

# Final Report



University Transportation Research Center - Region 2

## Exploring Applications for Unmanned Aerial Systems and Unmanned Ground Systems in Enhanced Incident Management, Bridge Inspection, and Other Transportation-related Operations



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## **EXECUTIVE SUMMARY**

This report addresses the feasibility and costs and benefits of using automated systems to perform transportation operations. It documents applications and demonstrations of unmanned aerial systems (UAS) and unmanned ground systems (UGS) technologies and potential deployment opportunities for NYSDOT in the near future. The report's first three sections discuss aerial systems and its fourth section focuses on ground systems. The first section discusses studies and specifications of UAS used for roadway mapping. The second section presents applications and specifications of using UAS to monitor structural systems including confined spaces, bridges, and other transportation infrastructure. The third section describes applications of UAS for traffic monitoring and management, including monitoring of road and traffic conditions and management of traffic incidents. The final section briefly discusses UGS and their deployment opportunities to improve road construction and maintenance worker safety. This section specifically reviews connected and autonomous vehicles (CAV), describing the communications technology and sensors used in CAVs and identifying the potential impacts of CAV technology.

### ***1 Unmanned Aerial Systems***

UAS are increasingly being employed to perform a number of transportation operations. They collect images which are processed to generate 3-D models capable of providing data for a wide range of transportation operations including roadway mapping, the inspection of bridge components, and documenting highway accidents. The traditional methods for performing these tasks are being augmented and replaced by carefully executed UAS data-gathering flights that are safer, faster, and less-expensive than those methods.

#### ***1.1 Automated Road Mapping***

Currently, road mapping is generally done through a combination of conventional surveying on foot and aerial imaging. UAS surveying is as accurate as conventional surveying, while requiring substantially less time to complete. Moreover, UAS imagery has been found to be superior to conventional aerial photography because the camera is closer to the subject, so it is less affected by atmospheric haze and vibration. Using UAS for surveying projects may decrease the need for on-the-ground surveying and outsourced aerial imaging.

## ***1.2 Automated Structural Inspection***

UAS are capable of performing structural condition monitoring in a safe and accurate manner, especially in locations that are not accessible by human inspectors. For the inspection of confined spaces, such as pump stations and culverts, smaller UAS are more appropriate as they can fly through small spaces easily and closer to walls and other objects without generating the vortices that can occur with larger UAS which can destabilize them and make them difficult to control. Given the low cost of many small UAS, they can easily be replaced if they are lost or damaged and they can help protect investigators by indicating whether it is safe to enter the confined space.

When compared to the standard methods of measuring and mapping bridge distresses, which include hammer sounding or chain drag techniques and closure of the bridge for the safety of inspectors, the remote sensing technologies of UAS can collect data in much less time, with fewer inspectors, and at lower cost without having to close the bridge. Given the size, weight, controllability and built-in fail safes of UAS, using them for bridge inspection involves very little risk for inspectors and the public. UAS provide a cost effective way to generate extremely detailed data which may not be acquired in traditional inspections and they minimize safety risks associated with traffic control, working at heights, and in traffic. They can also be used in pre-inspection to obtain important information for large-scale inspections planning. Using UAS for under-bridge inspections provides significant savings resulting from reduced or eliminated traffic control and reduced use of under bridge inspection vehicles and lifts. UAS are particularly useful for infrastructure inspections because they can change camera angles during flight and can fly without a GPS signal. There are, however, limits to the role that UAS can play in inspections as they cannot conduct these inspections independently and they cannot perform hands-on functions, such as cleaning, sounding, measuring, and testing.

UAS can be very useful for transportation applications that require high resolution aerial images, such as monitoring road construction and road condition and inventorying roadway structures. Aerial images acquired by UAS can be collected and available for viewing in just a few hours. UAS can also be used to regularly update aerial images in transportation agency GIS databases, which can help to improve the performance of many of its operations and its decision-making process.

### ***1.3 Automated Traffic Monitoring and Management***

UAS can be used for traffic monitoring and emergency identification and, with the incorporation of a video communications system; they can transmit real-time data to traffic authorities so that they can respond to incidents in a timely manner. In addition, the data obtained from UAS can be used to evaluate traffic conditions and enable operators to take steps to improve the level of service at congested intersections. This real-time traffic information can also be broadcast to drivers through radio or the internet to enable drivers to choose better, less congested routes thereby reducing their travel time and overall traffic congestion. Finally, the large amount of detailed traffic data collected by UAS can be used to develop better long term strategies for traffic management. UAS can perform these operations at substantially lower cost than current traffic monitoring systems which require satellites which are very costly to build and maintain.

Another transportation operation that can be performed by UAS is traffic incident management which involves detecting, responding to, and clearing traffic incidents in order to restore traffic flow as safely and quickly as possible. Before accident scenes can be cleared, they must be documented which is typically done by laser scanners, surveying, and photography on the ground which requires a lot of time and a number of trained individuals. UAS can accomplish the task by quickly flying to accident scenes and easily obtaining the necessary accident information. It is estimated that using UAS to document accident scenes decreases the time spent on the roadway by 80% and the time spent taking measurements by 65% compared to traditional methods of documenting accidents. These time reductions increase the safety of first responders, reduce the economic and time losses of drivers on the road, and reduce the probability of secondary collisions. The images collected in just one UAS flight can be processed to generate 3-D models and other outputs to determine how and why an accident occurred so that steps can be taken to prevent future accidents.

While UAS are capable of performing many transportation operations more safely and efficiently and at lower cost than traditional methods, there are issues that must be addressed when using UAS. Aerial image quality is crucial to successful UAS operations and it can be adversely affected by camera vibration. However, this can be reduced by the use of multi-rotor UAS. Another issue is that the effectiveness of UAS can be severely reduced when operating in inclement weather such as high winds, rain or snow. However, larger UAS tend to be able to

operate better in bad weather than small UAS. Finally UAS tend to have short battery lives, which, for multi-rotors, is around 20-30 minutes. These battery lives can be too short to accomplish some tasks such as traffic monitoring.

## ***2 Unmanned Ground Systems***

The UGS that this report analyzed is CAV technology. This technology connects vehicles through a secure wireless network allowing them to communicate with other vehicles, roadside infrastructure, and smart phones by sending and receiving alerts to avoid collisions or reduce their severity. Technology installed in vehicles allowing vehicles to communicate with one another is called Vehicle-to-Vehicle (V2V) communications. Equipped vehicles can also communicate with devices installed in transportation infrastructure, which is called Vehicle-to-Infrastructure (V2I) communications. CAV applications require the transmission of various sensing and measurement information to and from vehicles. The on-board computer must be able to process the large amount of information being transmitted through sensing technologies and communication media and provide the driver with appropriate warnings in connected vehicles or control the vehicle's movement in automated vehicles.

CAV technology has the potential for impacting roadway safety, public transit, and transportation infrastructure. According to the National Highway Traffic Safety Administration, human error plays a role in almost 90% of traffic crashes throughout the world. CAV can reduce human error and unpredictability by making drivers aware of potentially unsafe conditions in time to avoid them, reducing the amount of vehicle control that drivers have, or eliminating driver control altogether and thus reducing the frequency and severity of crashes.

One of the impacts that CAV technology may have on public transit is to reduce delay for public buses, thereby reducing transit travel time, crowding, pollution, and fuel consumption. It would also improve transit reliability and safety. CAV technology enables buses to communicate with one another and other vehicles in the transportation network, along with accommodating the needs of passengers through on-demand services, such as booking rides in advance and enabling flexible routes. Autonomous bus/shuttle applications are being developed and demonstrated across the globe.

CAV technology has the potential for impacting transportation infrastructure, including road signs, traffic and parking lanes, and traffic signals. Widespread adoption of CAV technology

could eliminate the need for directional signs and variable message signs along arterials as the information conveyed by these signs would be transmitted directly to vehicles and drivers. The increasing use of AVs will reduce the number of human drivers on the road which will mean less human error and unpredictability and will enable more vehicle coordination, thereby increasing traffic lane capacity and reducing congestion. Parking lanes could become obsolete with AVs driving themselves to parking garages and a decrease in car ownership resulting from increased ridesharing. With CAV technology, traffic signals can help to coordinate the movement of vehicles in platoons and give priority to public transit vehicles. This will reduce vehicle and passenger delay, travel time, and congestion, as well as increase the reliability of the transit system.

Although, the project found limited information related to deployment opportunities of UGS to improve road construction and maintenance worker safety for State DOTs, it was revealed that UGS are playing an increasingly important role in commercial and military applications for improving safety and significantly reducing the number of dangerous tasks performed by humans. UGS are being piloted on highway construction sites in Florida under a state Department of Transportation demonstration program.

As part of this project, a demonstration of UGS was conducted at the 2016 ITS-NY Twenty-Third Annual Meeting and Technology Exhibition held in Saratoga Spring, New York from June 9 to June 10, 2016. An inventory list of the equipment used in this demonstration and recommendations about the CVII Phase I and II Road Weather Applications Pooled Fund Study assets are contained in Appendix 1.

## **INTRODUCTION**

Unmanned aircraft systems (UAS) and unmanned ground systems (UGS) have the potential to change the way we perform a number of transportation-related operations. Nowadays, an opportunity arises to leverage various innovative technological capabilities to explore their use and value in real world operating environments. Specifically, exploring the capabilities of UAS, also called drones, and UGS in specific transportation areas appears to have significant potential.

Automated systems that can be deployed locally are emerging as a technological solution for the problem of roadway and work zone monitoring. These systems involve deploying a vehicle carrying appropriate equipment such as cameras to gather information or perform tasks that can be hazardous when performed by humans. As these systems generally do not involve a direct human operator, they are called unmanned systems. UAS and UGS are two common examples of automated systems. Unmanned aerial systems involve deployment of small aerial vehicles such as quadcopters and airplanes with appropriate equipment that can be remotely operated in real-time or using planned movements. These unmanned systems can also be ground-based.

This report summarizes the review performed by students from three schools affiliated with the University Transportation Research Center (UTRC) documenting applications and demonstrations of UAS and UGS technologies and potential deployment opportunities for NYSDOT in the near future. Specifically, NYSDOT would like to assess the existing capabilities of drones for responding to highway incidents including field surveying, accident information collection and reconstruction and other related activities required to clear a highway incident. As part of this effort, NYSDOT would also like to explore other transportation applications for these devices such as bridge inspection and traffic monitoring.

It is also recognized that significant progress has been made with true vehicle automation from both a network systems and an individual onboard vehicle systems perspective. NYSDOT would like to further explore and assess the capabilities of UAS and UGS automation within the operational environment to assess improvements in safety, cost, effectiveness and efficiencies. One area of concern is work zone intrusion and the corresponding safety issues and impacts to maintenance and contractor employees. This report aims to explore potential deployment of such UAS and UGS systems including assessment of the technology, literature searches,

demonstration and testing activities, feasibility and effectiveness, and costs and benefits of such capabilities.

The report is divided into four sections that follow the assignments as requested by the NYSDOT Project Manager. The first section presents a summary of the major provisions of the operation and certification of small unmanned aircraft systems, studies and specifications of UAS used for roadway or ground mapping. The second section presents applications and specifications of monitoring structural systems using UAS. The third section describes applications of UAS for traffic condition monitoring and management. The final section presents technologies involved, applications and impacts of UGS deployment.



## 1. SMALL UNMANNED AIRCRAFT SYSTEMS AND AUTOMATED ROADWAY MAPPING

### 1.1 Summary of the Operation and Certification of Small Unmanned Aircraft Systems

On June 2016, the Department of Transportation's Federal Aviation Administration (FAA) finalized the first operational rules for routine commercial use of small unmanned aircraft systems (UAS or "drones") in Part 107 of 14 CFR, opening pathways towards fully integrating UAS into the nation's airspace. This rule finalizes the notice of proposed rulemaking (the NPRM) entitled Operation and Certification of Small Unmanned Aircraft Systems. It set forth operating and certification requirements to allow small unmanned aircraft systems (small UAS) to operate for non-hobby and non-recreational purposes such as bridge inspection. The major provisions of the rule are summarized in Table 1.

*Table 1 Major Provisions of 14 CFR Part 107*

Operational Limitations	<ul style="list-style-type: none"><li>• Unmanned aircraft must weigh less than 55 lbs. (25 kg).</li><li>• Visual line-of-sight (VLOS) only; the unmanned aircraft must remain within VLOS of the remote pilot in command and the person manipulating the flight controls of the small UAS. Alternatively, the unmanned aircraft must remain within VLOS of the visual observer.</li><li>• At all times the small unmanned aircraft must remain close enough to the remote pilot in command and the person manipulating the flight controls of the small UAS for those people to be capable of seeing the aircraft with vision unaided by any device other than corrective lenses.</li><li>• Small unmanned aircraft may not operate over any persons not directly participating in the operation, not under a covered structure, and not inside a covered stationary vehicle.</li><li>• Daylight-only operations, or civil twilight (30 minutes before official sunrise to 30 minutes after official sunset, local time) with appropriate anti-collision lighting.</li><li>• Must yield right of way to other aircraft.</li><li>• May use visual observer (VO) but not required.</li><li>• First-person view camera cannot satisfy "see-and-avoid" requirement but can be used as long as requirement is satisfied in other ways.</li><li>• Maximum groundspeed of 100 mph (87 knots).</li><li>• Maximum altitude of 400 feet above ground level (AGL) or, if higher than 400 feet AGL, remain within 400 feet of a</li></ul>
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	<p>structure.</p> <ul style="list-style-type: none"> <li>• Minimum weather visibility of 3 miles from control station.</li> <li>• Operations in Class B, C, D and E airspace are allowed with the required air traffic control (ATC) permission.</li> <li>• Operations in Class G airspace are allowed without ATC permission.</li> <li>• No person may act as a remote pilot in command or VO for more than one unmanned aircraft operation at one time.</li> <li>• No operations from a moving aircraft.</li> <li>• No operations from a moving vehicle unless the operation is over a sparsely populated area.</li> <li>• No careless or reckless operations.</li> <li>• No carriage of hazardous materials.</li> <li>• Requires preflight inspection by the remote pilot in command.</li> <li>• A person may not operate a small unmanned aircraft if he or she knows or has reason to know of any physical or mental condition that would interfere with the safe operation of a small UAS.</li> <li>• Foreign-registered small unmanned aircraft are allowed to operate under 14 CFR Part 107 if they satisfy the requirements of 14 CFR Part 375.</li> <li>• External load operations are allowed if the object being carried by the unmanned aircraft is securely attached and does not adversely affect the flight characteristics or controllability of the aircraft.</li> <li>• Transportation of property for compensation or hire allowed provided that- <ul style="list-style-type: none"> <li>○ The aircraft, including its attached systems, payload and cargo weigh less than 55 pounds total;</li> <li>○ The flight is conducted within visual line of sight and not from a moving vehicle or aircraft; and</li> <li>○ The flight occurs wholly within the bounds of a State and does not involve transport between (1) Hawaii and another place in Hawaii through airspace outside Hawaii; (2) the District of Columbia and another place in the District of Columbia; or (3) a territory or possession of the United States and another place in the same territory or possession.</li> </ul> </li> <li>• Most of the restrictions discussed above are waivable if the applicant demonstrates that his or her operation can safely be conducted under the terms of a certificate of waiver.</li> </ul>
Remote Pilot in Command Certification and	<ul style="list-style-type: none"> <li>• Establishes a remote pilot in command position.</li> <li>• A person operating a small UAS must either hold a remote pilot</li> </ul>

Responsibilities	<p>airman certificate with a small UAS rating or be under the direct supervision of a person who does hold a remote pilot certificate (remote pilot in command).</p> <ul style="list-style-type: none"> <li>• To qualify for a remote pilot certificate, a person must: <ul style="list-style-type: none"> <li>○ Demonstrate aeronautical knowledge by either: <ul style="list-style-type: none"> <li>▪ Passing an initial aeronautical knowledge test at an FAA-approved knowledge testing center; or</li> <li>▪ Hold a 14 CFR Part 61 pilot certificate other than student pilot, complete a flight review within the previous 24 months, and complete a small UAS online training course provided by the FAA.</li> </ul> </li> <li>○ Be vetted by the Transportation Security Administration.</li> <li>○ Be at least 16 years old.</li> </ul> </li> <li>• Part 61 pilot certificate holders may obtain a temporary remote pilot certificate immediately upon submission of their application for a permanent certificate. Other applicants will obtain a temporary remote pilot certificate upon successful completion of TSA security vetting. The FAA anticipates that it will be able to issue a temporary remote pilot certificate within 10 business days after receiving a completed remote pilot certificate application.</li> <li>• Until international standards are developed, foreign- certificated UAS pilots will be required to obtain an FAA- issued remote pilot certificate with a small UAS rating.</li> </ul> <p>A remote pilot in command must:</p> <ul style="list-style-type: none"> <li>• Make available to the FAA, upon request, the small UAS for inspection or testing, and any associated documents/records required to be kept under the rule.</li> <li>• Report to the FAA within 10 days of any operation that results in at least serious injury, loss of consciousness, or property damage of at least \$500.</li> <li>• Conduct a preflight inspection, to include specific aircraft and control station systems checks, to ensure the small UAS is in a condition for safe operation.</li> <li>• Ensure that the small unmanned aircraft complies with the existing registration requirements specified in 14 CFR 91.203(a)(2).</li> <li>• A remote pilot in command may deviate from the requirements of this rule in response to an in-flight emergency.</li> </ul>
Aircraft Requirements	<ul style="list-style-type: none"> <li>• FAA airworthiness certification is not required. However, the remote pilot in command must conduct a preflight check of the small UAS to ensure that it is in a condition for safe operation.</li> </ul>
Model Aircraft	<ul style="list-style-type: none"> <li>• 14 CFR Part 107 does not apply to model aircraft that satisfy all</li> </ul>

	<p>of the criteria specified in section 336 of Public Law 112-95.</p> <ul style="list-style-type: none"> <li>• The rule codifies the FAA's enforcement authority in 14 CFR Part 101 by prohibiting model aircraft operators from endangering the safety of the National Airspace System (NAS).</li> </ul>
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## 1.2 Automated Roadway Mapping

Inspection and monitoring of land and facilities owned by agencies is a key part of asset management. To this end, generally, agencies use satellite images or photographs from helicopters or airplanes equipped with high resolution cameras. Deploying helicopters or airplanes is expensive and while using satellite images may be cheap, they may not provide the most up-to-date representation of the conditions. Unmanned aerial systems provide a viable alternative for mapping agency assets.

This section presents various studies performed for mapping by deploying UAS in the US. The specifications of equipment used and costs are also presented.

### 1.2.1 California State University

California State University conducted three UAS mapping projects (Munjy, 2015).

#### Project One:

In this project, the team used an Octocopter UAS which is a multi-rotor helicopter shown in Figure 1-1. This drone's flying height above terrain is 60 to 75 meters and it has a 80% forward and a 60% side lap.



*Figure 1-1 Octocopter UAS*

The testing ground is at the National University of Ireland, Maynooth, Republic of Ireland which is shown in Figure 1-2 and Figure 1-3.



*Figure 1-2 Test ground outline at National University of Ireland*

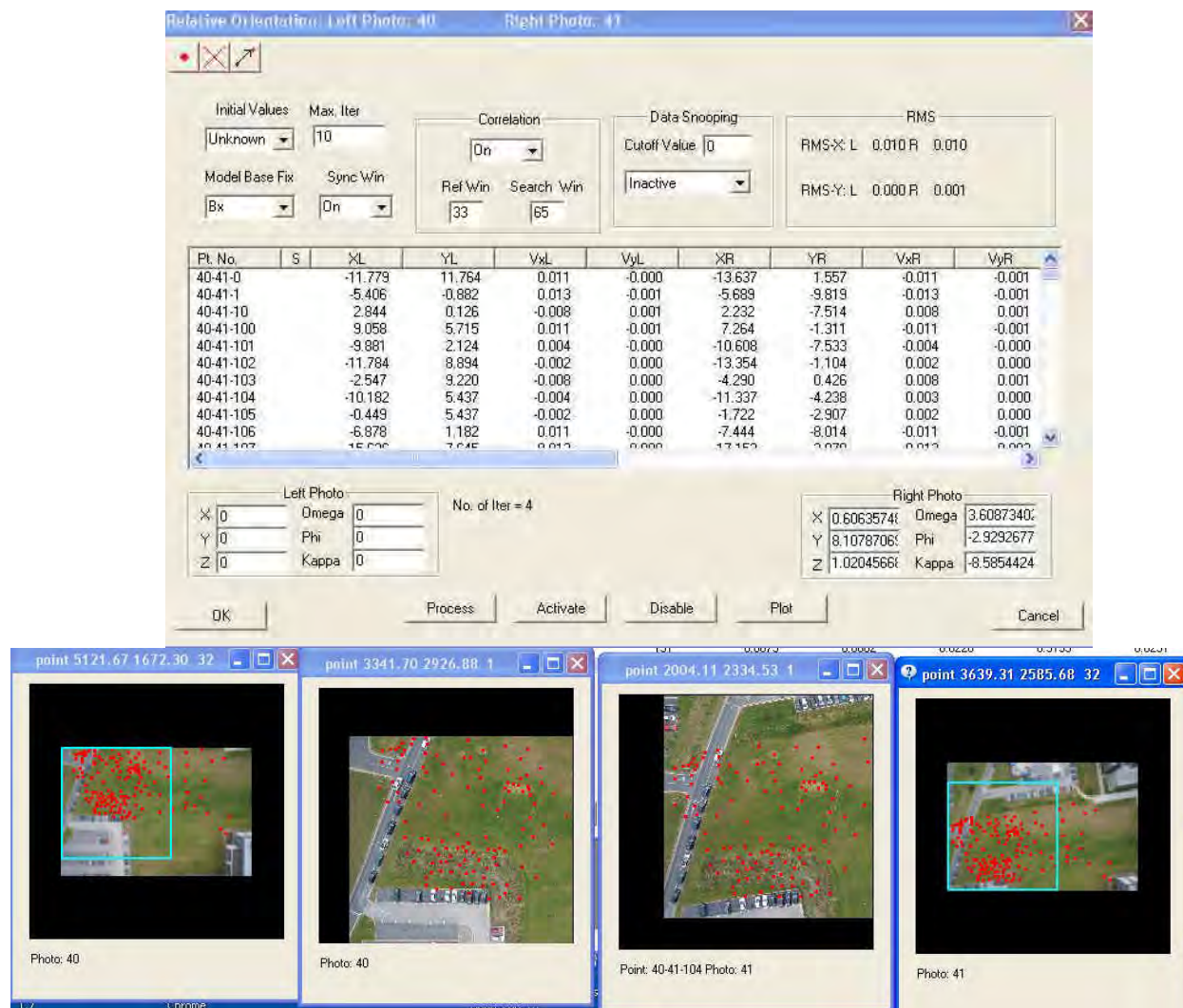


Figure 1-3 Automatic matching & REL ORI

### Project Two:

The UAS used in this project is an Inspire1 (T600), manufactured by DJI (Da-Jiang Innovations Science and Technology Co., Ltd). This is a quadcopter with a 4k Video camera as shown in Figure 1-4 with specs shown in Table 1-2. The modular has a 3 axis rotating gimbal allowing full tilt, roll and 360 degrees yaw. One controller can be used to control both the drone and the camera in one screen or two controllers can be used to control the drone and camera in two screens, separately. The price of this drone is \$1899.99 on amazon and \$1999.00 on the official website. More combinations are available on the website ([http://store.dji.com/product/inspire-1-v2?from=related\\_products](http://store.dji.com/product/inspire-1-v2?from=related_products) ).



*Figure 1-4 DJI Inspire1 (T600)*

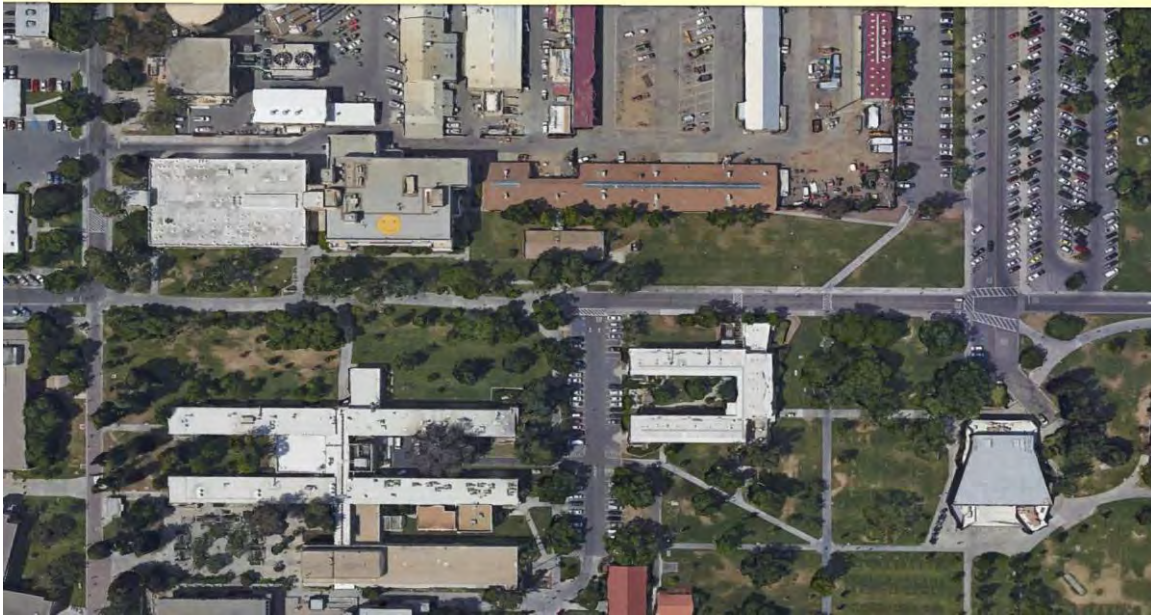
Table 1-2 Specs of DJI Inspire1 (T600)(DJI, 2016a)

SPECS	
AIRCRAFT	
Weight(Battery Included)	2935g
Hovering Accuracy(GPS mode)	Vertical:0.5m Horizontal:2.5m
Max Angular Velocity	Pitch:300°/s Yaw:150°/s
Max Tilt Angle	35°
Max Ascent Speed	5m/s
Max Descent Speed	4m/s
Max Speed	22m/s(ATTI mode, no wild)
Max Service Ceiling Above Sea Level	4500m (Default altitude limit:120m above takeoff point)
Max Wind Speed Resistance	10m/s
Max Flight Time	Approximately 18 minutes
Operation Temperature Range	=-10 to 40° C
Diagonal Distance	559 to 581 mm
Dimensions	438x451x301 mm
Power Spectral Density	9.06mW/MHz
CAMERA	
Name	X3
CMOS	Sony EXMOR 1/ 2.3
Focal Length	5.101mm (20mm, 35mm format equivalent)
Frame Size	3992x2992
Pixel Size	0.00134mm
Total Pixels	12.96M
Effective Pixels	12.4M
Image Max Size	4000x3000
ISO Range	100-3200 (video) 100-1600 (photo)
Supported SD Card Types	Micro SD Max capacity: 64GB. Class 10 or UHS-1 rating required
Operating Temperature Range	0 to 40°C

More details can be found on <http://www.dji.com/inspire-1/info> .

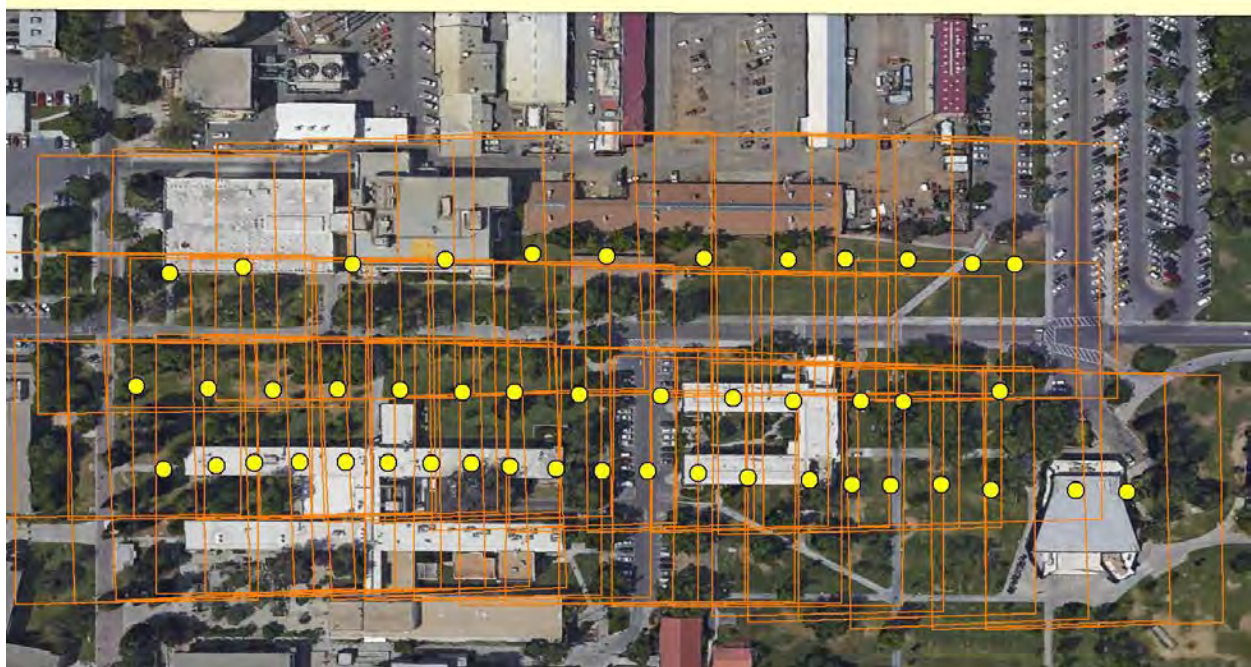
The project area is on the campus of California State University at Fresno which is shown in Figure 1-5.





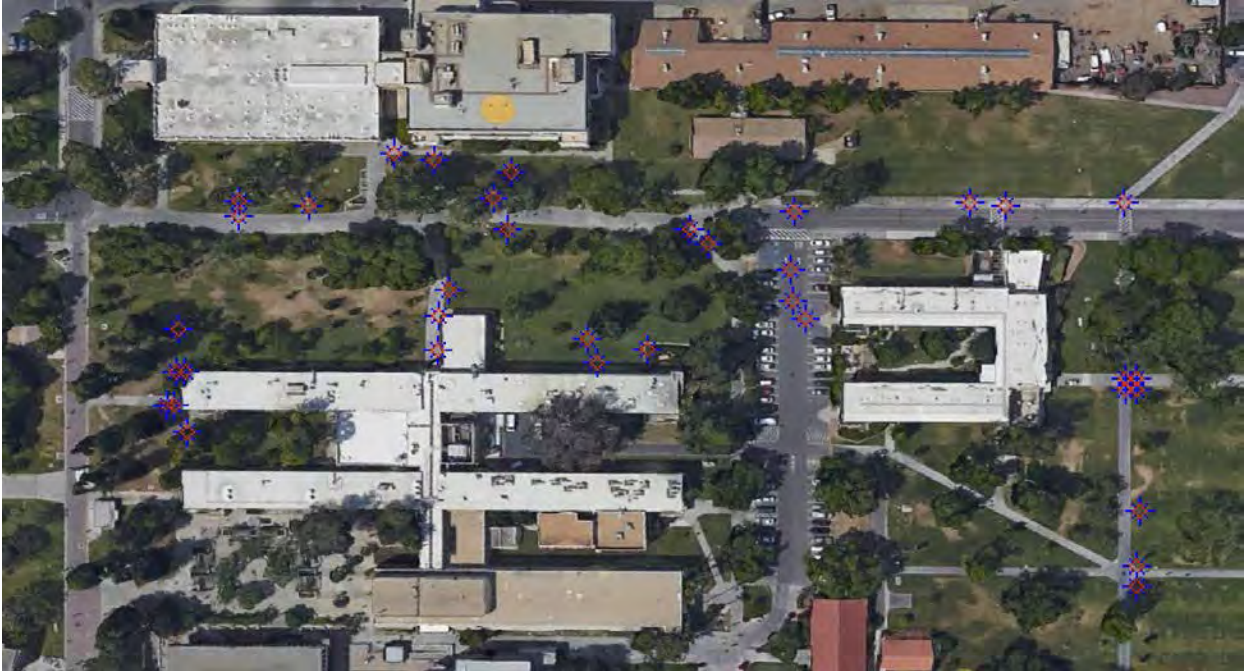
*Figure 1-5 Project area - campus of California State University Fresno*

In this project, the geometric standard deviation (GSD) is about 2cm, the image has a 60% forward and side overlap with 33 photo id ground control points. The drone did the mapping at a flying height of 61 meters. Images captured during the mapping are shown in Figures 1-6 to 1-8.



*Figure 1-6 Image foot prints*





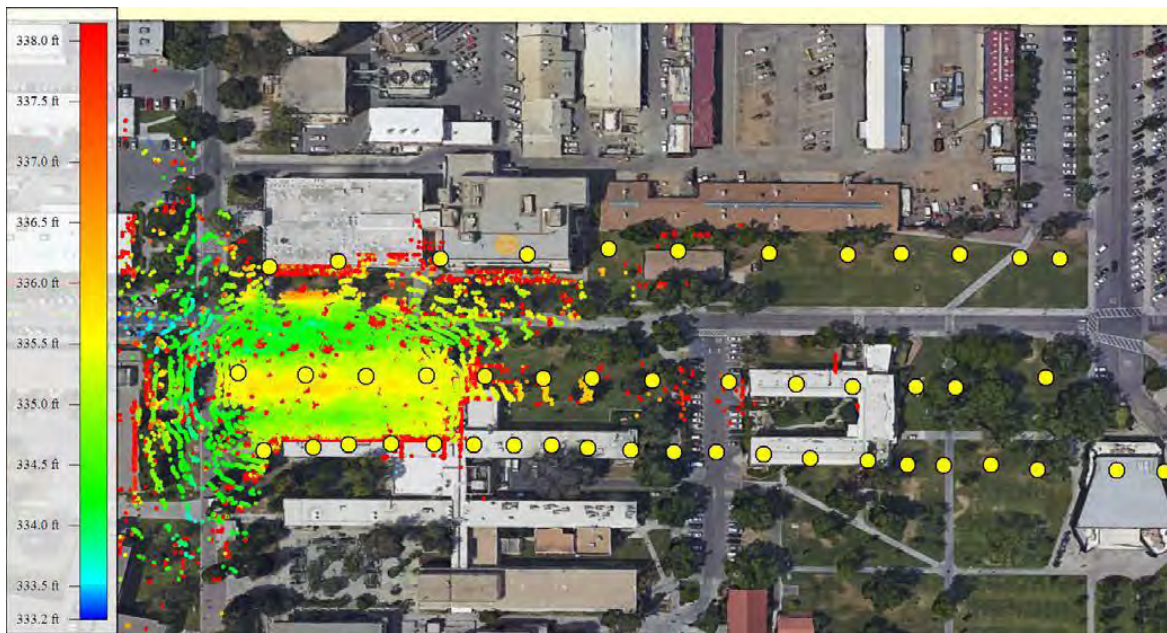
*Figure 1-7 Illustration of 33 photo id ground control points*



*Figure 1-8 Bundle solution*

They used 3 strips, 47 photos and 13129 ground points to obtain 49365 image points (with an average correlation of 0.92 and 557 image points rejected). The image point residuals are 0.0022

mm in the width direction and 0.0026 mm in the height direction. Then they used a Leica ScanStation2 to do a terrestrial laser scan to analyze the data 3 weeks after the drone flight as shown in Figure 1-9. The scan area included grass with about a 60cm change in elevation. The accuracy is about 1 cm and there are approximately 65 points per square meter. About 941 points were located with an average of 1.5cm and a standard deviation of 13cm.



*Figure 1-9 Laser scan area*

### Project Three:

In this project, California State University used a Phantom 2 quadcopter which is also manufactured by the DJI Company. The specs for this drone are shown in Table 1-3 and it is available for \$339.00 on the company's official website with several options ([http://store.dji.com/product/phantom-2?site=brandsite&from=buy\\_now\\_bar](http://store.dji.com/product/phantom-2?site=brandsite&from=buy_now_bar) ).

Table 1-3 Specs of DJI Phantom 2(DJI, 2016b)

SPECS	
AIRCRAFT	
Battery	6200mAh LiPo
Weight (Battery&Propellers included)	1160g/1000g(new model)
Hover Accuracy(Ready to Fly)	Vertical:0.8m Horizontal:2.5m
Max Yaw Angular Velocity	200°/s
Max Tilt Angle	35°
Max Ascent Speed	6m/s
Max Descent Speed	2m/s
Max Flight Speed	15m/s(Not Recommended)
Diagonal Length	350mm
Take-off Weight	<1300g
Tilting Range of Gimbal	0-60°
CAMERA (Default)	
Resolution	14Megapixels
CAMERA (Samsung S5-Smart Phone)	
Focal length	4.8mm
Pixel Size	0.00122mm
Sensor Resolution	16M
Video Recorder Resolution	3840 x 2160

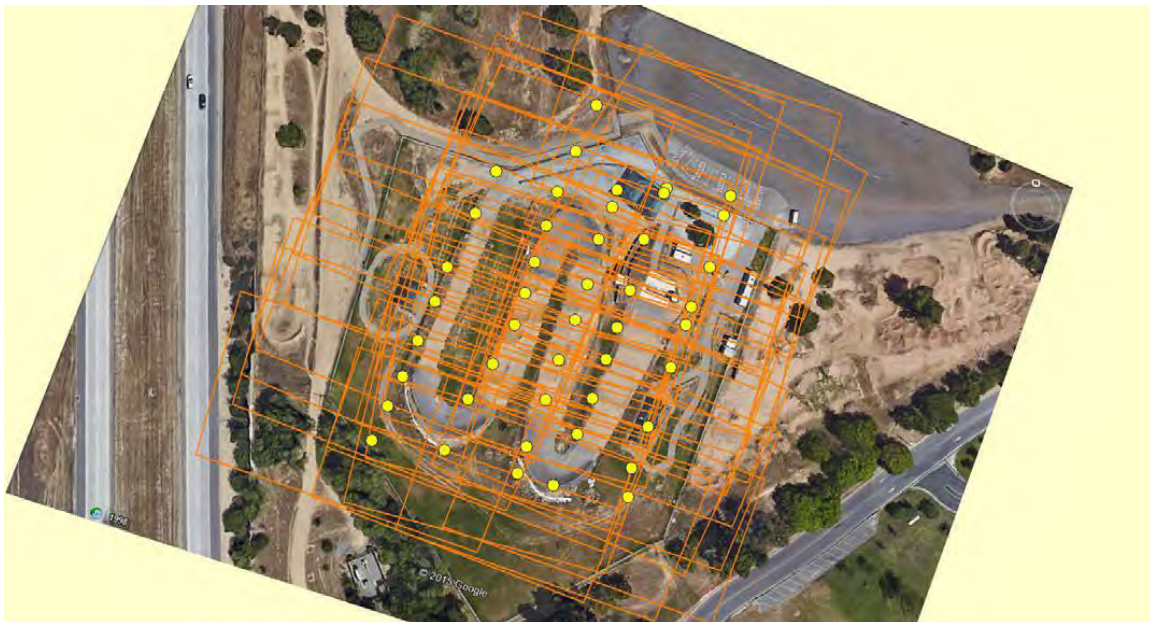
The project area is a 150m x 160m rectangle located in Woodward Park, Fresno, CA as shown in Figure 1-10.





*Figure 1-10 Project area - Woodward Park, Fresno, CA*

In this project, the image has a 70% forward and side overlap with 9 photo id ground control points. The drone did the mapping at a flying height of 85 meters. Images captured during the mapping are shown in Figures 1-11 to 1-13.



*Figure 1-11 Image foot prints*



*Figure 1-12 Illustration of 9 photo id ground control points*

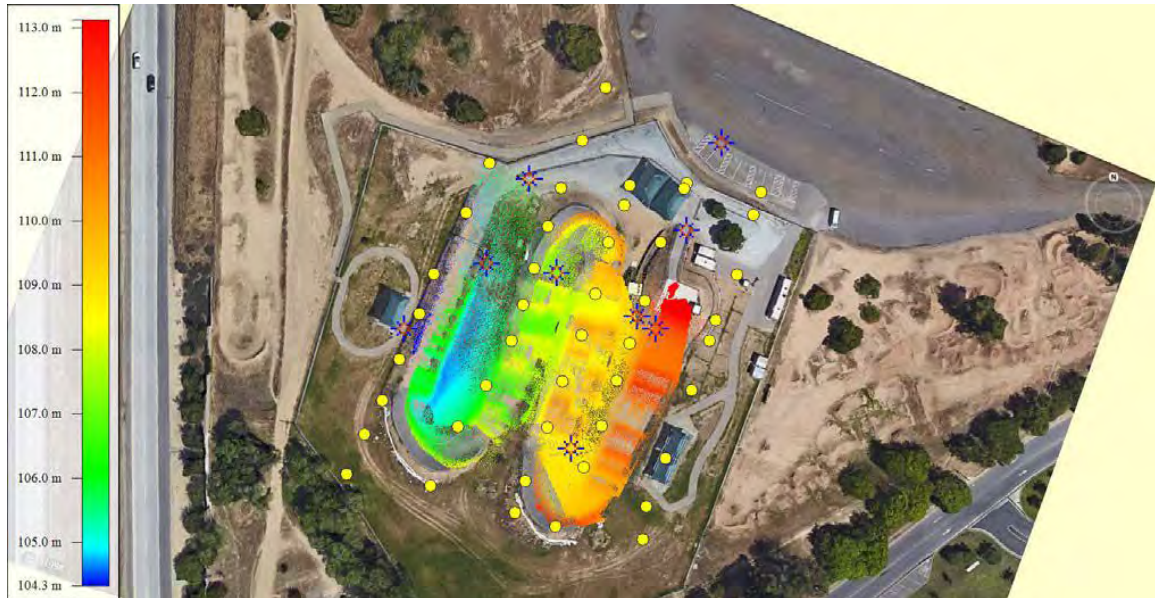


*Figure 1-13 Bundle solution*

They used 5 strips, 45 photos and 46111 ground points to obtain 198282 image points (with an average correlation of 0.89 and 1683 image points rejected). Image point residuals are 0.007 mm in the width direction and 0.007 mm in the height direction. Then they also used a Leica



ScanStation2 to do a terrestrial laser scan after the drone flight to analyze the data as show in Figure 1-14. The scan area has a 6m elevation change with an accuracy of about 0.5 cm and approximately 250 points per square meter.



*Figure 1-14 Laser scan area*

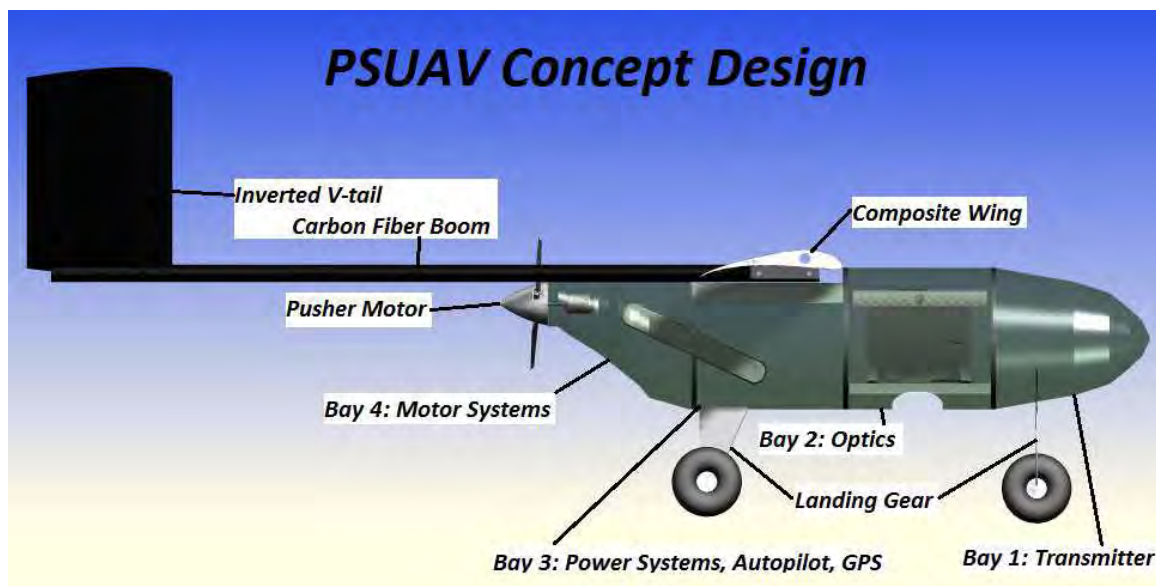
It located 20514 points with an average of 0.17 m and a standard deviation of 0.34 m.

As a result of these three projects, the researchers came up with several conclusions. First, without good Airborne GPS data, enough ground points need to be provided around and inside the block. Second, it is strongly recommended that camera vibration be minimized during flight as this affects the matching and final results. Last but not least, UAS photogrammetry can provide acceptable results if planned correctly.

### ***1.2.2 Michigan Technological University***

Michigan Technological University has used Photogrammetric Small UAV (PSUAV) in geospatial research (Eugen Levin, 2011). This PSUAV was designed by Student Aerospace Enterprise (SAE) and Surveying Engineering faculty and its design drawing is displayed in Figure 1-15. This PSUAV model has a wingspan of 72 inches and a chord of 10 inches supporting an angle of incidence of 5 degrees. The PSUAV has a Procerus autopilot system and

can handle up to 10 pounds of payload. It used a Cannon Rebel EOS 12MP camera in the research. Photos of the PSUAV are shown in Figure 1-. The research began with the development of calibration sites to deploy surveying quality equipment. The next step was to process the acquired datasets which involved camera calibration, bundle block adjustment, image co-registration, mosaic, and feature extraction from PSUAV imagery. The PSUAV results were compared to the results acquired from traditional aerial photogrammetry in order to investigate the accuracy, precision and applicability of PSUAV imagery for particular mapping tasks. As a result of the high variability of many application situations, the acquisition and processing of PSUAV data is able to meet the requirement of accuracy, information and productivity.



*Figure 1-15 PSUAV design*





*Figure 1-16 PSUAV appearance*

The PSUAV control electronics and software has two parts, the first is onboard and the second is ground based. The onboard flight control system is made up of an autopilot, drive motors, actuators and camera control, while the ground based control system consists of a laptop with control software, a CommBox handset, a RC Transmitter and a USB gamepad. There are two modes of UAV control from the ground, manual radio control (RC) and autopilot system (AUTO) control. The autopilot mode is particularly important for using PSUAV in classes because the manual RC mode requires significant training to operate safely. Virtual Cockpit is an easy to use software interface for setting up way-points on the mapping base and viewing and modifying all of the autopilot settings. Some examples of Virtual Cockpit control windows are shown in Figure 1-.

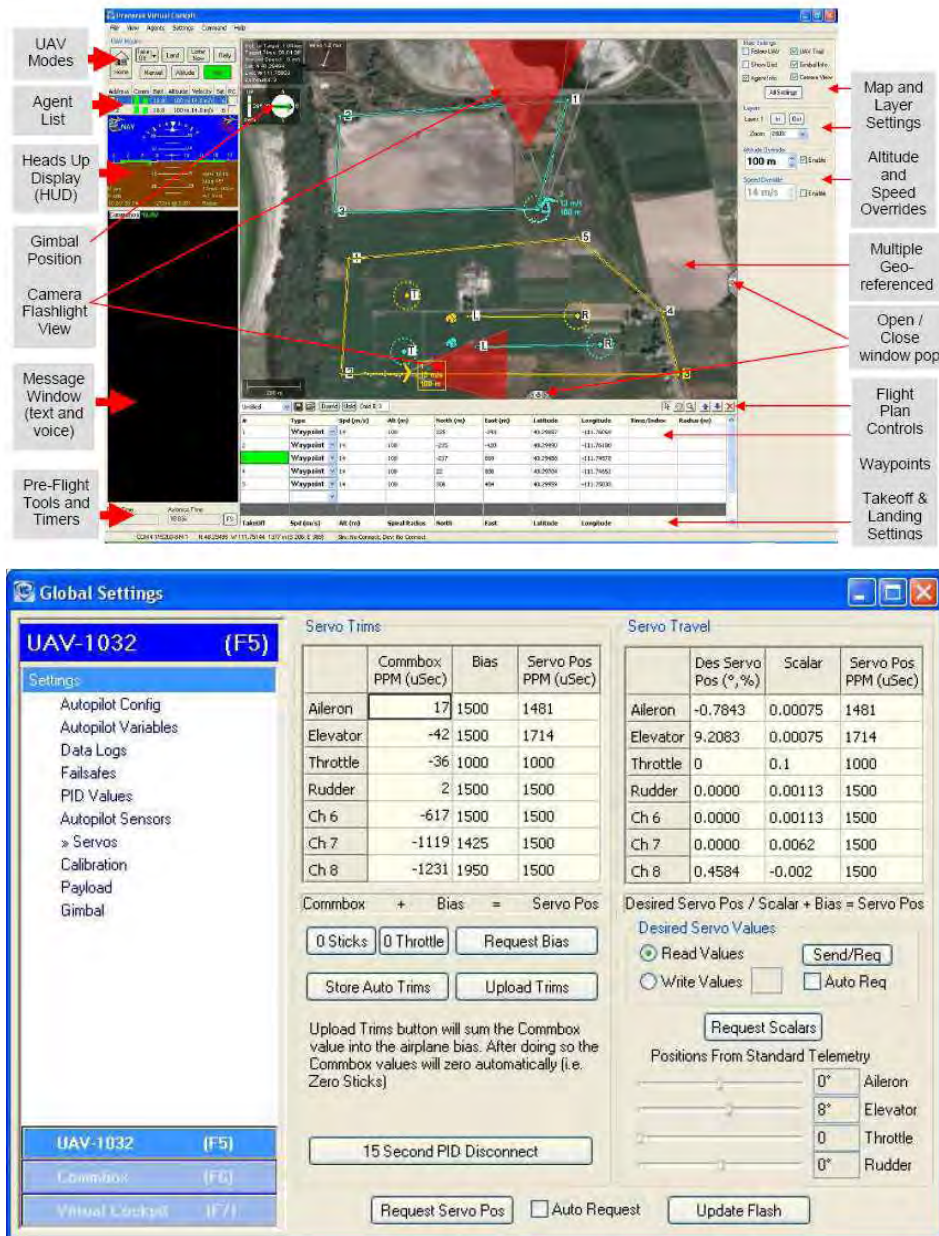


Figure 1-17 Virtual Cockpit man-machine interface examples

In a photogrammetry class, students designed a photogrammetric target “cross” out of cardboard as shown in Figure 1-.



*Figure 1-18 Photogrammetric target is installed on the ground*

The test-object configuration included 18 targets on the ground as shown in *Figure 1-9*. For calibration, nine targets were set inside the projected image footprint and the other targets were equally distributed across the projected flight strip.



*Figure 1-19 a) Target distribution over test-objects. b) Surveying engineering students coordinating targets using GPS RTK system*

A Trimble R8 GNSS system with real-time kinematic (RTK) technology was used to survey the targets. This technology has a positional accuracy of 10mm in the horizontal direction and 20mm in the vertical direction. Image acquisition was performed during a PSUAV flight. Figure 1-20 shows the PSUAV in air, as well as the photogrammetry class as viewed from the PSUAV.



*Figure 1-20 a) PSUAV during flight*



*b) Photogrammetry class-viewed from PSUAV*

Experiments were conducted at heights varying from 50 to 100 meters. Sample images from the experiments which were used to measure the targets in terms of ground sample distance (GSD) are shown in Figure 1-21.



*Figure 1-21 Sample image overview and sample target on this image*

The last step in these experiments was to process the results. This was accomplished through an application of the Direct Linear Transform method (Abdel-Aziz, 1971), since the team did not have the camera calibration parameters. This method was implemented through a Matlab program in which 6 points were used as ground control points and the other points were used as check points. A sample of the residuals obtained for the control points and for the check points are shown in Table 1-4 and Table 1-5 respectively.

*Table 1-4 Errors analysis on control points (units-centimeters)*

Point	Residual X	Residual Y	Position Residual
117	-2.1084	-1.5611	2.6235
119	0.6099	0.9947	1.1668
113	-0.1519	-0.513	0.535
109	3.8583	2.177	4.4301
108	-1.25	-0.5113	1.3506
102	-0.9673	-0.5949	1.1356

*Table 1-5 Errors analysis on Check points (units-centimeters)*

Point	Residual X	Residual Y	Position Residual
118	-17.7434	3.972	18.1826
116	-5.8124	40.7389	41.1515
115	-28.9724	1.8514	29.0315
114	-42.1072	-11.2191	43.5762
110	4.8258	-13.8923	14.7066
111	3.4105	-84.7896	84.8582
107	36.6145	-45.2785	58.2303

The numbers in these two tables correspond to the target distribution shown in *Figure 1-9a* above. The mean error and root mean square error for the control points and check points are given in Table 1-6.

*Table 1-6 PSUAV imagery accuracy analysis summary*

	Mean Error	RMSE
Control Points	1.8736	1.4288
Check Points	41.391	24.431

It is apparent from Table 1-6 that the accuracy of PSUAV imagery is comparable to the surveying sub-meter accuracy of on-the-ground mapping. Thus, this platform is potentially applicable to the scenarios described above. Its accuracy can be significantly improved by using rigorous sensor modeling for calibration. In conclusion, a PSUAV platform can provide sub-



meter mapping accuracy and be a useful asset for processes involving mapping and obtaining GIS data.

### ***1.2.3 Kentucky Transportation Cabinet UAS Program***

The Kentucky Transportation Cabinet UAS program identified a number of potential applications for UAS including surveying, design–digital terrain models, construction monitoring, as-built plans, structural inspections, measuring stockpile volumes, managing and clearing crash scenes, GIS, archeology, and public meetings (Siwula, 2016). They conducted an experiment to implement a surveying application of UAV. In this experiment, they used a 1550 mm Zeta FX-61 Phantom FPV Flying Wing EPO UAV and a 680mm quadrotor UAV, both of which had a Sony QX1 with a 16mm pancake lens. The UAV are shown in Figure 1-22. The cost of the quadrotor is \$1940 and the aircraft is \$1436 (which includes the camera).



*Figure 1-22 KYTC Aircraft appearance*

Ground control marks were placed in a 9"x12" chevron pattern on the ground as shown in Figure 1-23. The area to be photographed and the flight lines and image interval were then defined. The area and flight lines are shown in Figure 1-24 and Figure 1-5. After the UAV survey was completed, the images were processed using software such as PIX4D with the manual step of identifying each Ground Control Point X, Y, and Z Coordinates in at least 3 photos.



Figure 1-23 Place ground control markers-9"x12" chevron

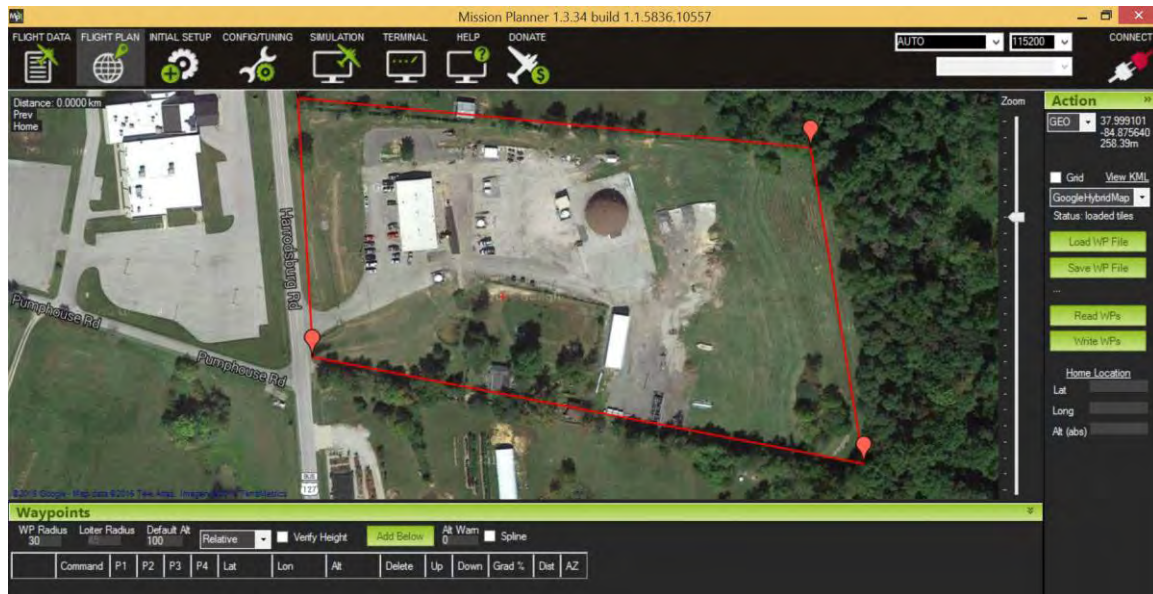
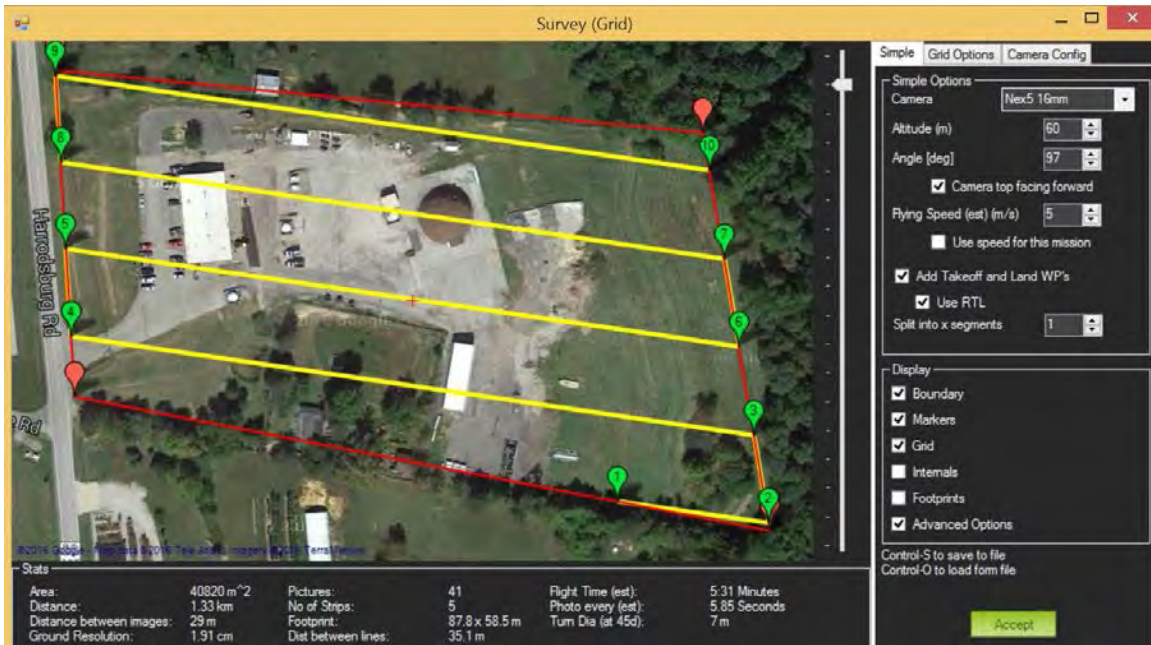


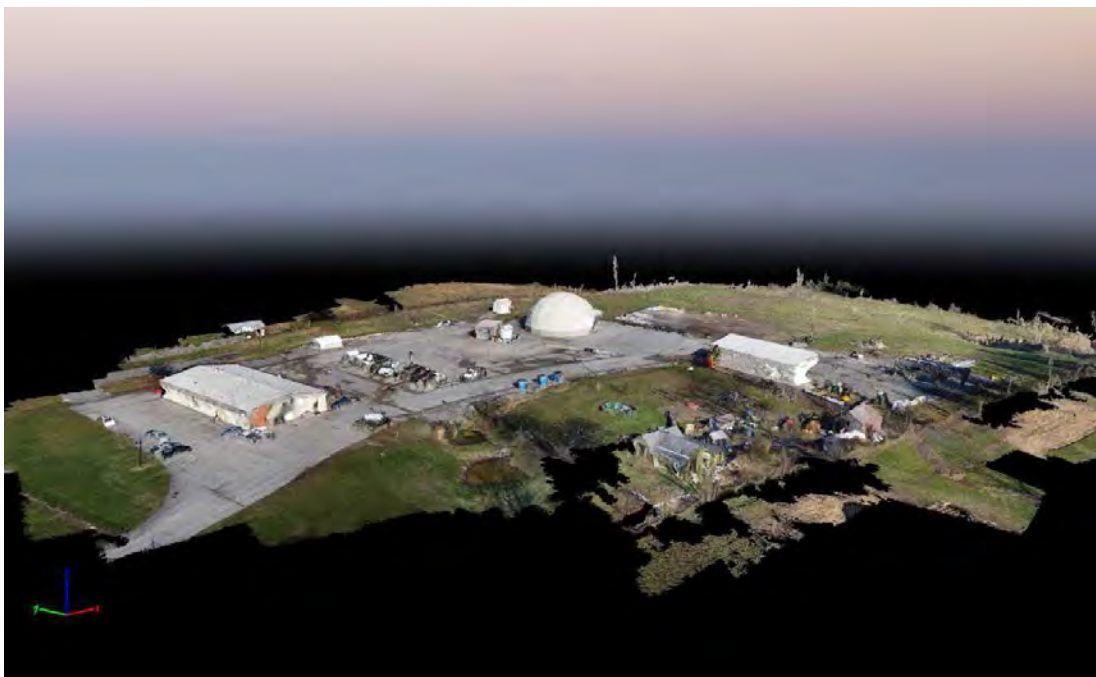
Figure 1-24 Defined area to photograph





*Figure 1-25 Defined flight lines and image interval*

It took a few hours of processing to obtain a 3D color point cloud, DTM and mesh shown in Figure 1-6, the contours in Figure 1-7, and a georeferenced TIF image in Figure 1-28.



*Figure 1-26 3D color point cloud, DTM and mesh*



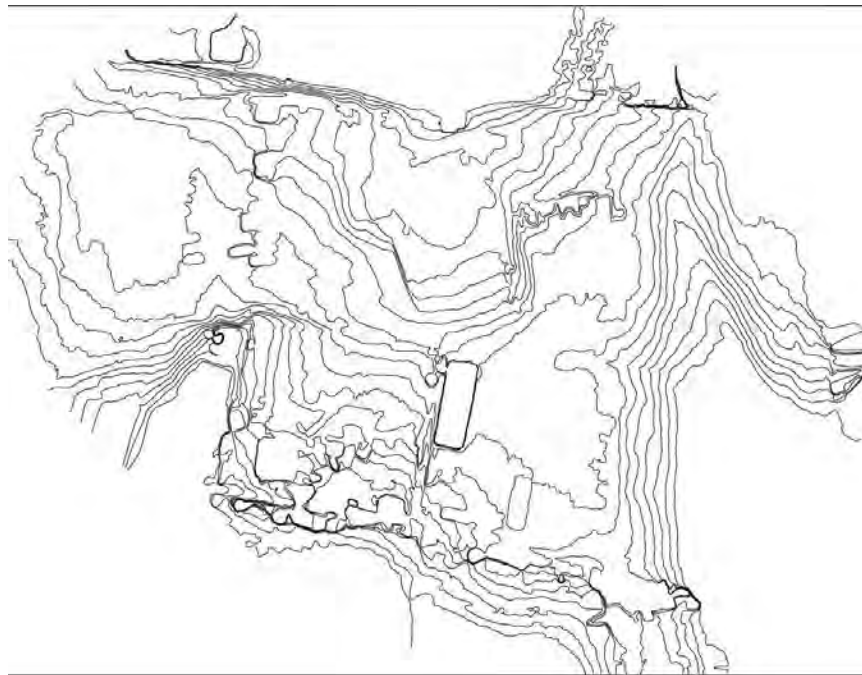


Figure 1-27 Contours

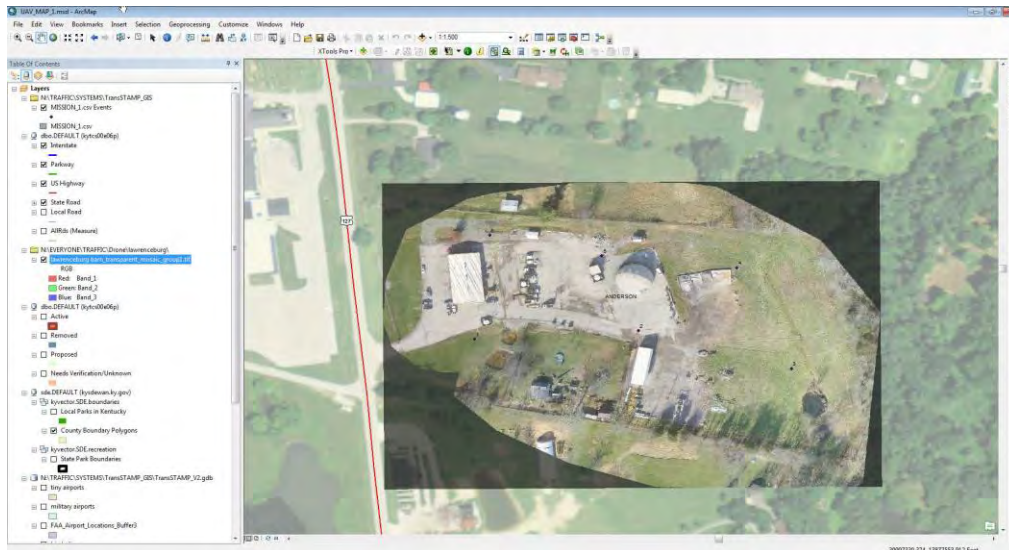


Figure 1-28 Georeferenced TIF

This experiment indicated that using UAV for surveying has a number of advantages over conventional surveying which are detailed in Table 1-7. Moreover, UAS imagery was found to

be superior to conventional aerial photography because the camera is closer to the subject, so it is less affected by atmospheric haze and vibration.

*Table 1-7 Comparison of Surveying with UAS and Conventional Surveying*

Surveying	Cost
Surveying with a UAS	2 people
	10 minute flight
	2 hours on site
	1 hour GCP placement (manual process)
	2-6 hour processing (unattended)
Conventional Surveying	2 people
	3 weeks on site needed to capture similar detail to the UAS point cloud

Research on the use of UAS for automated roadway mapping is being conducted by a number of universities and state departments of transportation. This chapter discussed the research programs at California State University and Michigan Technological University and at the Kentucky Transportation Cabinet, which is Kentucky's state transportation department. Other state DOTs that are also doing this research include Georgia DOT(Javier Irizarry, 2014), Ohio DOT (Ohio/Indiana UAS Center, 2016), West Virginia DOT(Gu, 2012), and Kansas DOT (Melissa McGuire, 2016). The surveying technique currently used by most DOTs is a combination of conventional surveying on foot and aerial imaging. Implementing a UAS for surveying projects may decrease the need for both traditional methods and outsourced aerial imaging.

## **2. AUTOMATED STRUCTURAL AND LAND INSPECTION**

Infrastructure monitoring is a critical aspect for addressing the poor rating of infrastructure systems in the United States<sup>1</sup>. However, deploying human inspectors for monitoring bridges, buildings, dams, etc. does not only involve safety hazards, but may not always provide accurate information and may not be economical. Thus, UAS provide a viable means of structural condition monitoring that is not only safe, but also accurate, especially, in locations that are not accessible by human inspectors.

This section provides a review of applications of UAS for structural condition monitoring, along with equipment specifications and costs.

### **2.1 Inspection in Confined Spaces (Michigan DOT/Michigan Technological University)**

Four UAVs were tested for use in confined spaces which are the DJI Phantom, the Heli-Max 1 Si, the Walkera QR 100S and the Blackout Mini H Quad(Colin Brooks, 2015). All of these have different capabilities and sizes. They all had the ability to capture pictures and video which would be useful for confined space inspection.

The DJI Phantom 1 (the old version of DJI Phantom Vision 2) was the first UAV to be tested for confined spaces. The DJI Phantom Vision 2 is a small quadcopter (<http://www.dji.com/product/phantom-2-vision> ), available on Amazon for \$799 (as of Oct. 21, 2014. DJI Phantom 1 and DJI Phantom Vision 2 are no longer being produced. DJI Phantom Vision 2 is \$359.00 available on amazon) that comes with an integrated 14 megapixel (mp) camera, onboard GPS, rechargeable battery capable of 25 minutes of flight time, and real-time video capabilities via a Wi-Fi range extender and smart phone app. The 14 megapixel camera sensor is capable of taking both JPEG and RAW image formats, can record 1080p HD video, and its wide angle lens photos can be corrected to a more “normal” look using an Adobe lens profile. The camera sensor and lens quality and type are not designed for making measurements or other uses needing high-resolution, high-quality imagery, but are meant for rapid, easy-to-collect aerial photography.

Figure 2-1 shows the small device, which has a 14.6 inch width x 8.3 inch height x 13.2 inch depth and weighs 2.6 pounds (1.1 kilogram). It has a reputation for being easy to learn to fly (and easy to fly) and having a wide user community. With the ability to take still images and record

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<sup>1</sup> [http://www.infrastructurereportcard.org/new\\_york/new-york-infrastructure/](http://www.infrastructurereportcard.org/new_york/new-york-infrastructure/)

video (to microSD cards) with a real-time video link of up to 300 meters (up to about 900 feet), it is very useful for applications where quick aerial images are needed.



*Figure 2-1 The DJI Phantom Vision 2 small quadcopter UAV*

In light of its small size, it was more suited to confined spaces. Testing was conducted first in the lab at the Michigan Tech Research Institute (MTRI) as shown in Figure 2-2. The first-generation Phantom carried a GoPro Hero 3 camera to record video or the take photos as shown in Figure 2-3. A FPV (first person viewer) was likewise included thus the pilot could fly it through confined spaces which were out of view.



*Figure 2-2 DJI Phantom testing in a confined space in the lab at MTRI*

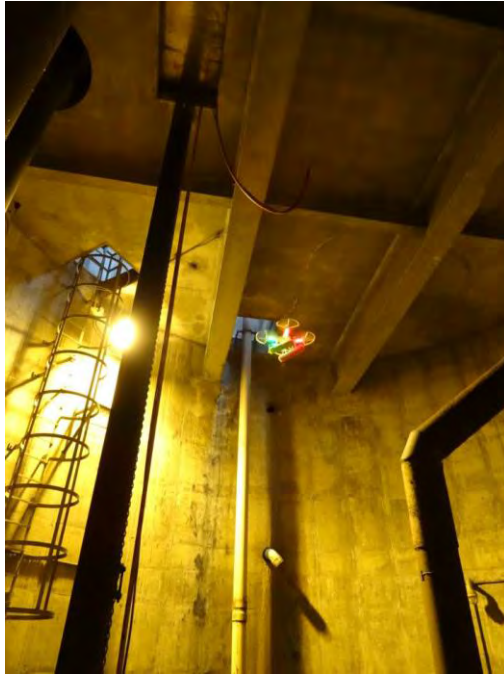


*Figure 2-3 Extracted frame from the GoPro video captured from the lab testing of the Phantom 1*

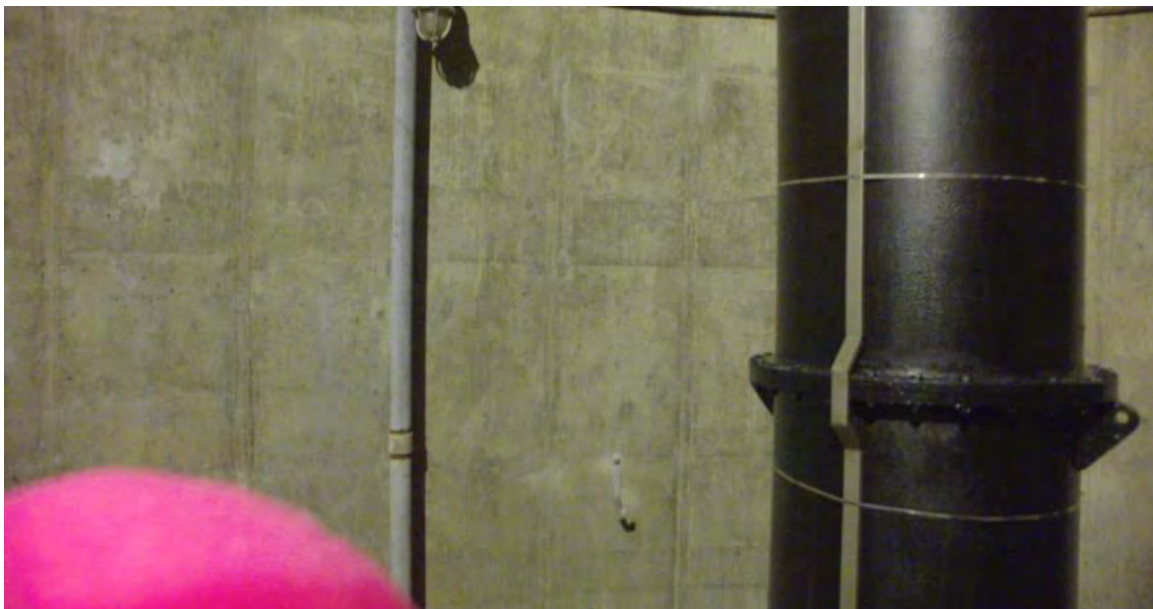
Successful lab experiments prompted a field test of a Phantom 1 inside a pump station. The initial tests were conducted with the Phantom taking off, flying and landing in the lower level of the pump station to better comprehend the requirements of flying a UAV in confined areas as shown in Figure 2-4. Likewise, as with the prior tests in the MTRI lab, a FPV was attached on



the Phantom. A GoPro was installed underneath and frames were extracted from the video of the flights as shown in Figure 2-5.



*Figure 2-4 DJI Phantom flying in a pump station*



*Figure 2-5 Extracted frame from the video captured by the DJI Phantom*

While the test demonstrated that the Phantom could fly in a confined space, any air streams or turbulence inside the confined space would take the Phantom in unexpected directions and must be immediately compensated for as there is very little space for moving. The Phantom likewise should be kept at least two feet from any walls or large objects. On the off chance that the Phantom got any closer, the air being pushed around the props would generate vortices that might pull it into the wall or large object. While the Phantom is a steady platform and was successful, these experiments indicated to the project team that a small UAV would be more suitable for confined spaces.

Micro-quadcopters like the Heli-Max 1Si and the Walkera QR 100S are smaller UAVs that would be more suitable for confined spaces. They are sufficiently small to fit on the palm of a hand. These small UAVs are helpful for confined spaces as they could fly through doorways, rooms and inside culverts easily. An onboard gyroscope helps to stabilize the quadcopters in flight. However, they do not have GPS installed like bigger UAVs. These two UAVs are additionally extremely inexpensive compared to other multi-rotor helicopters with a cost of under \$200 each (Walkera QR W100s is \$99.0 on amazon and Heli-Max 1 Si is \$99.99 without camera and \$119.99 with camera on the official site in 2016). They are less than half the size of the Phantom and cost under \$200 compared to the Phantom 1 which costs over \$400.

The Heli-Max 1 Si has a flight time of 10 minutes and it has a small camera that is able to capture 720p video or 1 megapixel stills as shown in Figure 2-6. A micro SD memory card of up to 32 gigabytes can be used to save video from the camera. The Heli-Max is 5.44 inches x 5.44 inches and is 1.77 inches tall with a weight of 0.10 pounds (46 grams).



*Figure 2-6 Heli-Max 1 Si micro UAV*

The Walkera QR 100S is similar to the Heli-Max in size (5.7 inches x 5.7 inches) with a weight of 0.20 pounds (89 grams) as shown in Figure 2-7. The flight time is also 10 minutes and it has an onboard camera. An advantage of the Walkera is that the camera can transmit the video live to a smart phone or tablet. Video can also be saved to the external device (smart phone) as there is no onboard storage capacity.





*Figure 2-7 Walkera QR 100S*

Both UAVs were tested in MTRI's lab as shown in Figure 2-8 to ensure they could be flown. These tests also included taking pictures and video to compare the quality with the GoPro as shown in Figure 2-9. The smaller size of both UAVs allowed them to have the ability to get closer to walls and other objects before vortices formed.



*Figure 2-8 Test the Heli-Max 1 Si in the MTRI Lab*



*Figure 2-9 Extracted frame captured by the Heli-Max 1Si During the lab testing*

Another type of confined space that was researched was culverts. The Blackout Mini H Quad was chosen because of its small size and mobility and reasonable cost. The Blackout Mini H Quad is a small quadcopter frame (<http://www.minihquad.com/frames/mini-h-quad>), available in a kit from the Blackout Mini H Quadcopter website for \$382(\$313.99 pre-order on the official website in 2016), almost ready to fly (ARF). This airborne vehicle is intended to be very light and customizable, making it a perfect base platform on which to build a framework for use in confined spaces. An Ardupilot Mega open source flight controller (\$50) was matched with a 3-D Robotics uBlox GPS/Compass module for control of the system. This Arduino-based flight controller allows application-particular sensors to be added to the platform in the future for flight control, e.g. a rangefinder(s) for automatic positioning in a confined space. The MTRI Blackout is also equipped with a FatShark FPV 720p system which enables the user to perceive what the Blackout “sees” and allows flying without being able to see the aircraft, which is valuable in confined spaces. The camera module of this system also records the video and saves it to a standard microSD memory card. This system can be found on Amazon for \$430 (as of Oct. 24, 2014, \$196.00 in 2016). This framework can be implemented with any four channel (or more) radio framework.



*Figure 2-10 MTRI Blackout Mini H Quad*

Figure 2-10 shows the assembled MTRI Blackout Mini H Quadcopter. This platform is 11 inch x 13 inch x 3 inch and weighs 1.50 pounds. This system is harder to fly than other platforms because of its custom nature and its capability to be controlled by the software in the flight controller. All things considered, this platform should not be flown by a beginner, but rather one who has experience flying other UAVs such as a DJI Phantom. Part of the explanation behind this is the MTRI platform is planned to fly in confined spaces, and thusly will not have the capacity to depend on the GPS or compass sensors for stabilization purposes. Flying the platform without these sensors requires more experience for users. The open source design of the flight controller will permit appropriate sensors to be added to the platform in the future to help with stabilizing the platform in these confined spaces.

A section of culvert that was 6 feet long and 4 feet wide was provided by the Road Commission for Oakland County (RCOC) for lab testing. The experiment focused on flying the platform inside this section of used culvert shown in Figure 2-11. Additionally, testing inside other confined spaces and sensor integration are required before this platform is a completely deployable system. Flight time is around 10-15 minutes in the current scenario.



*Figure 2-11 Blackout Mini H Quad flying inside a culvert*

Pump stations along freeways can be perilous for inspectors after major storm events or power outages as shown in Figure 2-12. An example of these sort of events would be the flooding of Detroit area freeways during a storm in August 2014. A small UAV has the ability of flying into a pump station while transmitting video back to the monitor without the inspector entering the station. Micro UAVs are small enough to fly through doorways, hatches and other small openings as shown in Figure 2-13.





*Figure 2-12 Dallas pump station along I-75*



*Figure 2-13 Example of a hatch that a UAV would have to fly through*

Confined space inspection, such as in pump stations and culverts, is not considered to be a traditional application for UAVs and larger conventional UAVs like the DJI productions are too big to fly into buildings or other structures. However, with advances in technology, there are UAVs which are small enough to fly into these areas. Since these UAVs are commonly under \$200 and the cost of micro UAVs are just around \$100, they can easily be replaced if they are lost or damaged in a pump station or culvert. They can also help protect investigators by indicating whether it is safe to enter the confined space.

## **2.2 Bridge Inspection**

### ***2.2.1 Michigan DOT (Michigan Technological University)***

Utilizing the principles of photogrammetry, the project team of Michigan Technological University inspected bridge components and measured bridge distress quantities successfully (e.g. percent spall and crack width) (Colin Brooks, 2015). Photogrammetry involves the generation of 3-D models from stereo pairs of photos in order to acquire height and depth data, and is part of the field of 3-D optics. Stereo images must be gathered with an approximate 60 percent overlap so as to develop these models (J.C. McGlone, 2004). 3-D optics/photogrammetry was a technology which the project team employed to perform a potentially low-cost remote sensing method not widely used within the transportation field (Luhmann, 2010).

Implementing photogrammetry techniques with remote sensors became possible by developing platforms such as the easily deployable 3-D Optical Bridge Evaluation System (3DOBS), which takes extremely high resolution optical images (up to 0.5 millimeters; 0.02 inches) at low speeds (under 10 miles per hour) as shown in Figure 2-14. The images collected by 3DOBS were processed by close-range photogrammetry software and recreated into a 3-D surface model and digital elevation maps (DEM) by using Agisoft PhotoScan. They also used ESRI's ArcMap to map the location, volume and area of spalls which were detected by 3DOBS. The software can be integrated into a low-cost system for providing critical indicators of bridge surface conditions. Additional funding, through a different MDOT research project, empowered 3DOBS to fly at higher speeds (at least 45 miles per hour) using a Red EPIC high-frame rate, high-resolution camera. The images captured by this system can be reconstructed into a 3-D model with 0.5 mm resolution. This upgraded platform and sensor costs around \$40,000 and can work at close to highway speed limits ( $\geq 45$  miles/72 km per hour). When compared to the standard method of

measuring and mapping bridge distresses, which include hammer sounding or chain drag techniques and closure of the bridge for the safety of inspectors, the remote sensing technologies and platforms offer faster data collection without having to close the bridge.



*Figure 2-14 3DOBS vehicle mount in the bed of a pickup truck*

The objective was to analyze bridge elements of two different bridges in Livonia, Michigan using sensors installed on a UAV for wider-area data collection. A Bergen Hexacopter was equipped with a 36 megapixel Nikon D800 camera. This optical system is implemented to construct sub-centimeter 3-D models for bridge decks in order to detect defects such as spalls (potholes). They used Agisoft PhotoScan to reconstruct the optical imagery and create a digital elevation model (DEM).

The Bergen Hexacopter is a multi-rotor helicopter which is a product of Bergen R/C (remote control) Helicopters. This UAV is intended to carry a camera payload to take photos or videos as shown in Figure 2-15. A large number of different payloads can be installed within the maximum payload limit of 11 pounds and the flying time ranges from 18 minutes up to 30 minutes under standard operation. The average cost of this hexacopter is \$5400 including a set of spare batteries but without any sensors.





*Figure 2-15 Bergen Hexacopter*

This UAV has two modes of operation. The first is a GPS mode in which a GPS receiver is installed on the hexacopter to make sure it keeps its position. The second is an altitude mode in which the UAV maintains the same level without using GPS. The UAV employed six rotors instead of a single rotor in order to achieve more stability, less vibration and to be easier to fly. The camera is installed on a two-axis gimbal under the body as shown in Figure 2-16. The gimbal can compensate for roll and pitch movement during flight. This function can insure that the camera always faces the same direction regardless of the movement of the hexacopter. The gimbal can also change the viewing angle of the camera by remote control. This function lets the camera assume any angle from straight forward to downward.





*Figure 2-16 Close up of a Nikon D800 mounted to the gimbal under the hexacopter*

There is a small camera underneath the gimbal which is used as a first-person viewer (FPV) as shown in Figure 2-16. This camera has a similar field of view (FOV) as the Nikon D800 with a 50-mm prime focal point. This permits users to see synchronous views with the camera during flight. A hand-held monitor can be used to receive high definition (HD) video from the camera and this screen additionally shows other essential information about UAVs, such as battery voltage, height and speed.

Many tests were performed to evaluate the camera and software limitations using a piece of foam board. Figure 2-17 has a sample photo of the foam board used to determine the restrictions of the AgiSoft Photoscan and Figure 2-18 shows the resulting 3-D model.



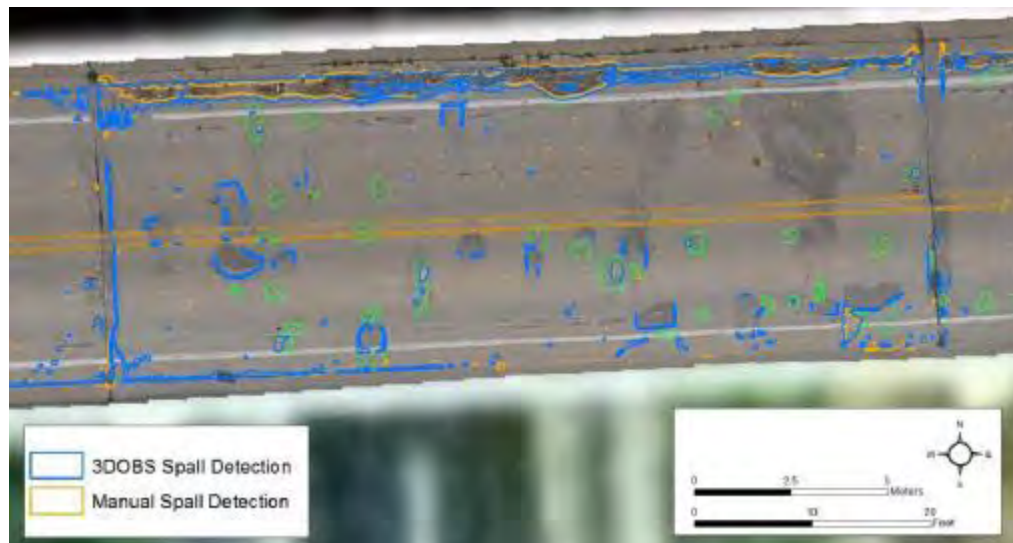
*Figure 2-17 Photo taken of the foam board used to determine the restrictions of AgiSoft Photoscan*



*Figure 2-18 The resulting AgiSoft Photoscan model. A total of five images were used to generate the model*

Additional tests were conducted in order to identify the factors which affected the model. The results show that, as number of photos and coverage increases, the noise is reduced and more accurate and clearer models are produced. Figure 2-19 shows the results of both lab tests and an

in-field test which was performed with a Nikon D500 camera installed above a bridge deck and a moving vehicle.



*Figure 2-19 The reconstructed orthophoto of Willow Road Bridge near Milan, Michigan and the detected spalls based on manual interpretation and automated detection*

A standard bridge deck inspection conducted by MDOT requires eight hours, 4 inspectors and heavy equipment with an approximate cost of \$4600. The same inspection can be conducted by a drone which is operated by two people for two hours at an approximate cost of \$250.

### **2.2.2 U.S. Forest Service & George Mason University & University of Alaska Fairbanks**

This project utilized small unmanned aircraft systems (sUAS), which are UAS weighing less than 55 lbs, to inspect the Placer River Trail Bridge (Mark Riley, 2015). The first goal of the project was to collect high resolution natural color stereo pair and video imagery of the Placer River Trail Bridge with UAVs and then to evaluate this approach as an alternative or supplement to traditional structure inspection methods. The second goal was to assess dense Structure from Motion (dSfM) image processing techniques to construct a measurable 3D wireframe bridge model. The third goal was to compare the dSfM point cloud to the laser scanner point cloud.

Figure 2-20 shows the Placer River Trail Bridge. This is the longest clear span, glued-laminated and timber truss pedestrian bridge in North America at 280 feet. It was completed in July 2013 and has an anticipated operational service life of 75 years. This bridge is managed for pedestrian use.





*Figure 2-20 Appearance of Placer River Trail Bridge*

The UAS platform is a “Ptarmigan” hexacopter based on a DJI S800 airframe (\$750.00 available on amazon) which has a gyrostabilized Sony Nex7 (\$670.80 - \$961.49 available on amazon) and a GoPro (\$175.00 - \$398.89 available on amazon). With LiPo batteries, the flight time is about 20 mins. This UAS is shown in Figure 2-21.



*Figure 2-21 Appearance of sUAS*

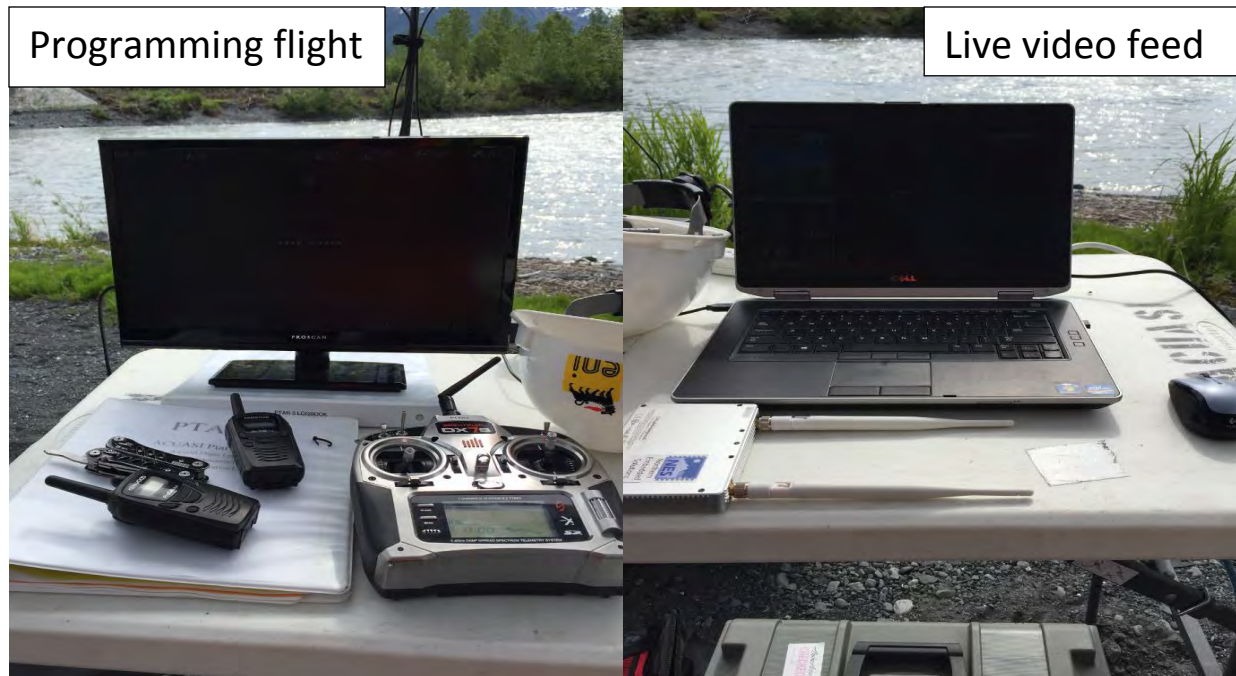
This project requires two pilots (with one acting as a spotter) and a generator to power the equipment. Less than an hour is required to set up the system and have a safety briefing. The working station is shown in Figure 2-22.



*Figure 2-22 Working station*

The base station consists of two parts shown in Figure 2-23. One is used for programming flights, for which a GPS or GNSS signal is essential. If the UAS is lost, this part has a return home function. The other part is used for a live video feed.





*Figure 2-23 Base station*

During the data collection process, vortex shedding and wind were a concern for UAV stability, but not an issue. Lighting was a minor issue. Most of the data collection was done with manual control. Bridge plans were used for reference and to assist with autopilot navigation. Sample data collection figures are shown in Figure 2-24. A FARO Focus laser scanner was set up in 12 locations to collect data to compare with the data collected by UAV.



*Figure 2-24 Data collection samples*

Table 2-1 shows a summary of the data acquisition mission. Still frames were collected with a nominal 90% overlap. More than 90% of the acquired imagery could be used for SfM (Photoscan Pro). The total flight time was approximately 4 hours.

*Table 2-1 Summary of data acquisition mission*

Type of Data	Sensor Type	No. Images/Scans	of Size (GB)	Note
Imaging	Nikon D800E	2222	34.9	Ground-based imagery
	Sony Alpha NEX-7	2626	24.7	UAS-based imagery
Video	GoPro	10	7.57	-
Laser scanning	FARO Focus 3D	24	4.26	-
3D Point Clouds		5	13.71	-

After data collection, data analysis was performed with the goals of recreating flaws, viewing the underside of the bridge deck and tracking long-term camber/motion. There were several challenges in this analysis including a massive data set, confusing data, image degradation and high contrast scenes. Figure 2-25 presents an example of recreating a flaw which shows a gap between the end of a kerf plate and sawn kerf in brace. Figure 2-26 shows the bridge deck's underside.



*Figure 2-25 Recreating flaws*





*Figure 2-26 Deck underside*

They also built an HPCG model using software called Photoscan and SURE which use structure-from-motion image processing to construct a 3D model as shown in Figure 2-27. The resulting model is very large with small details. The development of this model required 14 billion points and 500 hours of computation time, along with good rendering support.



*Figure 2-27 3D model processing*




They discovered that most of the bridge's structural defects could only be viewed by UASs. UASs can successfully acquire vast numbers of high resolution (about 0.5 cm) stereo pair pictures of a structure in a short time. In the experiment, vortex shedding was found to be a minor, surmountable issue with this bridge and the low wind speeds. dSfM image processing methods are the best approach for providing highly detailed and accurate quantifiable multispectral 3D models in a short amount of time. Contingent upon the data collection parameters, dSfM can deliver a denser point cloud than LiDAR (light detecting and ranging). The UAV system used in this experiment was unable to get interior views of the bridge because it was too cumbersome to fly safely with a hand-held Nikon D800E. A powerful computer requires several weeks to produce accurate and detailed dSfM models for data analysis. Proposed FAA rules are adequate for this type of project. Proof-of-concept expenses are not representative of future costs as they will decrease as technology develops.

Finally, it can be concluded that sUAVs can minimize the time spent on site and improve safety by removing potential points of failure and hazardous situations from traditional inspection methods. In addition, sUAVs can perform structural inspections at lower cost and more effectively than traditional methods.

### ***2.2.3 Minnesota DOT***

The Minnesota Department of Transportation and Collins Engineers conducted a demonstration experiment to evaluate the capability, safety and effectiveness of using UAVs for bridge inspection(Jennifer Zink, 2015). Four bridges located throughout Minnesota were inspected using UAVs. This project evaluated the UAV's effectiveness relative to other methods. Current and proposed Federal Aviation Administration (FAA) rules were analyzed with respect to their relationship to bridge safety inspection use. The current and future capabilities for bridge inspection of various UAVs were evaluated. The selection of the bridges to be studied was based on the factors shown in Table 2-2.

*Table 2-2 Bridge selection factors and selected bridges*

Selection factors		
Cooperation of Local Agency		
Safety		
Varied bridge types and sizes		
Location		
Requirements of FAA		
		
Bridge	Location	Type
Bridge 13509	Chisago County, MN	Prestressed Beam Bridge
Bridge 448	Oronoco, MN	Concrete Arch
Bridge 49553	Little Falls, MN	Pedestrian Steel Deck Truss
Acrola RR Bridge	Stillwater, MN	High Steel Arch Railroad Bridge

An Aeyron Skyranger UAV was selected for this project. The Aeyron Skyranger is shown in Figure 2-28 and its technical specifications are shown in Table 2-3. This UAV was designed for military, public safety and commercial uses. It can work in all weather conditions and can change payloads to accommodate a standard camera, an optical zoom camera, and an infrared camera. Compared to other UAVs, the Skyranger has a long battery life which allows it to fly for approximately 50 minutes. However, the Skyranger cannot fly under bridge decks, because it loses the GPS signal and, as a result, returns to the launch point. The price of the Skyranger platform is around \$140,000.



Figure 2-28 Aeyron Skyranger

Table 2-3 Technical specifications of Aeyron Skyranger(Aeryon, 2016)

Technical Specifications	
Endurance	Up to 50-minutes flight time
Wind Tolerance	50 mph (65 kph) sustained 55 mph (90 kph) gusts
Environmental Temperature Range	-22 to 122 °F (-33 to 50°C)
Beyond Line-of-sight Range	1.9 mi (3 km) integrated capability Extensible beyond 3.1 mi (5 km)
Altitude	1500ft. (450m) AGL 15000ft. (4500m) MSL
Launch & Recovery method	Vertical Take-off and Landing (VTOL)
Dimensions	Deployed: 40 in. (102cm) diameter, 9.3 in (24cm) height Folded: 20 in. (50cm) length, 10in. (25 cm) width
Weight (without payload)	5.3 lbs (2.4 kg)
Radio Frequencies:	900 mhz, 5.4 GHz, custom
Security	Secure network pairing, AES 256 bit encryption

The study arrived at the following conclusions as a result of the field tests and literature review:

- It is safe to use UAV for bridge inspections. In light of the size, weight, controllability and built-in fail safes of UAVs, the risks for inspectors and the public are extremely low.

- UAVs cannot conduct inspections independently, however, bridge inspectors can use them for viewing and assessing bridge component conditions.
- UAVs can recognize and view defects with the detail of a close-up photo. However, they cannot perform tactile functions, such as cleaning, measuring, and testing, which require a hands-on inspection.
- The UAV abilities to change camera angles and to fly without a GPS signal are vital functions during inspections.
- UAVs can be used in pre-inspection to obtain important information for large-scale inspections planning.
- UAVs provide a cost effective way to generate extremely detailed data which may not acquired in traditional inspections and they minimize safety risks associated with traffic control, working at heights, and in traffic.

#### ***2.2.4 Tufts University***

Two engineering teams from Tufts University are working together to develop a bridge inspection platform with damage-detection algorithms, wireless vibration sensors, cameras, and drones(Jones, 2016). The platform is also equipped with radio frequency identification (RFID) chips and computer processing units. The data can be stored on the RFID chips and can be extracted by drones equipped with computers hovering close to the sensors. Cameras on the drones can take photos of locations where the data indicate that there is damage. A color coded system is used to indicate the condition of the bridge elements. Green means there is no problem that needs inspection, yellow means there might be a problem, and red means there is definitely a problem with the structure. If the data shows that there may be a defect, the drone's camera will take a photo and transmit it wirelessly to the central computer along with its color status. Rather than inspecting the bridge every two years according to the Federal Highway Administration's National Bridge Inspection Standards, the inspectors will inspect the bridge only in the cases of yellow or red status.

The drones also have the ability to reprogram the sensors. For example, if it is known that the bridge will experience an extremely high amount of stress during a certain time, the UAVs can communicate to the sensors that they should collect data more frequently. The UAV can also

start this function automatically according to weather or traffic conditions which it detected. Once the UAV has finished its tasks, it will fly back to base automatically and be recharged for its next deployment.

## **2.3 Transportation Infrastructure**

### ***2.3.1 Michigan DOT (Michigan Technological University)***

Michigan Technological University did experiments about mapping of unpaved road conditions by using remote sensing (Colin Brooks, 2015; Colin N. Brooks, 2015). The researchers employed a Bergen Hexacopter (described above in Section 2.2.1) to collect overlapping imagery from about 80 feet above the road surface. The images generated from this project are shown in Figure 2-29, Figure 2-30, and Figure 2-31.

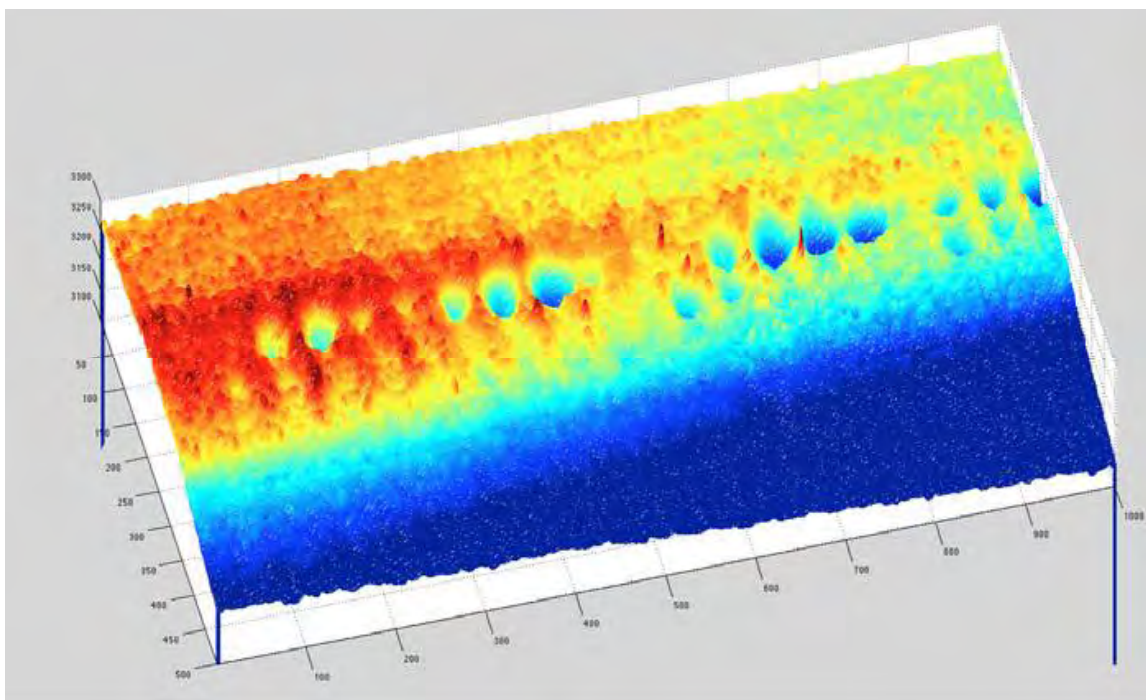


*Figure 2-29 3D point cloud of an unpaved road generated using image reconstruction*





*Figure 2-30 Aerial photo of unpaved road from UAV*



*Figure 2-31 3D height field showing potholes on an unpaved road*

### ***2.3.2 Georgia DOT***

It is very important to inspect and monitor linear infrastructures, for example, road line segments, pipelines, aqueducts and canals, in order to ensure their safety and life expectancy (Javier Irizarry, 2014). UAVs can inspect and monitor these structures by staying or flying on top of them and transmitting detailed photos or video streams.

Georgia DOT employed a semi-supervised learning algorithm, so that various linear infrastructures can be evaluated through a vision-based system. The result is a cross-sectional profile of the target element. The UAV used in this project is a Sig Rascal model aircraft with a 9.2 ft (2.8 m) wingspan and a 12 lb (5.5 kg) empty weight. A camera was installed on this aircraft at a 30 degree angle with respect to the aircraft's yaw axis. The resulting image and video outputs were simulated with a real-time 3-D visualization software package.

Cutting edge UAS/drone technology allows all types of precision sensors, from visual and infrared cameras to LiDAR tools, to be placed in optimum data gathering locations quickly, at low risk and low cost. Collected data can be quickly analyzed, interpreted, and reported.

Progressive companies with substantial, widely-distributed assets like natural gas facilities, cell towers, and wind turbines are realizing that they can no longer ignore the powerful efficiencies and new data sets available with UAS technology. Inspections that have required humans to climb around towers and bridges, putting them at risk, are being augmented, and even replaced, by carefully executed UAS data-gathering flights that are safer, faster, and less-expensive.

### **3. AUTOMATED TRAFFIC MONITORING AND MANAGEMENT**

Traffic monitoring and management are areas in which UAVs may be very useful as they can be deployed on an as-needed basis and can provide information very quickly. This section describes studies where UAS has been deployed for road condition monitoring, traffic monitoring, and traffic management. Additionally, equipment specifications and costs are also presented.

#### **3.1 Road Construction and Condition Monitoring**

UAVs, with their ability to fly at low altitudes on flexible routes, can provide a very good tool to monitor road conditions, particularly for unpaved roads. According to the Federal Highway Administration (FHWA), in 2008 there were 1,324,245 miles of unpaved road in the United States, accounting for almost 33% of the over 4 million miles of road in our national transportation infrastructure (FHWA and USDOT 2010). Local governments and transportation agencies are responsible for a large part of this unpaved infrastructure. These agencies need to be able to assess the condition of the infrastructure on a periodic basis in a cost-effective manner in order to effectively manage these roads and to optimize resource allocation. Paved and unpaved road conditions can be easily assessed visually; the texture, color, shape, surface imperfections, and other characteristics allow agencies to identify and classify various problems with the roads. With proper software and sensors (such as mini-LiDAR), the assessment of road conditions could be more precise. The following subsection describes a research project that evaluated the requirements for UAVs to be used for road construction and road condition monitoring, as well as the cost effectiveness of this approach.

##### ***3.1.1 Utah DOT***

Utah Department of Transportation (UDOT) captured high-resolution photos using UAVs, to monitor State Roadway structures as well as to document associated problems (Clemens, 2012; Steven Barfuss, 2012). The photographic imagery project documented all stages of the Southern Parkway construction near the new Saint George International Airport. Geo-referenced UAV high resolution images were taken during the progress of this construction project and in addition, wetland plant species in the nearby Utah Lake wetland mitigation bank were photographed and classified.

The UAV technology used in this project was called AggieAir, which is an autonomous, multispectral remote sensing platform. The operation of AggieAir only requires two operators

and does not depend on a runway. Its purpose is to provide greater access to aerial imaging to more people in a low cost, easy to use manner.

The specifications of AggieAir are shown in Table 3-1 and the component layouts are shown in Figure 3-1 and Figure 3-2. There were eight 12v batteries in the battery bay located in the front of the aircraft, which supply about one hour of flight time. The payload and inertial measurement unit (IMU) were located in the main bay, which consists of two cameras; one capturing images in the visual band of the spectrum and the other in the near infrared band of the spectrum. The GPS receiver and IMU were the two main sensors in the aircraft which measure the position and orientation of the aircraft respectively. The data collected by the GPS receiver and IMU were processed by Gumstix, the on-board computer, and sent to the autopilot. These data are sent to the ground control station (GCS), which allows the operator to view the aircraft and give commands. In addition to processing the data and sending it to autopilot, Gumstix also controls the cameras and other payloads. The autopilot uses a preprogrammed flight plan to navigate the aircraft through the elevons (for rotating), the propeller (for accelerating), and the winglets (for stabilizing the aircraft in the z-axis). Manual control by a radio controlled (RC) transmitter was also an option. Operators can send various commands to control the aircraft using the RC transmitter which moves the elevons and propeller and can switch between the autopilot and manual modes.

*Table 3-1 AggieAir Aircraft Specifications*

AggieAir Aircraft Specifications	
Wingspan	1.8m (72 inch)
Weight	3.62kg (8 lbs)
Nominal Air Speed	15m/s (33mile/hr)
Max flight duration	45min-1h
Battery capacity	16,000mAh
Payload capacity	1.36kg (3 lbs)

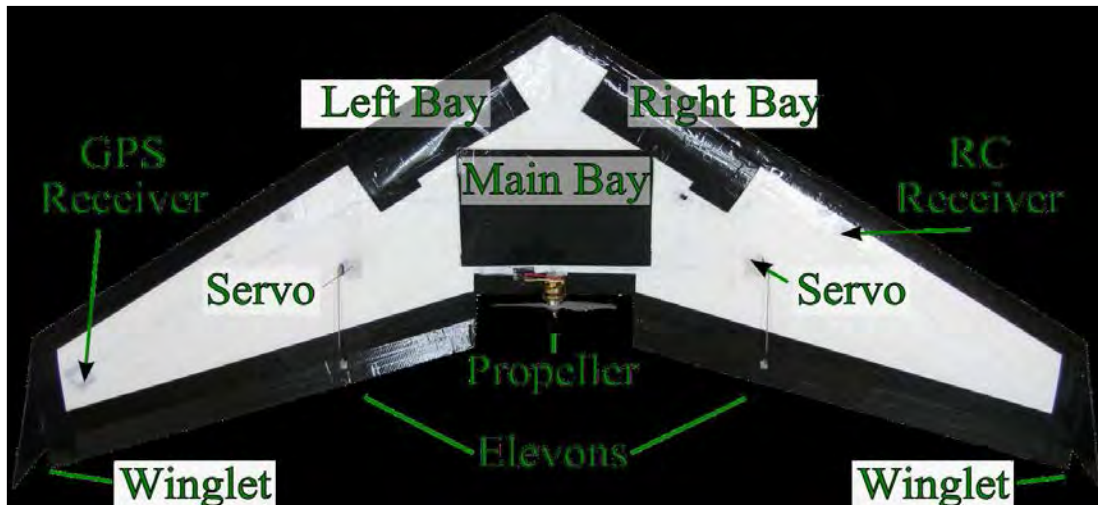


Figure 3-1 Aircraft Layout

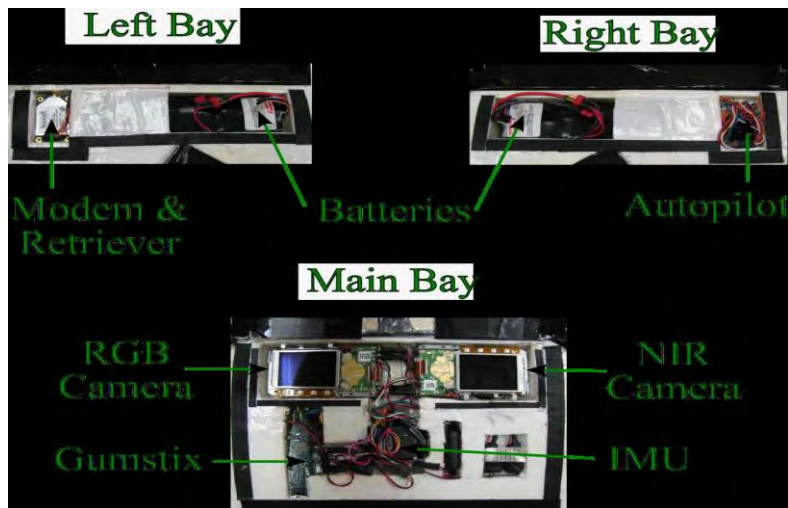


Figure 3-2 Bay Layout

While the design of AggieAir allows the aircraft to hold many payloads, GhostFoto (GFoto) is the only payload that is currently in use. GFoto is a Canon camera controlled by the on board computer, Gumstix, through a USB connection. Gumstix instructs the camera to take pictures and records the position and orientation of the aircraft. GFoto also sends messages to the GCS regarding the status of aircraft. At the end of the flight, an operator can download the images and the datalog from the aircraft into the Geo-spatial Real-Time Aerial Image Display (gRAID) plugin for World Wind. gRAID uses the respective telemetry data to orthorectify the captured images and display them on the earth. It can export the images so that Geographic Information Systems



(GIS) software can view them and help to increase the accuracy of the orthorectification of the images and to make a mosaic of them. Another payload that can be installed on the aircraft is a GhostVideo (GVideo), which can stream low resolution videos from a video camera back to the GCS through a video transmitter. Two drawbacks with GVideo are that its low resolution videos result in poor image quality and that the aircraft must always be within the range of signal communication. Table 3-2 shows the image specifications.

*Table 3-2 Image Specifications*

Image Specifications			
Flight Altitude (About Ground)	200m	500m	1000m
Swath Width	190m	475m	950m
Ground Resolution	0.06m	0.15m	0.30m

The project demonstrated the value of using UAVs as a tool for UDOT applications to acquire high resolution aerial images. As aerial images acquired by UAVs can be collected and viewed in just a few hours, UAVs are very valuable for many UDOT applications, such as monitoring road construction and road damage and inventorying roadway structures. In addition to evaluating the applicability of UAVs for UDOT purposes, the project also aimed at improving UAV functions to more closely match UDOT's needs. For example, safety concerns about flying UAVs around and over the highways will be addressed in the development and flight planning in future projects.

The project demonstrated that UAVs would provide benefits to UDOT for tasks that required immediate aerial images of Utah roadways UAVs can route through and perform tasks over many sites, such as roadways that are under construction or are in need of repair. Moreover, UAVs could be used to regularly update aerial images in the GIS database of UDOT which could help improve many of its functions and its decision-making process.

## **3.2 Traffic Monitoring**

### ***3.2.1 Michigan DOT (Michigan Technological University)***

This experiment tested a 15 foot long tethered blimp with a net lift of around 8 pounds for traffic monitoring (Colin Brooks, 2015). The payload included a camera, gimbal and battery which weighed around 4.5 pounds. The inflation of the blimp required about 30 minutes with about 290

cubic feet of helium. A Samsung 4G camera was selected to test the video stream transmission quality through a 4G cellular network, which was found to have only a 10-15 second delay. Moreover, MTRI set up an account for USTREAM, which is a cloud based video platform, in order to save the video and review it after the experiments. A battery powered gimbal was mounted to stabilize the camera and point it at locations of interest.

A field demonstration of the blimp traffic monitoring system was given at the ITS World Congress in Detroit September 8-11, 2014 on Belle Isle for four days as shown in Figure 3-3. Camera images were transmitted by a 4G wireless system from the demonstration site to a mocked-up Traffic Operation Center in downtown Detroit. The blimp was flown continuously during the day and stored at night in a rental truck while still inflated.



*Figure 3-3 The traffic monitoring blimp collecting near-live video data over Belle Isle*

The blimp was flown over a mock incident on Belle Isle during testing and images of the accident are shown in Figure 3-4.

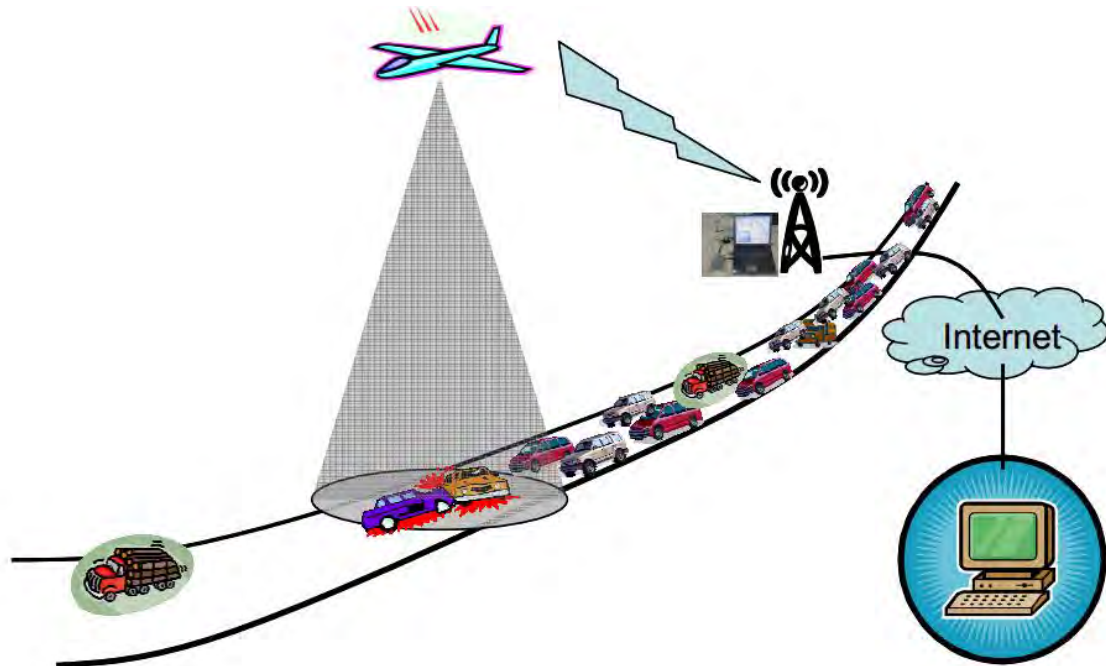


*Figure 3-4 Screenshots from the MTRI blimp video feed of the emergency response mock incident. The blimp was approximately 100 feet in the air when these shots were captured.*

### **3.2.1 Western Michigan University**

The main goal of this project was to develop a cost-effective traffic monitoring system using UAVs particularly in suburban and rural areas (Kapseong Ro, 2007). Particular objectives in the initial phase were to evaluate the capability of UAVs in traffic monitoring and emergency identification and to develop a transmission system for sending live video images from UAVs to the traffic management agencies.

The project concept is shown in Figure 3-5 with a UAV outfitted with a video camera transmitting real-time video to a ground station. During recording, the images were additionally sent by wireless internet to a fixed server in communication with various traffic authorities enabling them to make quick decisions when an incident has been identified.



*Figure 3-5 Project Concept Overview*

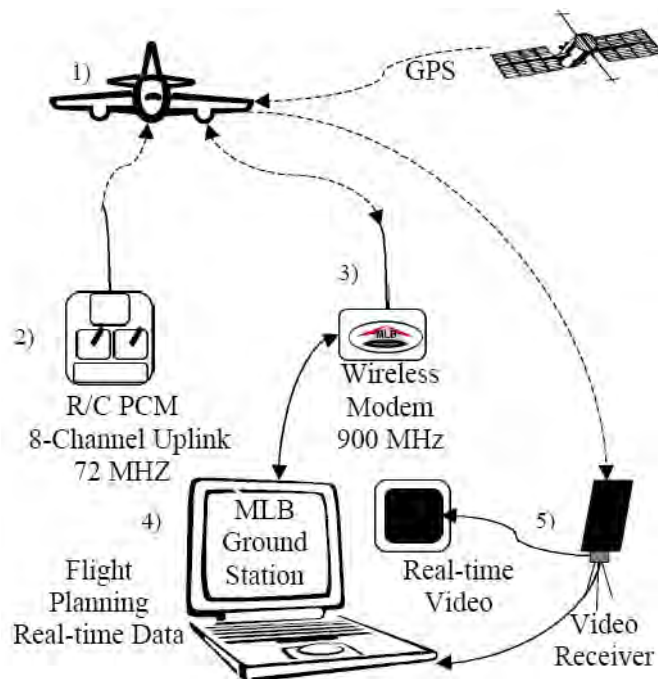
The UAV used in this test was a BAT III from the MLB Company as shown in Figure 3-6. It is a small UAV (sUAV) platform which can operate autonomously and transmit real-time high quality video images and sensor data. It weighs 10 lbs with a 6 ft wing span. The flight duration is up to 6 hours, the range of telemetry is 7 miles and the maximum payload capacity is 4 lbs. As shown in Figure 3-7, it also consists of the following 5 communication components:

- GPS signal receiver to operate an autonomous flight computer
- 72 MHz radio control transmitter for manual piloting, which can be disengaged by a 900MHz upload command signal
- 900 MHz 2-way modem for flight data and in-flight task changes and a 10km range with omnidirectional antenna
- A notebook PC with flight data, moving map display of the UAV, and graphical user interface for mission planning and updating
- 2.4 GHz real-time video downlink; 10 km range with 12 dB directional antenna





*Figure 3-6 BAT III Small UAV*



*Figure 3-7 BAT III Communication System*

In this project, video communication systems were incorporated into an existing small UAV platform to transmit real-time data to traffic authorities so that they can respond to incidents in a timely manner.

In addition to universities, state departments of transportation across the country are exploring the use of UAVs for traffic monitoring. The Arkansas State Highway and Transportation Department uses UAVs to monitor traffic and collect HD video and turning movements. The Virginia DOT has implemented the Airborne Data Acquisition System (ADAS) to do real-time traffic surveillance and monitor traffic incidents. The Florida DOT has also implemented real-time traffic monitoring(JR., 2016).

### **3.2.3 Cisco Dubai**

Cisco conducted a demonstration to show the potential of using UAV for traffic monitoring and control in Dubai in October, 2016(Gandhi, 2016). They wanted to show the capabilities of UAVs Including:

- Flying safely through crowded urban areas
- Collecting detailed data and providing accurate images of what is happening on the ground by using different kinds of cameras and sensors
- Integrating UAV control and sensor data into collaborative and Internet of Things (IoT) applications
- Providing real-time information and alarms through the use of fog computing and analytics

One of the big obstacles that Cisco had to overcome before presenting the demonstration was to obtain the Dubai Civil Aviation Authority's permission to fly UAVs over urban areas within Dubai. Once approval for these flights was obtained, 24 missions were conducted over both desert and urban areas by UAVs with fully autonomous capabilities. The total distance covered by these remotely-piloted flights was 180 kilometers. The UAVs were equipped with both high-resolution video and thermal cameras. The images could be shared in real time over Cisco's WebEx collaboration platform through a 4G network.

In addition to the live video feed providing a very good picture of overall ground traffic conditions, the demonstration had photogrammetry capabilities. By combining photographic images with geometric information, real distances could be precisely measured, such as how high a pole is, how long a motor vehicle is, or how deep a pothole is. This type of real-time monitoring can help critical situations be identified and responded to as they occur. Furthermore,

it can also help provide accurate measurements for new construction without engineers having to visit the site.

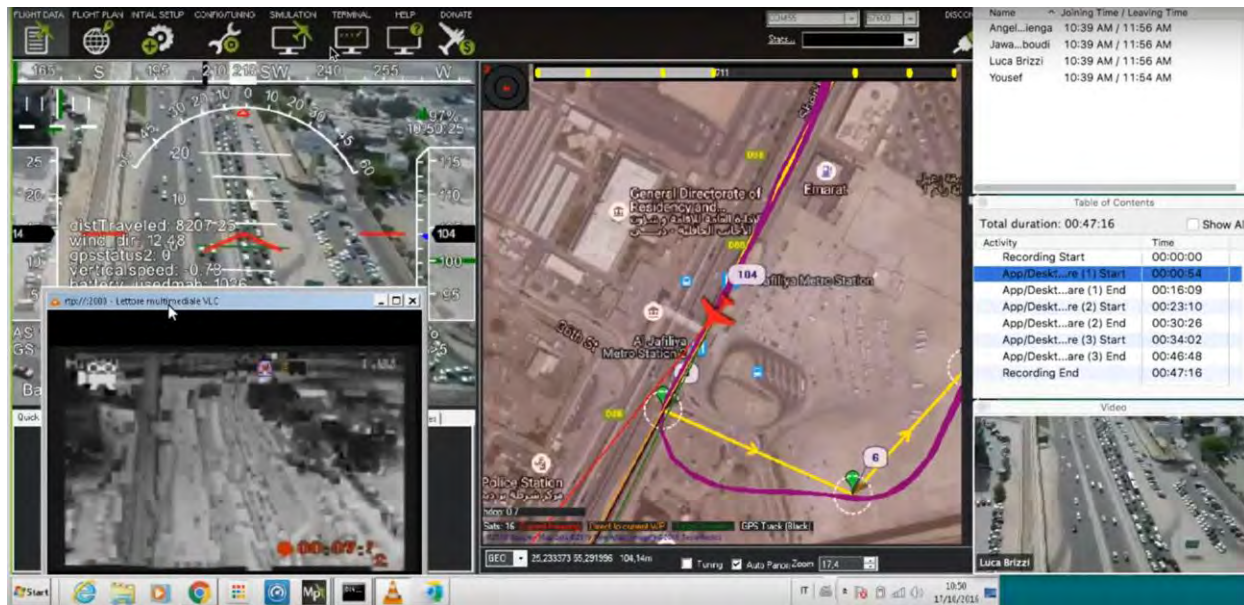


Figure 3-8 A WebEx live stream enabled both remote monitoring and control

In the traffic monitoring application shown in Figure 3-8, the WebEx connection allows traffic controllers to pinpoint traffic issues as they occur and to issue an alarm or change the signal timing of a traffic light to remedy the traffic jam. Cisco's ultimate goal is to use intelligent learning algorithms to process all data acquired by UAVs with fog analytics and to issue automatic alerts and recommendations.

### 3.2.4 Advantages of Using Drone Surveillance for Reducing Traffic Jams

There are many advantages to employing UAVs to do traffic monitoring, which can acquire telemetry data very easily and inexpensively (Naveed, 2015), as outlined below:

- **No Satellites Required:** It is very costly to build and maintain the satellites required by current traffic monitoring systems. UAVs present a less expensive alternative which can achieve comparable results. UAVs can be positioned at various intersections to ensure continuous monitoring during peak hours.
- **Improved Decision Making:** The data obtained from UAVs can be used to evaluate traffic conditions and enable operators to take steps to improve the level of service at congested intersections and reduce traffic jams.

- **Informing Commuters:** Real-time traffic information collected by UAVs can be broadcast to drivers through radio or the internet. This would enable drivers to choose better, less congested routes which would reduce their travel time and help reduce traffic congestion.
- **Good Data Acquisition Possibilities:** The data obtained from UAVs can not only be used for real-time decisions, it can also be used for long term decisions by operators. With the large amount of detailed traffic data, authorities can develop better strategies for traffic management.

### ***3.2.5 Disadvantages of Using Drone Surveillance for Reducing Traffic Jams***

While there are a number of advantages to UAV use for traffic monitoring, a number of disadvantages are outlined below (Naveed, 2015):

- **Weather Dependence:** The effectiveness of UAVs can be severely reduced when operating in inclement weather such as high winds, rain or snow. Although there are some large UAVs that can operate in harsh weather, they are extremely heavy and only suitable for videography.
- **Short Battery life:** The average flight time for the most suitable type of UAV, multirotors, is around 20-30 minutes which is too short to accomplish the task of traffic monitoring.

Despite the fact that UAVs can be used for traffic monitoring, there are a number of issues that affect their practicability. The feasibility of using UAVs for this purpose largely depends on developing multirotor UAVs with battery lives greater than an hour.

## **3.3 Traffic Management**

### ***3.3.1 Traffic Incident Management***

#### ***3.3.1.1 Ontario Provincial Police (Muir, 2014)***

Traffic incident management (TIM) involves detecting, responding to, and clearing traffic incidents in order to restore traffic flow as safely and quickly as possible. It is a process that requires planning and coordination among a number of public and private entities. Its two main goals are to reduce the duration and impacts of traffic incidents and to improve the safety of drivers, crash victims, and first responders. (Jodoin, 2016) Recently, many law enforcement agencies have incorporated a new tool into their TIM strategies—unmanned aerial systems (UAS). These small, battery-powered devices can be carried in a patrol car trunk and quickly deployed, and a UAS can capture an entire scene on high-definition video in minutes. Typically



operating at an altitude of less than 100 feet, UAS provide overhead views that can document complete scenes in great detail. The imagery can then be imported into a computer where investigators can view the scene from any angle and even conduct a virtual walk-through.

The Ontario Provincial Police (OPP), Traffic Safety and Operational Support Command has been operating UAS since 2012. This technology is utilized to enhance search and rescue capabilities and for forensic identification purposes, as well as collision scene mapping as part of the Rapid Clearance mandate within the Highway Safety Division (HSD).

The UAS complements, but does not replace, the OPP's aviation assets. The current OPP UAS provide imagery through high-resolution digital video, still images, and forward-looking infrared cameras (FLIR). Their small size and autonomy allow these UAS units to reach areas that may be too treacherous or difficult for officers. The resilience that UAS have to snow, rain, and wind provide search managers with continued, low-maintenance aerial assets that are available at all times. The UAS also allow for aerial photography and 3-D modeling of complex crime scenes.

The OPP was one of the first police services in Ontario to utilize UAS for major collision investigations. In 2013, the Traffic Support Unit–HSD deployed two units in the Greater Toronto Region. The UAS utilize aerial photography and video to create ortho-mosaic aerial images of collision scenes. The aerial images provide officers with the ability to collect evidence from crash scenes in significantly less time, and the small unit replaces the traditional Robotic Total Station for mapping at collision scenes. The UAS have a proven ability to provide a faster investigative process through a photo “grid-map.” On average, the Traffic Support Unit–HSD maps a major collision scene in 22 minutes using UAS.

The UAS software also provides crash scene reconstructionists with better analysis tools to review and document a collision scene. The UAS software is capable of creating 2-D and 3-D images of a scene. These images can be processed to create views of an accident scene from different vantage points, and the images can be linked together to allow for a visual representation moving through the collision scene, for example, a vehicle path of travel. The UAS images are accurate within one centimeter per pixel which is comparable to those generated by traditional scene mapping tools. The more technologically advanced UAS images and visual representations provide invaluable representations of the collision scene to both the

reconstructionist and the court, when applicable. UAS directly contribute to rapid clearance while allowing proper investigation at collision scenes.

The UAV used in the HSD UAV program is an Aeryon Scout UAV (purchased in April, 2013 and June, 2013) and its appearance and specifications are shown in Figure 3-9 and Table 3-3, respectively.



*Figure 3-9 Aeryon Scout*

Table 3-3 Aeryon Scout Specifications(Wikipedia, 2013)

Specifications	
General characteristics	
Length	80cm (28.2 in)
Rotor diameter	80cm (28.2 in)
Height	30cm (1 ft)
Loaded weight	1.4kg (3.1 lb)
Max takeoff weight	1.7kg (3.74 lb)
Power plant	4 x Electric motor, Intelligent LiPo battery each
Propeller diameter	30 cm (12 inch)
Performance	
Maximum speed	50km/h (31mph)
Cruise speed	40km/h
Range	3km (2mi)
Service ceiling	1000ft/3000m AGL (15000ft/5000m ASL)
Rate of climb	2m/s (6ft/s)

The OPP implemented UAVs for crash scene mapping beyond aerial photography/video to photo “grid-Map” crash scenes with a resulting ortho-mosaic aerial image accuracy to 1cm/per pixel. With this process, a 300m x 30m scene could be mapped in only 10 minutes. Figures 3-10 and 3-11 show UAV control panels.

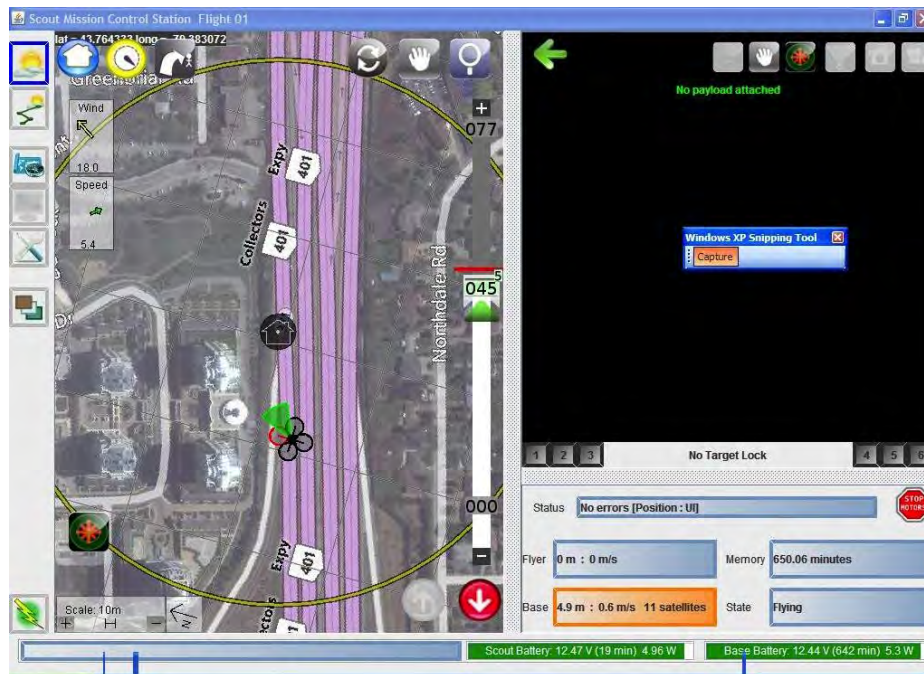


Figure 3-10 Flight Controls

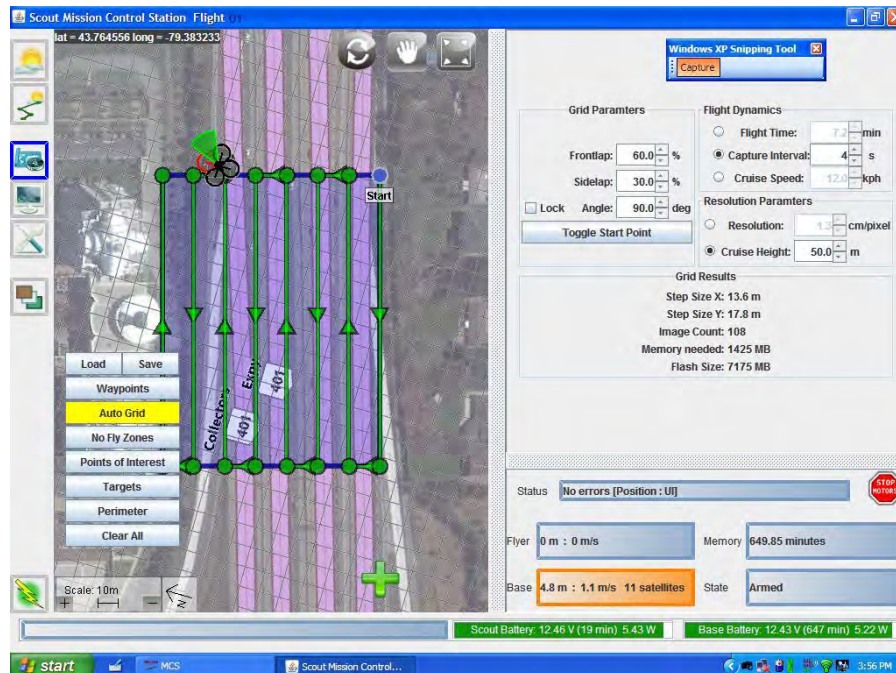
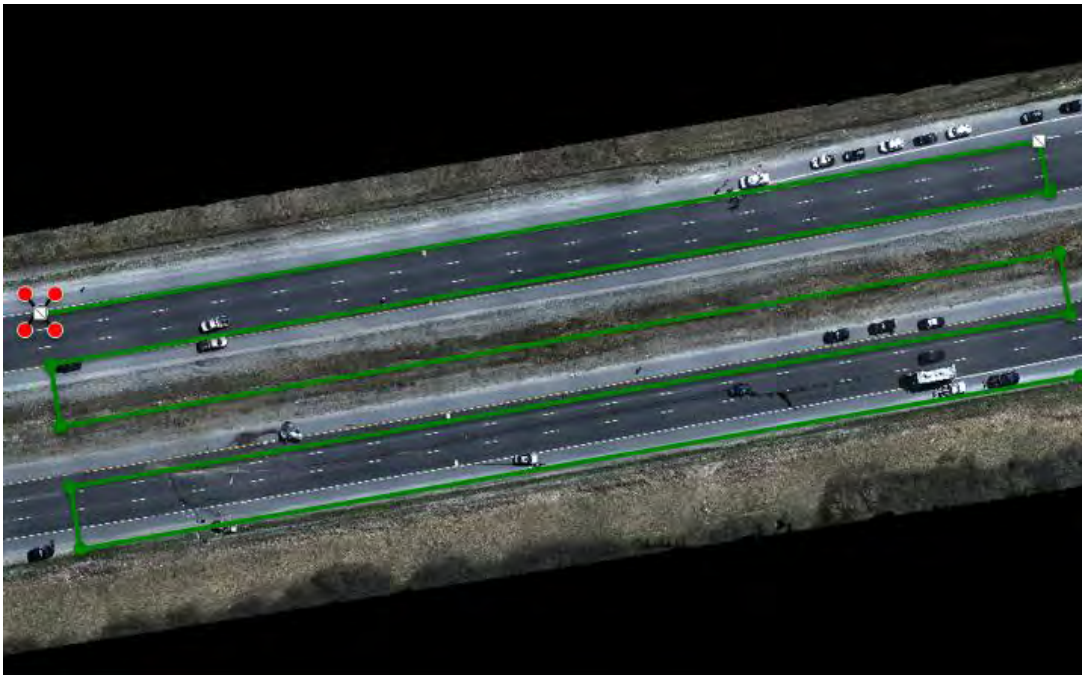


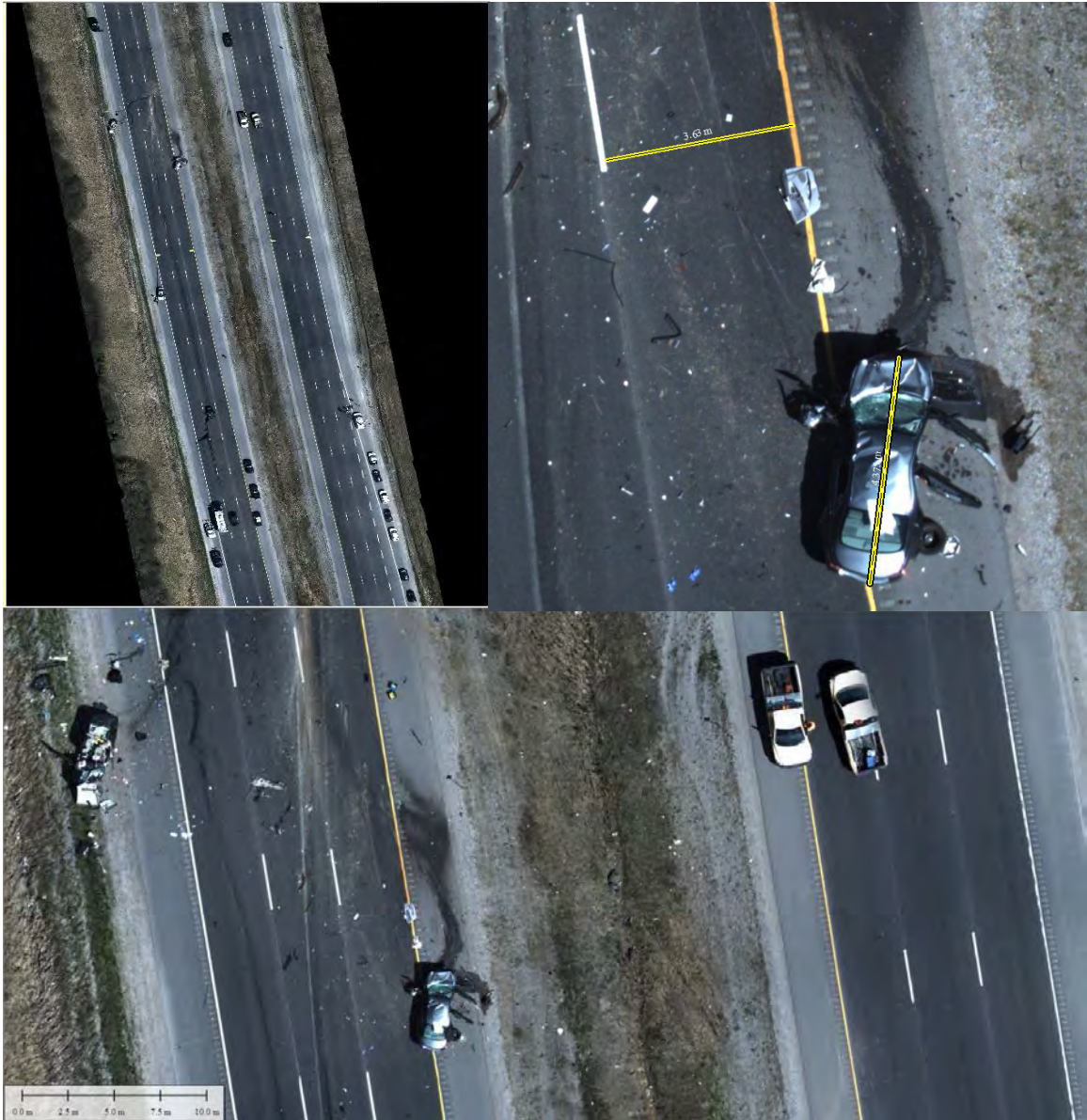
Figure 3-11 Auto-Grid Mapping

Figure 3-12 shows a sample UAV scene mapping. A UAV flies in a pre-programmed pattern taking photos about every 4-5 seconds. Software is used to stitch the images together. Figure 3-13 shows an incident mapping example. This is an overview of Highway 404 north of Toronto. A vehicle crossed through the median striking a vehicle traveling in the opposite direction resulting in two fatalities, one in the northbound vehicle that crossed over the median and the other in the southbound vehicle. The mapping of this incident by a UAV took 15 minutes from set-up to completion and an accurate, measurable photo-mosaic was generated. Extensive scene evidence such as tire marks, vehicles, and barrier impacts were captured in the scene mapping.



*Figure 3-12 UAV Scene Mapping*



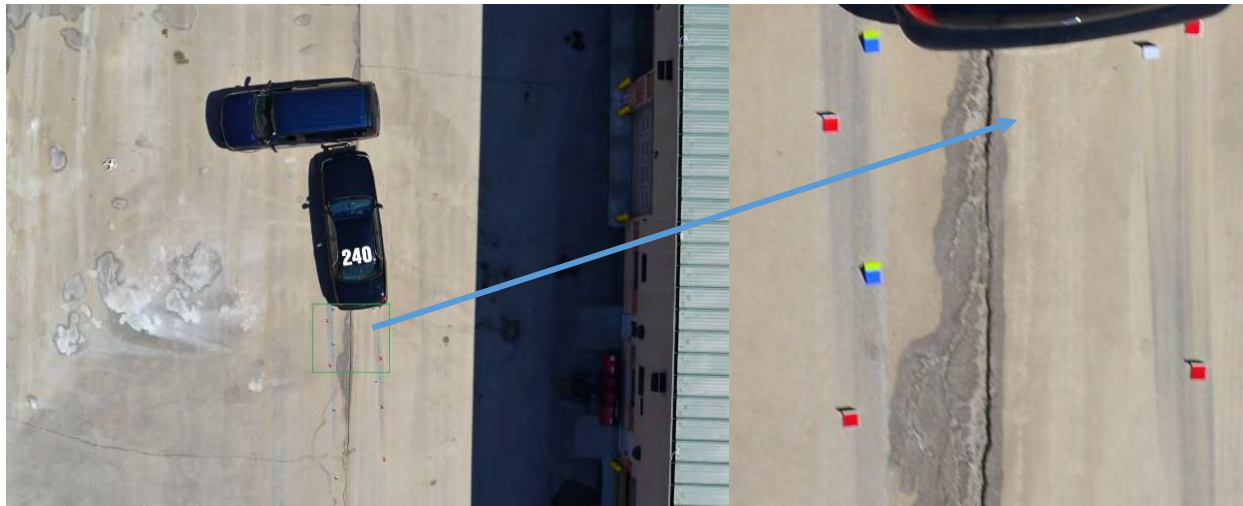


*Figure 3-13 UAV Scene Mapping incident example*

### *3.3.1.2 Crash Scene Reconstruction - MDOT (Colin Brooks, 2015)*

Michigan DOT conducted three demonstrations of using UAVs for crash scene reconstruction: 1) one for the Michigan State Police (MSP) in August 2013; 2) one for the Southeast Oakland County Crash Investigation Team (SOCCIT) in April 2014; and 3) one for the ITS World Congress Emergency Response Day in September 2014. The first demonstration showed that a small quadcopter could quickly gather images which the MSP Crash Scene Evaluation team could use to obtain important information about crash scenes.

Figure 3-14 shows an image taken from the second demonstration. This figure shows the crash scene markers (represented by small red and blue rectangles) which were set up near a vehicle and its tire marks. A Bergen hexacopter, a DJI Phantom 1 and a DJI Phantom 2 were used in this demonstration. The DJI Phantoms were equipped with GoPro cameras and were used for quick and lower resolution images. Meanwhile, the Bergen hexacopter was equipped with a larger Nikon D800 camera and used for taking higher resolution (36 megapixel) imagery which is required for accurate and precise crash scene measurements.



*Figure 3-14 Example crash scene image hexacopter-based collection demonstration*

An example of a high-resolution image that was taken at the ITS World Congress is shown in Figure 3-15.



*Figure 3-15 Crash scene image collected by the hexacopter-based system*

#### *3.3.1.3 Accident Scene Response(Pix4D, 2016)*

UAVs can provide advantages over traditional traffic monitoring methods. UAVs can fly at higher speeds and are not limited to particular routes or infrastructures. They can also operate in inclement weather conditions.

PIX4D develops photogrammetry software for drones. This software can process images collected by UAVs to create professional orthomosaics, point clouds, and models from which 2D and 3D information can be obtained as shown in Figure 3-16. One area in which UAVs can be particularly useful is in accident scene response for the reasons discussed below.

##### *(1) UAVs can document accident scenes much faster*

After an accident happens, it is desirable that it is cleared as soon as possible, but this cannot happen until the accident scene is documented. Typically, accident scenes are documented by laser scanners, total stations, and photography to obtain data and generate a 3-D point cloud of the site. However, this approach requires a lot of time and trained individuals who may not always be immediately available. UAVs can easily overcome these problems by quickly flying to accident scenes and easily obtaining information from large areas. According to Drew Jurkofsky,



a Colorado police officer and accident reconstructionist for approximately 20 years, an UAV can reduce the time spent in the roadway by four-fifths and measuring time by two-thirds compared to traditional methods of documenting accidents(Pix4D, 2016).

(2) The reduction in time spent at the scene lowers human and financial costs

There are time and economic costs to responders and drivers when roads are closed or traffic flow is reduced for the documentation of accident scenes, but there are also significant safety costs, As indicated by the Federal Highway Administration(FHWA), for every minute an accident remains on the roadway, the probability of additional accidents increases by 2.8 percent (Vasconez, 2015).

UAS is a tool which can help document and clear accident scenes faster than traditional methods thereby increasing the safety of first responders, reducing economic and time losses, and reducing the probability of secondary collisions.



*Figure 3-16 Linear and surface measurements made on a 3D point cloud in Pix4D mapper*

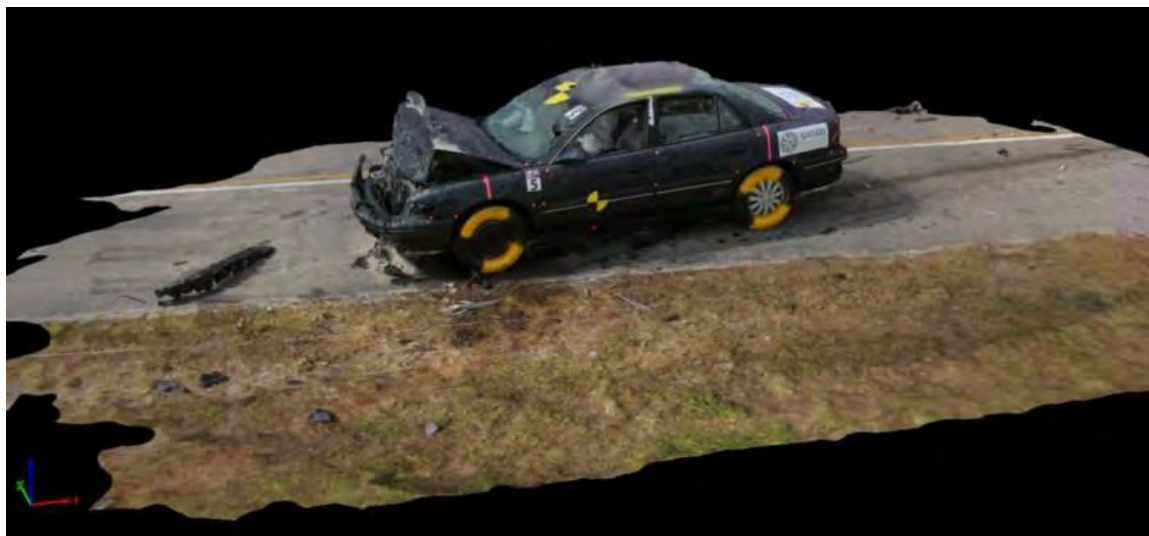
(3) The measurable outputs from UAV photogrammetry can be used as evidence in court

The objective of data gathering is to generate a reliable and accurate depiction of an accident which can be presented in court to determine its cause. Imagery collected in just one UAV flight

can be processed with photogrammetry software to generate a 3-D point cloud, models, orthomosaics and detailed reports. Figure 3-17 shows an example of an orthomosaic map and Figure 3-18 shows a 3D mesh model.



*Figure 3-17 Measurement diagram containing orthomosaic maps produced in Pix4Dmapper from drone imagery*



*Figure 3-18 3D mesh model of a staged accident scene*



(4) UAVs make data collection easier, requiring less training with greater accessibility

As the capturing and processing of accident scene images acquired by UAVs is becoming increasingly automated, less technical expertise and expensive equipment are required to perform these tasks accurately. Images from any type of camera can be used by photogrammetry software, even video from smart phones.

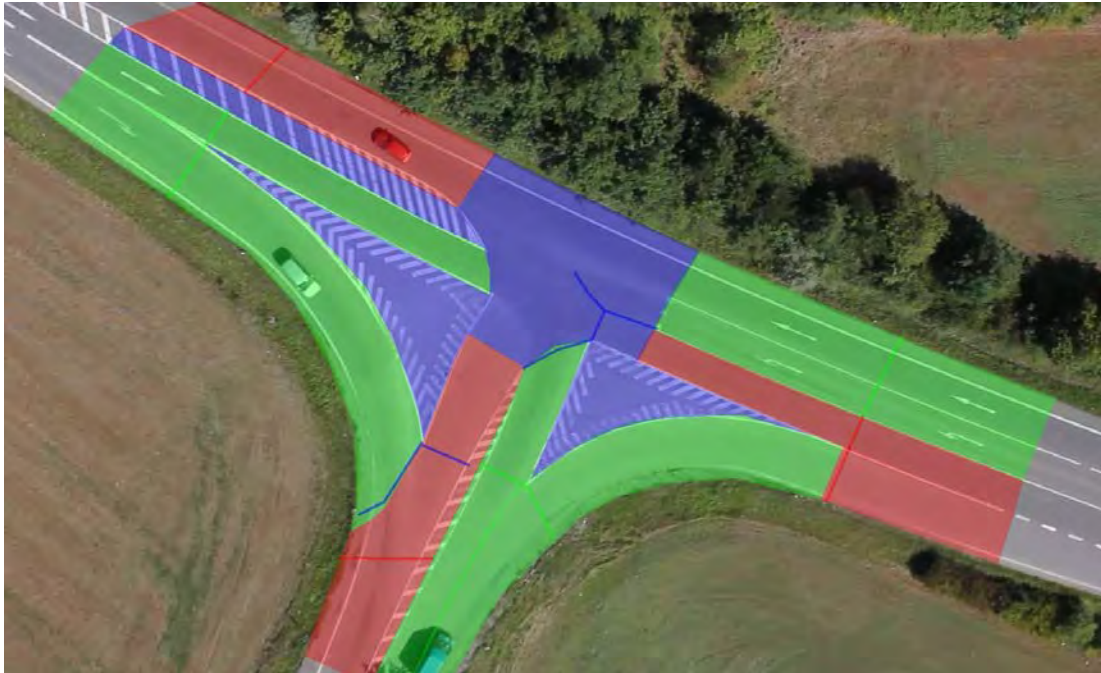
### ***3.3.2 Traffic Data Collection***

A number of state DOTs and universities are using UAVs to collect traffic data, such as the University of Arkansas, Georgia DOT and Washington DOT (DataFromSky, 2016a).

One company that uses UAVs for all aspects of traffic data collection is DataFromSky. DataFromSky's system only requires aerial video and a description of the scene that was videoed. UAVs or cameras installed high above the scene can capture the video. The first step of the analysis is to generate the trajectories of every detected vehicle in the video which are labeled by a unique ID, along with a record of the vehicle's position, speed, and acceleration.

#### **a) Traffic counting(DataFromSky, 2016c)**

One of the basic tools for transportation analysis is traffic counting which DataFromSky can perform on highways, at intersections, and at roundabouts. In addition to vehicle counts, DataFromSky can provide vehicle flows, gap time, follow time and Origin-Destination (OD) information. On highways, spatial distributions of vehicles can be generated which show the directional distribution and lane volume distribution. An example is shown in Figure 3-19



*Figure 3-19 Example of counting vehicles on a highway*

While counting vehicles is more difficult at intersections than on straight highway segments, DataFromSky can accomplish this task. The output consists vehicles counts, OD matrix, flow, gap time and follow time information. Examples of output are shown in Figure 3-20 and Figure 3-21



*Figure 3-20 Example of counting vehicles at intersections*

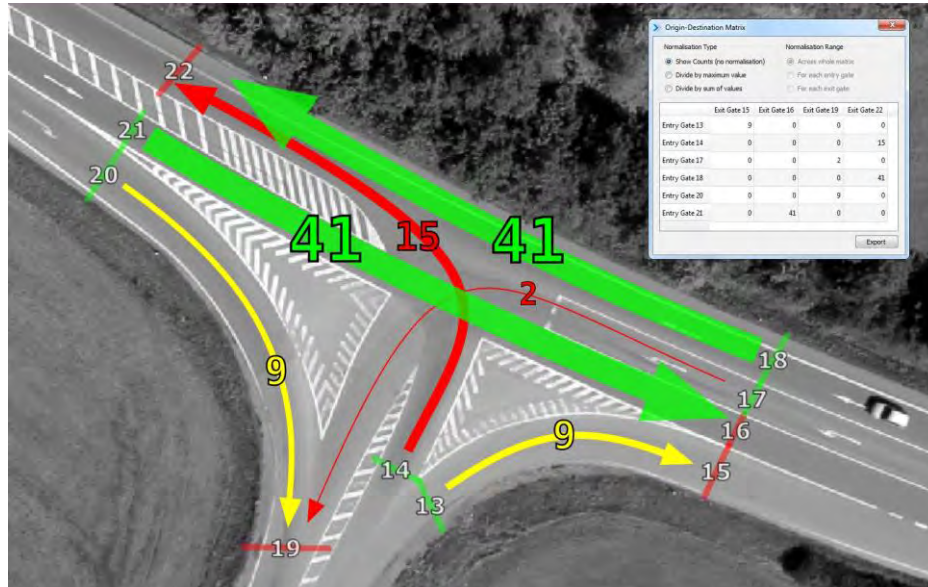


Figure 3-21 Example of OD matrix

b) Speed and acceleration (DataFromSky, 2016b)

Detailed speed and acceleration for every vehicle detected in the video can be extracted as shown in Figure 3-22. In addition, various aggregate values can be calculated such as average speed and travel time.

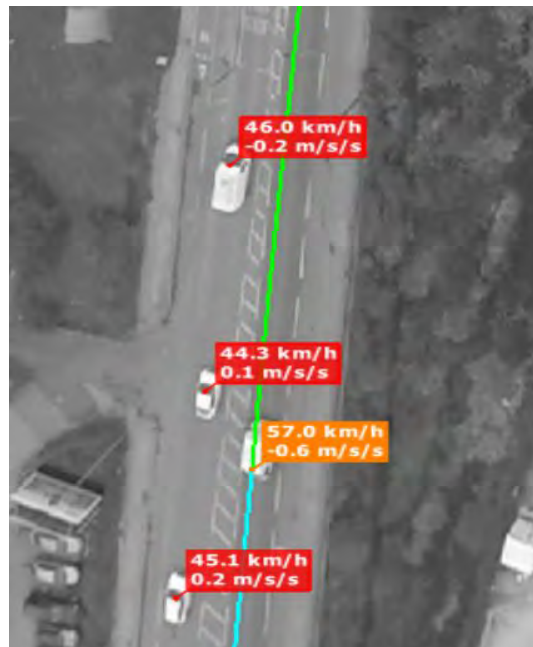


Figure 3-22 Example of speed and acceleration

c) Traffic flow (DataFromSky, 2016d)

DataFromSky analyzes vehicle trajectories to calculate the traffic flow characteristics that are defined by the Highway Capacity Manual 2010. These characteristics include occupancy, density, flow, and average speed. An example of a traffic load diagram and a flow vs density graph is shown in Figure 3-23. DataFromSky can also provide more advanced traffic flow characteristics such as gap acceptance, critical gaps, capacity, and capacity estimations. It can also estimate the dynamic properties of traffic flow.

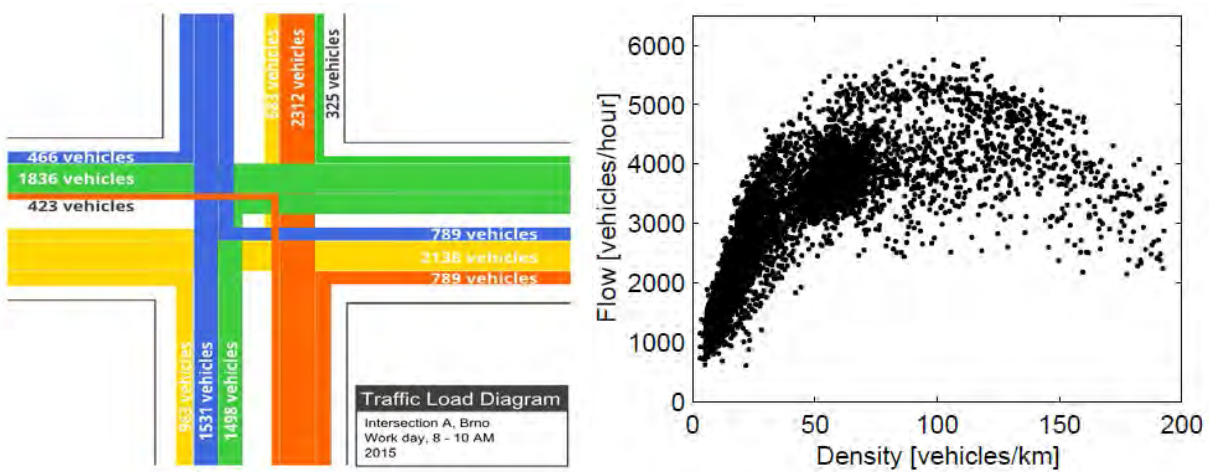


Figure 3-23 Example of a traffic load diagram and a flow vs density graph

d) Vehicle classification (DataFromSky, 2016e)

DataFromSky can classify vehicles in terms of weight, size, use and number of axles as illustrated in Figure 3-24.



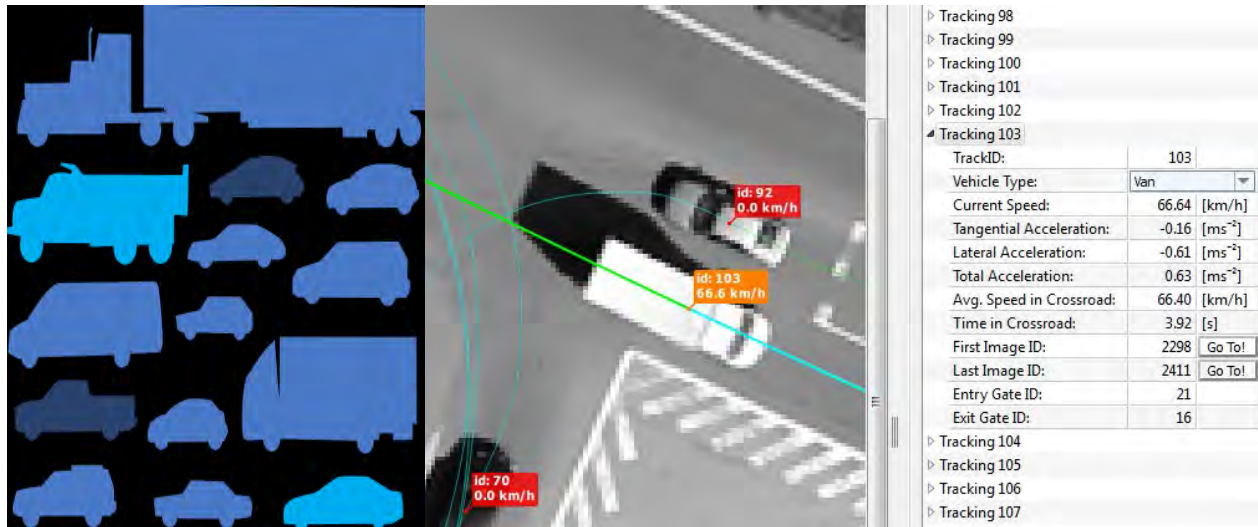


Figure 3-24 Example of vehicle classification



#### **4. AUTOMATED VEHICULAR TRANSPORTATION**

The project team looked at UGS's deployment opportunities to improve road construction and maintenance worker safety. Limited information related to UGS's deployment opportunities by State DOTs was found. The review revealed that UGS are playing an increasingly important role in commercial and military applications for improving safety and significantly reducing the number of dangerous tasks performed by humans. UGS are being piloted on highway construction sites in Florida under a state Department of Transportation demonstration program. In order to keep driver safe from the danger of crashes while operating a truck-mounted attenuator (TMA), the pilot program is transforming TMA truck into a UGV enables autonomous driving capability (Stoikes, 2015). However, the project team couldn't find the lessons learned from this pilot program.

Given the lack of documented information on UGS deployment by State DOTs, the project team focused mainly on the review of technologies for Connected and Autonomous Vehicle (CAV). CAV technology connects vehicles through a secure wireless network which allows them to communicate with other vehicles, roadside infrastructure, and smart phones by sending and receiving alerts to avoid collisions or reduce their severity. Technology installed in vehicles allowing vehicles to communicate with one another is called Vehicle-to-Vehicle (V2V) communications. Equipped vehicles can also communicate with devices installed in transportation infrastructure, which is called Vehicle-to-Infrastructure (V2I) communications. In December 2016, USDOT's National Highway Transportation Safety Administration (NHTSA) announced a Notice of Proposed Rulemaking (NPMR) that would require automakers to install V2V technologies in all new light-duty vehicles. In addition, USDOT's Federal Highway Administration is developing guidance for V2I communications to help transportation planners with the integration of these technologies into roadway infrastructure such as traffic lights and other roadside units in order to improve safety and mobility, while reducing congestion. The first new cars with CAV technology as an option have become available for sale or lease and aftermarket devices can be installed in older vehicles. It is likely that CAV technology will be deployed nationally by 2020. The NHTSA estimates that CV safety applications could eliminate or reduce the severity of up to 80 percent of vehicle accidents involving non-impaired drivers, (NHTSA, 2016).

This chapter has five sections which cover the following topics: the communications technology used in CAVs, the sensors used in CAVs; the levels of vehicle autonomy and automation; the potential impacts of CAVs on public transit, safety, and infrastructure; and the current and future development of CAV technology by private companies.

#### **4.1 CAV Communications Technology**

For connected and autonomous vehicle (CAV) applications to be successfully implemented, various sensing and measurement information about vehicles needs to be transmitted to and received from other vehicles. Both transmission and reception of this information forms a critical part of communication technology of CAV applications. The vehicles communicate this information through a network of nodes. The nodes in traditional network infrastructure are fixed in a location, whereas the nodes in the vehicular network are highly mobile. In other words, CAVs can be categorized as ad hoc networks, also called vehicular ad hoc networks (VANETs). VANET information generated by the vehicle's on-board computer, control system, on-board sensors or passengers can be effectively disseminated to vehicles in close proximity or to vehicles farther away by multiple hops. Without the assistance of any built infrastructure, a variety of active road safety applications (e.g., collision detection, lane changing warning, and cooperative merging) (Baykas et. al, 2011) and infotainment applications (e.g., interactive gaming, and file and other valuable information sharing) (Bai & Krishnamachari, 2010) are enabled by inter-vehicle wireless links. Hence, the communication within VANETs is achieved through various communication technologies discussed below.

**Dedicated Short-Range Communication (DSRC):** This technology is based on Wi-Fi that facilitates the wireless, low-latency transmission of information over a limited geographic area. It operates at 5.9 GHz which is the frequency designated for transportation use by the Federal Communications Commission. DSRC can act as an additional sensor, enabling positive identification of other road users or objects, as well as function in non-line-of-sight scenarios to reduce crashes and relieve congestion by enabling vehicles to travel at reduced headways and higher speeds, while communicating about potential road hazards ahead (RITA, 2012). DSRC is considered a key technology to enable connections between vehicles and ITS infrastructure, such as traffic lights, street signs, and roadside sensors. DSRC delivers information about truck

parking, weather warnings to drivers, and warnings about pedestrians and vehicles to enhance safety on roadways.

Some of the DSRC applications that have been envisioned are: transit signal priority, transit vehicle refueling management, personalized taxi dispatch services, integrated transportation financial transactions (including toll collection, parking payments, and rental car payments and processing), enhanced truck roadside inspection, real time freight logistics, pedestrian safety at intersections, vehicle safety (including blind spot warnings, forward collision warnings, sudden braking ahead warnings, and do not pass warnings), routing and scene management for emergency services, and advanced highway-rail and highway-transit grade crossings.

Dynamic Spectrum Access (DSA): due to recent advances in cognitive radio, DSA is becoming a possible complementary technology for DSRC. DSA allows vehicles to communicate opportunistically on a spatially and/or temporally vacant licensed spectrum for other communication systems (Luan, Shen & Bai, 2013).

Visible Light Communication (VLC): this technology transmits data by using light-emitting diodes (LEDs) and has been proposed for infrastructure-to-vehicle ITS applications, such as traffic light control at intersections (Wada et al., 2005). VLC is still in the introductory phase and substantial efforts are needed before it can be widely deployed for short-range ITS applications.

Other wireless technologies used for CAV applications include: Wi-Fi, Bluetooth, ZigBee (a specification for wireless personal area networks that are simpler and less expensive than Bluetooth or Wi-Fi), Passive RFID (Tonguz, 2006), ultra-wide band (UWB), 60 GHz mmWave (ECMA, 2008) and cellular communication.

#### ***4.1.1 Algorithmic and Computing Technologies in CAV***

Given that there is large amount of information being transmitted through sensing technologies and communication media, it is imperative that the CAV can process this information optimally. Once the information is processed, the on-board computer must be able to provide the driver with appropriate warnings for CVs or to control the vehicle's movement for AVs. This requires very efficient algorithms that can perceive the information and respond to it as a human being does. The algorithms in CAV applications can broadly be classified into three areas:

- 1- Location information improvement: This is a GPS-based inertial measurement algorithm which provides accurate location-based information about an AV by calibrating the data coming from different sources such as LIDAR (Levinson, Montemerlo, Thrun, 2007).
- 2- Object recognition: since the vehicles travel at high speeds, the image processing must be performed in real-time. Hence, algorithms for CAV applications must be able to detect and identify various objects in the driving environment, such as vehicles, pedestrians, lane marking, traffic signals and signs, trees etc. (Teichman, Lebnison & Thrun, 2011).
- 3- Dynamic control: these algorithms deal with controlling the vehicular trajectory of AVs, including the lateral and longitudinal trajectory for applications such as collision avoidance systems and controlling vehicle speed and acceleration.

CAV applications rely on camera, radar and other sensing technologies described earlier. Thus, the CAVs should be able to stream a large amount of data, processing approximately 1 GB of data in each second (Intel, 2016). So, the vehicle needs to have a powerful and high-performance processing technology to do real-time imaging, which in itself involves processing voluminous amounts of data. Furthermore, CAVs must do computations and then make decisions accurately. Meanwhile, deep learning techniques have been developed to help with computing problems by using algorithms to analyze data and enable CAVs to make accurate decisions.

#### ***4.1.2 Security Protocol of Autonomous Vehicle Technology***

The communication protocol of autonomous vehicles is VANET which uses many vehicles as nodes in a network and transmits information through V2V or V2I communication technology. In V2V communication, vehicles with the on-board equipment transmit real-time information about vehicle and traffic conditions like accidents, congestion, the vehicle's direction of movement, geographical location, speed, acceleration, etc. On the other hand, V2I communication comprises the communication between vehicles and roadside infrastructure known as Road Side Units (RSUs). Also, RSUs communicate with each other through wireless or wired connections (Viola & Jones, 2001). Although VANET technology supports intelligent transportation systems through a variety of wireless technologies such as DSRC, its security and privacy issues must be carefully managed.

There are several important requirements for achieving privacy and security in CAV communication. The challenges for security in these communications can be classified as

- 1- Security of access to the vehicle internal network;
- 2- Trustworthiness of information from vehicles in vulnerable environments;
- 3- Handling prevalent insider attacks, as a vehicle's valid security credential can be used to mount such attacks;
- 4- Managing security credentials for a huge number of spare electronic control units (ECU);
- 5- Reducing severe consequences when vehicles encounter security compromises (e.g. malware infections) that are hard to remediate;
- 6- Minimizing user inconvenience caused by security operations (provisioning, updates, threat remediation, etc.);
- 7- Supporting high scalability (secure connections, security credential management);
- 8- Securing in-vehicle devices, software and applications as in-vehicle devices use a multitude of legacy networks (Zhang, 2015).

VANET is a promising technology and a developing research area which can be used in many applications. It connects each vehicle to a complex mobile ad hoc network to share collective environmental data on a big scale and this connection makes each vehicle prone to a lot of security challenges and attacks. Hence, providing security to VANET is crucial in terms of giving clients validation, privacy, and authentication to provide data-integrity and safeguarding the propagation of information.

## **4.2 Types and Characteristics of the Sensors Used by CAVs**

### ***4.2.1 Exterior Sensors - Vision (LIDAR, RADAR, Ultrasonic Sonar, Video Camera + Infrared)***

#### ***4.2.1.1 LIDAR***

One of the most common exterior sensor used for autonomous vehicle vision is LIDAR (Light Detection and Ranging). It typically utilizes a beam of light with an infrared laser diode that is reflected off of a rotating mirror. As the light hits non-absorbing objects, it is reflected back to a sensor that creates a map. To overcome semi-porous materials and various weather conditions,



higher-end LIDAR systems utilize multiple beams to provide multiple distance measurements simultaneously.

Although LIDAR systems tend to be more accurate than RADAR, they typically have higher costs and require additional packaging space that prohibit their use. For example, the spinning LIDAR system used in Google's autonomous vehicle costs approximately \$75,000 (The Money Fool, 2016). Also, LIDAR systems are typically not as accurate as RADAR systems for detecting speed. This is due to the inability to utilize the Doppler Effect compared to RADAR. For this reason, the Google vehicle utilizes both LIDAR and RADAR sensors.

Some automotive suppliers have made available low speed LIDAR systems, like Continental AG, which typically utilize 4 beams of light, but the system used by Google for full autonomy, from Velodyne Inc., utilizes 32-64 beams for higher fidelity measurements. Many industry analysts expect LIDAR to become increasingly preferred because of its capability for producing much more accurate measurements as the automotive industry demands increased autonomous capability.

The most prominent company that produces LIDAR detectors is Velodyne. Figure 4-1 shows the available models and their technical specifications. Velodyne's 3D, real-time LiDAR sensors measure distances by measuring the Time of Flight (TOF) that it takes a short laser pulse to travel from the sensor to an object and back, calculating the distance from the known speed of light. Combining multiple laser/detector pairs (up to 64) into one sensor and pulsing each at 20 kHz allows for measurements of up to 1.3million data points per second. Vertical fields of view of 30° to 40° (depending on model) are covered with a full 360° horizontal field of view by rotating the laser/detector pairs up to 20 times per second (Velodyne LIDAR, 2016a). In addition to each distance measurement, Velodyne's LiDAR sensors also measure calibrated reflectivity that allows for easy detection of retroreflectors like street-signs, license-plates and lane-markings. The prices for Velodyne LIDAR start at \$8000 for the Velodyne PUCK model and range up to \$100,000.


			
Features	HDL-64	HDL-32	VLP-16
Channels	64	32	16
Range	100-120 m	80-100 m	100 m
Accuracy	+/- 2cm	+/- 2cm	+/- 3cm
Data	Distance / Intensity	Distance / Calibrated Reflectivities	Distance / Calibrated Reflectivities
Data Rate	1.3M pts/sec	700,000 pts/sec	300,000 pts/sec
Vertical FOV	26.8°	40°	30°
Vertical Resolution	~ 0.4°	~ 1.3°	~ 2.0°
Horizontal FOV	360°	360°	360°
Horizontal Resolution	5Hz: 0.08° 10Hz: 0.17° 20Hz: 0.35°	5Hz: 0.08° 10Hz: 0.17° 20Hz: 0.35°	5Hz: 0.1° 10Hz: 0.2° 20Hz: 0.4°
Input Voltage (with interface box and regulated power supply)	10-32 VDC	9-32 VDC	9-32 VDC
Power	60W	12W	8W
Environmental	IP67	IP67	IP67
Operating Temperature	-10° to 50° C	-10° to 60° C	-10° to 60° C
Size	203mm x 284mm (~8" x ~11")	86mm x 145mm (~3.4" x ~5.7")	104mm x 72mm (~4.1" x ~2.8")
Weight	15kg (33lbs)	1kg (2.2lbs)	0.83kg (1.8lbs)

Figure 4-1 Velodyne LIDAR product specifications (Velodyne LIDAR, 2016b)

#### 4.2.1.2 RADAR

RADAR, or radio detection and ranging, is used in automotive applications for both near and far obstacle detection (Microwave Journal, 2013). Generally, the typical radar system is a tradeoff between range and field of view. For example, a typical system used for adaptive cruise control has a range of approximately 150-meters and a field of view of approximately 20 degrees.

Utilizing the Doppler Effect, they also provide speed as a direct output. Instead of using a rotating antenna, modern systems utilize a patch antenna with a digital signal processing (DSP)-based pattern beam-forming methodology to measure azimuth angles. Radar systems also function in a wide range of environmental conditions. Generally, they are immune to high luminosity, rain, fog, snow, and even dust. This capability along with their lower cost compared to LIDAR systems have made them more attractive for vehicle applications. Adaptive cruise control (ACC) typically utilizes radar because of its dynamic ability to detect object distance and also speed. Utilizing RADAR for object speed and position information, the host vehicle is able to vary cruising speed to safely follow the next vehicle ahead. If the target vehicle is outside of the range or speed threshold, the system works as a conventional cruise control system. When the switching logic applies within the defined ACC parameters, the requested speed is reduced as necessary. This speed reduction is done utilizing the brake controller and throttle input. These controllers are then tuned for optimal performance.

The prices for RADAR sensors are \$50-100 (short range), and \$125-150 (long-range).

#### *4.2.1.3 Ultrasonic Sonar.*

Utilizing sonar, sound navigation and ranging, above the range of human hearing, a sound wave is reflected from various objects in range, and the frequency of the return pulses is utilized to indicate the distance of these objects. A piezoelectric material is charged with an alternating electrical voltage causing it to fluctuate and produce a sound wave. As the sound wave travels through the air, the pressure difference created resonates through the air transferring the energy from each particle of the air until the wave is dissipated or reflected. The reverse of the process is generally how the return wave is deciphered. Similar to a microphone, as the diaphragm fluctuates due to a sound wave, the electrical charge produced by the piezoelectric material is converted to an A/D signal. This is the ideal function of an ultrasonic system.

Propagation of a sound wave requires a medium through which the wave can travel. Without a medium, the energy cannot be transferred to continue resonation. As the wave travels through the medium, various changes can occur that affect the wave. Reflection is the return of a wave as it meets a medium with a greater density than that of the original medium. Ideally, all of the sound wave is reflected back to the source. However depending on the medium that is met by the sound wave, the return wave will have varying degrees of phase change and amplitude modulation

when reflected. When the wave is not reflected back to the source, the ray can be classified as being refracted, diffracted or absorbed. Refraction is the change in angle of a ray as it passes through various mediums. When a wave passes on the fringe of two mediums where only a portion of the wave is bent, it is called diffraction. Absorption is characterized by the exponential decrease in amplitude of the wave as it passes through a material. This energy is absorbed by the atoms of the traversed medium. This technology is available to every manufacturer today. For example, a Chrysler 300 is equipped with this type of system in its rear bumpers which use ultrasonic sonars for reverse parking. Ultrasonic systems tend to be the cheapest of the technologies discussed (MaxBotix, 2016). However, they are typically more affected by blockages or disturbances than RADAR systems based on the physics of operation described above. Because they can only operate in a medium, unlike electromagnetic waves, they are heavily influenced by the medium of the sound wave propagation. As the temperature, humidity, and environmental conditions of the medium vary, so do the sensing capabilities of the ultrasonic sensor. To accommodate for changes in temperature, many sensors utilize an algorithm that adjusts readings based on ambient temperature. With these limitations and to remain cost effective, ultrasonic sensors are generally used for parking sensors or other close range applications. Also, for autonomous vehicles, ultrasonic sensors tend to be the most accurate in closer proximity situations.

The prices for ultrasonic sonars are usually very low, starting at \$29-80 (Parallax, 2016).

#### *4.2.1.4 Video Camera + Infrared*

Camera systems are used in almost all autonomous vehicles. Current production vehicles utilize them for lane departure and lane keeping algorithms (Mobileye, 2016). Also, camera systems are being developed for road sign reading applications.

Camera systems absorb light that bounces off of an object similar to how the human eye functions. The beam of light is separated into red, blue and green colors and fed into a complementary metal oxide semiconductor (CMOS) or a charge coupled (CCD) sensor. The light is converted into an electric charge and this is how a digital camera interprets an image. CCD sensors typically create higher quality images, but utilize much more power than CMOS sensors. Most vehicle applications are based on CCD sensors due to the level of maturity and availability of the sensor. For higher resolution, 3 separate sensors are utilized. Another method

is to take in the light and sequentially rotate each color filter, and this is then fed into the single sensor that overlays each of the colors on top of one another. This method does not work well for moving images, which makes it impractical for automotive applications. The most economical and common way of capturing the various colors is to utilize a single filter that is separated into various colors where each cell can only take in specific colors.

The most common autonomous application that uses a camera system is lane detection (Autonomous Labs, 2015). The basic algorithms utilize a dynamic range to create an optimal contrast difference between the black in the road and the white or yellow in lane markings. This is also fed forward to help predict future lane markings and trajectory calculations. Assuming parallel lane markers, a polynomial is fit to the lane that utilizes far ahead detections. This overall interpretation is typically utilized to create a bird's eye view for a vehicle path. The curve fitting analysis helps account for roads with dashed lines and has the capability to make approximations for short durations of missing lane lines. A typical system relies on being able to at least decipher one side of the vehicle's lane. Stereo vision is the application of two or more cameras to provide the fidelity necessary to distinguish depth and height of objects. The typical configuration utilizes two cameras separated by a horizontal distance. This distance is correlated to a desired depth of field and resolution. The concept is similar to the position of a person's eyes. By providing two different perspectives of the same object, depth can be distinguished. The difficulty of this technique in camera systems is the capability to detect the same object in each camera. Various techniques exist to achieve this including corner detection, identifying recognizable features (NVIDIA, 2016), dimensioning, and utilizing reference objects. The procedure for interpreting stereo vision systems can be broken down into the following steps:

1. Corrections for camera and lens-based image distortions;
2. Rectification of both images to a common reference plane;
3. Identification of features visible in both images and measuring the displacement in order to compute disparity;
4. Using camera and mounting parameters, the disparity is converted into a height or depth map.

Another application of vision systems utilizes thermal imaging (Engineering.com, 2016). By utilizing or creating light above the range of human sight, in the infrared, these systems provide



greater resolution in low lit conditions. This technology is the primary enabler to night vision systems in vehicles.

In a passive infrared system, the thermal radiation of emitting objects is captured by a thermographic camera. This black body radiation is captured by a sensor similar to a typical camera that captures visible light. The sensors utilized in thermographic cameras are based on pyroelectric or ferroelectric materials that produce an electrical charge that is correlated to pixels with a varying temperature gradient image. In an active infrared system, additional light is added to the environment in the infrared spectrum to provide increased resolution of particularly inanimate objects.

The prices for the cameras are not very high, starting at \$125-150 for mono cameras and at \$150-200 for stereo cameras.

#### ***4.2.2 Positioning Sensors (GPS, GLONASS, and Others Under Development)***

##### ***4.2.2.1 GPS***

GPS, or global positioning systems, is based on the utilization of a receiver and antenna that communicate with various satellites to triangulate vehicle absolute position. Absolute position can be defined based on latitude-longitude-altitude, X-Y-Z Earth centered Earth Fixed, or UTM. This data, when paired with a precise map, can be utilized in autonomous vehicles to compute optimal routes, driving directions, topographic features, lane mapping, and even obstacle detection. Most modern vehicle systems utilize GPS for navigation, but do not have the accuracy required for a fully autonomous vehicle (NovAtel, 2016).

GPS technology is based on RF signal propagation. As an RF signal is sent by a satellite, it is picked up by the GPS antenna which then approximates the position anywhere in the sphere of the signal propagation. When two satellites are picked up by the antenna, the receiver approximates the position to the intersection of the two spheres which is generally a circle of intersection. This is why a minimum of at least three satellites is required for signal propagations. This leaves two possible points of the signal, one of which is rejected due to its location off of the Earth's surface.

A typical GPS receiver in a modern vehicle with poor visibility or limited satellite connectivity has an accuracy of approximately 5-15 meters. This accuracy is sufficient for providing route navigation, but is insufficient for assessing vehicle lane measurements. For this reason, correction signals are available from various sources including Nationwide Differential Global Positioning System (NDGPS), Wide Area Augmentation System (WAAS), and European Global Navigation Overlay Service (EGNOS). These sources provide signals to GPS receivers that improve positional accuracy to approximately 1-2 meters. This level of accuracy is capable of increasing safety and reliability for route navigation, but is still not accurate enough to resolve lane boundaries.

More sophisticated correction sources have the capability of up to 1-2cm, but require much more expensive GPS hardware. Also, because these systems do not have the capability of detecting other vehicles, they still require camera and radar systems for use in uncontrolled environments. Omnistar HP is an example of one these high accuracy sources that is currently utilized in autonomous vehicles. This technology is mainly utilized in agriculture, aviation, surveying, and mining.

At this time, a fully autonomous vehicle requires highly accurate GPS in conditions where other sensors may be blinded, but the higher cost of implementation has limited their application in production vehicles. Also, GPS systems have the capability to utilize vehicle internal sensors to provide data for confirmation or in cases of poor GPS visibility, but error factors exponentially grow as vehicle internal data is continuously utilized. This data includes yaw rate, lateral acceleration, longitudinal acceleration, and steering input. Utilization of 3 gyroscopes and 3 accelerometers is typically referred to as a vehicle's inertial measurement unit, or IMU. This is necessary for systems that require high fidelity measurement of vehicle motion in typical autonomous vehicles that heavily utilize GPS.

Although a primary use of GPS in autonomous vehicles is environmental sensing, many GPS outputs have applications in internal vehicle systems, such as velocity, acceleration, and pulse-synchronized time. This data is utilized to verify internal vehicle sensor data and provide feedback to other vehicle systems.

The prices for GPS modules start at \$50 and range up to \$10000 when combined with internal sensors like tachometers, altimeters and gyroscopes.

#### 4.2.2.2 *GLONASS*

GLONASS is an acronym, which stands for Globalnaya Navigazionnaya Sputnikovaya Sistema, or Global Navigation Satellite System. GLONASS is Russia's version of GPS. The Soviet Union started the development of GLONASS in 1976. GLONASS is the most expensive program of the Russian Federal Space Agency, consuming a third of its budget in 2010. This has a network of 24 satellites covering the earth. GPS developed by the USA has a network of 31 satellites covering this planet and has been widely used in commercial devices like mobile phones, navigators etc. Table 4-1 contains a comparison of GPS vs GLONASS.

*Table 4-1 A comparison of GLONASS and GPS*

Specification	GLONASS	GPS
Owner	Russian Federation	United States
Coding	FDMA	CDMA
Number of satellites	At-least 24	31
Orbital Height	21150 Km	19130 km
Accuracy	Position: 5–10 m	Position: 3.5-7.8 m
Orbital plane inclination	64.8 degree	55 degree
Orbital period	11 hours and 16 minutes	11 hours and 58 minutes
Frequency	Around 1.602 GHz (SP) Around 1.246 GHz (SP)	1.57542 GHz (L1 signal) 1.2276 GHz (L2 signal)

When used alone GLONASS does not have as strong coverage as GPS has, but when both are used together accuracy increases with coverage. In addition, GLONASS is more useful in northern latitudes as Russia developed GLONASS originally for use in Russia.

GPS + GLONASS allows a device to be pin-pointed by a group of 55 satellites all across the globe (Digital Yacht, 2014). So in places where GPS signals cannot be received such as between tall buildings or on subways, GLONASS satellites can accurately track location.

The GLONASS modules are inexpensive and start at around \$40 and range up to \$200.

#### *4.2.2.3 Other Global Navigation Systems Being Developed*

The European Union is currently working on a system called Galileo (European Commission, 2017) which provides highly accurate global positioning services under civilian control. The Galileo system consists of 30 satellites (27 operational and 3 active spares), positioned in three circular Medium Earth Orbit planes at 23 222 km altitude above the Earth and at an inclination of the orbital planes of 56 degrees to the equator.

China is developing its own constellation of 35 satellites called BeiDou Navigation Satellite System (Beidou, 2016) which has been under construction since January 2015. It will offer more capabilities than current GPS. It is currently operational in China and the Asia Pacific region with 11 satellites in use and will be globally available by 2020.

The IRNSS or Indian Regional Navigation Satellite System is an autonomous satellite system being developed by ISRO (Indian Space Research Organization) (ISRO, 2017) and will offer public service and restricted service (authorized users like military). This system will consist of a constellation of 7 satellites, 4 of which are already in orbit.

### **4.3 Levels of Autonomy and Automation**

Automation of cars is generally defined as the minimization of human driver involvement in controlling the car and interacting with it. A car with automation has well-defined and predetermined rule-based responses to well-known situations. An automated car is generally defined as an intelligent system capable of learning and adapting to new conditions on the road and generating an adequate response to them. Such cars are capable of complete self-governance and self-directed behavior and must be adaptive to and/or learn from an ever-changing environment (with the human's proxy for decisions). For example, the cruise control feature available in numerous modern cars is a type of automation. An example of a fully automated car is Google's self-driving car. The direction that the autonomous vehicle research and industry is



taking is to transition from cars with partial automation to cars with full automation, i.e. fully autonomous.

On May 30, 2013, the U.S. Department of Transportation (DOT) released its Policy on Automated Vehicle Development (NHTSA, 2013). In this policy statement, DOT defines 5 levels of vehicle automation:

Level 0 - No-Automation. The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls.

Level 1 - Function-specific-Automation. Automation at this level involves one or more specific control functions; if multiple functions are automated, they operate independently from each other. The driver has overall control, and is solely responsible for safe operation, but can choose to cede limited authority over a primary control.

Level 2 - Combined Function Automation. This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Vehicles at this level of automation can utilize shared authority when the driver cedes active primary control in certain limited driving situations.

Level 3 - Limited Self-Driving Automation. Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control.

Level 4 - Full Self-Driving Automation. The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

In 2016, the Society of Automotive Engineers (SAE) International introduced a classification system with six levels of automation as shown in Figure 4-2 (SAE International, 2016). In September, 2016, the NHTSA's "Federal Automated Vehicles Policy" adopted the SAE International's classification system of automation. This document is an agency guidance to help

facilitate the development of a regulatory framework and best practices for guiding manufacturers and other entities with the design, development, and deployment of AVs. (NHTSA, September, 2016).

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
<b>Human driver monitors the driving environment</b>						
<b>0</b>	<b>No Automation</b>	the full-time performance by the <i>human driver</i> of all aspects of the <i>dynamic driving task</i> , even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
<b>1</b>	<b>Driver Assistance</b>	the <i>driving mode</i> -specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	Human driver and system	Human driver	Human driver	Some driving modes
<b>2</b>	<b>Partial Automation</b>	the <i>driving mode</i> -specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	<b>System</b>	Human driver	Human driver	Some driving modes
<b>Automated driving system ("system") monitors the driving environment</b>						
<b>3</b>	<b>Conditional Automation</b>	the <i>driving mode</i> -specific performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> with the expectation that the <i>human driver</i> will respond appropriately to a <i>request to intervene</i>	System	<b>System</b>	Human driver	Some driving modes
<b>4</b>	<b>High Automation</b>	the <i>driving mode</i> -specific performance by an automated driving system of all aspects of the <i>dynamic driving task</i> , even if a <i>human driver</i> does not respond appropriately to a <i>request to intervene</i>	System	System	<b>System</b>	Some driving modes
<b>5</b>	<b>Full Automation</b>	the full-time performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> under all roadway and environmental conditions that can be managed by a <i>human driver</i>	System	System	System	<b>All driving modes</b>

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Figure 4-2 SAE International's levels of driving automation

## 4.4 Impacts of Autonomous Vehicles

### 4.4.1 Impacts on Transit and Taxis

The impacts that CAV technology may have on demand for public transit are uncertain. It may reduce public transit's mode share. However, the use of V2I technology will reduce delay for public buses, so that transit travel time, crowding, pollution, and fuel consumption will all be reduced. It would also improve transit reliability and safety. CAV technology in buses involves developing a lot of algorithms that enable buses to communicate with one another and other vehicles in the transportation network, along with accommodating the needs of passengers through on-demand services, such as booking rides in advance and enabling flexible routes.

Some manufacturing companies have been developing autonomous bus/shuttle applications which are being demonstrated across the globe. This section describes some of these applications.

#### *4.4.1.1 Minnesota Valley Transit Authority*

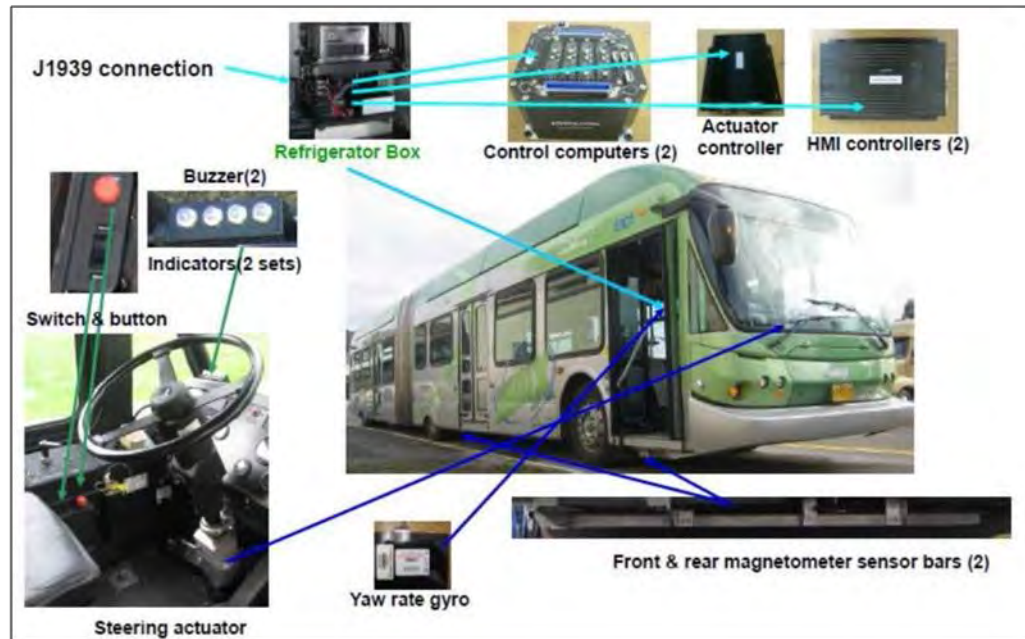
In Minnesota, buses are allowed by state law to use highway shoulder lanes when speeds in the general-purpose lanes drop below 35 miles per hour. Minnesota Valley Transit Authority was interested in developing a tool that would encourage bus drivers to use shoulder lanes during severe weather when the shoulder boundaries are obscured by snow. MVTA used a GPS-based driver assistant system (DAS) for bus-on-shoulder (BOS) operations that was developed by the Intelligent Vehicles Lab at the University of Minnesota. It combines GPS and a highly accurate digital map to track the exact position of the bus within the shoulder lane. DAS is a lane keeping assist and collision warning system that drivers use when driving on a shoulder. It was installed on 10 buses which travel on a six-lane highway called Cedar Avenue.

This system used three forms of feedback, visual, tactile, and haptic. With this technology, bus drivers can always determine where exactly the vehicle is in relation to shoulder boundaries. In 2011, the total project cost was \$5.3 million to outfit ten buses with the technology and to create a DAS simulator (NCTR, 2015). In 2015, The Federal Transit Administration awarded MVTA \$1.79M to equip 11 more buses with DAS (NCTR, 2016). Improvements to the previous system included using a series of light emitting diodes (LEDs), liquid crystal display (LCD) touch panel, and adding radar for side collision sensing. The primary goal of DAS was to enhance driver confidence when operating on road shoulders during bad weather with poor visibility and the secondary goal was improving travel time, reliability, safety, and customer satisfaction.

#### *4.4.1.2 Lane Transit District*

Lane Transit District in Eugene, Oregon partnered with Caltrans and the Advance Transit and Highway Program at UC Berkley to develop a magnetic guidance system for precision docking in its bus rapid transit (BRT) system which is shown in Figure 4-3. The technology was installed at three stations along 1.5 miles of the Franklin Corridor. The magnetic track was created by installing single rare earth magnets in concrete 3 to 4.24 feet apart. They also equipped an articulated New Flyer bus with two magnetometer sensor bars, one in front of the front wheels

and the other one under the middle door, to measure the lateral position of the bus relative to the magnetic track. Based on the magnetometer data, a lateral control computer sends commands to control the steering wheel. The target horizontal gap between the bus and the platform with the technology was 4 cm and the actual gap based on twelve runs was +2 cm (NCTR, 2015).



*Figure 4-3 System Components of Lane Transit District Magnetic Guidance System (NCTR, 2015)*

#### *4.4.1.3 Personal Rapid Transit*

Personal Rapid Transit (PRT) can be defined as a system of driverless vehicles that transport passengers along a dedicated guideway. It has been implemented in some cities around the world and is currently operating at the West Virginia campus in Morgantown carrying 15,000 passengers per day during the school year. PRT was also developed in 2010 in the city of Masdar, U.A.E., by a company called 2getthere. This system is shown in Figure 4-4. Since 2011, PRT has been operating at Heathrow Airport in London by the company ULTra. This system carries 800 riders per day (NCTR, 2015) and is shown in Figure 4-5. Another PRT system is operating in Suncheon Bay coastal eco-park in South Korea in 2013 with a ridership of 5000 riders per day.





*Figure 4-4 Automated PRT in the City of Masdar (U.A.E.)*



*Figure 4-5 Automated PRT at London Heathrow Airport*

#### *4.4.1.4 Impacts of Autonomous Taxis*

Autonomous taxis, which are considered to be a type of paratransit, are a developing transportation service and are being tested in Singapore and Dubai, U.A.E. In August 2016, nuTonomy, an MIT spin-off technology startup company that makes software to build self-



driving cars and autonomous mobile robots, launched their first pilot project in Singapore through partnership with Singapore's Land Transport Authority. Singapore has started the process of approving ride-hailing taxi services and nuTonomy hopes to be able to deploy an on-demand network of self-driving taxis by 2018. The pilot project uses Renault Zoes and Mitsubishi i-MiEVs with a driver in the front seat ready to take control of the vehicle. A taxicab is shown in Figure 4-6. The world's first self-driving taxi service currently consists of six self-driving taxis running in a 2.5-square-mile business and residential district called "one-north" in Singapore with limited pick-up and drop-off locations (the big story, 2016). The cars are fitted with six sets of Lidar including one that spins on the roof of the car. Two cameras are mounted on the dashboard to scan for obstacles and detect traffic signal changes. In the system, riders use their smart phones to hail taxis and indicate their destination and then sit back and let the driverless car take them there.



*Figure 4-6 Autonomous taxi developed by nuTonomy in Singapore*

#### ***4.4.2 Potential Impacts of CAVs on Safety***

According to the National Highway Traffic Safety, Administration human error plays a role in almost 90% of traffic crashes throughout the world and CAV technology has the potential to reduce the number of accidents. CAV technology reduces the amount of control that drivers have or eliminates driver control altogether thus reducing human error and human unpredictability. As a result, the number of crashes will be reduced and transportation safety will

be improved, as well as a reduction in congestion and an improvement in fuel economy and mobility of people and goods.

CAVs deploy V2V and V2I communication to provide real-time warnings to drivers to help them avoid crashes. Additional information can include traffic signal status, traffic congestion and construction warnings, as well as impending severe weather events. CAV technologies can also allow back office systems such as a traffic signal control system to react to real-time information from the vehicle.

The U.S. DOT has sponsored projects in the last several years to develop and test new technologies with the goal to further reduce vehicle collisions (Najm, Toma & Brewer, 2011). These new technologies will be designed to increase situational awareness and reduce or eliminate crashes through V2V data transmissions that support driver advisories, driver warnings, and vehicle controls. Some of applications related to connected vehicles are the following.

**Emergency Electronic Brake Light (EEBL):** The EEBL application enables a host vehicle to automatically broadcast self-generated brake events to surrounding remote vehicles. Upon receiving the event information, remote vehicles determine the relevance of the event and provide a warning to their driver if appropriate (Najm, Toma & Brewer, 2011). This application is useful in situations where vision, speed, curvature, or weather make it difficult for drivers to see that a vehicle in front of them has made an abrupt movement. In 2011, the Volpe National Transportation Systems Center tested a pre-crash crash avoidance system based on vehicle-to-vehicle communication by broadcasting a self-generated emergency brake event to surrounding remote vehicles.

**Forward Collision Warning (FCW):** Warns the driver of the host vehicle of an impending rear-end collision with a remote vehicle ahead in traffic traveling in the same lane and direction. FCW will be applicable to vehicles closing in on a stopped, constantly moving or suddenly decelerating lead vehicle (Najm, Toma & Brewer, 2011).

**Intersection Movement Assist (IMA):** Warns the driver of a host vehicle when it is not safe to enter an intersection due to a high collision probability with remote vehicles at stop sign controlled and uncontrolled intersections. USDOT has concluded that the technology would help

avoid collisions at uncontrolled intersections and at intersections with stop signs (Najm, Toma & Brewer, 2011).

**Blind Spot Warning + lane Change Warning (BSW+LCW):** Warns the driver of the host vehicle during a lane change attempt if the blind spot zone into which the host vehicle intends to move is, or will soon be, occupied by another vehicle traveling in the same direction. The application also provides the driver of the host vehicle with advisory information that a vehicle in an adjacent lane is positioned in the blind spot zone when a lane change is not being attempted.

**Do not Pass Warning (DNPW):** Warns the driver of the host vehicle during a passing maneuver attempt when a slower moving vehicle, ahead and in the same lane, cannot be safely passed using a passing zone that is occupied by vehicles in the opposite direction of travel. The application also provides the driver of the host vehicle with advisory information that the passing zone is occupied when a passing maneuver is not being attempted. DNPW could be very effective on curves, however, it seems that it would be more effective in rural areas than urban areas as very few accidents in this category occur in urban areas.

Work zones on highways or urban roads can potentially cause significant disruption to traffic and cause safety problems for trucks and other vehicles. One of the benefits of CAV technology is to use V2V communication to improve safety around work zones (Olia, Gender & Razavi, 2013). V2V technologies enable vehicles to avoid using congested roads and to take an alternative route and can prevent sudden lane changing maneuvers which result in accidents. In addition, receiving information about downstream construction zones, accident scenes, or any sudden bottlenecks can make drivers and vehicles aware of an upcoming situation and take a more cautious approach to these hazards. As a result, the communication technology would help to reduce crashes (Olia et al., 2014).

#### ***4.4.3 Potential Impacts of CAVs on Existing Infrastructure***

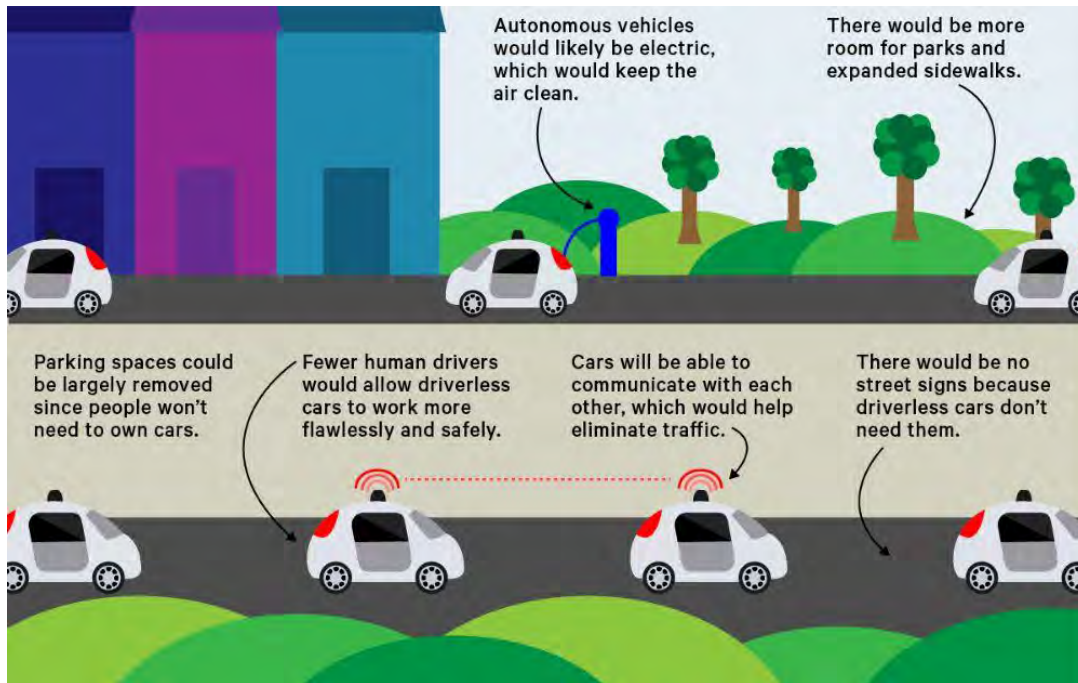
This section lists the potential impacts of CAVs on transportation infrastructure as follows.

**Road Signs:** Eliminating the need for directional signs and variable message signs along arterials as the information presented in these signs would be transmitted directly to vehicles and drivers.

**Lane Capacity of Roadways:** Increasing traffic flow and capacity which will lower congestion, allowing lane widths to be decreased (from 12 feet to 10 feet for through lanes and to 9 feet for left-turn lanes) and reducing the width of emergency lanes, shoulders, medians, and clear zones; which can provide room for an additional lane in roads. AVs will reduce the number of human drivers on the road which will mean less human error and human unpredictability and will enable more vehicle coordination, which will end up reducing traffic jams.

Autonomous vehicles can provide a fully automated road transport system (ARTS) that can enable car-sharing and vehicle movements with platooning and automatic reposition (Alessandrini et al., 2015). Platooning means that vehicles can travel closer together to increase road capacity and reduce delay and air pollution. It can provide additional throughput in bottlenecks such as tunnels (Chris, Biehler, Mashayekh, 2012). Platooning requires communication between vehicles and its benefits depend on the number of vehicles involved in a platoon and the fraction of their trip that they spend in the platoon. In addition, AV technology can provide benefits to freight vehicles.

**Parking Lanes:** By year 2040, parking lanes could become obsolete with autonomous vehicles driving themselves to parking garages and increased ridesharing and use of shared taxis decreasing car ownership (Chris, Biehler, Mashayekh, 2012). That means there would be more space available for bicycle lanes and expanded sidewalks (see Figure 4-7).



*Figure 4-7 The city of future driverless car (Business Insider, 2016)*

**Bicycles and Pedestrians:** CAV technology will increase safety for bicycles and pedestrians by allowing more room for them with bike lanes and wider sidewalks as well as by enabling vehicles to detect their presence.

**Traffic Signals:** As discussed above, V2V technology allows vehicles to move together as a platoon and traffic signals can help to coordinate this movement with efficient signal control such as self-organizing traffic signal control. (Moghimidarzi, Furth & Cesme, 2016). In addition, V2I technology enables traffic signals to give priority to public transit vehicles such as buses and trams. The public transit vehicle transmits messages to the traffic signal about its position and the traffic signal can adjust its signal timing to give the vehicle priority at the intersection. This technology benefits public transit by reducing vehicle and passenger delay, travel time, crowding and, more importantly, by increasing the reliability of the transit system.

**Land Use:** It has a significant impact on land use and urban sprawl.

**Lane marking:** CAV applications are dependent on clear lane markings because faded, missing, or old lane markings that can still be seen, as well as markings covered in snow, can hinder the ability of these technologies to function properly (Richard, 2014).



#### 4.5 Current and Future Roll-out of Important AV-related Companies

The development of CAV technology is being carried out by many different companies, universities, and research and development centers, as well as by government at the federal, state, and local level. This work is being done in many different fields including IT, sensors, communications, and vehicle technology. This section will focus on just some of the work being done by private companies.

##### a) Google

Google has never announced any formal deadline for rolling out its autonomous cars, but has suggested that the technology will be ready before 2020. Google is taking a different approach from other companies who are showing/testing semi-autonomous technology over time. Google, on the other hand, intends to produce a fully driverless car without brakes or a steering wheel. Figure 4-8 shows the evolution of Google's autonomous car.



*Figure 4-8 Evolution of Google driverless car (Business Insider, 2016)*

##### b) Uber

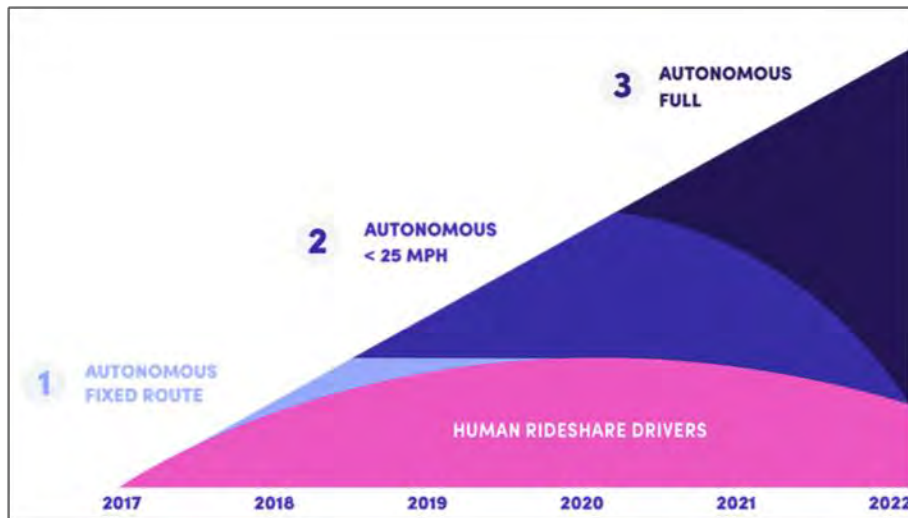
Uber is trying to make its cars autonomous so that users can hail them as part of its business. Uber is developing small features and new high-tech applications in collaboration with Carnegie Mellon University's robotics department. Uber did a pilot test in September 2016 in Pittsburgh on a Ford Fusion car (see Figure 4-9 below). It also has an agreement with Volvo for about \$300 million to develop driverless cars.



*Figure 4-9 Uber released autonomous cars in Pittsburgh as part of a pilot program*

#### c) Lyft

Lyft is going to have semi-autonomous cars driving along fixed-routes in 2017, while low-speed (under 25MPH) autonomy on changeable routes would start as soon as 2018 as shown in Figure 4-10. Moreover, full autonomy would just be the next logical step. In January 2016, GM invested \$500 million in Lyft to build autonomous vehicles together.

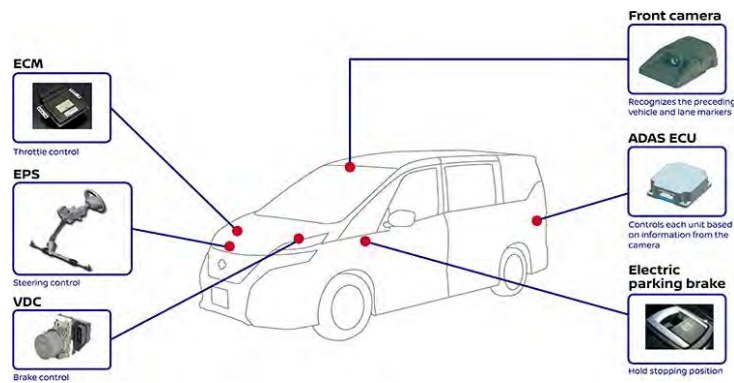


*Figure 4-10 Lyft's autonomous roll out (recode, 2016)*

#### d) Nissan

Nissan is releasing ProPILOT (shown in Figure 4-11), an autonomous drive technology designed for highways and urban roads, and is working on vehicle intelligence to make the corporate vision of "Zero Emissions" and "Zero Fatalities" a reality. ProPILOT will be introduced into

other vehicles, including the Qashqai in Europe in 2017. A multi-lane autonomous driving technology will enable automatic lane changes on highways and is planned for introduction in 2018, while Nissan will continue to add driverless capabilities to ProPILOT until it has a fully self-driving car in 2020.



*Figure 4-11 Nissan ProPILOT car configurations (Nissan News, 2016)*

#### e) Tesla

CEO Elon Musk committed to a 2018 timeline for releasing a fully self-driving car but he said it is unlikely to hit the road by 2018. Tesla's Model X and Model S vehicles currently in production will have a lot more cameras, sensors and radars to enable full autonomy. Specifically, the sensor suite, which Musk called "hardware 2," will include eight 360-degree cameras, 12 ultrasonic radars and forward-facing radar. The company also updated its software to Version 8, which made it more expensive.

#### f) BMW

BMW has committed to releasing an all-electric car with autonomous capabilities in China in 2021 as part of its Project i20. Some of the features of all-electronic autonomous vehicles are lane keeping assist, side collision protection, self-parking, and being able to pick up the driver whenever he/she is ready to go. By 2025, the Project i20 will be fully autonomous.

#### g) Volvo

Volvo is trying to release a fully autonomous car by 2020. It is going to roll out an advanced autonomous driving experiment in China, where 100 volunteers will be able to test driverless Volvo XC90s on public roads. The experiment is a part of program called DriveMe which will

also test 100 driverless Volvos in Gothenburg, Sweden and London in 2017. Volvo also has a partnership with Uber under way.

#### h) Ford

Ford is also going to roll out self-driving cars for ride-hailing and sharing services by 2021. These cars will not have steering wheels, brakes or gas pedals. Ford and a Chinese company, Baidu, have a partnership with Velodyne for \$150 million to manufacture Lidar systems. Meanwhile, the company is doubling its Silicon Valley workforce and dramatically expanding its research and innovation center in Palo Alto. 30 driverless cars have been tested and the company plans to triple the number of tested cars in 2017. Ford has acquired an Israel-based computer vision company called SAIPS, which specializes in deep learning and machine learning.

#### i) Toyota

Toyota is planning to release its self-driving car by 2020. The Japanese automaker is mapping routes to help achieve this goal, along with making huge investments in artificial intelligent and robotics.

#### j) General Motors

GM has not said exactly when its autonomous car technology is coming to the market but told Business Insider that it is coming much faster than people anticipate. The company has invested in Lyft and recently bought a start-up called Cruise Automation.

#### k) Hyundai

Hyundai is aiming to incorporate features of self-driving cars by 2020 but fully autonomous cars will not be on the market until 2030.

Other companies like Apple, LeEco, Faraday Future, PSA Groupe, Bosch, Honda, Baidu, Audi, and Daimler are also aiming to release autonomous car technology, mostly by 2020

## **FINDINGS AND CONCLUSIONS**

This report summarizes studies documenting applications and demonstrations of UAS and UGS technologies and potential deployment opportunities for NYSDOT in the near future. Three of the report's four sections discuss aerial systems and the fourth section focuses on ground systems. The first section presents a summary of the major provisions of the operation and certification of small unmanned aircraft systems, as well as studies and specifications of UAS used for roadway mapping. The second section presents applications and specifications of using UAS to monitor structural systems including confined spaces, bridges, and other transportation infrastructure. The third section describes applications of UAS for traffic condition monitoring and management. These applications include monitoring of road and traffic conditions and traffic management such as traffic incident management and traffic data collection. The final section discusses UGS, specifically connected and autonomous vehicles (CAV). It covers the communications technology and sensors used in CAVs; the levels of vehicle autonomy; the potential impacts of CAVs on public transit, safety, and infrastructure; and the current and future development of CAV technology.

The UAS research studies described in this report clearly indicate that these aerial systems are capable of performing many transportation monitoring and management operations more safely and efficiently and at lower cost than traditional methods. However, there are issues that must be addressed when using UAS. Aerial image quality is crucial to successful UAS operations and it can be adversely affected by camera vibration. This can be reduced by the use of multi-rotor UAS. Another issue is that the effectiveness of UAS can be severely reduced when operating in inclement weather such as high winds, rain or snow. Larger UAS tend to be able to operate better in bad weather than small UAS. Finally, UAS tend to have short battery lives, which, for multi-rotors, is around 20-30 minutes. These battery lives can be too short to accomplish some operations such as traffic monitoring.

The UGS discussed in this report, CAVs, represent one of the most important trends in transportation today and they have great potential for improving the safety and efficiency of ground transportation networks. CAV technology can reduce human error and unpredictability by making drivers aware of potentially unsafe conditions in time to avoid them, reducing the



amount of vehicle control that drivers have, or eliminating driver control altogether and thereby reducing the frequency and severity of vehicle crashes. CAV technology can improve the efficiency of road networks by reducing delay for both private and public transit vehicles, thereby reducing travel time, pollution, and fuel consumption, as well as reducing public transit crowding and increasing its reliability.

## **STATEMENT ON IMPLEMENTATION**

The review of applications and demonstrations of UAS and UGS technologies in this report can be used to help identify potential implementation opportunities for NYSDOT in the near future. The report describes the unmanned systems, including equipment specifications, availability, and cost, that researchers at universities and other state transportation departments have used to perform a variety of transportation operations. Specifically to UGS applications, it was revealed that these systems may offer promising benefits for road construction and maintenance worker safety at work zones as the CAV technology increases driver awareness through open communications with enabled vehicles, roadside infrastructure, and smart phones by sending and receiving alerts to avoid collisions or reduce their severity. Future investigation of these technologies after deployment tests by State DOTs will be necessary to comprehensively identify potential benefits. As such, the report can help NYSDOT determine which systems are most appropriate for which operations and avoid any pitfalls that were encountered in these previous research activities.

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## **APPENDIX: Inventory of Equipment for 2016 ITS-NY Annual Meeting and Technology Exhibition**

### **Inventory:**

1. 2 Jeep Grand Cherokees (each has the following equipment):
  - a. Video display
  - b. VGA cable
  - c. Kapsch eWAVE (5.9 GHz DSRC system)
  - d. Volvo telematics gateway
  - e. Ethernet switch
  - f. Ethernet cables
  - g. Power cables
  - h. Application software
2. Both jeeps were shipped from Greensboro, NC to Albany, NY in May 2016 prior to the ITS New York annual meeting

### **Recommendations:**

1. Upgrade equipment and applications to support the latest standards versions to ensure compatibility with the USDOT pilot deployments and other regional deployments.
2. Integrate the CVII and Weather apps onto the same OBU platform.