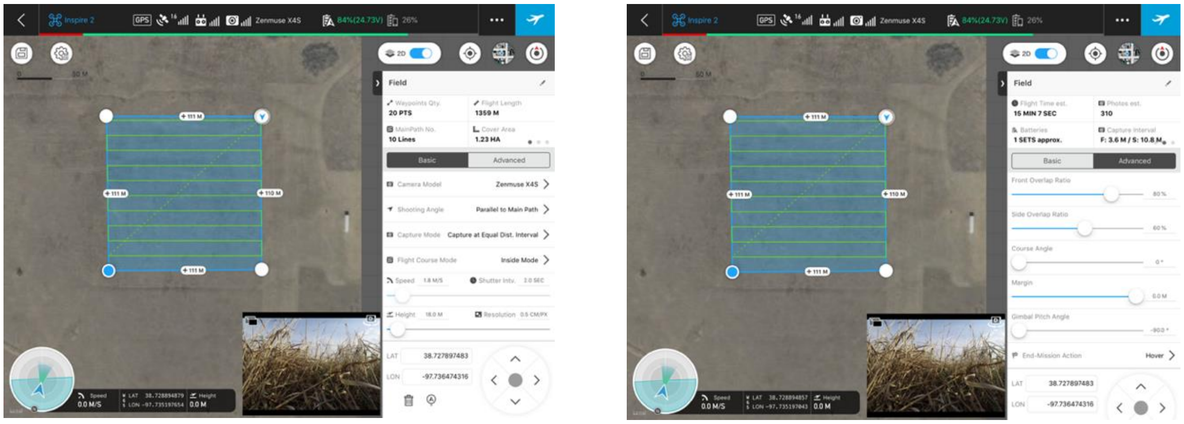

Figure 6. Single-Grid Mission Planning for Field Scenario

The double-grid method established by the research team incorporated a perpendicular grid pattern using a 70-degree oblique camera angle. Coupled with 80% forward and 70% side overlap, these flight parameter techniques were integrated to improve the quality of façade reconstruction. The sUAS altitude was established at 30 meters AGL. These flights were only conducted during the day because the change in camera angle would mean the light from the sUAS, which was fixed and illuminated perpendicular to the earth's surface, would not illuminate the AOI in the camera's FOV which would have resulted in significant noise and data voids. Default auto-exposure camera settings were used for this application as the mission planning software did not permit the user to set the camera exposure settings manually. Screen captures from the double-grid mission planning application using Pix4D Capture is depicted in Figure 7.

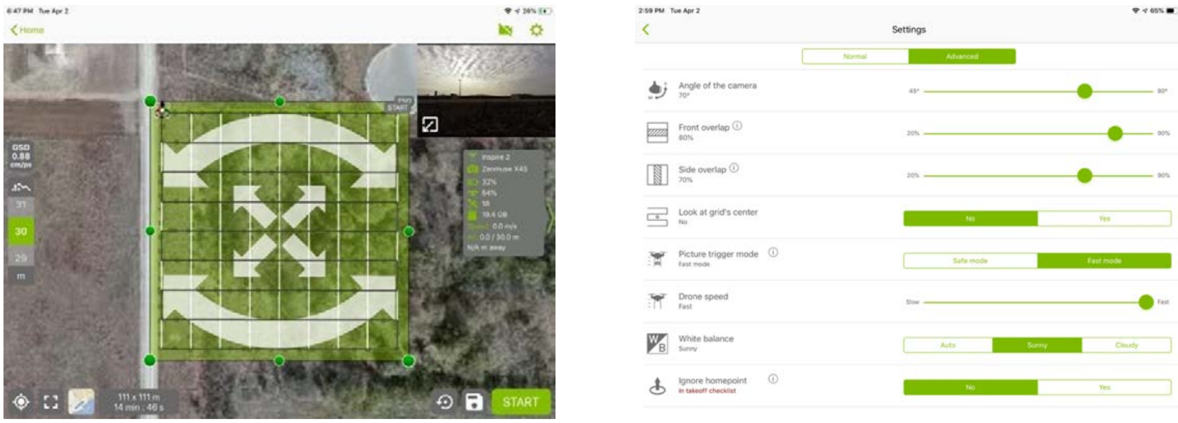

Figure 7. Double-Grid Mission for Forest Scenario

Data Processing

Data collected from each sensor required slightly different processing methodologies to produce a point cloud of each particular crime scene. For instance, the laser-based methods (i.e., TLS and LIDAR) record laser returns as points and then associate IMU and GPS information to these points. In contrast, the SfM method starts with overlapping two-dimensional imagery, which is then processed into a point cloud.

Terrestrial Laser Scanning (TLS)

In order to process the TLS data, the KBI team first combined each consecutive scan captured for each scene. Also known as registering, this is an automatic software execution process resulting in a high fidelity point cloud data, provided a scene contains easily distinguishable objects (e.g. evidence markers). Alternately, registration could be a long and tedious task when artifacts on the ground cannot be distinguished, as was experienced in the forest scenario where small features (e.g. small tree branches) were indistinguishable.

Light Detection and Ranging (LIDAR)

Due to its novel and less integrated nature when compared to the TLS, more effort was required to translate LIDAR raw data into usable point cloud information. The LIDAR data began as unreferenced laser point returns which was processed by the sensor manufacturer's proprietary software to incorporate the GPS and IMU metadata. This processing formed point clouds, which were then refined using Global Mapper's LIDAR Module to remove noise and register the scans into a unified point cloud map similar to the process used for the TLS data.

Structure from Motion (SfM) Photogrammetry

Last, the SfM data was processed by the research team using Agisoft Metashape. This process first involved embedding the corrected geo-locations from the direct georeferencing system in the EXIF data of the source images by using proprietary software from the direct georeferencing system manufacturer. Next, the lens calibration file was added. The research team then used the recommended settings from the manufacturer of the direct georeferencing system to produce an orthomosaic.

The camera settings used for SfM photogrammetry are listed below:

1. Align Photos
    a. Accuracy: High
    b. Reference preselection: Active
    c. Key point limit: 40,000
    d. Tie point limit: 4,000
    e. Adaptive camera model fitting: Disabled
2. Optimize with all parameters unchecked
3. Build Dense Cloud
    a. Quality: Medium
    b. Depth filtering: Moderate

4. Build Mesh
    a. Surface type: Height Field
    b. Source data: Dense Cloud
    c. Face count: High
5. Build Orthomosaic
    a. Surface: Mesh
    b. Blending mode: Mosaic
    c. Set Projection

Analytical and Data Analysis Techniques

The point clouds from each data collection method were analyzed using the quantitative and qualitative variables listed in Table 1. The techniques used to assess measurement error differed for each remote sensing modality. The SfM data was evaluated based on the average measurement deviation from the true measurements of the scale bars. This analysis was accomplished by placing a measuring tool on the modeled scale bar within the software. This measurement was then compared to the known length of the scale bar to find the measurement deviation. The reported mean absolute error reported by the Leica Cyclone software quantified the error for the TLS data. The LIDAR data error was quantified by the sensor's specification. Point cloud density was determined by calculating the average points per square meter for each respective point cloud. Time to collect data was obtained by recording the time it required to set up the equipment, collect data, back up the data, make field notes, and pack up the equipment. The cost metric is simply a compilation of equipment purchase costs. The parameters of ease of data acquisition and environmental effects were captured in the notes of the personnel who operated the equipment to collect the data. Completeness of model, the final qualitative parameter, was evaluated by the research team and their law enforcement partners as they assessed each data set, recorded pertinent features, and detected evidence.

1.4 Expected Applicability of the Research

The purpose of this research was to evaluate three remote sensing modalities: (1) SfM photogrammetry, (2) aerial LIDAR, and (3) TLS. The applicability of this work corresponds particularly to law enforcement entities seeking to implement novel methods for crime scene data collection. Traditional methods for crime scene data collection may be limited by their time-intensive and subjective nature, such as capturing pictures with a handheld camera. This research is expected to apply to entities seeking opportunities to supplement existing TLS data collection methods, as well as groups who are looking for a lower-cost alternative to crime scene reconstruction. An advantage of sUAS remote sensing is that the data is collected from an aerial perspective. This means the entirety of an area is reconstructed and is not reliant on multiple scans from subjective perspectives as is the case with TLS scanning. Though not yet at a level where they can be accepted as physical evidence, models produced by sUAS SfM methods could provide criminal justice professionals and juries with the ability to review the scene in a complete and relatively unaltered state. A limiting factor of TLS scanning is the high expense of its equipment. The equipment required for sUAS SfM photogrammetry is much less expensive than TLS equipment, thereby making crime scene digital reconstruction accessible to agencies with smaller budgets. This technology may provide an evolutionary step in crime scene investigations by reducing scene contamination, creating models with sufficient accuracy, and by reducing the cost and time spent on scene.

2. Participants and Other Collaborating Organizations

The following participants were associated with this research effort:

Name	Affiliation	Job Title	Project Role
Kurt Carraway	Kansas State University AARC	UAS Executive Director	Principal Investigator
Trevor Witt	Kansas State University AARC	UAS Data Analyst	Project Lead
Dr. Tom Haritos	Kansas State University AARC	UAS Research Program Manager	Feedback on analysis and report reviewer. Arthur of scholarly journal article
Duke Papworth	Kansas State University AARC	UAS Technologist	Sensor Installation & UAS Maintenance
Beth Drescher	Kansas State University	Grant Reviewer	Proposal and Report Reviewer
Jacob Cowart	Kansas State University AARC	UAS Undergrad Student	Assistance with data handling
M. Wade Cherms	Riley County PD	CSI Lab Technician	Subject Matter Expert
Jeremy Chappell	Kansas City PD	Crime Scene Supervisor	Subject Matter Expert
Robert Jacobs	Kansas Bureau of Investigation	Assistant Special Agent in Charge	Subject Matter Expert
Beth Brooks	Kansas Bureau of Investigation	Senior Special Agent	Subject Matter Expert & TLS Lead
Traci Allen	Kansas Bureau of Investigation		Terrestrial Laser Scanning Assistance
Randi Johnson	Kansas Bureau of Investigation		Terrestrial Laser Scanning Assistance
Dan Hubert	Modus Robotics	Owner	UAS LiDAR Tech Support

Tammy Shea	State of Kansas	Crisis City Training Center Facilities Coordinator

3. Changes in Approach from Original Design and Justification

Adjustments from the original design included the following; (1) the use of an alternate LIDAR sensor, (2) the use of an additional TLS, (3) a reduction in scale bars, (4) flight altitude for the forest scenario, and (5) adjusting the means of determining the point cloud accuracies and density.

The research team originally intended to use the Geodetics Geo-MMS LIDAR sensor for the sUAS-borne LIDAR mission. However, this model was not available, so an alternate LIDAR system with nearly identical specifications was substituted (i.e. USA Snoopy A-Series 60). Regarding the TLS, the original proposal stated that the C10 was the only TLS used by the KBI; however, it was learned they also use the BLK360. The research team was able to include both the C10 and BLK360 in the study.

The research team determined that a reduction of scale bars from twenty-eight to nine per scene would suffice to establish the measurement accuracies desired. The National Institute of Standards and Technology (NIST) standard for evaluating accuracy using TLS equipment suggests the use of a single scale bar in the first and last scan of the crime scene capture. A reduction to nine scale bars per scene provided more points of reference than the single scale bar standard used by crime scene investigators today.

Next, a flight altitude adjustment was made for the forest scenario to ensure a safe sUAS operating clearance from the trees. The initial compromise of flying higher for the SfM data corresponded to a reduction in spatial resolution, yet the data yielded sufficient detail to distinguish artifacts within the forest scene as accurately as those in the higher spatial resolution urban and field scenes. The most significant challenge was the nighttime data set, which failed to process. The increased distance from the on-board LED to the ground reduced the amount of light available, and the images were inadequately exposed.

Scale bars were originally expected to provide the most direct and consistent assessment of measurement accuracy for each remote sensing modality. However, results from the analysis of the TLS and LIDAR point clouds prompted a change in this approach. Researchers using the TLS sensors were unable to view the horizontal scale bars due to the line-of-sight perspective from the tripod-mounted position of the TLS. To compensate for this limitation, the research team used a NIST pole in the first and last scans per the original equipment manufacturer (OEM) guidelines and recorded the mean absolute error as reported from the Leica Cyclone processing software. The researchers were unable to distinguish the scale bars in the LIDAR point clouds due to the sensor's low sensitivity in correlation to the scale bar's size. As a result, the research team used the manufacturer's specification for accuracy instead of a reported accuracy from the point clouds.

Initially, the research team sought to describe the level of distinguishable detail by the point cloud density and a simple measurement of points per square meter. The research team discovered this metric did not achieve its intended goal because a point cloud can be dense yet imprecise, thereby limiting the ability to distinguish small objects. This problem is demonstrated by the description of the LIDAR results in the *Results and Findings* section of this report. Density must be paired with point cloud precision to achieve higher levels of distinguishable detail. Such precision must be better than the three-centimeter precision of the LIDAR sensor used for this project. Point cloud density can also be highly variable within a point cloud depending on the sensor's distance to the scanned objects. Regardless, point cloud density was still reported but was not solely relied upon to describe the complete level of distinguishable detail. Instead, the "completeness of model" qualitative metric can be used to discern the level of distinguishable detail by the number of artifacts identified in each model.

4. Outcomes

4.1 Activities/accomplishments

This project produced TLS, LIDAR, and SfM data sets of urban, forest, and field crime scene scenarios during the day and night. The analysis of these data sets contributed to the development of the primary products of this project; the final cumulative report, a final summary overview (i.e. final research report), and a publication for the law enforcement community.

4.2 Results and Findings

Quantitative metrics included time to collect data, measurement error, point cloud density, and cost. Qualitative metrics were recorded anecdotally and were analyzed as a product of this work. The qualitative parameters of ease of data acquisition and environmental effects were captured through field notes prior to the start of each data collection activity. Completeness of the model was evaluated using an inter-rater scale methodology in which multiple subject matter experts analyzed and annotated their results of pertinent features and evidence as recorded by the various sensors across each scene. Cost was evaluated by calculating the financial investment required for a law enforcement entity to purchase sUAS, TLS, and sUAS with LIDAR.

4.2.1 Time to Collect Data

Time to collect evidence data is a critical component for any crime scene investigation. Potential for crime scene contamination increases as time elapses after the crime. Therefore, law enforcement personnel aspire to maximize the quality and quantity of data captured about a scene in as little time as possible. Table 2 provides the data collection time across each sensing modality. As evident in Table 2, data voids were presented in the single-grid forest night SFM scene and in all the double grid night scenes. These data sets were omitted due to the limitations of night data collection using SFM and onboard spotlight illumination.

When observing time to complete data collection as a component of this research, it is evident that the TLS trial iteration was the most cumbersome with a mean score of 33 minutes for the field day and night scene, 82 minutes for the forest day and night scene, and 93.5 minutes for the urban day and night scene. In comparison, sUAS LIDAR data collection times recorded were 16 minutes for the field day and night scene, 7 minutes for the forest day and night scene, and 24 minutes for the urban day and night scene. Alternatively, the single grid SFM data collection was recorded at 12 minutes for the field day and night scene, 4 minutes for the forest day only, and 14 minutes for the urban day and night scenarios. Last, the double grid SFM data collection was recorded at 14 minutes for the field day scene, 12 minutes for the forest day scene, and 12 minutes for the urban day scene.

Table 2.

Data Collection Time

Data Set Location and Ambient Condition	Time in Minutes			
	TLS	sUAS LIDAR (% of TLS)	SfM Double Grid (% of TLS)	SfM Single Grid (% of TLS)
Field Day	36	16 (44%)	14 (39%)	12 (33%)
Field Night	30	16 (53%)		12 (40%)
Forest Day	95	7 (7%)	12 (13%)	4 (4%)

Forest Night	70	7 (10%)		
Urban Day	127	24 (19%)	12 (9%)	17 (13%)
Urban Night	60	24 (40%)		11 (18%)

4.2.2 Measurement Error

Measurement error is a critical parameter for airborne data collection and photogrammetry as measurement error corresponds to the level of confidence in the data collected. By rule of thumb, there is always a level of acceptable error in remotely sensed data. Therefore, the user of this data must understand the sources of error, implement means to mitigate errors and use methods to measure and articulate these errors effectively.

The mean absolute error reported from Leica Cyclone was the indicator for accuracy in the TLS data, and the average scale bar error was used for the SfM data sets. The measurement error for the TLS and SfM data sets is shown in Figure 8, with the average error for all the TLS data sets slightly higher than 1mm, and the average scale bar error for all the SfM data sets marginally higher than 2mm. Instead of a validated accuracy for the LIDAR data, the research team elected to use the sensor manufacturer's specified typical accuracy of +/- 3cm. The justification is described in Section 3 of this report.

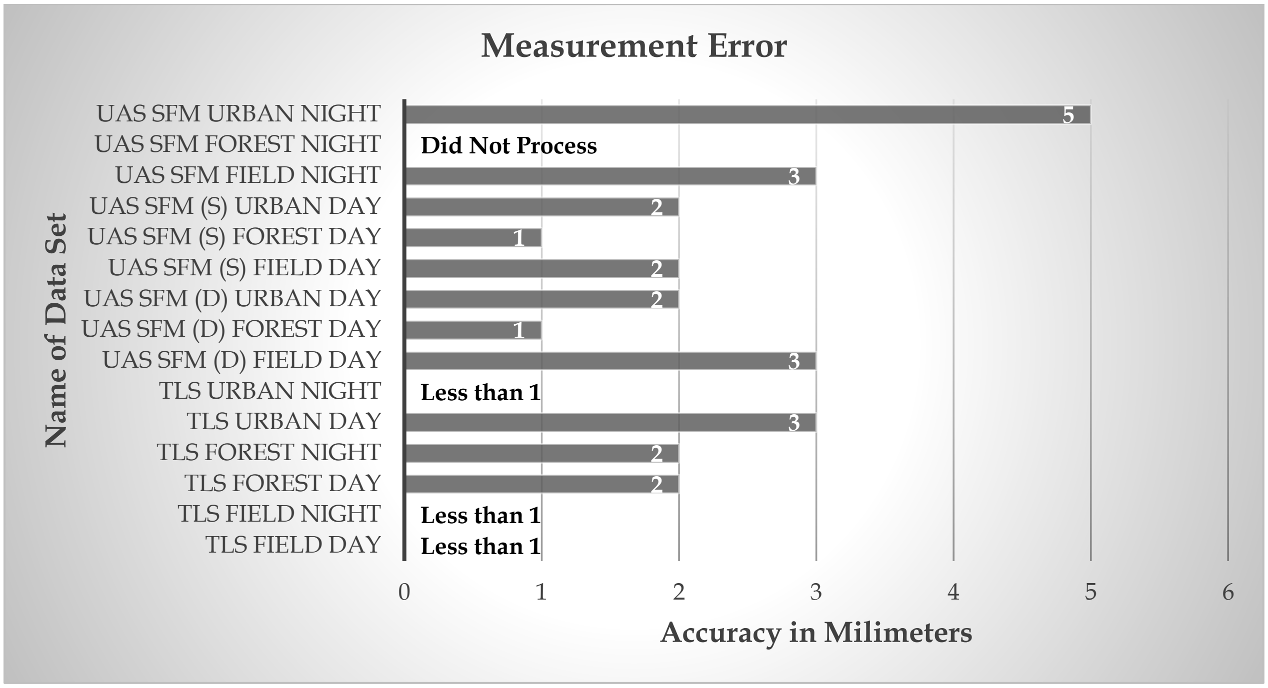

Figure 8. Measurement Error for the TLS and SfM Data Sets

The error for the SfM data sets makes no claim to vertical or z-axis measurement accuracy. This clarification is necessary because only horizontal scale bars were used, thereby enabling only planimetric error assessment. Multiple vertical scale bars would be required to successfully reconstruct the models to ensure a vertical accuracy assessment. It is also important to note that due to the unique and contrasting design of the scale bars, the degree of error will always be smaller on scale bars; SfM software easily reconstructs these types of features. Other real-world items throughout the scenes such as trees, moving objects, thin linear features such as guardrails and powerlines, and reflective surfaces such as glass are difficult to process in SfM software because SfM relies on multiple perspectives of an object to successfully reconstruct it. Modeling becomes difficult when the ability to obtain multiple perspectives of defining features is reduced, and these features tend to produce artifacts that introduce noise that results in error for that area of the scene. Also impacting scale bar error is the possibility for user bias, since the extents of the scale bar are determined by the technician performing the analysis. For future research, it is recommended that scale bars whose extents are automatically detected by the software be used. Last, it is imperative that the actual measurement error cannot be more than the ground sample distance (GSD) of the source imagery; errors cannot be smaller than the smallest spatial piece of data (i.e., the pixel). As a result, the actual measurement error was likely to be equal to the GSD of the source imagery, which was 10mm and 5mm for the high and low altitudes.

4.2.3 Point Cloud Density

Point cloud density can indicate the amount of distinguishable detail in the model; high density should indicate more distinguishable detail than low density. Originally, this was thought to be a simple measurement of points per square meter, however the research team discovered this unit of analysis did not achieve its intended goal. Some of the point clouds were imprecise as described in the *Changes in Approach from Original Design and Reason for Change* section of this report. The results indicated that even if there is a sufficient density of points in the TLS or LIDAR data, it does not necessarily mean that features are distinguishable when observing these data sets.

The results of this analysis indicated that TLS data was more dense than the methods used for sUAS scanning. The average density for LIDAR and SfM point clouds were respectively 7% and 11% of the average density of the TLS data sets. TLS point cloud density was also impacted by the number of scans and the resolution setting used. A higher resolution setting produced a denser cloud, and from field to forest to urban, the scenes became progressively more complex. This meant that additional scans were required to prevent data voids. Adding scans subsequently led to progressively denser data sets, which did increase detail and reduced the possibility of data voids. Density increased in the SfM point clouds as the GSD increased. However, there was some random variability in the density of the nighttime SfM data sets, as the field night data set was over 18 times denser than the urban night data set. This difference could be due to variations in the features of the scenes, randomness introduced by the noise in the source imagery, or another reason not identified by the research team. Full details on point cloud density are shown in Figure 9.

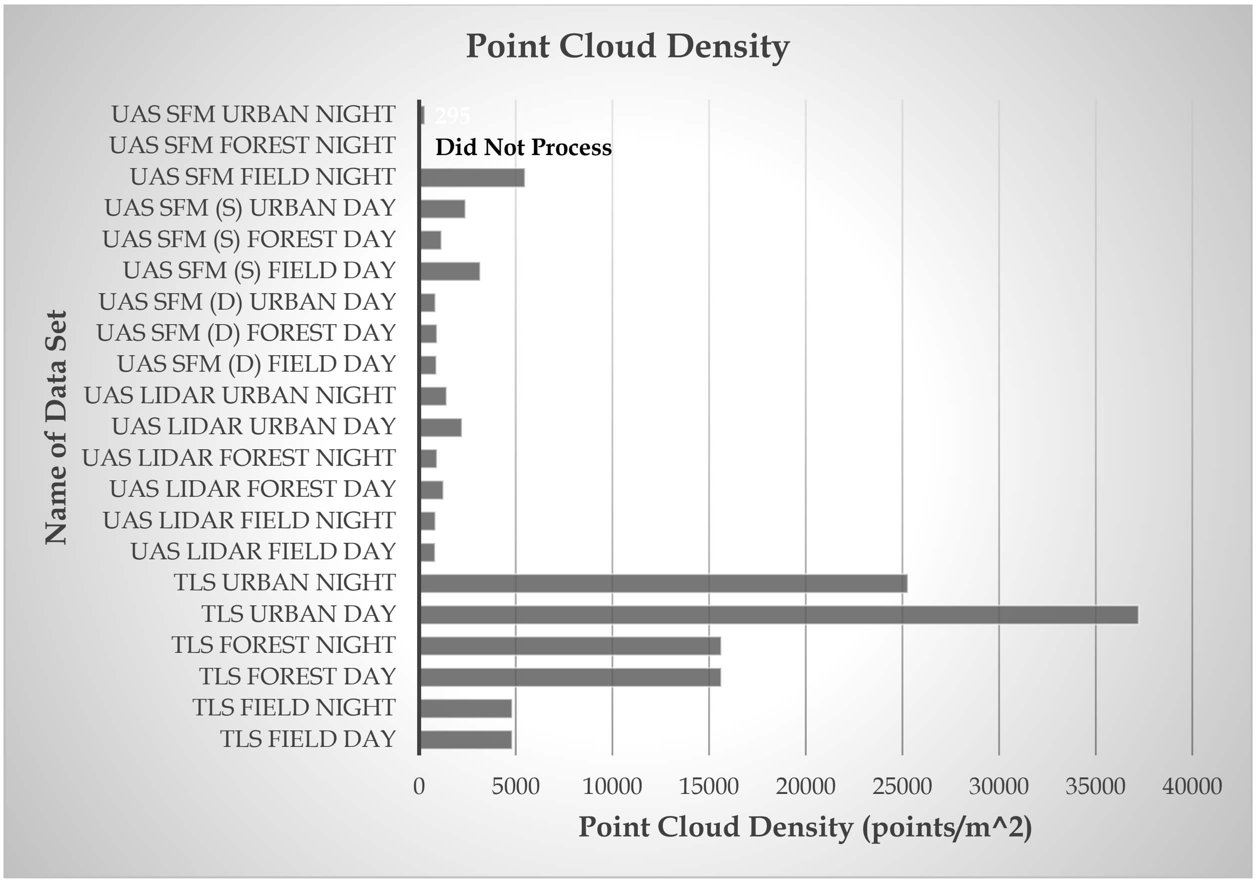

Figure 9. Point Cloud Density

As explained in the previous discussion of measurement error, the TLS sensors were unable to view most of the horizontal scale bars due to their line-of-sight perspective from their tripod-mounted position. At approximately 1.5 meters above the ground, the TLS equipment rotated to scan 360 degrees horizontally and nearly 360 degrees vertically. By inherent design, the TLS can only scan objects visible from its line-of-sight angle. This perspective made it difficult for the sensor to scan the upward face of an object lying parallel to the ground. Since the research team was not aware of this limitation during data collection, only a few horizontal scale bars were optimally placed to be visible in the TLS data. In retrospect, a direct comparison could not be achieved, since accuracy was assessed by methods specific to each remote sensing modality. For the TLS data, a NIST pole was placed in the first and last scans per the original equipment manufacturer (OEM) guidelines. The mean absolute error was reported by the Leica Cyclone processing software. The research team was unable to validate sUAS-borne LIDAR data and was only able to use the manufacturer's specification for accuracy in lieu of a reported accuracy from the point clouds. The SfM data was evaluated for accuracy using the scale bars.

4.2.4 Cost

The last quantitative metric evaluated was the cost of technology acquisition. Typically, sUAS airborne technologies offer a lower acquisition cost when compared to TLS and LIDAR scanning tools. As a component of this study, the KBI's TLS equipment was used as an estimate cost regarding TLS. The approximate cost of the Leica C10 was $20,000 (used), and the Leica BLK360s approximate cost per unit was $16,000. However, the Leica C10 is an outdated technology and is no longer sold as a new product. A more comparable price comparison for state-of-the-art equipment is the Leica RTC360, which costs approximately $75,000. The cost of sUAS-borne LIDAR rivaled the cost of TLS equipment; a LIDAR payload sensor costs about $55,000. However, in addition to the sensor acquisition cost, support equipment is required. An average of $15,000 may be needed for the acquisition of a sUAS platform and other support equipment. The SfM equipment was identified as the least expensive with a minimum total value of $15,000, which included the sUAS platform, an electro-optical sensor, sUAS, and other support equipment. As previously mentioned, the system acquisition costs for sUAS may range from approximately

$20,000 to $60,000 for multiple systems with electro-optical and thermal imaging payloads. The system cost is summarized and depicted in Table 3. Financial considerations should include a buffer for crew qualification training and maintenance costs.

Table 3.

System Costs

Remote Sensing Technology	System Make & Model	System Cost
TLS	Leica C10	$250,000 (new) $20,000 (used)
	Leica BLK360	$16,000
	Leica RTC360	$75,000
sUAS LIDAR	DJI M600, LIDAR-USA Snoopy A-Series 60	$70,000
sUAS SfM	DJI Inspire 2, DJI X4S, AirGon Loki	$15,000

4.2.5 Ease of Data Acquisition

The ease of data acquisition was the first qualitative metric evaluated by the research team. This metric was closely related to the time to collect data. Factors such as ease of transportation, the complexity of the operation, and the extent of mission planning were sub-factored into this metric. When disassembled, the TLS equipment can be carried by a single operator, with the Leica C10 being slightly more cumbersome to transport than the BLK360. The sUAS airborne LIDAR equipment was the most difficult for several reasons. A DJI M600 was used for the LIDAR data acquisition. This platform is larger than the traditional DJI Inspire 2 used for the SfM data collection and must be transported in a pelican case that often requires two people to lift and carry to a launch location. Presumably, a wheeled pelican case can incorporate the flexibility to be set-up by one individual. The sUAS also needed to be instrumented for data collection once it was in the field. The portability of the sUAS-borne SfM equipment was similar to the TLS equipment; a single person could carry all the primary and supporting equipment to the site. Overall, the DJI suite of products is often selected as the most suitable for law enforcement applications. The M600 is useful because of its higher payload carrying capability, but requires a more substantial financial investment. Many agencies have successfully used lower-cost platforms such as the Inspire and Mavic series.

The next factors within the ease of data acquisition metric were the complexity of operation and level of mission planning. Complexity is a subjective metric depending on the level of experience of the operator. However, the number of steps required to perform the data collection is an indicator of operational complexity. The BLK360 TLS equipment included an auto-leveling feature which made it less complex to operate than the C10. Overall, the TLS reconstruction method required the professional opinions of the operators to determine the number of scans, which scanner to use, placement of the scans, and scanner resolution setting. This may add a level of method-produced bias; the aforementioned constructs are subjective and ultimately increase the complexity and time of equipment set-up and data capture. The sUAS airborne collection methods have a similar subjective element; the operator must determine multiple parameters that include airframe and payload selection, flight altitude, flight speed, overlap percentages, flight plan configuration, camera orientation, and camera settings. The sUAS level of subjectivity is slightly reduced by its ability to fly the entire AOI without stopping once the parameters are set. Further research is needed to develop standardized guidelines for sUAS data collection and post-processing.

4.2.6 Environmental Effects

Environmental effects with the potential to impact data quality include ambient light conditions, weather, topography, and contents of the AOI. Throughout the 24-hour data collection period, the temperature ranged from 44 to 56 degrees Fahrenheit, wind speed varied from 4 to 8 knots, and cloud conditions alternated from clear to scattered cumulus and stratus. None of these effects caused a noticeable impact on the quality of the data captured. All of the noticeable environmental effects were due to the day and night differences. During the day, the TLS collected some erroneous data when the sun reflected in the lens of the TLS scanner and caused a trajectory of false points. This erroneous data was removed in post processing. There was no color information associated with the nighttime TLS point clouds because of the lack of ambient light for the integrated imaging sensor. This decreased the level of distinguishable detail in the resulting point clouds. Also due to the nighttime conditions, the night SfM data set over the forest area failed to reconstruct.

4.2.7 Completeness of the Model

The completeness of the model, which corresponds to the level of distinguishable detail, was the last qualitative metric evaluated. This metric was subjectively evaluated through image interpretation with the goal of identifying distinguishable features, gaps, and artifacts in the scene. For this case, distinguishable evidence captured on the ground was a factor in the completeness of the model. The urban data sets for both the day and night contained artifacts specifically around the railings of the Conex containers. However, other areas of the scene accurately reflected the true scene. These features are shown in photographs A and B of Figure 10. In this figure, the railing artifacts are visible, yet the evidence on the ground next to railing is true to the scene. Also depicted in these photographs are the impacts of ambient conditions and the resulting increase in SfM artifacts at night.

The clandestine grave was not distinguishable in the TLS point cloud data. The large volume of data points from the grass effectively concealed the clandestine grave and the tire tracks in the AOI. Though the TLS is more accurate than the SfM methods, data saturation is burdensome and limiting in certain situations. Even though the SfM method did not reconstruct the grass as completely as the TLS did, this lack of data made the evidence within the AOI, particularly the clandestine grave, shovel, and tire tracks, stand out. The aerial view perspective of the SfM data sets contributed to this improved look, filling in the "shadows" or gaps in the TLS data caused by a lack of sufficient scan locations.

The LIDAR sensor produced a final product that contained a point cloud density similar to the SfM. However, the LIDAR models only reconstructed large features such as buildings, trees, and cars (Picture C Figure 10). The low accuracy and precision of this sensor and the lack of color information resulted in minimal detail.

(A) 

 (B)

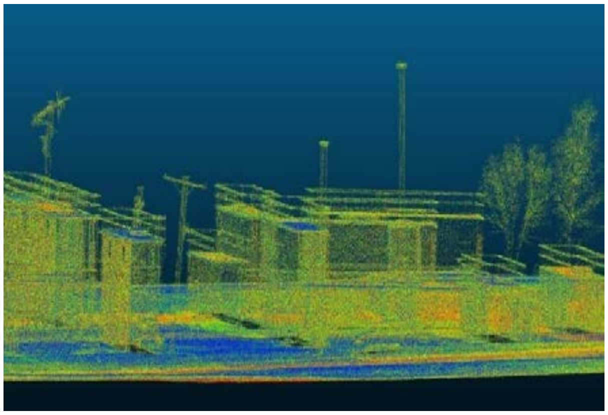 (C)

Figure 10. Screenshots for Urban Day SFM (A), Urban Night SFM (B) and LIDAR (C) of the Urban Scene

The research team established detection rates of evidence by recording whether a piece of evidence could be visually identified by one of the researchers. Although the research team could not distinguish any piece of evidence in LIDAR data, the SfM and TLS data contained enough detail to identify pieces of evidence. There were slightly lower detection rates at night compared to the daytime data sets. The TLS could detect smaller items (i.e. bullet casings) than the SfM, but SfM showed flat ground features (i.e. a bloody footprint) when the TLS did not. The SfM double-grid captured more pieces of evidence in the forest scene than the single-grid; the angle of the camera in the double-grid mission provided a better perspective to see between the tree limbs.

Table 4.

Urban Scene Evidence Detection

Urban							
Artifact	Aerial LIDAR		SfM Single Grid		SfM Double Grid	TLS	
	Day	Night	Day	Night	Day	Day	Night
Rifle Shell Casings	No	No	No	No	No	No	No
Broken Glass	No	No	Yes	No	Yes	Yes	Yes
Rifle Shell Casings	No	No	No	No	No	Yes	Yes
Rifle Shell Casings	No	No	No	No	No	Yes	Yes
Rifle Magazine	No	No	Yes	Yes	Yes	Yes	Yes
Bloody Footprint	No	No	Yes	No	Yes	No	No
Rifle	No	No	Yes	Yes	Yes	Yes	Yes
Pistol Shell Casings	No	No	No	No	No	No	No
Pistol Shell Casings	No	No	No	No	No	No	No
Clothing	No	No	Yes	No	Yes	Yes	Yes
Bullet	No	No	No	No	No	No	No
Handgun	No	No	Yes	Yes	Yes	Yes	Yes
Blood pool	No	No	Yes	Yes	Yes	Yes	Yes
Cigarette Butts	No	No	No	No	No	No	No
Beer Can	No	No	Yes	No	Yes	Yes	Yes

Table 5.

Field Scene Evidence Detection

Field							
Artifact	Aerial LIDAR		SfM Single Grid		SfM Double Grid	TLS	
	Day	Night	Day	Night	Day	Day	Night
Handcuffs	No	No	No	No	No	Yes	Yes
Chain	No	No	Yes	No	Yes	Yes	Yes
Body/Gravesite	No	No	Yes	Yes	Yes	Yes	Yes
Shotgun Shells	No	No	Yes	No	Yes	Yes	No
Cell Phone	No	No	Yes	Yes	Yes	Yes	No
Shovel	No	No	Yes	Yes	Yes	Yes	Yes

Table 6.

Forest Scene Evidence Detection

Forest						
Artifact	Aerial LIDAR		SfM Single Grid Day	SfM Double Grid Day	TLS	
	Day	Night			Day	Night
Shirt	No	No	Yes	Yes	Yes	Yes
Beer Can	No	No	Yes	Yes	Yes	Yes
Pants	No	No	Yes	Yes	Yes	Yes
Simulated Drugs (Green)	No	No	No	No	No	No
Simulated Drugs (white)	No	No	Yes	No	Yes	No
Beer Bottle	No	No	Yes	Yes	Yes	No
Beer Can	No	No	No	Yes	Yes	Yes
Rope (Ground)	No	No	No	Yes	Yes	No
Cellphone	No	No	No	No	Yes	No
Rope (Tree)	No	No	No	Yes	Yes	Yes

4.2.8 Research Questions

(RQ1) What is the level of error for the models generated with each reconstruction method?

As detailed in item 4.2.2 of this report, the TLS method maintained the lowest level of error, with the cumulative mean absolute error slightly higher than 1mm. Though restricted to reporting only planimetric error, the SfM method had the next best error performance with the cumulative mean scale bar deviation error under 1cm. The LIDAR data contained the highest error, with the sensor-specified error of 3cm.

(RQ2) How complete is each model?

The TLS data sets were the most complete with data products that contained a larger volume of accurate point clouds when compared to the other methods. These qualities contributed to the TLS method's ability to identify the most evidence. However, the superiority of TLS models comes at the consequence of being more time and personnel intensive. Also, if there were not enough scan positions within the scene, then data voids (also known as shadows) were produced because the TLS was not able to "see" these areas. These shadows were eliminated with the SfM method, which captured the entirety of the scene. Although an aerial perspective could be advantageous, the SfM and LIDAR methods have a lower accuracy threshold when compared to TLS. The SfM is especially at an accuracy disadvantage during night data collection because of the increased number of artifacts. The LIDAR method produced the least complete models. The level of distinguishable detail was low; only large features such as buildings and cars could be identified.

(RQ3) How do environmental factors affect the quality of the digital model (sun, clouds, wind, night, day, precipitation)? What are the environmental limitations of each method?

Environmental factors impact data quality in many ways. For instance, high wind can cause objects within the AOI to move and thereby contribute to noise in the digital models. Also, extreme temperatures can exceed the OEM's guidelines, preventing the ability to use the equipment. The weather conditions at the time of this study's data capture were consistent, and the research team did not identify any noticeable changes due to slightly varying cloud conditions. The greatest environmental limitation was the ability to capture high-quality data at night for all of the modalities. The TLS method preserved data quality in both day and night conditions. However, a TLS limitation was its inability to generate color information at night. The SfM method at night was effective for the urban and field scenarios but not effective in the forest scenario because the sUAS was required to fly higher, resulting in less available light from the onboard LED to illuminate the scene below. The LIDAR method maintained its same low level of distinguishable detail for both the day and night data sets.

(RQ4) What is the appropriate selection of sensing technology based on crime scene variables?

At present, the TLS sensing modality is an industry standard. Other techniques, such as terrestrial photography, are often used. There are many factors that must be considered to make the most appropriate selection of utilities in crime scene data collection. The purpose of this project was to introduce and explore aerial data collection using sUAS remote sensing as a mechanism to complement current and existing crime scene technologies and techniques. Ultimately, it is up to the end-user of these remote sensing modalities to determine which advantages are compelling and which disadvantages are not too debilitating to prevent the data's use for forensic crime scene analysis.

The research team also determined the following to be significant findings. First is that the LIDAR method is insufficient for this application. LIDAR systems with the specifications used in this research may not be the most suitable for crime scene data collection because they do not produce high enough quality point clouds to identify typical evidence that may be found in a crime scene. This LIDAR was selected because it was comparably priced with TLS. More advanced LIDAR systems cost two to five times as much as the one used in this research. The second finding is that TLS was most effective to reconstruct a crime scene. However, limitations with the TLS method include: (1) high initial purchasing cost, (2) personnel-intensive implementation, and (3) susceptibility to data voids. Last, it has been shown that SfM methods have substantial merit.

Particularly in the daytime data sets, the SfM method captured data quickly over the entire scene while maintaining high accuracy. This method also demonstrated that it is possible to "see-through" a forested area and reconstruct the forest floor in leaf-off conditions. Daytime SfM methods are nearing refinement and now require industry consensus and standards for data collection and techniques to assess error. Such standards would ensure the consistency and quality of models produced by SfM methods. Nighttime SfM methods still need improvement; quality is much lower than the daytime models, as discussed previously in this report.

4.3 Limitations

The research team encountered many limitations in this research. Changes to the methodology were made because of these limitations which may reduce the applicability of the results. The primary limitation of this research is that it applies only to the reconstruction of outdoor crime scenes. Some of the limitations identified through this project justify future research.

The LIDAR method performed the least effectively. However, other LIDAR units with improved specifications may yield better results and may be more effective for crime scene data collection. Increasing the precision of the GPS and IMU data of the LIDAR system and maintaining the same or higher point cloud density would allow smaller objects to be detected. Also, capturing imagery simultaneously with the LIDAR data would allow the point clouds to be colorized, which would improve their detail. Last, increasing the number of detectable returns from two to five may help produce more effective point clouds in vegetated areas. These increased specifications would come at a much higher cost though, such systems are priced at $200,000 to $300,000.

The next limitation was found in the nighttime data sets. Crime scene investigators seek to accurately capture the scene as it was when the crime was committed. However, this is a challenge for crimes committed at night when the lack of ambient light severely limits remote sensing technologies. Supplemental lighting, specifically the use of flashlights and lights mounted on the mobile command center (Figure 1), are used to illuminate the scene to help personnel navigate the scene and set up the equipment, but were not used for the nighttime TLS collections. The research detailed in this report was the first to implement a lighting source onboard a sUAS for the purpose of data collection at night. This method was able to produce SfM models, but they contained numerous errors that limited the models' usefulness. Additional research is required to develop techniques to overcome the limitations of this approach. Such work would explore other lighting systems, sensors more suited for low-light conditions, and adjusted flying parameters.

The final limitation centered on assessing accuracy. Initially, the research team sought to compare the accuracy of all methodologies via scale bars spread throughout each scene in horizontal and vertical orientations. However, as previously described, this was not feasible so methods unique to each technology were used. The variety of techniques used limited the research team's ability to compare technologies accurately. There is a need for a standard to determine measurement accuracy in all axes across the remote sensing methodologies. Such a standard would need to be statistically sound if the data is to reach the physical evidence level of quality. The standard would also need to be practical in its implementation for it to be useful for end-users.

5. Artifacts

5.1 List of products

The results of this research generated a list of products such as data sets, charts, and graphs to depict the findings of this work. The research team developed a Guide for Crime Scene Reconstruction Using Structure from Motion Techniques in Small UAS, found in Appendix D. Also, the research team generated an industry publication (see Appendix E) for the law enforcement community. Additionally, the data sets generated through this work serve as a baseline for follow-on work to expand the state-of-the-art in sUAS remote sensing for crime scene reconstruction.

5.2 Data sets generated

The data sets generated for this research are topographic in nature. As previously mentioned, there were two different types of data collected. The LIDAR and TLS output data was collected as a series of discrete laser light data points often referred to as point clouds. Alternatively, the SfM photogrammetry data was consolidated and collected using a series of overlapping aerial photographs. As applicable, these data sets included both day and night models. Additionally, data was collected as it pertained to the dependent variables established as a component of this study. The primary data sets generated were the data collection time, evidence detection and system costs.

5.3 Dissemination Activities

The research team has provided cumulative reports throughout the duration of this project. This final research report is the culmination of the study. It articulates and presents the analysis and findings associated with sUAS in crime scene investigation. Additionally, the research team has generated a manuscript for publication to inform public use agencies about the advantages of sUAS for law enforcement. The manuscript draft for *Police Chief Magazine* is presented in Appendix E of this report. The research team has also submitted an abstract to present this research at the largest unmanned aircraft systems conference in North America, XPONENTIAL 2020 hosted by the Association for Unmanned Vehicle Systems International (AUVSI). The research team will identify additional venues to disseminate this work whenever possible and appropriate.

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APPENDIX A

Equipment Specifications

Terrestrial Laser Scanning

Leica C10

General

- Instrument type: Compact, pulsed, dual-axis compensated, very high-speed laser scanner, with survey-grade accuracy, range, and field-of-view; integrated camera and laser plummet
- User interface: Onboard control, notebook, tablet PC or remote controller
- Data storage: Integrated solid-state drive (SSD), external PC or external USB device
- Camera: Auto-adjusting, integrated high-resolution digital camera with zoom video

System Performance

- Accuracy of single measurement: Position (At 1 m – 50 m range, one sigma) 6 mm; Distance (At 1 m – 50 m range, one sigma) 4 mm; Angle (horizontal/vertical) 60 µrad / 60 µrad (12" / 12")
- Modeled surface precision (Subject to modeling methodology for modeled surface)/noise: 2 mm
- Target acquisition (Algorithmic fit to planar HDS targets): 2 mm std. deviation
- Dual-axis compensator: Selectable on/off, resolution 1", dynamic range +/- 5', accuracy 1.5"

Laser Scanning System

- Type: Pulsed; proprietary microchip
- Color: Green, wavelength = 532 nm visible
- Laser: Class 3R (IEC 60825-1)
- Range: 300 m @ 90%; 134 m @ 18% albedo (minimum range 0.1 m)
- Scan rate: Up to 50,000 points/sec, maximum instantaneous rate
- Scan resolution: Spot size (From 0 – 50 m: 4.5 mm (FWHH-based); 7 mm (Gaussian-based)); Point spacing (Fully selectable horizontal and vertical; <1 mm minimum spacing, through full range; single point dwell capacity)
- Field-of-View: Horizontal (360° (maximum)); Vertical (270° (maximum)); Aiming/Sighting (Parallax-free, integrated zoom video)
- Scanning Optics: Vertically rotating mirror on horizontally rotating base; Smart X-Mirror™ automatically spins or oscillates for minimum scan time
- Data storage capacity: 80 GB onboard solid-state drive (SSD) or external USB device

- Communications: Dynamic Internet Protocol (IP) Address, Ethernet or wireless LAN (WLAN) with external adapter
- Integrated color digital camera with zoom video: Single 17° x 17° image: 1920 x 1920 pixels (4 megapixels); Full 360° x 270° dome: 260 images; streaming video with zoom; auto-adjusts to ambient lighting
- Onboard display: Touchscreen control with stylus, full color graphic display, QVGA (320 x 240 pixels)
- Level indicator: External bubble, electronic bubble in onboard control and Cyclone software
- Data transfer: Ethernet, WLAN or USB 2.0 device
- Laser plummet: Laser class: 2 (IEC 60825-1); Centering accuracy: 1.5 mm @ 1.5 m; Laser dot diameter: 2.5 mm @ 1.5 m; Selectable ON/OFF

Electrical

- Power supply: 15 V DC, 90 – 260 V AC
- Power Consumption: <50 W avg.
- Battery Type: Internal: Li-Ion; External: Li-Ion
- Power Ports: Internal: 2, External: 1 (simultaneous use, hot swappable)
- Duration: Internal: >3.5 h (2 batteries), External: >6 h (room temp)

Environmental

- Operating temperature: 0° C to 40° C / 32° F to 104° F
- Storage temperature: -25° C to +65° C / -13° F to 149° F
- Lighting: Fully operational between bright sunlight and complete darkness
- Humidity: Non-condensing
- Dust/humidity: IP54 (IEC 60529)

Physical

- Scanner: Dimensions (D x W x H) 238 mm x 358 mm x 395 mm / 9.4" x 14.1" x 15.6"; Weight 13 kg / 28.7 lbs., nominal (w/o batteries)
- Battery (internal): Dimensions (D x W x H) 40 mm x 72 mm x 77 mm / 1.6" x 2.8" x 3.0"; Weight 0.4 kg / 0.9 lbs.
- Battery (external): Dimensions (D x W x H) 95 mm x 248 mm x 60 mm / 3.7" x 9.8" x 2.4"; Weight 1.9 kg / 4.2 lbs.
- AC Power Supply: Dimensions (D x W x H) 85 mm x 170 mm x 41 mm / 3.4" x 6.7" x 1.6"; Weight 0.9 kg / 1.9 lbs.

Standard Accessories Included

- Scanner transport case
- Tribrach (Leica Professional Series)
- 4x Internal batteries
- Battery charger/AC power cable, Car adapter, Daisy chain cable
- Data cable

- Height meter and distance holder for height meter
- Cleaning kit
- Cyclone™ SCAN software
- 1year CCP Basic support agreement

Additional Accessories

- HDS scan targets and target accessories
- Service agreement for Leica ScanStation C10
- Extended warranty for Leica ScanStation C10
- External battery with charging station, AC power supply and power cable
- Professional charger for internal batteries
- AC power supply for scanner
- Tripod, tripod star, rolling base, external wireless LAN adapter (third-party)
- Notebook PC for scanning with Cyclone software D (Minimum requirements for modeling operations are different. Refer to Cyclone data sheet specifications)
    - Processor: 1.7 GHz Pentium M or higher
    - RAM: 1 GB (2 GB for Windows Vista)
    - Network card: Ethernet
    - Display: SVGA or OpenGL accelerated graphics card (with latest drivers)
    - Operating system: Windows XP Professional (SP2 or higher) (32 or 64) Windows Vista (32 or 64), Windows 7 (32 or 64)

Control Options

- Full color touch screen for onboard scan control
- Leica Cyclone SCAN software for laptop PC (see Leica Cyclone SCAN data sheet for full list of features)
- Remote controller (Leica CS10/15 or any other remote desktop capable device)

Leica BLK360

General

- Imaging scanner: 3D scanner with integrated spherical imaging system and thermography panorama sensor system

Design & Physical

- Housing: Black anodized aluminum
- Dimensions: Height: 165 mm / Diameter: 100 mm
- Weight: 1kg
- Transport cover: Hood with integrated floor stand
- Mounting mechanism: Button-press quick release

Operation

- Stand-alone operation: One-button operation

- Remote operation: iPad app, Apple iPad Pro® 12.9”/iOS 10 or later
- Wireless communication: Integrated wireless LAN (802.11 b/g/n)
- Internal memory: Storage for > 100 setups
- Instrument orientation: Upright and upside down

Power

- Battery type: Internal, rechargeable Li-Ion battery (Leica GEB212)
- Capacity: Typically, >40 setups

Scanning

- Distance measurement system: High speed time of flight enhanced by Waveform Digitizing (WFD) technology
- Laser class 1: (in accordance with IEC 60825-1:2014)
- Wavelength: 830 nm
- Field of view: 360° (horizontal) / 300° (vertical)
- Range (at 78% albedo): min. 0.6 - up to 60 m
- Point measurement rate: up to 360,000 pts / sec
- Ranging accuracy (at 78% albedo): 4mm @ 10m / 7mm @ 20m
- Measurement modes: 3 user selectable resolution settings

Imaging

- Camera System: 15 MP 3-camera system, 150Mpx full dome capture, HDR, LED flash Calibrated spherical image, 360° x 300°
- Thermal Camera: FLIR technology based longwave infrared camera; Thermal panoramic image, 360° x 70°

Performance

- Measurement speed: < 3 min for complete full dome scan, spherical image & thermal image
- 3D point accuracy (at 78% albedo): 6mm @ 10m / 8mm @ 20m

Environmental

- Robustness: Designed for indoor and outdoor use
- Operating temperature: +5 to +40° C
- Dust/Humidity: Solid particle/liquid ingress protection IP54 (IEC 60529)

Data Acquisition

- Live image and scanned data streaming
- Live data viewing and editing
- Automatic tilt measurements

APPENDIX B

Equipment Specifications

Small Unmanned Aircraft-borne Structure from Motion Photogrammetry

DJI Inspire 2

Aircraft

- Model: T650A
- Weight: 7.58 lbs. (3440 g, including propellers and two batteries, without gimbal and camera)
- Max Takeoff Weight: 9.37lbs (4250 g)
- GPS Hovering Accuracy: Vertical: ±1.64 feet (0.5 m) or ±0.33 feet (0.1 m, Downward Vision System enabled)
- Horizontal: ±4.92 feet (1.5 m) or ±0.98 feet (0.3 m, Downward Vision System enabled)
- Max Angular Velocity: Pitch: 300°/s; Yaw: 150°/s
- Max Tilt Angle: P-mode: 35° (Forward Vision System enabled: 25°); A-mode: 35°; S-mode: 40°
- Max Ascent Speed: P-mode/A-mode: 16.4 ft/s (5 m/s); S-mode: 19.7 ft/s (6 m/s)
- Max Descent Speed: Vertical: 13.1 ft/s (4 m/s); Tilt: 13.1-29.5 ft/s (4-9 m/s)
- Max Takeoff Sea Level: 1.55 mi (2500 m): 3.1 mi (5000 m with specially-designed propeller)
- Max Wind Speed Resistance: 10 m/s
- Max Flight Time: Approx. 27min (with Zenmuse X4S); Approx. 23min (with Zenmuse X7) (Hovering at sea level with no wind.)
- Motor Model: DJI 3512
- Propeller Model: DJI 1550T
- Indoor Hovering: Enabled by default
- Operating Temperature: -4° to 104° F (-20° to 40° C)
- Diagonal Distance (propeller excluded): 23.8 inch (605 mm, Landing Mode)
- Max Speed: 58 mph or 94 kph (Sport mode)

Remote Controller

- Model: GL6D10A
- Operating Frequency: 2.400-2.483 GHz; 5.725-5.850 GHz
- Max Transmitting Distance (unobstructed, free of interference): 2.4 GHz: FCC: 4.3 miles (7 km); CE: 2.2 miles (3.5 km); SRRC: 2.5 miles (4 km); MIC: 2.5 miles (4 km); 5.8 GHz: FCC: 4.3 miles (7 km); CE: 1.2 miles (2 km); SRRC: 3.1 miles (5 km); MIC: -;
- EIRP: 2.4 GHz: FCC: 26 dBm; CE: 17 dBm; SRRC: 20 dBm; MIC: 17dBm; 5.8 GHz: FCC: 28 dBm; CE:14 dBm; SRRC: 20 dBm; MIC: -;
- Video Output Ports: USB, HDMI
- Power Supply: Built-in battery

- Charging: DJI charger
- Dual User Capability: Host-and-Slave connection
- Mobile Device Holder: Tablet or Smart Phone
- Max Mobile Device Width: 170 mm
- Output Power: 9 W (Without supplying power to smart device)
- Operating Temperature: -4° to 104° F (-20° to 40° C)
- Storage Temperature: Less than 3 months: -4° to 113° F (-20° to 45° C); More than 3 months: 72° to 82° F (22° to 28° C)
- Charging Temperature: 32° to 104° F (0° to 40° C)
- Battery: 6000mAh 2S LiPo
- USB Supply Power: iOS: 1 A @ 5.2 V (Max); Android: 1.5 A @ 5.2 V (Max)

Battery (Standard)
- Model: TB50
- Capacity: 4280 mAh
- Voltage: 22.8 V
- Battery Type: LiPo 6S
- Energy: 97.58 Wh
- Net Weight: 515 g
- Charging Temperature: 41° to 104° F (5° to 40° C)
- Operating Temperature: -4° to 104° F (-20° to 40° C)
- Max Charging Power: 180 W
- Storage Temperature: Less than 3 months: -4° to 113° F (-20° to 45° C); More than 3 months: 72° to 82° F (22° to 28° C)

Downward Vision System
- Velocity Range: <32.8 ft/s (10 m/s) at height of 6.56 feet (2 m)
- Altitude Range: <32.8 feet (10 m)
- Operating Range: <32.8 feet (10 m)
- Operating Environment: Surfaces with clear patterns and adequate lighting (> 15 lux)
- Ultrasonic Sensor Operating Range: 0.33-16.4 feet (10-500 cm)
- Ultrasonic Sensor Operating Environment: Non-absorbing material, rigid surface (thick indoor carpeting will reduce performance)

Upward Infrared Sensor
- Obstacle Sensing Range: 0-16.4 feet (0-5 m)
- FOV: ±5°
- Operating Environment: Large-size non-reflective obstacles

Gimbal
- Model: ZENMUSE X7(optional); ZENMUSE X5S(optional); ZENMUSE X4S(optional)
- Angular Vibration Range: ±0.01°
- Controllable Range: Pitch: -130° to+40°; Roll: ±20°; Pan: ±320°

- Max Controllable Speed: Pitch: 180°/s; Roll: 180°/s; Pan: 270°/s
- Interface Type : Detachable
- Mechanical Range: Pitch: -140° to+50°; Roll: -50° to+90°; Pan: ±330°

Charger
- Model: IN2C180
- Voltage: 26.1 V
- Rated Power: 180 W

Charging Hub
- Model: IN2CH
- Input Voltage: 26.1 V
- Input Current: 6.9 A

Forward Vision System
- Obstacle Sensing Range: 2.3-98.4 feet (0.7-30 m)
- FOV: Horizontal: 60°; Vertical: 54°
- Operating Environment: Surfaces with clear patterns and adequate lighting (> 15 lux)

DJI Zenmuse X4S

General
- Dimensions: 125×100×80 mm
- Weight: 253 g

Camera
- Sensor: CMOS, 1"
- Effective Pixels: 20 MP
- Lens: F/2.8-11, 8.8mm (35 mm Equivalent: 24mm)
- FOV: 84°
- Photo Resolutions: 3:2, 5472×3648; 4:3, 4864×3648; 16:9, 5472×3078
- Video Resolutions: **H.264**; C4K: 4096×2160; 23.976/24/25/29.97/47.95/50/59.94p @100Mbps; 4K: 3840×2160; 23.976/24/25/29.97/47.95/50/59.94p @100Mbps; 2.7K: 2720×1530; 23.976/24/25/29.97p @80Mbps; 47.95/50/59.94p @100Mbps; FHD: 1920×1080; 23.976/24/25/29.97p @60Mbps; 47.95/50/59.94p @80Mbps; 119.88p @100Mbps: **H.265**; C4K: 4096×2160; 23.976/24/25/29.97p @100Mbps; 4K: 3840×2160; 23.976/24/25/29.97p @100Mbps; 2.7K: 2720×1530; 23.976/24/25/29.97p @65Mbps; 47.95/50/59.94p @80Mbps; FHD: 1920×1080; 23.976/24/25/29.97p @50Mbps; 47.95/50/59.94p @65Mbps; 119.88p @100Mbps
- Photo Formats : DNG, JPEG, DNG+JPEG
- Video Formats: MOV, MP4
- Operation Modes: Capture, Record, Playback

- Still Photography Modes: Single shot, Burst shooting: 3/5/7/10/14 frames, Auto Exposure
- Bracketing, 3/5 bracketed frames at 0.7EV bias, Interval
- Exposure Mode: Auto, Manual, Shutter Priority, Aperture Priority
- Exposure Compensation: ±3.0 (1/3 increments)
- Metering Mode: Center-weighted metering, Spot metering (area option 12×8)
- AE Lock: Supported
- Shutter Speed Mechanical Shutter: 8 – 1/2000s; Electronic Shutter: 1/2000 – 1/8000s
- White Balance: Auto, Sunny, Cloudy, Incandescent, Neon, Custom (2000K – 10000K)
- ISO Range: 100 – 6400 (Video); 100 – 12800 (Stills)
- Video Captions: Supported
- Anti-Flicker: Auto, 50Hz, 60Hz
- PAL/NTSC: Supported

Gimbal

- Angular Vibration Range: ±0.01°
- Mount: Detachable
- Controllable Range: Tilt: +30° to -90°, Pan: ±320°
- Mechanical Range: Tilt: +50° to -140°, Pan: ±330°, Roll: +90° to -50°
- Max Controllable Angular Speed: Tilt: 90°/s, Pan: 90°/s

Environmental

- Operating Temperature: 14° – 104°F (-10 to 40℃)
- Storage Temperature: -4° – 140°F (-20 to 60℃)

GeoCue Loki

- GNSS Engine Make and Model: Septentrio N. V. AsteRx-m2
- GPS: L1, L2, L5 (enabled)
- GLONASS: L1, L2, L3 (enabled)
- Support for: Galileo, BeiDou, IRNSS, QZSS (optional)
- Hardware Channels: 448
- Advanced Ionospheric Correction: IONO+
- Multi-path Mitigation: APME+
- Antenna: Maxtena (M1227HCT-A2-SMA)
- Typical Accuracy: 4.0 cm planimetric and 6.5 cm vertical

APPENDIX C

Equipment Specifications

Small Unmanned Aircraft-borne Light Detection and Ranging

Aircraft *(DJI M600)*

- Diagonal Wheelbase: 1133 mm
- Dimensions: 1668 mm × 1518 mm × 727 mm with propellers, frame arms and GPS mount unfolded (including landing gear) 437 mm × 402 mm × 553 mm with propellers, frame arms and GPS mount folded (excluding landing gear)
- Package Dimensions: 525 mm × 480 mm × 640 mm
- Weight (with six TB47S batteries): 9.5 kg
- Weight (with six TB48S batteries): 10 kg
- Max Takeoff Weight Recommended: 15.5 kg
- Hovering Accuracy (P-GPS): Vertical: ±0.5 m, Horizontal: ±1.5 m
- Max Angular Velocity: Pitch: 300°/s, Yaw: 150°/s
- Max Pitch Angle: 25°
- Max Wind Resistance: 8 m/s
- Max Ascent Speed: 5 m/s
- Max Descent Speed: 3 m/s
- Max Speed: 40 mph / 65 kph (no wind)
- Hovering Time* (with six TB47S batteries): No payload: 32 min, 6 kg payload: 16 min
- Hovering Time* (with six TB48S batteries): No payload: 38 min, 5.5 kg payload: 18 min
- Supported DJI Gimbals: Ronin-MX; Zenmuse Z30, Zenmuse X5/X5R, Zenmuse X3, Zenmuse XT; Zenmuse Z15 Series HD Gimbal: Z15-A7, Z15-BMPCC, Z15-5D III, Z15-GH4
- Flight Control System: A3 Pro
- Propulsion System: Motor model: DJI 6010, Propeller model: DJI 2170R
- Retractable Landing Gear: Standard
- Operating Temperature: 14° F to 104° F (-10° C to 40° C)

Charger (Model: MC6S600)

- Voltage Output: 26.1 V
- Rated Power: 600 W
- Single Battery Port Output Power: 100 W

Standard Battery (Model: TB47S)

- Capacity: 4500 mAh
- Voltage: 22.2 V
- Battery Type: LiPo 6S
- Energy: 99.9 Wh
- Net Weight: 595 g

- Operating Temperature: 14° F to 104° F (-10°C to 40° C)
- Max Charging Power: 180 W

Optional Battery (Model: TB48S)
- Capacity: 5700 mAh
- Voltage: 22.8 V
- Battery Type: LiPo 6S
- Energy: 129.96 Wh
- Net Weight: 680 g
- Operating Temperature: 14°F to 104° F (-10°C to 40° C)
- Max Charging Power: 180 W

Remote Controller
- Operating Frequency: 920.6 MHz to 928 MHz (Japan); 5.725 GHz to 5.825 GHz; 2.400 GHz to 2.483 GHz
- Max Transmission Distance: FCC Compliant: 3.1 mi (5 km), CE Compliant: 2.2 mi (3.5 km) (Unobstructed, free of interference)
- Transmitter Power (EIRP): 10 dBm @ 900M, 13 dBm @ 5.8G, 20 dBm @ 2.4G
- Video Output Port: HDMI, SDI, USB
- Operating Temperature: 14°F to 104° F (-10° to 40° C)
- Battery: 6000 mAh LiPo 2S

<u>LIDAR USA Snoopy A-Series 60</u>

- Laser Class: Class I (Eye Safe)
- Wavelength: 905 nm
- Measurement Technique: Time of Flight
- Minimum Range: 1 m (80% reflectivity)
- Maximum Range: 100m (80% reflectivity)
- Range Accuracy (1σ at 50 m): 25mm
- Laser Elements: 16
- Field of View: 360° Horizontal 20° Vertical
- Returns: Two
- Output Rate: 300,000 Points per second (1 return)
- Number of GNSS Antennas: One
- Support Navigation: L1 GPS
- Accuracy: 50mm (x, y) at 50 m AGL
- System Weight: 4.3lb / 1.95kg
- Battery Duration: LiPo 3S – (Two hours)
- Memory: Removable SD card

APPENDIX D

A Guide for Crime Scene Reconstruction Using Structure from Motion Techniques in Small UAS

Introduction

Small unmanned aircraft systems (sUAS), more commonly referred to as drones, can be used to collect imagery that can be processed into 2D and 3D models through structure from motion (SfM) software. This guide is intended to provide 95% of the content needed to collect imagery that will lead to high-quality models. The other 5% will be specific to your equipment and unique scenarios. As a result, we encourage you to take the information in this guide and adapt it to fit your specific needs. This guide does not cover nighttime image capture, SfM processing settings, nor does it include the implementation of ground control points, scale bars, or highly-accurate geotagged imagery. This guide contains the following sections:

- Legal Constraints
- Equipment Selection
- Data Collection
- Other Insights

It is highly recommended that a checklist be created for your sUAS data capturing missions. Following your checklist will ensure you capture consistent high-quality data.

Legal Constraints

It is critical to know the legal requirements for flying sUAS before you purchase and operate your equipment. This information is found through the following links:

- https://www.faa.gov/uas/
- https://www.faa.gov/uas/public_safety_gov/

It may be helpful to become familiar with the Department of Justice's UAS policy:

- https://www.justice.gov/jm/9-95000-unmanned-aircraft-systems-uas
- https://www.justice.gov/opa/pr/department-justice-announces-update-policy-use-unmanned-aircraft-systems

Equipment Selection

Payload and Aircraft

The sUAS should be selected based on its compatibility with appropriate imaging payload(s). These minimum specifications are common to most popular payloads:

Payload Minimum Specifications	
Item	**Explanation**
Capture visible light	This is red, green, and blue light, or simply, what human eyes can see.
Non-fisheye lens	A fisheye lens like those used in GoPro cameras should be avoided. Extensive image overlap is needed when using fisheye lenses due to their high distortion.
Fixed focal length lens	To ensure that the focal length of the lens is constant throughout data capture. Avoid zoom lenses. Inconsistent focal lengths will lead to an erroneous lens calibration.
One-inch sensor with 20-megapixels	A sensor of this size and megapixel count will typically have an acceptable balance of spatial resolution and low-light performance. Increasing the image sensor size while maintaining the same megapixel count would improve low-light performance (reduce the amount of noise in low-light imagery).
Three-axis gimbal with vibration dampening	This will reduce the likelihood of motion blur and will enable the user to point the camera in various angles.
Global shutter	This will ensure that the entire image captures one moment in time. Rolling shutters can be used, but they are not ideal. The term "mechanical shutter" is not synonymous with a global shutter. A mechanical shutter means there is a physical shutter that opens to expose light to the imaging sensor.

At least three 32 GB high-speed memory cards should be kept on-hand. The selection of the sUAS should be made based upon the ease of operation, encrypted communications (if applicable), and price. Nearly all sUAS used for scene reconstruction will have a multi-rotor configuration. These systems typically fly for 20 minutes, which is sufficient to cover most scenes in one flight. It is very important to become familiar with the sUAS you are operating. You can accomplish this by reading manuals, watching tutorial videos, and practicing missions.

Select a Mission Planning Application

There are endless paid and free choices for mission planning applications. They include DroneDeploy, Pix4D Capture, DJI Ground Station Pro, Litchi, UgCS, and Maps Made Easy. Our experience is primarily with Pix4D Capture and DJI Ground Station Pro, so this guide is written within the context of that experience. DJI Ground Station Pro is used if the camera settings must be set manually, otherwise Pix4D Capture is used.

Device (Apple, Android, Proprietary)

Each sUAS needs a unique device to interface with it. Most popular sUAS interface best with Apple iPads, and secondarily Android tablets. Some systems interface only with a laptop and others use a proprietary interface that is specific to the platform.

Data Collection

Data Collection Steps Become familiar with the procedures specific to your sUAS before using these steps. Combine the system-specific guidelines and the general steps outlined below to create a checklist for your sUAS data capturing missions. Following your checklist will ensure you capture consistent, high-quality data.	
Step	**Explanation**
Cache Base Maps and Check for Equipment Updates	Your device's access to an internet connection is an important consideration. Though not typically mission-critical, an internet connection is helpful for loading satellite imagery for base maps and for updating the equipment firmware. When an internet connection is unavailable, it is vital to ensure the equipment is updated and the satellite imagery of the area of interest (AOI) is cached before deploying to the mission location.
Power on sUAS on a Flat Surface in an Open Area	Most sUAS record a home waypoint when the system is first turned on. Because of this, it is vital to place the sUAS on a flat surface in an open area to ensure that the sUAS gets a good GPS signal. Also, it is essential to set the home waypoint away from large metal objects; they can interfere with the sUAS internal compass. Even rebar under paved concrete can cause this interference.
Camera Settings	
Manually Set the White Balance	Do not use the automatic white balance setting. This can cause the resulting 2D or 3D models to have inconsistent coloring. Since most imagery is captured in a JPEG format, the white balance cannot be changed in post-processing without data loss. Instead of auto white balance, use the sunny, cloudy, or manual settings to ensure the white balance is consistent throughout a mission.
Set the Focus to Infinity	The camera needs to have the same focus throughout the flight. Changing the focus will change the calibration parameters of the lens. When possible, manually adjust the focus to infinity. Sometimes this may not be an option, and only autofocus can be used. Autofocus is typically not a problem, because the camera will remain at an infinity focus regardless of the flight altitudes used. However, it is essential to know that autofocus introduces the possibility of a slightly erroneous lens calibration.
Adjust Exposure to -0.7 – 0.0 by Adjusting the Next Three Settings	Whether using auto exposure or adjusting settings manually, you are trying to achieve a properly exposed image. Most mission planning applications will show this exposure on a scale from -3 (completely black) to +3 (completely white) with steps of 0.3 and 0.7 between each whole number. Set the exposure anywhere from -0. to 0.0 depending on the sun conditions and the contents of the AOI. Full sun at midday with white reflective objects in the scene (such as cars), requires the exposure to be set at -0.7 to ensure

	that white objects are not washed out. Remember, it is better to have a darker image than to have an image with washed out areas.
Set Shutter to 1/800 of a Second or Faster	Proper shutter speed is one of the most critical settings. If you can adjust your camera settings manually, then use a shutter priority setting and set the shutter to 1/800 second or faster. This feature will lock-in the shutter speed and then adjust the ISO and aperture automatically to achieve the desired exposure.
Set ISO to Below 400	The next important camera setting is ISO. After manually setting the shutter speed, adjust the ISO to 400 or below if you can. Otherwise, set ISO to auto, knowing that ISO settings above 400 will introduce more noise into your imagery, thereby reducing their quality.
Set Aperture One Stop Lower than Full Open	Aperture is the least essential setting. Its primary effect, depth of field, is not noticeable when flying at typical sUAS altitudes. Aperture can remain on an auto setting, but it is useful to have it set a few settings smaller than its largest opening. This will reduce the vignetting impact on the images.
Adjust Camera Gimbal Setting to Fixed Pointing Forward	It is essential to pay attention to the gimbal mode before embarking on a mission. Some sUAS have the option to control the camera gimbal independently with a secondary controller. Such systems have a gimbal mode called "free" where the camera will maintain its field of view independent of the sUAS' rotation. This mode is not appropriate for SfM missions. Instead, set the gimbal mode to where it is fixed, pointing forward with the aircraft's nose.
Mission Parameters	
Set Mission Altitude to 10m Above Highest Obstacle	It is essential to be aware of any obstacles that are tall enough that your sUAS could contact them. This problem is typically more of an issue for very high spatial resolution and orbit flights, which are typically flown at lower altitudes. If there is a concern, perform a manual flight next to the tallest object to determine the object’s height and then set the automated mission to be at least 10 meters above that object.
Set Return to Home Altitude to 10m Above Highest Obstacle	An important consideration for flight altitude is the return to home (RTH) altitude, which is standard on most sUAS. This setting is the height at which the sUAS will automatically travel if the RTH feature is initiated. Remember to verify that the RTH altitude is at least 10 meters higher than the tallest object in your flight area.
Set Mission Altitude to Achieve Ideal GSD of ½cm to 1cm	The amount of coverage area and the spatial resolution, also known as ground sample distance (GSD), are inversely related. Covering more space in a flight means that you will need to fly higher, and thereby your spatial resolution will be reduced. The opposite is also true: high spatial resolution data requires a lower flight altitude, which means that less area can be covered in a flight. It is up to you as the user to determine if coverage area or spatial resolution is the higher priority. Typically, for small areas such as crime scenes, it is good to aim for ½ cm to 1 cm GSD.
Choose a Mission Profile: Single-grid (2D), Double-grid	Single-grid, double-grid, and orbit are the three categories of mission profiles you can use. The **single-grid** is the most common; it commands the sUAS to travel in a back-and-forth grid pattern over the AOI. This profile

(3D), Orbit (3D, small area)	is for larger, flat areas, where the primary goal is to obtain a 2D model. The camera angle is set to 90° straight at the ground (nadir). The **double-grid** pattern adds a perpendicular grid on top of a single-grid. This change adds flight time. Still, when combined with an off-nadir camera angle (pitch) (typically 70°), this mission profile improves the façade modeling of buildings and other 3D objects within the AOI. Keep in mind that double-grid missions require twice the flight time to cover the same area as a single-grid mission. The **orbit** mission profile is used for small areas where you need a 3D model. This profile sets the sUAS to orbit around the AOI with the camera pointing inwards. Then, images are captured at degree intervals around the orbit based on the user's preference, and the camera's pitch is set automatically. Typically, multiple orbits are used at different altitudes to gather additional camera angles of the AOI, which improves the model quality.
Use 75% Forward and Side Overlap	The literature varies widely on how much image overlap is needed to produce high-quality SfM data products. As a general rule, forward and side overlap will vary between 60%-80%, with a safe default of 75%-When mapping large areas and battery resources are low, then a compromise can be made by reducing the side overlap to 60% and increasing the forward overlap to 80%. This adjustment will reduce the number of transects, and as a result, will reduce the required flight time. However, you may need to fly the sUAS at a slower speed so the camera can keep up with the higher forward overlap. If the speed is not reduced, especially in low light conditions, you will increase the likelihood of motion blur in your images.
Overshoot Mission AOI by 10%	To ensure sufficient data capture of the AOI, always overshoot the mission by 10% of the total dimensions. If a crime scene is 100ft x 100ft, then you should overshoot the dimensions of the polygon so that it is 110ft x 110ft.
Establish the Flight Speed Slower than 10 meters per second	Slower flight speeds are required as flight altitude and ambient light decrease. Slower speeds are used to ensure that the camera has enough time to capture an image. This reduces the chance of motion blur and the potential for images to skip. An option for missions where motion blur is of particular concern is to use a "safe mode," also referred to as "stop and capture." This flight mode causes the sUAS to pause for each image capture. However, this mode creates a waypoint for each image capture, and most mission planning applications limit the number of waypoints per mission. This flight mode will also increase flight time.
Adjust the Flight Plan so the Last Waypoint is Closest to Your Location	When creating your flight plan, make sure that the ending waypoint (the end of the flight path), is the closest part of the flight plan to your takeoff location. This practice will ensure that your sUAS is close to where you want to land when its charge is low at the end of the flight.
Confirm Number of Batteries to Complete the Mission	Most mission planning applications will tell you how many sets of batteries it will take to complete the mission. If multiple batteries are required, then most apps will automatically send the sUAS to land at the home/takeoff location when the current batter reaches approximately 25%. Then you will power off the sUAS, remove the existing batteries, install fully charged batteries, and power on the sUAS. So long as the remote controller and

	tablet are kept on during this procedure, the mission planning application will then prompt you to resume the mission where the previous flight ended.
Set to Pause at the End of the Mission	Most mission planning applications allow you to preset the sUAS actions at the end of the mapping mission. It is best to have the sUAS pause. This will make sure you are intentional about when you want the aircraft to return home to land.
During Mission	
Verify Images are Being Captured	To ensure that images are saving during a flight, keep track of your memory card storage. Most mission planning applications will tell you how many more images can be stored on that card. You should see that number decreasing throughout the flight.
View Live Video to Ensure Correct Area is Being Captured	Most mission planning applications have a feature where you can see the live view of the imaging payload as it flies over the AOI. Use this feature to check that you are flying over the intended area.
After Mission	
Verify Image Quality	Upon completion of a flight, remove the memory card and view the imagery on a laptop or a larger screen. Inspect the imagery to verify it is properly exposed (not too dark, and no white-washed areas), is in focus, and does not have motion blur. Most SfM software has an image quality check feature that takes a couple of minutes to run and will automatically score the quality of the imagery.
Back up Imagery According to Your Data Storage Protocol	Follow your organization's data storage protocol first, and then use this guide as a supplement. A consistent naming scheme will reduce confusion and enable others to search and find specific data sets efficiently. Create a mission file that contains the date (YYYY/MM/DD), sUAS, sensor, and the location or another identifier. Then create sub-folders within this one to store your source imagery, processing files, data products, and any other data categories. Example: --20201125 M210 X4S Memorial Park --Source Imagery --Processing --Data Products If a mission requires multiple flights, remove the memory card and replace it with a new one for the next flight. Back up all of the imagery from the first memory card to a hard drive. After the mission is complete, back up all imagery to two hard drives, preferably in separate buildings. This protocol will help protect the data you have captured.
Record the Ambient Conditions	Record the wind, cloud cover, temperature, and any other condition that could impact the quality of the data you have captured. Save these notes in your mission folder.

Other Insights

Implementing Scale

There are no industry consensus standards for evaluating the measurement accuracy of an SfM model. The closest thing to these standards is one from the ASPRS, but this standard relates to the use of ground control points (GCP). GCPs are cumbersome and time-intensive, particularly if they are surveyed with RTK survey equipment. However, a faster and simpler alternative is found in Propeller's Aeropoints, which are GCPs with an integrated GPS receiver. The best GCPs have a contrasting gray and black checkered pattern or have a unique design, much like a QR code, to automatically tag the GCP. The quantity and spacing of GCPs are not clearly defined. Also, GCP implementation is financially expensive and adds time to the collection process. Simpler than ground control points are scale bars. A scale bar is any ridgid object with a known length. A good scale bar has a high contrast intersection (like the checkered GCPs) at the extents of the scale bars, so that its length is easily identifiable in the model.

Rapid 2D Mapping (Non-SfM Software)

The primary deterrent to SfM processing is the required time and computing resources necessary to generate the data products. There are alternatives to SfM processing that quickly produce only 2D models. Pix4D React and DroneDeploy LiveMap are examples of this category of providers. Such software has minimal computing requirements and will process the imagery into a seamless map in a few minutes if not in real-time. This software also requires less image overlap, sometimes as low as 50%. However, as with SfM, there are no industry standards for validating the accuracy of these products.

Sensor Lens Calibration

SfM software automatically performs a lens calibration for your specific sensing payload. This step provides a high level of accuracy in the 2D and 3D models that used to be available only with metric-quality lenses. You can choose to have the SfM software perform this calibration for every flight, or you can calibrate your lens in a lab setting, save the calibration as a file, and use this file for all subsequent datasets. The latter option may lead to more consistent SfM data products.

JPG vs RAW

Most mission planning applications will only allow you to capture in the JPEG format, which is sufficient for most uses. However, data captured in a RAW image format is uncompressed data (stores the most amount of information).

Ambient Conditions

Winds: It is important to be aware of how the ambient environmental conditions will impact the operation of the sUAS and the quality of the imagery. Winds higher than 25mph can exceed some sUAS operational constraints. Winds 15mph-25mph can cause extensive movement of objects within a scene such as crime scene tape or vegetation. These objects will likely be blurry in the imagery due to this movement. If the blur is extensive, it could cause holes in the resulting models.

Precipitation: Collecting imagery in precipitation is not recommended.

Temperature: Most sUAS have an ambient temperature operating range of 32°F-100°F. Temperatures outside of this range primarily impact battery performance. Below this threshold, batteries need to be warmed. Above this threshold, batteries risk overheating.

Clouds: Cloud cover can impact the quality of the imagery. Completely sunny or completely overcast conditions are preferred. Partly cloudy conditions can lead to shadowy imagery where passing clouds cause some areas to be darker than others.

Sun Angle: It is vital to consider the angle of the sun. To avoid elongated shadows cast by objects within the AOI, the user should collect imagery when the sun is 30° above the horizon. During summer months and in locations close to the equator, there is an increased likelihood of hot spots in the imagery. A hot spot is when the sun is behind the imaging sensor and causes a whitewashed area in the images. Hot spots will occur more often over homogenous regions, such as open fields, and with cameras with shorter focal lengths. Extremely homogenous areas (such as fields), my not process in SfM software. If the AOI is uniform, the SfM software is unable to recognize unique features. Holes are left in the model where this uniformity is present.

Geotags

Most sUAS will automatically tag the imagery with a GPS location and altitude above sea level. This is known as geotagging the image. These tags are accurate to within 1to 3 meters. Geotagged pictures process faster than non-geotagged images. Also, these geotags enable the resulting 2D and 3D models to be placed close to their real-world location in a geographic information system (GIS) such as Google Earth. If more geographic accuracy is desired, then high-accuracy geotags or GCPs can be used.

APPENDIX E

Manuscript

This last year, the Applied Aviation Research Center (AARC) at Kansas State University Polytechnic (KSUP) has been working with the Kansas Bureau of Investigation, the Riley County Police Department and the Kansas City Police Department in Missouri to evaluate and compare small unmanned aircraft systems (sUAS) remote sensing technologies to the conventional methods of terrestrial laser scanning (TLS) for forensic documentation, identification, processing and reconstruction. Funded through the National Institute of Justice, a subset agency of the Department of Justice, the Research and Development in Forensic Science for Criminal Justice Purposes Program afforded KSUP and their law enforcement partners the opportunity to explore the integration of public use UAS remote sensing in crime scene data collection and reconstruction. This research, titled "Evaluation of Terrestrial Laser Scanning and Aerial Remote Sensing with sUAS for Forensic Crime Scene Reconstruction" comes from a seven-month sponsored grant with the intent introduce commercial sUAS as a utility to public use agencies. Applications involving the use of sUAS, also referred to as drones, promote safety and efficiencies and could revolutionize the methods in which law enforcement agencies conduct crime scene investigations. Pragmatic use of UAS for law enforcement may include: (1) search and rescue missions, (2) damage assessment, (3) disaster response and recovery, (3) explosive ordinance disposal, (4) response and assessment of hazardous materials (HAZMAT), (4) aerial surveillance, (5) and crime scenes/crime scene reconstruction, to name a few. The primary objective of this project was to:

1. Compare the efficiency and quality of sUAS airborne based electro-optical sensors to ground-based methods (i.e. Terrestrial Laser Scanning) for crime scene reconstruction.

2. Compare the efficiency and quality of sUAS airborne based LIDAR sensor to ground-based methods (i.e. Terrestrial Laser Scanning) for crime scene reconstruction.

Crime-scene reconstruction is the forensic scientific discipline dedicated to sequencing and understanding the events surrounding a criminal event. Reconstruction of a crime scene aids and contributes to the historic preservation of information and could assist investigators to better understand the totality of the circumstances, to identify the cause, and potentially could provide valuable information for law enforcement to apprehend the offender(s). In court proceedings, the reconstruction of a crime plays an important role by providing a visual depiction of the crime scene environment in time and space. Data collected at a crime scene during investigation is a time-sensitive and meticulous task that requires a level of high fidelity and integrity in the data captured to ensure accurate collection of evidence all while avoiding evidence contamination. Currently, there are a variety of terrestrial remote sensing aids used by crime scene investigators and forensic scientists to gather evidence and details of a scene. Technologies include hand-held cameras, terrestrial laser scanners, and other measurement devices. Incorporating the use of sUAS airborne based remote sensing in crime scene investigations and reconstruction could offer an advantageous vantage point (i.e. aerial perspective) in a cost-affordable, efficient and safe manner. There is an inherent need across the law enforcement community to streamline data analysis by enhancing automation and computer system interfaces to minimize back-end work all while enhancing data preservation and distribution. The use of digital data captured from an aerial perspective with sUAS could aid to reduce contamination and streamline data collection and analysis.

Additionally, capturing evidence from an aerial perspective may increase details collected at a crime scene by providing an aerial vantage point not often attained through terrestrial applications and collection methods. Aerial data acquisition using sUAS equipped with a high-resolution sensor payload offers a significant advantage in terms of effectiveness and efficiency on the time required to set-up and launch equipment for data collection. Ultimately, minimizing the data collection time may decrease instances of crime scene contamination thereby enhancing the preservation of evidence. Although there are technological and operational advantages of incorporating sUAS systems for law enforcement use, the exponential and rapid growth of this technology implicates procedure, training, and policy challenges. The aim of this article is to expand the scientific basis of sUAS use for forensic data collection by sharing the lessons learned from our experiences in implementing sUAS in a law enforcement paradigm for crime scene reconstruction. Additionally, this article aims to inform police chiefs across the country on the utility and cost for implementing such programs within their respective agencies.

Remote Sensing and Photogrammetry

"Photogrammetry and remote sensing is the art, science, and technology of obtaining reliable information about physical objects and the environment through the process of recording, measuring and interpreting imagery and digital representations of energy patterns derived from non-contact sensor systems." [1].

Photogrammetry describes the science of making accurate measurements through the use of aerial imagery. An aerial photograph can be captured from a vertical or oblique vantage point. A vertical photograph as depicted in figure 1 is obtained when a camera's optical axis is within +/- 3 degrees of being perpendicular (i.e. vertical) to the earth's surface [1]. An oblique aerial photograph is captured when the camera's optical axis exceeds +/- 3 degrees of the vertical as depicted in figure 2.

A series of aerial photographs along a flight line encompassing stereoscopic overlap forms the basis for structure from motion (SfM) digital photogrammetry and three-dimensional (3D) image reconstruction. The term overlap is an important construct as it provides, at a minimum, at least two digital vantage views of an object, artifact, or coordinate of the real world across the flight line in consecutive photographs. To cover a geographic area of interest effectively, multiple flight lines of digital aerial photos with calculated overlap is required. In traditional aerial photography, a 60% front overlap and 20-30% side overlap is required to establish stereoscopic parallax in a final processed data set to establish stereoscopic viewing.

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1. Jensen, J. R. (2007). *Remote sensing of the environment: An earth resource perspective* (Second Ed.). Upper Saddle River, N.J: Pearson.

Regarding airborne sUAS aerial photographs acquired with high resolution payload onboard sUAS, a higher degree of image overlap (i.e. approximately 80%) is utilized to ensure a greater degree of accuracy in image construction (i.e. mosaics) when using industry standard software applications such as Pix4D Mapper and Agisoft Metashape. With that stated, precise quantitative planimetric object locations (e.g., evidence markers, footprints, tire tread markings, buildings, streets, etc.) could be extrapolated from digital stereoscopic image evaluation to aid law enforcement methods for data collection and crime scene analysis.

Figure 1. Vertical Aerial Photograph.

Figure 2. Oblique Aerial Photograph.

As previously mentioned, the key aspect to photogrammetry is the acquisition of consecutive overlapping aerial photographs (see Figure 3). Sophisticated industry standard software applications afford the ability to generate mosaics of orthoimages images captured by remotely sensed photographs. Orthorectification is a post processing technique used to reduce terrain and artifact induced displacement (i.e. tilt and relief, respectively) to enhance planimetric accuracy. The orthorectification process ensures a consistent scale across the images in which features as represented on the ground are in their true positions in the images captured. Overall, the accuracy of a digitized orthoimage is a function of image quality, ground control, and triangulation [1]. The necessary components to support this photogrammetry application include: (1) a small unmanned aircraft system, (2) a calibrated high-resolution camera payload, (3) a computer with quality graphics cards and fast processing speeds, and (4) mapping software to process the images collected. On scene, all that is required is the unmanned system with a selected payload.

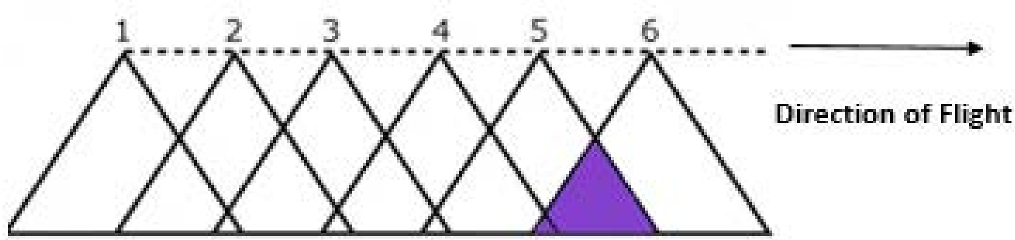

Figure 3. Overlapping Aerial Photographs

The final output is often a high resolution 3-D model of the real-world object or scene as depicted in figure 4. In retrospect, multiple overlapping photos (i.e. blocks of aerial photographs) within the instantaneous field of view on the ground are captured as the aircraft flies along a specified flight path. These images can be maintained on-board the unmanned aircraft via an SD card or streamed to a ground control station in near-real-time where the images can be stored and post-processed using the aforementioned software applications. The resultant output is a high-resolution map or high-fidelity 3D model (see Figure 4) of the scene in which distance measurements could be attained.

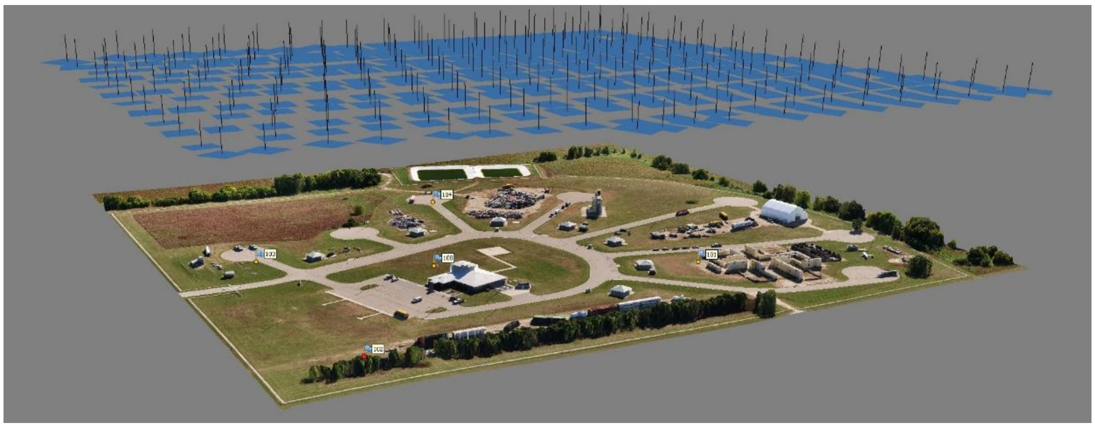

Figure 4. 3-Dimensional Model with Camera Position

In retrospect, photogrammetry is not new. In fact, photogrammetry has existed nearly as long as photography has been in fruition [2]. Certainly, we have experienced a shift from pure analog methods of photogrammetry (i.e. hardcopy photogrammetry) to digital applications of photogrammetry (i.e. softcopy photogrammetry) based on computer vision applications and digital imagery. Nonetheless, the basic principles of photogrammetry and photogrammetric measurements relies on the geometrical and mathematical reconstruction of electromagnetic energy patterns collected at a sensor [2]. With the advent of sUAS applications and airborne based data collection, the UAS industry has experienced a rapid transformation in the availability of photogrammetric software applications. This rapidly evolving field of photogrammetric software offers practitioners an opportunity to establish robust data products using commercial-off-the-shelf (COTS) software that is effective, efficient and easy to use. Departments that may not have access to traditional aviation assets may find that implementing a sUAS program is a worthwhile and cost-effective solution to aid first responder's with specific mission sets (i.e. surveillance, search and rescue, crime scene data collection, SWAT).

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2. Aber, J. S., Marzolff, I., & Ries, J. B. (2010). *Small-Format Aerial Photography: Principles, Techniques and Geoscience Applications*. https://doi.org/https://doi.org/10.1016/C2009-0-18493-3
3. U.S. Department of Justice, National Institute of Justice (2016). *Considerations and Recommendations for Implementing an Unmanned Aircraft Systems (UAS) Program* (NCJ Publication No. 250283). Washington D.C. Retrieved from National Criminal Justice Reference Service: https://www.ncjrs.gov/App/Publications/abstract.aspx?ID=272443

According to a 2016 report by the U.S. Department of Justice, there were approximately 350 law enforcement agencies in the United States with active aviation programs in place [3]. The substantial cost associated with implementing and maintaining a traditional aviation program or aviation units on the premise of operating fixed and rotary wing aircraft may be prohibitive for some agencies across the country. Additionally, depending on the technical requirements related with some public safety missions, manned aviation assets may not always be the most suitable technology in a response scenario [3]. Rapid advances in sUAS technology may aid to remediate the cost and complexities of establishing law enforcement aviation programs. A cost-effective approach may be achieved by leveraging COTS unmanned systems as an alternative to a traditional aviation unit based on manned aircraft as in existence today. On average and in comparison with implementing a traditional aviation unit, the cost of implementing a sUAS aviation unit is relatively lower with costs ranging from $21,000 to $60,000 depending on the type of system(s) and payload selected. Training, operator certification, and support equipment (i.e. spare batteries, generators, tooling, high-processing computers, tablets, external hard drives etc.) has been considered in this approximation.

Implementing sUAS Technologies in Crime Scene Reconstruction

In 2018, the NIJ Forensic Science Technology Working Group identified the need to improve technologies and capabilities for crime scene data collection and visualization. The purpose of this research sought to address this need by providing crime scene investigators and forensic scientists with a thorough understanding on the effectiveness, efficiency and reliability achieved with sUAS airborne remote sensing for crime scene reconstruction. To accomplish this, the research team conducted both quantitative and qualitative assessments of three remote sensing methods: (1) aerial structure from motion (SfM) photogrammetry, (2) aerial laser scanning, and (3) terrestrial laser scanning with an overarching goal to develop a roadmap that can serve as a guide for law enforcement to select appropriate sUAS tools for crime-scene data collection and reconstruction. Provided the potential advantages associated with implementing sUAS airborne remote sensing for law enforcement applications, the following research questions were investigated as part of this study:

1. What is the level of error for the models generated with each reconstruction method?
2. How complete is each model?
3. What are the environmental limitations of each method?
4. How do environmental factors such as sun, clouds, wind, night, day, precipitation affect the quality of the digital model?
5. What is the appropriate selection of sensing technology based on crime scene variables?

Methodology

The Crisis City Training Center (CCTC), a disaster training center for emergency response personnel located eight miles southwest of Salina, Kansas, served as the testbed for this research. Crisis City is operated by the Kansas Division of Emergency Management and boasts acres for local, state, and federal responders, emergency managers and public and private safety professionals to utilize this full functioning training complex for safety awareness and disaster response training. Overall, CCTC is a multi-agency and multi-disciplinary training environment.

Access to the CCTC was available for use through a collaborative relationship with Kansas State University. At CCTC, three mock crime scenes were simulated as depicted in figure 5 to include:

1. An urban scene established to resemble a carjacking/shooting. The urban scene included broken glass, bullet casings of various calibers, pseudo-blood trails/pools, and firearms.
2. A forest area scenario involving a hanging/suicide. This scene contained multiple pieces of clothing, empty alcohol containers, simulated narcotics representations, and rope.
3. A clandestine grave in an open field. This scene included a shovel, cell phone, clothing in plain sight and partially buried, and restraints.

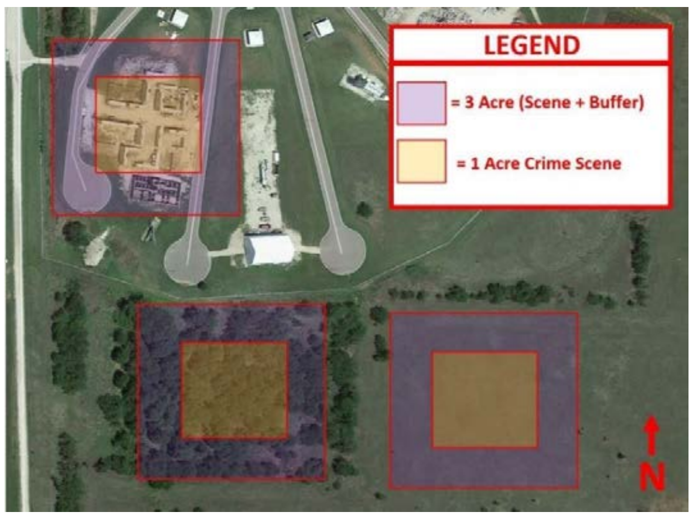


Figure 5. Mock Crime Scene Locations at Crisis City Training Center

Experimental Design

This project utilized an exploratory applied research method and case study approach. Both quantitative and qualitative data was collected as a component of this study. For each simulated crime scene, the data collection and reconstruction was evaluated during day and night conditions. Measurement error and point cloud density served as the primary quantitative metrics. Qualitative metrics included: (1) ease of data acquisition, (2) completeness of the model, and (3) environmental effects. Table 1 provides a visual depiction of the data evaluation matrix as established for this research study.

Table 1

Data Evaluation Matrix

Method/Sensor	Ambient Light	Data Collect Flights	Metrics	
			Quantitative	**Qualitative**
Terrestrial laser scanner	Day	1	• Measurement error • Point cloud density • Time to collect data • Cost	• Ease of data acquisition • Environment effects • Completeness of model
	Night	1		
Airborne EO for SfM	Day	1		
	Night	2		
Airborne LIDAR	Day	1		
	Night	2		

Artifacts, essentially pseudo-evidence, was inventoried for each simulated crime scene by physical description, quantity, and location (i.e. latitude and longitude) and distributed across three simulated scenes on one acre of the CCTC facility (Figure 6). The “evidence,” or articles used in each of the crime scenes were placed by our law enforcement forensic subject matter experts. A general assumption established by the research team as regards the placement of evidence was that each scene should be located outdoors and accessible from any direction. Figure 6 depicts crime scene marking tools, evidence, and the Major Incident Response Command Center provided and utilized by one of our industry partners, the Kansas Bureau of Investigation (KBI).

(A) (B) (C) (D)

Figure 6. Evidence: (A) Firearm Casing and (B) Shovel, and (C) Broken Glass, and (D) KBI’s Major Incident Response Command Center

Data Collection

Terrestrial Laser Scanning (TLS)

A team of four KBI agents collected TLS data on each scene during day and night. The team used the Leica C10 and BLK360 at various resolution settings for data acquisition. These scanners were placed strategically in multiple locations throughout each of the scenes based upon the KBI team's subject matter expertise and experience. In total, the KBI team utilized two C10s and three BLK360s. This afforded the agency to utilize multiple scanners simultaneously. The final product from the TLS data collection was a point cloud database established for each scene during both day and night conditions.

Structure from motion Photogrammetry

The sUAS airborne SfM photogrammetry data was collected using two different data collection methods (i.e., single-grid and double-grid image capture). A flight plan at 18 meters above ground level (AGL) with 80% forward overlap and 60% side overlap was used to capture imagery for the urban and field scenes following established SfM industry standards for electro-optical photogrammetry. Alternately, the forest scene flight plan was established at 30 meters AGL to avoid vertical obstructions. Single-grid missions were flown for both day and night data collection. The camera was positioned 90 degrees perpendicular to the Earth's surface (nadir) and the white balance electro-optical camera parameter was set to sunny or cloudy based on the ambient conditions during data collection.

The second SfM method implemented for data collection was a double-grid flight pattern utilizing a low oblique camera position (i.e., 70 degree viewing angle). The double grid data collection method was used to structure a perpendicular overlay grid pattern as a complement to the initial single-grid flight pattern. Similar to the single grid method, an 80% front overlap was utilized with a slight increase of side overlap established at 70% to compensate for off-nadir viewing. Altitude for data collection was established at 30 meters AGL. Figure 7 and figure 8 provide a visual depiction of the single and double grid mission plan, respectively. Regarding low oblique camera positions, this change in camera viewing perspective, in combination with enhanced side overlap, often improves the quality of data rendering and reconstruction for certain mission sets. Specific to the urban scene, this technique was useful to capture the façade of structures when using SfM photogrammetry software to reconstruct structures in an urban environment. The double-grid flights were only conducted during the day because the change in camera angle (i.e. oblique) would omit the possibility of illuminating the AOI with the spotlight on-board the sUAS. At present, Title 14 Code of Federal Regulations (CFR) part 107 establishes the regulatory framework to operate sUAS in the National Airspace System; however, an important consideration is that night operations are prohibited under the confounds of this regulation and a waiver petition to the Federal Aviation Administration (FAA) was submitted to operate outside the scope of 14 CFR part 107. Regarding camera settings for the night data capture, the white balance was set to the same parameter as with the single-grid mission.

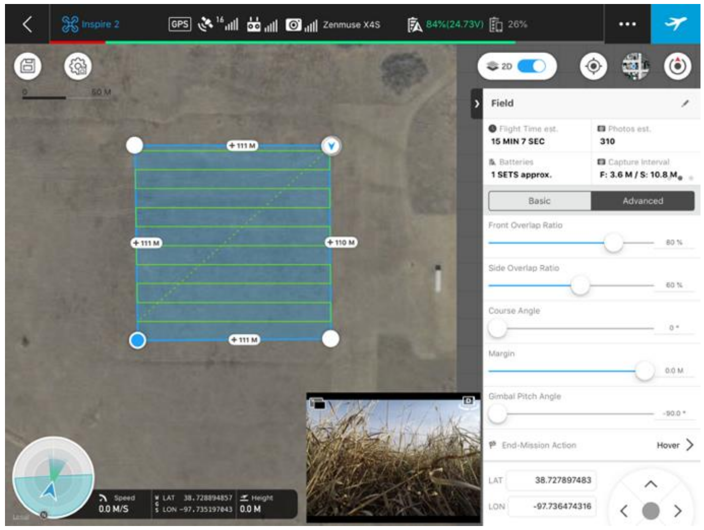


Figure 7. Single-Grid Mission Planning (DJI Specific)

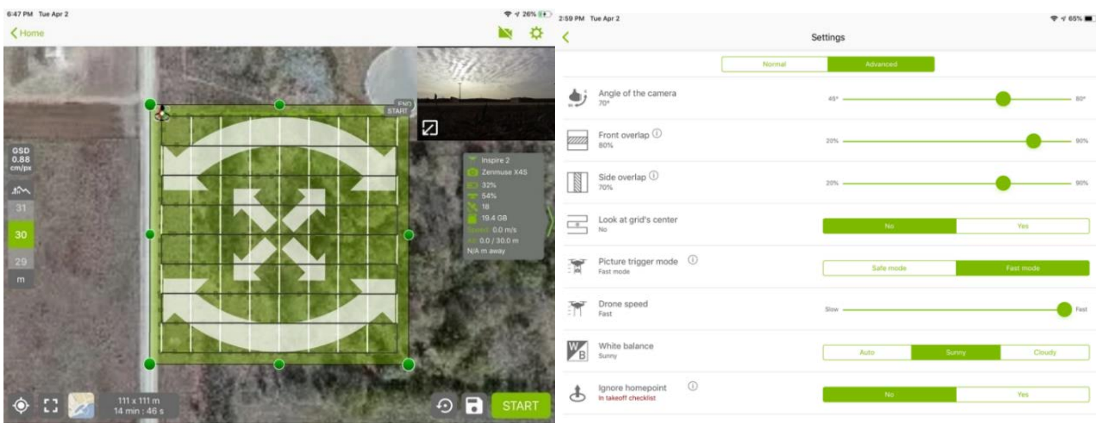


Figure 8. Double-Grid Mission Planning (Pix4D Capture)

Light Detection and Ranging (LIDAR)

The sUAS airborne LIDAR flight was executed using a raster pattern at 18 and 36 meters AGL. To ensure superior coverage, the sUAS was launched at the start end of the area of interest (AOI), traversed the AOI using waypoint navigation similar to the single grid plan, and returned utilizing the same grid path to ensure adequate data collection coverage throughout the entire AOI. Transects in flight were established to extend past the AOI by approximately 15 meters as a mechanism to generate useful overlap. This supported data collection to ensure sufficient data capture for post-processing. Alternately, these flight and data collection techniques help to minimize method-produced errors thereby enhancing the confidence interval for the data collected. Other advantages for incorporating this method include onboard Inertial Measurement Unit (IMU) stabilization. This minimizes gyroscope tumbling and erroneous outputs. Any abrupt turns extended outside the parameter of a standard-rate turn could lead to erroneous point cloud data, ultimately, a result of noise in the final data sets. All LIDAR data sets had a path spacing of 30 meters with the sUAS-borne LIDAR field of view (FOV) at 90 degrees. The resultant swath overlap was 17% for the low altitude and 60% for the higher altitude flights.

The sUAS was flown at a velocity of 4.5 meters per second with a LIDAR head speed established at 1200 RPM.

Results and Analysis

Quantitative variables to include time to collect data, measurement error, point cloud density, and cost were analyzed as a product of this work. Qualitative metrics were recorded anecdotally. The qualitative parameters as regards ease of data acquisition and environmental effects were captured through field notes prior to the start of each data collection activity. Completeness of model, the final qualitative parameter, was evaluated using an inter-rater scale methodology in which multiple subject matter experts analyzed and annotated their results of pertinent features and evidence as recorded by the various sensors across each scene. Last, cost was evaluated by establishing the financial investment required by a law enforcement entity to purchase sUAS for SfM, TLS, and sUAS with LIDAR.

Time to Collect Data:

Time to collect evidence data is a critical component for any crime scene investigation. The potential for crime scene contamination increases as time elapses after the crime. Therefore, law enforcement personnel aspire to maximize the quality and quantity of data captured about a scene in as little time as possible. Table 2 provides the data collection time across each sensing modality. As evident in Table 2, data voids were presented in the SfM double grid missions for each scene and the single grid forest night SfM scene. These data sets were omitted as night data collection using SfM photogrammetry and onboard illumination via a spotlight has limitations.

When observing time to complete data collection as a component of this research, it is evident that the TLS trial iteration was the most cumbersome with a mean score of 33 minutes for the field day and night scene, 82 minutes for the forest day and night scene, and 93.5 minutes for the urban day and night scene. In comparison, the mean scores for the sUAS LIDAR data collection was 16 minutes for the field day and night scene, 7 minutes for the forest day and night scene, and 24 minutes for the urban day and night scene. Alternately, the mean scores for the single grid SfM data collection was 12 minutes for the field day and night scene, 4 minutes for the forest day only, and 14 minutes for the urban day and night scenarios. Last, the mean scores for the double grid SfM data collection was 14 minutes for the field day scene, 12 minutes for the forest day scene, and 12 minutes for the urban day scene. The oblique vantage point was a limiting factor for accurate night data collection using a double-grid SFM photogrammetry paradigm across each simulated scenario and therefore, time to collect data was not captured under this construct. Last, as represented in Table 2, the forest night scene using a SfM single grid format also encompassed data voids and therefore, data collection time was not captured.

Table 2.

Data Collection time

Data Set Location and Ambient Condition	Time in Minutes			
	TLS	sUAS LIDAR (% of TLS)	SfM Double Grid (% of TLS)	SfM Single Grid (% of TLS)
Field Day	36	16 (44%)	14 (39%)	12 (33%)
Field Night	30	16 (53%)		12 (40%)
Forest Day	95	7 (7%)	12 (13%)	4 (4%)
Forest Night	70	7 (10%)		
Urban Day	127	24 (19%)	12 (9%)	17 (13%)
Urban Night	60	24 (40%)		11 (18%)

Measurement Error:

Measurement error is a critical parameter for airborne data collection and photogrammetry as measurement error corresponds to the level of confidence in the data collected. By rule of thumb, there is always a level of acceptable error in remotely sensed data and therefore, the user of this data must understand the sources of error, implement means to mitigate errors, and use methods to measure and articulate these errors effectively. To ensure maximum accuracy, the team placed scale bars (Figure 9) of known measures throughout the scene and used this known measurement as a comparison to the dimension recorded by the sensor at altitude.

Figure 9. Scale Bar

Unfortunately, the research team was unable to use this method across each of the remote sensing modalities. The original proposal suggested the need for 28 scale bars per scene oriented in horizontal and vertical positions. Using an in-situ approach, the researchers determined that nine scale bars per scene would suffice to establish the measurement accuracies desired. In the field, five scale bars were placed within the scene area while the other four scale bars were placed around the border of the scene to establish the perimeter. The National Institute of Standards and Technology (NIST) standard for evaluating accuracy using industry-standard TLS equipment suggests the use of a single scale bar in the first and last scan of the crime scene capture. Therefore, a reduction in scale bars for this research was complimentary at nine when compared to the single scale bar standard used by crime scene investigators today but fell short of what is truly required in the field. Instead, sensor-specific evaluation methods were used. Instead of a validated accuracy using a scale bar approach across each sensor modality, the research team elected to use the sensor manufacturer's specified typical accuracy of +/- 3cm. For the TLS, the mean absolute error reported from Leica Cyclone was used as an indicator, and the average scale bar error was used for the sUAS-borne SfM data sets. The results for measurement error for TLS and SfM set is presented in Figure 11.

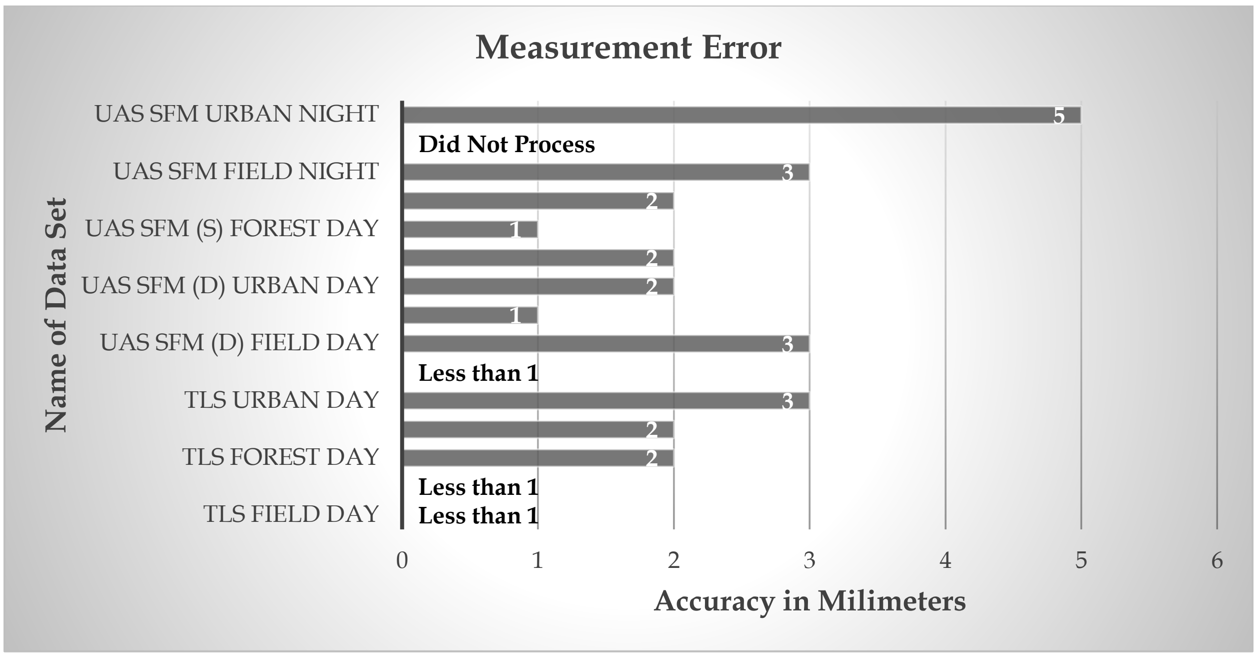


Figure 10. Measurement Error

Point Cloud Density:

The final quantitative metric, point cloud density, indicates the amount of distinguishable detail in the model. The final development with regards to the quantitative metrics was the ability to evaluate point cloud density for TLS and sUAS LIDAR airborne data collection. Originally, this was thought to be a simple measurement of points per square meter; however, the research team discovered this unit of analysis did not achieve its indented goal, which was to describe the level of distinguishable detail in the point clouds across sensing modalities. The results indicated that even if there is a sufficient density of points in the TLS or LIDAR data, it does not necessarily mean that features are distinguishable when observing these data sets.

As with measurement error, The TLS sensors were unable to view most of the horizontal scale bars due to their line-of-sight perspective from their tripod-mounted position. At approximately 1.5 meters above the ground, the TLS equipment rotated to scan 360 degrees horizontally and nearly 360 degrees vertically. By inherent design, the TLS can only scan objects visible from its line-of-sight angle. This perspective made it difficult for the sensor to scan the upward face of an object lying perpendicular on the ground. Since the research team was not aware of this limitation during data collection, only a few horizontal scale bars were optimally spaced from the TLS for them to be visible in the data. In retrospect, since a direct comparison could not be achieved, accuracy was assessed by methods specific to each remote sensing modality. For the TLS data, a NIST pole in the first and last scans per the original equipment manufacturer (OEM) guidelines was implemented in addition to the mean absolute error as reported by the Leica Cyclone processing software. The research team was unable to validate sUAS-borne LIDAR data and was only able to use the manufacturer's specification for accuracy in lieu of a reported accuracy from the point clouds. Last, the SfM data was evaluated for accuracy using the scale bars.

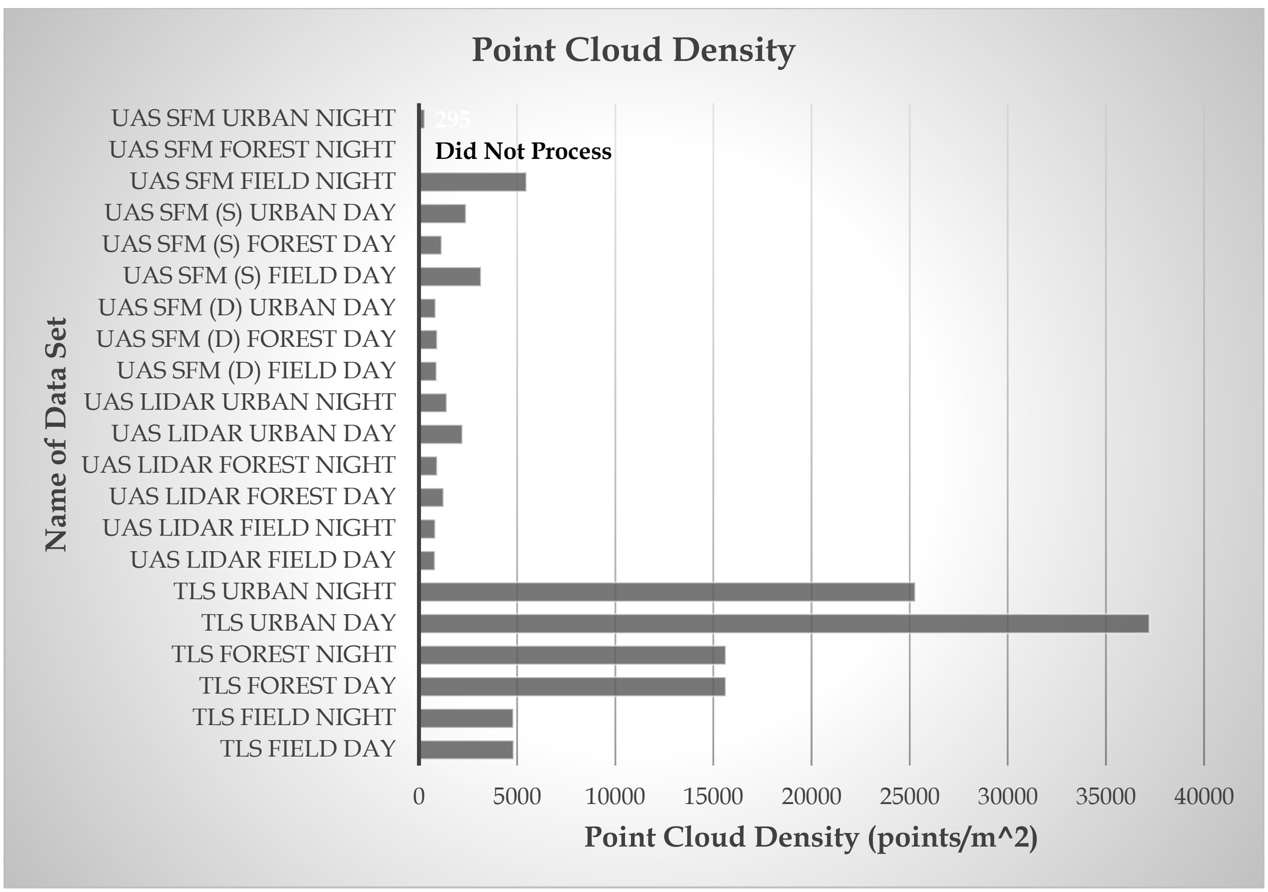


Figure 11. Point Cloud Density

Cost:

The last quantitative metric evaluated was cost of technology acquisition. As previously mentioned, only a small sector of law enforcement agencies have the monetary resources to establish aviation units based on traditional aircraft. Small UAS could serve as an aviation technology to bridge this gap. Typically, sUAS airborne technologies offer a lower acquisition cost when compared to TLS and LIDAR scanning tools. As a component of this study, the KBI's TLS equipment was used as an estimate cost. On average, the Leica C10 was approximated at $20,000 (used) with the Leica BLK360s approximated each at $16,000. As the Leica C10 is an antiquated technology and no longer sold as a new product, a more helpful price comparison for a state-of-the-art replacement to the C10 is the Leica RTC360. The approximate cost for the RTC360 is $75,000. As regards sUAS-borne LIDAR, the cost of the LIDAR rivaled the cost of TLS equipment with a LIDAR payload sensor cost of $55,000. In addition to the sensor acquisition cost, additional cost for support equipment is required. An average of $15,000 may be required for the acquisition of a sUAS platform and other support equipment. Last, the SfM equipment was identified as the least expensive with a minimum total value of $15,000, which included the sUAS platform, an electro-optical sensor, and other support equipment. As previously mentioned, the system acquisition costs for sUAS may range from approximately $20,000 - $ 60,000 for multiple systems with electro-optical payload. System cost is summarized and depicted in Table 3. Last, financial considerations should also include a buffer for crew qualification training, recurrent training, and maintenance costs.

Table 3.

System Costs

Remote Sensing Technology	System Make & Model	System Cost
TLS	Leica C10	$250,000 (new) $20,000 (used)
	Leica BLK360	$16,000
	Leica RTC360	$75,000
sUAS LIDAR	DJI M600, LIDAR-USA Snoopy A-Series 60	$70,000
sUAS SfM	DJI Inspire 2, DJI X4S, AirGon Loki	$15,000

Ease of Data Acquisition:

The ease of data acquisition was the first qualitative metric evaluated by the research team. This metric was closely related to the time to collect data. Factors such as ease of transportation, the complexity of the operation, and the extent of mission planning were sub-factored into this metric. When disassembled, the TLS equipment can be carried by a single operator, with the Leica C10 being slightly more cumbersome to transport when compared to the BLK360. The sUAS airborne LIDAR equipment was the most difficult as the sUAS was required to be instrumented in the field for data collection. A DJI M600 was used for the LIDAR data acquisition. This platform is larger than the traditional DJI Inspire 2 used for the SfM data collection. The DJI M600 is transported in a pelican case and often requires two people to lift and carry to a launch location. Presumably, a wheeled pelican case can incorporate the flexibility to be set-up by one individual. The portability of the sUAS-borne SfM equipment was similar to the TLS equipment, as a single person could carry all the primary and supporting equipment on site. Overall, the DJI suite of products is often selected as units of choice with the M600 most suitable for law enforcement applications due to its higher payload carrying capacity. Nonetheless, many agencies have leveraged lower cost platforms such as the Inspire and Mavic series with great success.

The next factors within the ease of data acquisition metric was the complexity of operation and level of mission planning. Regarding the TLS equipment, the BLK360 with its auto-leveling feature was less complex to operate than the C10. Overall, the TLS reconstruction method required the professional opinions of the operators to determine the number of scans, which scanner to use, placement of the scans, and scanner resolution setting. This may incorporate a level of method-produced bias as the aforementioned constructs are subjective in nature and ultimately increases the complexity and time of equipment set-up and data capture. Regarding sUAS airborne data collection, the level of subjectivity in establishing the data collection parameters is slightly reduced as sUAS can fly the entire AOI. However, sUAS airborne collection methods have a similar subjective element as the operator must determine a number of parameters to include airframe and payload selection, flight altitude, flight speed, overlap percentages, flight plan configuration, camera orientation, and camera settings. Further research is deemed necessary and recommended to develop standardized guidelines for sUAS data collection and post-processing.

Completeness of the Model:

The completeness of the model was the last qualitative metric evaluated. The completeness of the model corresponds to the level of distinguishable detail. This metric is subjectively evaluated through image interpretation with the goal of identifying distinguishable features, gaps, and artifacts in the scene. For this case, distinguishable evidence captured on the ground was a factor on the completeness of the model. Figure 12 provides a sample of the urban scene in the day and at night regarding evidence capture while Table 4, 5 and 6 present evidence detection for the urban, field and forest crime scene, respectively.

(A)  (B)

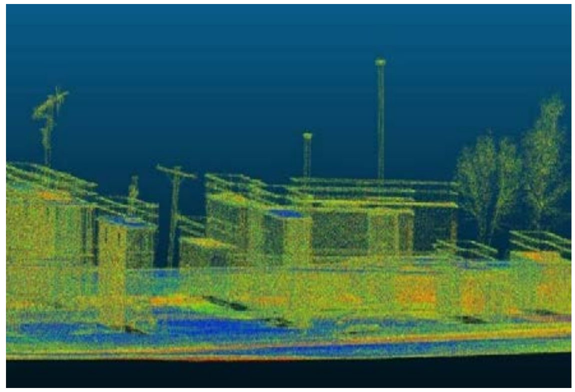
(C) 

Figure 12. *Screenshots for Day SfM (A), Night SfM (B) and LIDAR (C) of the Urban Scene*

Table 4.

Urban Scene Evidence Detection

Urban							
Artifact	Aerial LIDAR		SfM Single Grid		SfM Double Grid	TLS	
	Day	Night	Day	Night	Day	Day	Night
Rifle Shell Casings	No	No	No	No	No	No	No
Broken Glass	No	No	Yes	No	Yes	Yes	Yes
Rifle Shell Casings	No	No	No	No	No	Yes	Yes
Rifle Shell Casings	No	No	No	No	No	Yes	Yes
Rifle Magazine	No	No	Yes	Yes	Yes	Yes	Yes
Bloody Footprint	No	No	Yes	No	Yes	No	No
Rifle	No	No	Yes	Yes	Yes	Yes	Yes
Pistol Shell Casings	No	No	No	No	No	No	No
Pistol Shell Casings	No	No	No	No	No	No	No
Clothing	No	No	Yes	No	Yes	Yes	Yes
Bullet	No	No	No	No	No	No	No
Handgun	No	No	Yes	Yes	Yes	Yes	Yes
Blood pool	No	No	Yes	Yes	Yes	Yes	Yes
Cigarette Butts	No	No	No	No	No	No	No
Beer Can	No	No	Yes	No	Yes	Yes	Yes

Table 5.

Field Scene Evidence Detection

Field							
Artifact	Aerial LIDAR		SfM Single Grid		SfM Double Grid	TLS	
	Day	Night	Day	Night	Day	Day	Night
Handcuffs	No	No	No	No	No	Yes	Yes
Chain	No	No	Yes	No	Yes	Yes	Yes
Body/Gravesite	No	No	Yes	Yes	Yes	Yes	Yes
Shotgun Shells	No	No	Yes	No	Yes	Yes	No

Cell Phone	No	No	Yes	Yes	Yes	Yes	No
Shovel	No	No	Yes	Yes	Yes	Yes	Yes

Table 6.

Forest Scene Evidence Detection

Forest						
Artifact	Aerial LIDAR		SfM Single Grid	SfM Double Grid	TLS	
	Day	Night			Day	Night
Shirt	No	No	Yes	Yes	Yes	Yes
Beer Can	No	No	Yes	Yes	Yes	Yes
Pants	No	No	Yes	Yes	Yes	Yes
Simulated Contraband (Green)	No	No	No	No	No	No
Simulated Contraband (white)	No	No	Yes	No	Yes	No
Beer Bottle	No	No	Yes	Yes	Yes	No
Beer Can	No	No	No	Yes	Yes	Yes
Rope (Ground)	No	No	No	Yes	Yes	No
Cellphone	No	No	No	No	Yes	No
Rope (Tree)	No	No	No	Yes	Yes	Yes

Conclusion

The use of unmanned aircraft systems to reconstruct crime scenes has implications beyond the benefits of an aerial view. Unmanned aircraft systems (UAS) may provide an evolutionary step in crime scene investigations by reducing scene contamination, creating models with sufficient accuracy, and reducing the time spent on scene. Airborne data collection allows crime scenes to be mapped without the investigator(s) needing to disrupt the scene. The result is reconstructed crime scenes without disturbing crucial evidence. UAS technologies offer the potential to increase efficiency while maintaining acceptable quality. An additional advantage of airborne remote sensing technology is the data collected from airborne sensors is objective; the significance of this objectivity is that law enforcement, prosecutors, defense attorneys, judges and juries can all benefit from the ability to review the scene in a complete or relatively unaltered state.

In closing, the results of this research highlight the advantages and disadvantages of the remote sensing modalities examined as a component of this research. While the TLS was the most labor-intensive method used, at present it remains the best modality for accuracy and level of distinguishable detail in crime scene data collection and crime scene reconstruction. Regarding, sUAS airborne SfM photogrammetry, this method of data and processing provided sub-centimeter accuracies and an advantageous aerial perspective that could potentially serve to complement the data collected by industry standard TLS systems during daytime investigations or, to be used as a utility in itself for agencies that cannot procure systems as such. Although limitations were presented with sUAS nighttime SfM photogrammetry, the data captured from the night scenes were successfully reconstructed using sUAS SfM post-processing techniques; however, the reconstructed models contained significant noise and artifacts which minimized the accuracy for real-world use. Last, the sUAS-borne LIDAR data was the least effective due to moderate sensor sensitivity to distinguish and discern small details in the scene (e.g. evidence marker). Overall and despite the challenges associated with the analysis of these data, the research team provided an understanding on the effectiveness and efficiency of remote sensing technologies for law enforcement crime scene investigations. Further research is deemed necessary to attain a more robust understanding on the accuracy of sUAS SfM photogrammetry for crime scene reconstruction.

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