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THE USE OF UNMANNED AERIAL SYSTEMS TO REMOTELY COLLECT DATA FOR ROAD INFRASTRUCTURE

A SPECIAL PROJECT OF THE WORLD ROAD ASSOCIATION

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THE USE OF UNMANNED AERIAL SYSTEMS TO REMOTELY COLLECT DATA FOR ROAD INFRASTRUCTURE

From Canada to Tanzania, transportation agencies are using unmanned aerial systems (UASs), also known as drones, to collect data, design and construct road infrastructure, inspect bridges, monitor roads for avalanche and mudslide dangers, identify flood damage risks in urban areas, reconstruct crash scenes, and monitor traffic and road conditions. Public agencies, under pressure to reduce costs and to be adaptable, are turning to drones as one means of improving operations and cutting costs.

Road infrastructure constitutes one of the largest assets and is owned by Road administrations. Road infrastructure comprises of paved, unpaved roads, bridges, over passes, under passes, traffic signs and lights, street lights etc. As the owner of these public assets, Road administrations have the responsibility and accountability to maintain, improve, operate, replace and preserve these assets in good condition to provide improved level of service to the public by effectively managing the tight budget and limited human resources.

Many road administrations are continuously searching for innovative ways for monitoring and collecting data to become more efficient and cost effective. As a result of this search, road administrations had been exploring the use of Unmanned Aerial Systems (UAS) in roadway sector.

Unmanned Aerial Systems (UAS), Unmanned Aerial Vehicle (UAV) and drones are most common names used in the industry. Due to advancements in the technology sector, UAS are becoming more affordable and gaining lot of popularity for civilian applications such as agriculture, forestry, highway construction and monitoring, surveillance, surveying, photogrammetry, emergency response, mapping etc.

Based on the survey results collected as part of this study Austria, Belgium, Canada, Germany, Iran, Japan, Malaysia, Norway, Tanzania and USA, have performed a number of research projects for the use of UAS in civilian applications such as pre-construction surveys, construction inspections, asset monitoring and maintenance, traffic management, natural disaster response etc.

The biggest benefits of using UAS is its low cost, readily available (buy it off the shelf and customize as required), efficiency, quick turnaround, safety and the ability to reach remote location that are hard for human to access. At the same time the industry is facing many challenges due to stringent regulations and bylaws by national and local governments, as unsafe use of UAS can pose danger to public life and security.

In spite of these hurdles, a large number of organizations have used this technology successfully in various fields. An extensive literature research was conducted to explore the use of UAS in various sectors, mainly related to roadway infrastructure. These case studies are presented in section 4 of this report. The report also describes how the information from these case studies can be used for implementing UAS in roadway sector.

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UAS APPLICATIONS IN THE ROAD SECTOR

There is a huge potential for UAS applications. Based on the literature research and case studies mentioned in this report, the biggest benefits can be achieved in:

- **Bridge inspection applications:** A rotary UAS is a good alternative over manual inspection using aerial work platform (AWP) and rope access methods. See more information on Table 1.
- **Unpaved/Gravel Road Condition Monitoring:** A rotary or a fixed wing UAS are very beneficial for performing unpaved road monitoring compared to manual visual inspection. See more information on Table 1.
- **Automated Asphalt Pavement Inspection:** Currently asphalt pavement inspection is performed by manual visual inspection and as well as using Automatic Road Analyzer (ARAN) vehicle. Potentially an UAS can be used for inspecting asphalt pavement for different distress. See more information on Table 1.

The report also offers information on further UAS applications such as:

- **Pre-construction land surveying**
- **Roadway construction monitoring**
- **Traffic monitoring**
- **Urban mapping**
- **Avalanche monitoring**
- **Crash scene analysis**

ADVANTAGES

Compared with traditional methods of collecting data, the study found that drones have high potential for the transportation sector. The reasons involve five factors:

- Low cost
- Ready availability off the shelf, with customizing as required
- Quick turnaround in data download and efficiency
- Ability to access remote locations
- Enhanced safety for humans

Challenges

The study found certain challenges associated with the use of UASs. One is finding ample storage for the huge amount of data collected from a UAS. One contractor uses a separate server just for drone data. Other users employ external hard drives or storage in the cloud.

In addition, standardized data-sharing specifications are lacking in the current guidelines within road administrations. Their availability would facilitate using UASs to their full potential.

Further, safety concerns exist when operating in populated areas. The current generation of UASs has obstacle-avoidance systems to prevent crashing into structures, but a system capable of preventing a crash in a situation where a UAS loses control could greatly reduce the risk to the public.

Also, some low-end UASs have limited battery life and thus flight time, typically varying between 15 and 30 minutes. A longer battery life certainly will improve overall efficiency.

Finally, more extensive studies need to be done over a diverse region to validate performance in terms of accuracy and efficiency.

RECOMMENDATIONS

The report recommends a general process for new users of projects involving UASs. The process consists of three broad phases: preliminary, intermediate, and final. Users can adapt the process and further develop it for each region or specific project.

ADAPTED SOLUTIONS

When it comes to selection of UAS, there is no one-size-fits-all solution, each organization needs to examine their requirement and resources to decide what is best for their environment. A Multi-rotor maybe better suited for inspecting small areas, where as a fixed wing will be better for larger areas requiring orthoimagery. It is also recommended that any organization that wishes to use this technology, familiarize themselves with the best practices and technologies available in the market as this technology and the rules and regulations are changing very rapidly. The data collected from UAS can be analyzed and easily integrated or imported into Geographical Information Systems (GIS) and asset management system.

PILOT PROJECT

A successful use of UAS in an area or industry does not guarantee success for potential users due to various factors such as experience and expertise of the project team, the weather, technology constraints etc. The best approach is to try a pilot project on a selected sample area and evaluate the performance accordingly. Further recommendations based on the corps of the report are provided in the next section.

Bridge inspection	
UAS Advantages	**Aerial Work Platform (AWP) Disadvantages**
• Low capital and maintenance costs • Increased safety of inspector and public • No bridge weight restrictions • No Lane closures required • Less mobilization Time and Cost	• High capital and maintenance costs • Safety of inspector and public • Bridge weight restrictions • May require Lane closures • Huge mobilization Time and Cost
AWP Advantages	**UAS Disadvantages**
• Ability for inspector to be within arm's reach of bridge components. • More reliable as inspector can touch and feel the bridge components • Ability to perform non-destructive tests • Continuous uninterrupted inspection for long hours	• Inspection within inspector's arm's reach not possible. • Less reliable as the inspections can only be done from a distance • Non-destructive tests cannot be performed • Limited flight time due to battery life

Table 1: Advantages and disadvantages of UAS over traditional methods.

Bridge inspection	
UAS Advantages	**Rope Access Disadvantages**
• Easy and fast • More efficient • Safe to operate	• Cumbersome process • Less efficient • Less safe for inspector
Rope Access Advantages	**UAS Disadvantages**
• Ability for inspector to be within arm's reach of bridge components. • More reliable as inspector can touch and feel the bridge components • Ability to perform non-destructive tests • Low equipment cost	• Inspection within inspector's arm's reach not possible. • Less reliable as the inspections can only be done from a distance • Non-destructive tests cannot be performed • Equipment cost is high compared to rope access

Unpaved/Gravel Road Condition Monitoring	
UAS Advantages	**Manual Visual Inspection Disadvantages**
• Low data collection cost • More frequent surveys possible • Minimum lane closure • Re-measurement possible from collected data without field visit • Ability to create accurate 3D model for potholes, rutting, corrugation etc.	• High labour cost – labour intensive • Survey done occasionally • Lane closure for extended period • Field visit required for re-measurement • No 3D models, but potholes, rutting, corrugation etc. can be accurately measured.
Manual Visual Inspection Advantages	**UAS Disadvantages**
• High winds does not affect the data quality • Does not requires image processing • Low initial cost	• High wind resistance can compromise the quality of the data • Requires after survey work for image processing • Initial cost is high

Automated Asphalt Pavement Inspection	
UAS Advantages	**ARAN Vehicle Disadvantages**
• Low initial cost – in house operation • Distress survey is faster as UAS can scan wide areas in single pass • Data can be collected more frequently due to low cost	• High initial cost – in house operation • Distress survey is slow as driving in each lane is required • Higher cost limits the frequency of data collection.
ARAN Vehicle Advantages	**UAS Disadvantages**
• High accuracy • Can be used in urban scenario • More data coverage • Continuous data collection for extended period •	• Low accuracy • Special permission required for urban scenario • Loss of data due to distresses covered by moving vehicles on the road • Can be operated for limited time depending on battery life

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RECOMMENDATIONS BASED ON THE CORPS OF THE REPORT

Based on the cases studies presented in this report and in the analysis produced of them, several recommendations can be provided. We present these recommendation in this first chapter as a resume of the outcomes of this report. Readers willing to understand the origin and explanation of these recommendations are encouraged to read the whole report.

A great amount of research has been done in high income countries to explore, understand the use and identify limitations of UAS. Based on literature research conducted, there is a huge potential for a high return on investment for using UAS in various areas related to roadway infrastructure. This advantage does comes with some limitations posed by government rules and regulations around the use of UAS in order to ensure a safe and secure use of UAS.

The case studies presented in this report provides a good base for the organizations looking forward to using UAS.

RECOMMENDATION 1: UAS have proved to be more cost-effective as the initial capital cost is low and they are more efficient with quick turnaround and the ability to reach remote location; in a number of scenarios. Road authorities are encouraged to explore the use of UAS in those scenarios, mentioned in recommendation 2.

RECOMMENDATION 2: We invite road asset owners, managers and builders to analyze if the following tasks that they might be conducting today could be performed in a more efficient way with the use of UAS:

- Construction monitoring
- Bridge Inspection (recommended for LMIC)
- Asset inventories and Maintenance monitoring
- Pre-construction survey (green and brown field projects)
- Automated Asphalt Pavement Inspection *(recommended for LMIC)*
- Unpaved/Gravel roads condition monitoring *(recommended for LMIC)*
- Avalanche monitoring
- Traffic monitoring
- Urban mapping for road infrastructure flood prevention (recommended for LMIC)
- Law enforcement

RECOMMENDATION 3: Construction Monitoring

Pros:

- The use of sUAS and GNSS technology for construction engineering and inspection has resulted in a positive Return on Investment (ROI) for UDOT.
- The use of UAS along with other geospatial technologies can increase the efficiency. (Work was completed 25 days ahead of schedules, as mentioned in case study 4.1.1)
- Some cost savings can be achieved by using UAS.

Cons:

- Accuracy of the data can be an issue, which may require addressing discrepancies between design and actual construction quantities.

RECOMMENDATION 4: Bridge Inspection (Concrete and steel bridges) *(recommended for LMIC)*

Pros:

1. UASs can be successfully used for concrete bridge inspection for identifying the concrete delaminations. Use of better thermal sensor may produce better results.
2. Infrared images of bridge decks and elements are already a common and accepted way to obtain information on concrete delaminations. UAVs can provide a very efficient way to collect infrared images of bridge decks and elements as they can be equipped with an infrared camera.
3. UASs can be used in the field during bridge inspections safely. Based on the UASs size, weight, controllability and built-in fail safes, the risk to inspection personnel and public is very low.
4. UASs are more suitable as a tool for inspections of larger bridges, but there can also be some advantages for smaller bridge inspections. (i.e. short span bridges and culverts)
5. UASs themselves cannot perform inspections independently but can be used as a tool for bridge inspectors to view and assess bridge element conditions.
6. Defects can be identified and viewed with a level of detail equivalent to a close-up photo for the areas that are not easily accessible.
7. UASs with the ability to direct cameras upward and the ability to fly without a GPS signal are important features when using this technology as an inspection tool.
8. UAS technology is evolving rapidly and inspection-specific UAS features are just coming into the marketplace that will increase their effectiveness as it relates to bridge safety inspection.
9. In some type of inspections, a UAS has the capabilities to be used in lieu of an under bridge inspection vehicle and would provide significant savings. These savings would come in the form of reduced or eliminated traffic control and reduced use of under bridge inspection vehicles and lifts.

10. Safety risks associated with traffic control, working at height and in traffic could be minimized with the use of UASs. Additionally, UASs can be utilized as an effective method to determine stream or river bank conditions upstream or downstream of the bridge as well as capture large overall aerial maps of dynamic bank erosion and lateral scour conditions.
11. UASs can provide important pre-inspection information for planning large-scale inspections. Information such as clearances, rope access anchor points and general conditions can easily be obtained with a UAV and would aid in the planning of an inspection.
12. The use of UAVs to aid bridge inspection should be considered as a tool to a qualified team leader when a hands-on inspection is not required.
13. The use of UAVs to aid bridge inspections should be considered for routine inspections to improve the quality of the inspection by obtaining information and detail that may not be readily obtained without expensive access methods. They should also be considered where they can increase safety for inspection personnel and the traveling public.
14. Topics for investigations in a future phase include:
    a. Cost comparison with Aerial Work Platforms and traffic control.
    b. Explore inspection-specific UAS technology.
    c. Compile a best practices document.
    d. Incorporate UAS technology into an actual inspection.

Cons:

1. Measurements can be estimated from images, but tactile functions (e.g., cleaning, sounding, measuring, and testing) equivalent to a hands-on inspection cannot be replicated using UASs.
2. Other non-destructive tests performed by an experienced inspector cannot be done by using UAS.

RECOMMENDATION 5: Automated Asphalt Pavement Inspection *(recommended for LMIC)*

Pros:

1. Equipment Cost - UAS equipped with laser sensors, RTK GPS and high resolution camera is close to hundred thousand dollars compared to a van that can cost few million dollars.
2. Speed - UAS can perform the distress survey much faster than a van, as they have the ability to scan large and wide areas in a single pass.
3. Survey Cost – As UAS can collect data faster, the survey cost is significantly lower.
4. Safe – in rural areas it is safer to use UAS as there is no interference with traffic
5. The aerial images collected from UAS can be used for comparing the pavement condition after every survey.
6. Data can be collected more frequently i.e. multiple times a year instead of once a year and so on, as the cost of data collection is less compared to other methods.

Cons:

1. Rules and restrictions – Use of UAS is restricted by many national and local government laws in urban areas with some exceptions, whereas van has no restriction and just need to follow the driving rules.
2. Distress survey in high traffic areas – As a van follows the driving rules and follows the traffic, the data collected is clear from obstructions, and whereas data collected using UAS may capture the vehicles on the road instead of the distress hidden under the vehicles.
3. Reduced efficiency due to limited battery life of UAS. Enough batteries should be made available during the survey to minimize the disruption.

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RECOMMENDATION 6: Unpaved/Gravel roads condition monitoring *(recommended for LMIC)*

Pros:

1. There is a potential increase of efficiency in the use of UAS for monitoring surface characteristics of unpaved roads compared to visual inspections although further research should be done in a variety of regions to validate results.
2. UAS can help in identifying the following:
   a. Potholes
   b. Loss of crown
   c. Corrugation
   d. Rutting
3. Data collected through UAS can be used for generating 3D models for rut and potholes depth measurement.
4. Due to the high cost and difficulty of manual ground measurement, such survey is not affordable to most of the local road management authorities, and is conducted only occasionally. Local transportation management agencies largely rely on simple windshield inspection, or even no survey at all in many regions. Use of UAS can increase the frequency of these surveys and can provide more accurate data than windshield survey.
5. In contrast to conventional road condition data collection approaches, UAS does not require field work. Even field visit is not needed. Therefore, it enables local agencies more quickly, efficiently and safely collect data needed for rural road condition assessment.
6. Since the road data are documented in digital imagery, re-measurement is possible whenever is necessary.
7. Condition of gravel roads deteriorates significantly during rainy season; UAS can be used effectively for identifying the areas in need of immediate and major maintenance.
8. Laser scanning sensors are not yet available for UAS, whereas most vehicles used for pavement data collection uses laser scanners.

Cons:

1. The helicopter UAV did not follow exactly the predefined path during the missions. The actual route varies as a result disturbances such as air resistance, wind, vibration etc. Poor along-track overlap (~20%) has been observed. This has posed challenges for image orientation and 3D reconstruction.
2. Although UAS are more efficient in gravel road condition survey, but if they are not operated under suitable condition (as mentioned above), the survey cost can increase.
3. The time and cost associated with image processing and creation of 3D models needs further research and study.

RECOMMENDATION 7: Emergency response – Avalanche monitoring

Pros:

- When road infrastructure faces snow avalanches the UAS of drones has been proved very efficient at least for two applications:
  1. To provoke controlled avalanches by dropping explosive charges at predetermined avalanche trigger zones.
  2. To provide current condition of the infrastructure right after an avalanche occurred, in order to better organize the snow clearing works.
- UAS have showed considerable potential for aerial roadway surveillance when the infrastructure was not easily accessible for road vehicles. They have proofed to be able to obtain clear and usable videos of the roadway at a height that allows an efficient viewing of roadway conditions and traffic. This opens a series of potential use of UAS on the road sector when the road is not accessible:
  1. Monitoring of a blocked road after a landslide.
  2. Monitoring of road infrastructure after a natural disaster: floods, hurricanes, earthquakes…
  3. First monitoring of an accident under traffic congested road.

Cons:

- However, when UAS are used in a high mountainous area, particular attention should be given to flight conditions because of lower air pressure and climate conditions (potential strong wings, changes of air temperatures, etc.)

RECOMMENDATION 8: Traffic Monitoring

Pros:

1. UAS can be used to monitor high incident locations.
2. Further analysis can be done to identify the root causes such as human errors, improper geometric design of the roadway, any elements obstructing the driver's view etc. and implementing the solution to resolve the root cause.
3. UASs promise to be the lowest cost aircraft to operate.
4. Airborne cameras offer many benefits over ground-based detectors.
5. The bird's eye view can help in identifying the traffic congestion location.

Cons:

1. It may be hard to determine the speed of the vehicles from the sequence of the images for monitoring the traffic flow.
2. The wider turning radius of the fixed wing UAS can result in large portions of the area left unobserved. This can be addressed by using a rotary UAS, but the speed of rotary UAS can be another issue.

RECOMMENDATION 9: Urban Mapping *(recommended for LMIC)*

Pros:

1. UAS can be used for collecting accurate geographic data (Ortho-imagery) in areas where satellite imagery is not available or is expensive.
2. The cost of using a manned aircraft is also extremely high.
3. The aerial images can be used for creating the elevation model.
4. Elevation model created from UAS data helps in identifying the road infrastructure in low lying areas that are susceptible to flooding.

Cons:

1. Large amount of digital data is produced from aerial images requiring proper and huge storage space.

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RECOMMENDATION 10: Law Enforcement

Pros:

1. UAS can be used for reconstructing the crash scenes by using the quantitative measurements.
2. Rapid collection of aerial imagery of a crash scene using a low-cost (~$1,000) UAS.
3. Quantitative measurements could be made using the high resolution (36 megapixel) images collected from UAS.
4. Birdseye view images from the UAS helps in looking at a broader picture and helps in capturing the information that can sometimes be missed by the police staff.
5. UAS can potentially reduce time spent measuring data (increase safety, reduce traffic impact)

Cons:

1. The lower resolution of imagery should not be used to make measurements.
2. Cannot be used during night time or when day light conditions are low.

A step by step process is outlined below. These steps may be required if the organization wants to operate and collect the UAS data by themselves. If a consultant or a contractor will be performing the UAS operation, these steps can be used as a reference.

Project Process

RECOMMENDATION 11: As a general UAS project process we recommend using the following process in 3 phases of 6 and 7 steps each. This process can be adapted and further develop for each country. Note that this process applies if and when a decision has been made to use UAS technology, which has to be done after careful consideration of pros and cons.

Preliminary steps:

Step 1
- First and foremost step is to check if your country legally allows the use of UAS, as some countries do not allow UAS operations.

Step 2
- Familiarize yourself with the rules and regulations and licensing requirements with the national and local governments.

Step 3
- Make sure the project area falls under the allowed airspace for UAS operation, and fulfills all other requirements set by governing authority, example safe distance from public, airports, heliports, urban areas, built up areas etc.

Step 4
- Gather the project requirements such as type of data need to be collected i.e. Imagery, elevation, digital photos, thermal and infrared images, LiDAR etc. , accuracy of the data, image resolution, data output format, amount of data and data storage and management.

Step 5
- Once the project requirements are set, next set is to evaluate the UASs available in the industry and select the ones that are best suited for the job within the available budget.

Step 6
- Select the payloads as required (payload is any equipment transported by the unmanned aircraft: cameras, sensors...). Sometimes the cost of payloads can exceed the cost of UAS, therefore is necessary to check what is required.
- Estimate project costs in detail and compare with business as usual scenario.

Intermediate Steps:

- **Step 1**
  - Select the project team, define their roles and responsibilities clearly based on their experience and expertise.
- **Step 2**
  - Within the project area, select a sample area to perform a pilot project, this would provide the organization with an opportunity to understand and evaluate the potential of UAS without huge financial risk.
- **Step 3**
  - Develop a communication plan, outlining main point of contact, mode of communication (Cell phones, radios, walky talky etc.)
- **Step 4**
  - Develop an emergency plan describing the personnel and equipment available to respond to anticipated emergencies, including incidents and accidents, or medical emergencies.
- **Step 5**
  - If required, coordinate roadway closure, detours and alternate access route for emergency vehicles.
- **Step 6**
  - Select the date and time for the UAS operation and communicate it to all parties involved, most importantly the aviation department.

Final Steps:

Step 1	• Set up the equipment, perform necessary checks to make sure all equipment is working fine. (Having a check list is handy).
Step 2	• Set up traffic closures and detours as required, and have emergency team ready on site.
Step 3	• Perform the flight operation and collect all necessary data.
Step 4	• If possible, check the data for completeness and quality, before leaving the site. This helps in avoiding any re-flying operation.
Step 5	• Secure the data by uploading it to the server, cloud and external hard disk as applicable.
Step 6	• Process and analyse the data as required and compare with the project requirements outlined initially.
Step 7	• Evaluate the project, if results from this pilot project are satifactory, apply the same process for the entire project. Else, modify the process based on lessons learned.

Other General Recommendations for all Audience

Other recommendations coming up from this report are:

RECOMMENDATION 12: It is recommended that the organizations exercise due diligence while evaluating the available options for UAS projects. The projects should be evaluated on case by case basis and there is no one size fits all solution available in the market. Best approach is to identify the project requirements, outline these requirements and compare with UAS specifications.

RECOMMENDATION 13: We invite road authorities, manufactures and international organizations to seize the opportunity of having a recent technology still under development to set interoperability standards for data integration all over the world.

RECOMMENDATION 14: Rotary micro drones are more suitable for inspecting enclosed and tight areas, where as large fixed wing UAS are more suitable for inspecting and mapping large areas as they have extended flight time and faster speed.

RECOMMENDATION 15: As the UAS industry is rapidly changing (2018) with advancement in Information Technology, a fresh evaluation is recommended for each and every project. LMICs are invited to evaluate the topnotch technologies in order to use the most adapted technology, budget permitting. The older or outdated technology can still be used if they are useful for certain projects. For example: a low cost UAS can be used for collecting aerial images, if high resolution images are not a requirement.

RECOMMENDATION 16: National regulations for the use of UAS are evolving very quickly in different countries. During this study of a few months, even some of them changed in the meantime. Therefore, we strongly recommend consulting the relevant updated regulation before and during each project evolving UAS. Some LMIC that do not have specific regulation at this moment might establish new regulation on UAS in the coming years.

RECOMMENDATION 17: We invite road administrations and relevant organizations to update asset inspection specifications with geospatial technology and include them in their guidelines in order to foster and ensure a proper use of UAS in construction and asset inspections. An UAS has an important potential to increase the efficiency of construction and asset inspections.

CONTENTS

1. INTRODUCTION

This report is an outcome of the World Road Association (PIARC) mechanism for Special Projects, which is PIARC instrument to respond quickly to emerging issues for PIARC member countries.

The report explores "The use of Unmanned Aerial Systems (UAS) to Remotely Collect Data for Road infrastructure". It is a special project, funded and supervised by the World Road Association (PIARC) and conducted by Rednoa Inc. as an external consultant.

Special Project mechanism intends to answer to emerging issues for PIARC member countries within a limited time, usually under one year. The Special Project is produced with the support of an external consultant which work is overviewed and supported by a World Road Association team including members of the relevant PIARC Technical Committees, PIARC Strategic Planning Commission and PIARC General Secretariat.

Unmanned Aerial System (UAS) or Unmanned Aerial Vehicle (UAV) are most commonly known as drones. UAS are gaining lot of popularity in many industries due to its low cost, quick turnaround, and the ability to reach remote locations that are hard for humans to access. At the same time, the industry is facing many challenges due to stringent regulations and bylaws, as unsafe use of UAS can pose danger to public life and security.

There are numerous opportunities for the use of UAS in the road sector. This report will help to understand the international usage and associated success. Additionally, this report will look at how the technology supports the national and international security of our highways. This will allow the World Road Association (PIARC) members the opportunity to leverage the experience of others to expedite the efficient, economical, and safe international deployment and mainstreaming of the technology.

There is the added benefit that since this technology is relatively new, there are still the opportunities to foster common approaches in data integration rather than seeing a proliferation of divergent approaches, as we do work and live in an international economy. At the same time a cautious approach is required to leverage the experience of others by independently evaluating the UAS technology for each prospective project on a case by case basis.

RECOMMENDATION: We invite road authorities, manufactures and international organizations to seize the opportunity of having a recent technology still under development to set interoperability standards for data integration all over the world.

1.1. METHODOLOGY

The information provided in this report is gathered through literature research and a survey questionnaire.

Various case studies were collected through literature research and from drone manufacturing companies as well as authorities/organizations who have used and or are looking to use drones. A survey questionnaire was developed and distributed to various organizations around the world. Thirty-Five responses were received, these responses are discussed in detail in section 5.

All the case studies reviewed during the literature research were classified into the following categories:

- Highway inspection and Asset Monitoring
- Emergency Response
- Traffic Monitoring
- Mapping
- Emergency Recovery
- Law Enforcement and
- Wildlife monitoring

The rationale behind this approach was to cover different aspects related to roadway infrastructure. It was recognized that case studies may not be available for all the categories mentioned above. In that case, efforts were made to review the existing practices and identify the opportunity for use of UAS technology in those categories.

2. OVERVIEW OF UNMANNED AERIAL SYSTEMS (UAS)

The UASs are often referred to as unmanned aircraft vehicles (UAVs) or drones. The Federal Aviation Administration (FAA) defines a UAS as a system to include the aircraft and all of the associated support equipment for its operation, such as its ground control station (GCS), data and telemetry links, navigation system, and payload sensors (FAA 2015). The payload of an unmanned aircraft can be equipped with a variety of passive or active sensors, such as video and red-green-blue (RGB) cameras, near infrared, hyperspectral, radar, thermal, and lidar sensors, as well as combinations of these sensor types. Because of this payload versatility, UASs can economically collect a variety of remote sensing data. UASs comes in various shapes and sizes, ranging from inexpensive mini drones to expensive, large fixed wings. They are broadly classified as Rotary and Fixed wings (Figure 1).

Figure 3.1: Top left is a multi-rotor Ghostdrone 2.0. Top right is a fixed wing eBee Plus UAS. Bottom is fixed wing PD-1 UAS.

Figure 3.1 shows different, types of UASs and their weight and size. The UASs are used for various applications as discussed in this report. The selection of UAS depends on various factors and the ones most suitable for performing specific tasks should be used. For example micro drones are more suitable for inspecting enclosed and tight areas, where as large fixed wing UAS are more suitable for inspecting and mapping large areas as they have extended flight time.

RECOMMENDATION: Rotary micro drones are more suitable for inspecting enclosed and tight areas, where as large fixed wing UAS are more suitable for inspecting and mapping large areas as they have extended flight time and faster speed.

The available UAS options should be carefully evaluated based on the project requirements and UAS specifications. As the UAS industry is rapidly changing with advancement in Information Technology, a fresh evaluation is recommended for each and every project.

RECOMMENDATION: As the UAS industry is rapidly changing (2018) with advancement in Information Technology, a fresh evaluation of available technologies is recommended for each and every project.

Basic Components of UAS[1]:

As discussed above, there is a wide range of different types of unmanned aircrafts, all UAVs typically consist of the following basic components (Figure 3.2):

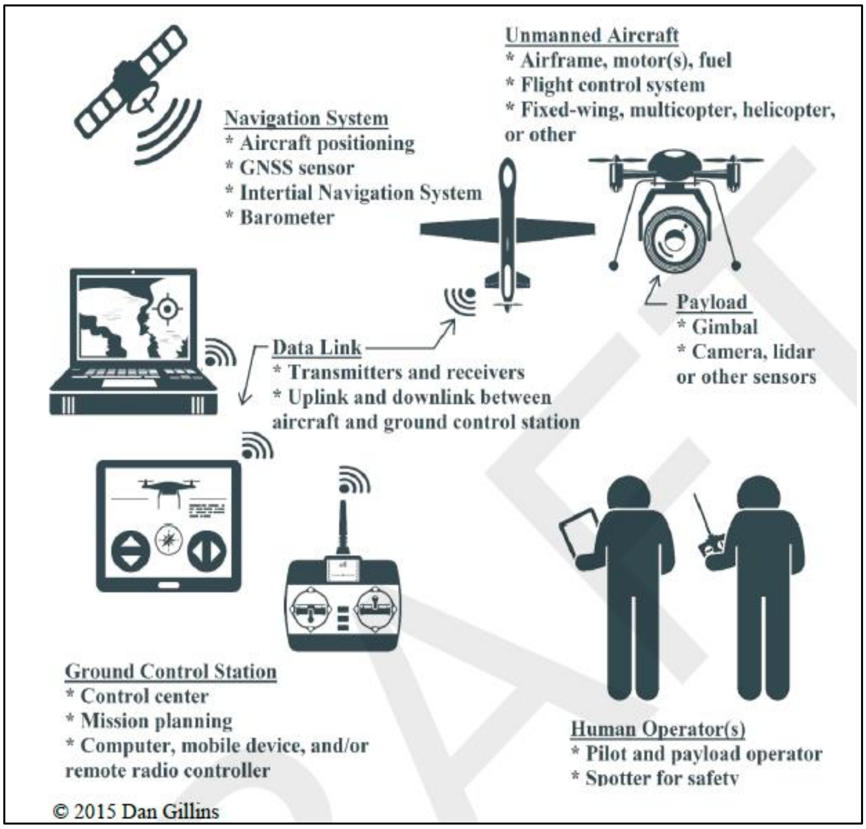


Figure 3.2. Illustration. Basic components of a UAS.

[1] Source: Effective Use of Geospatial Tools in Highway Construction-FHWA-HRT

• **Aircraft:** The aircraft is the flying portion of the system, often referred to as a “platform” or a UAS. In addition to the airframe, the aircraft includes the motor(s) and fuel, such as batteries or gasoline.

• **Ground Control Station (GCS):** The GCS is the control center for the operation of the UAS. It is usually the center in which the UAS mission is pre-planned. A typical GCS allows the operator to fly the aircraft and control the payload. For many systems, mission plans can be pre-loaded into the aircraft prior to takeoff so that the operator can control the aircraft without a joystick and can monitor its performance and movement on a digital map. A GCS typically includes a computer, laptop, mobile device, and/or radio remote controller.

• **Data Link:** The data link is the data transmission system enabling uplink and downlink between the GCS and the operator. The operator uses an uplink to transmit the mission plans to the aircraft prior to takeoff. These mission plans are then stored in the automatic flight control system of the aircraft. The uplink is also used to communicate real-time flight control commands to the aircraft when needed and to send commands to the payload sensor. Using the downlink, the aircraft returns status information on the performance of the aircraft’s system (e.g., fuel level, engine temperature), sends its positioning data, and, depending on the system, the data from the payload sensor back to the operator.

• **Navigation System:** The navigation system allows the operator to monitor the aircraft’s 3D position (as well as its velocity, altitude, and possibly other variables) in real-time. The aircraft uses its navigation system in real-time when flying a pre-programmed mission or when triggered to return to its takeoff position as a safety feature during an unexpected emergency. Furthermore, the data collected by the aircraft uses the navigation system data to georeference the data and correct errors in the raw data through post-processing routines. The navigation system may comprise one or more GNSS receivers, inertial sensors (gyroscopes and accelerometers, typically mounted in orthogonal triads), barometers, and magnetometers.

• **Payload:** The payload is any equipment transported by the unmanned aircraft. Geospatial professionals will attach remote sensing equipment to the aircraft, such as video, RGB, thermal, infrared, and/or multispectral cameras. Lightweight video and RGB cameras are commonly used today; however, some UASs can carry heavier payloads, such as lidar sensors. The payload sensors are frequently attached to the airframe on two- or three-axis gimbals to reduce vibrations and motion blur, as well as enabling the operator to point the sensor at an object of interest.

• **Launch, Recovery, and Retrieval Equipment:** The launch, recovery, and retrieval equipment are necessary equipment for aircraft that are incapable of vertical takeoffs and landings. Launch equipment may include ramps, catapults, rubber bungees, compressed air, and/or rockets. Recovery equipment may be required for bringing a flying aircraft safely down, such as a parachute, a large net, or a carousel apparatus. Retrieval equipment is necessary for transporting the aircraft from its landing point to the launch position.

• **Human Operator(s):** The human operator(s) are necessary to supervise the safe and efficient operation of the unmanned aircraft, including a pilot, payload operator, and/or a spotter.

1.2. Regulations, Legislation, License process and requirements

Note: Information provided in this section is for reference only. This information may change and may not be valid in future, as rules and regulations around legal use of UAS are changing.

Most of the UAS governing organizations, categorizes UAS based on their size and weight and have different rules and regulations. It is very important to check and familiarize yourself with these regulations and licensing process with the regulatory authorities of the country where project is planned.

For example, in the U.S.A. for commercial use of UAS a Remote Pilot Airman Certificate is required and must pass Transportation Security Administration (TSA) vetting along with other requirements summarized in table 3.1.1. In Canada a Special Flight Operators Certificate (SFOC) is required from Transport Canada (TC) in order to commercially operate a UAS, with other requirements. Table 3.1.2 and Figure 3.2 summarizes the requirements and process.

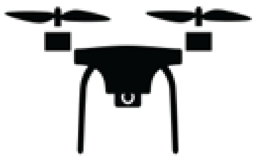
The following tables summarizes the rules from Federal Aviation Administration (FAA) and Transport Canada (TC).

	Fly for Fun	Fly for Work
Pilot Requirements	No pilot requirements	Must have Remote Pilot Airman Certificate Must be 16 years old Must pass TSA vetting
Aircraft Requirements	Must be less than 55 lbs. Unless exclusively operated in compliance with Section 336 of Public Law 112-95 (Special Rule for Model Aircraft), the aircraft must be registered if over 0.55 lbs.	Must be less than 55 lbs. Must be registered if over 0.55 lbs. (online) Must undergo pre-flight check to ensure UAS is in condition for safe operation
Location Requirements	5 miles from airports without prior notification to airport and air traffic control	Class G airspace*
Operating Rules	Must ALWAYS yield right of way to manned aircraft Must keep the aircraft in sight (visual line-of-sight) Must follow community-based safety guidelines Must notify airport and air traffic control tower before flying within 5 miles of an airport	Must keep the aircraft in sight (visual line-of-sight)* Must fly under 400 feet* Must fly during the day* Must fly at or below 100 mph* Must yield right of way to manned aircraft* Must NOT fly over people* Must NOT fly from a moving vehicle*

	Fly for Fun	Fly for Work
Example Applications	Educational or recreational flying only	Flying for commercial use (e.g. providing aerial surveying or photography services) Flying incidental to a business (e.g. doing roof inspections or real estate photography)
Legal or Regulatory Basis	Public Law 112-95, Section 336 – Special Rule for Model Aircraft FAA Interpretation of the Special Rule for Model Aircraft	Title 14 of the Code of Federal Regulation (14 CFR) Part 107

Table 1: U.S.A's FAA rules for operating UAS

Table 3.1.2: UAS rules for Canada. Source Transport Canada

Very small drone operations	Limited operations (rural)	Complex operations (urban)
Very small drone more than 250 g to 1 kg	Small drone more than 1 kg to 25 kg	Small drone more than 1 kg to 25 kg
		
Most recreational users will fit into this category. The rules that apply are easy to understand and follow.	This category is for users operating in rural areas (e.g., agricultural purposes, wildlife surveys, natural resources).	This category is for users who intend to fly in urban areas, within controlled airspace or close to anywhere that airplanes, helicopters and floatplanes land and take off.
Pilots must be 14 years old or older and will be required to:	Pilot must be 16 years old or older and will be required to:	Pilot must be 16 years or older and will be required to:
mark their device with their name and contact information;	mark their device with their name and contact information;	hold a pilot permit that is specific to small drones;
pass a basic knowledge test;	pass a basic knowledge test;	have liability insurance;
have liability insurance; and	have liability insurance; and	register and mark their device with a unique identification Transport Canada will provide;
fly at least:	fly at least:	operate a drone that meets a design standard;
5.5 km from airports	5.5 km from airports	follow a set of flight rules;
1.85 km from heliports	1.85 km from heliports	get approval from air traffic control when flying in ontrolled airspace or near aerodromes; and
30 m from people	150 m from open-air assemblies of people (i.e. outdoor concert)	fly at least: 150 m from open-air assemblies of people (i.e. outdoor concert) unless at least 90 m high 30 m from people, vehicles, vessels
	75 m from people, vehicles, vessels	
	1 km from built-up areas	

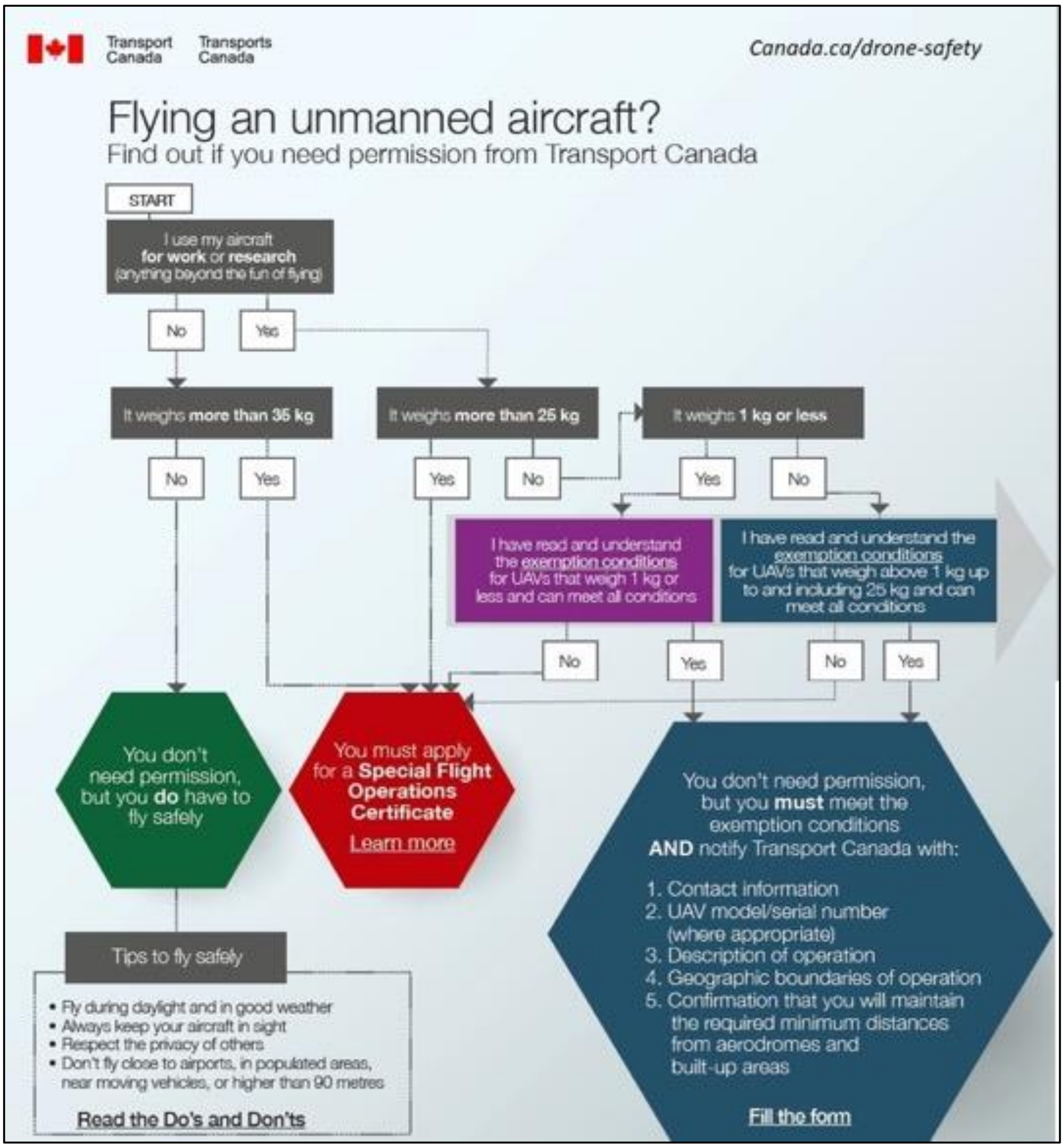


Figure 3.2: Flow diagram from Transport Canada to check if permission is required to fly UAS

In **Ireland**, the Small Unmanned Aircraft (Drones) rules are as follows:

Source:https://www.iaa.ie/docs/default-source/publications/legislation/statutory-instruments-(orders)/small-unmanned-aircraft-(drones)-and-rockets-order-s-i-563-of-2015.pdf?sfvrsn=26f50bf3_6

- Aircraft subject to this order shall be required to be registered in a manner established by the Authority.
- A person who has charge of the operation of a small unmanned aircraft shall not permit that aircraft to be operated:
- so as to cause a hazard to another aircraft; or
- in the vicinity of aircraft maneuvering in an aerodrome traffic circuit; or
- in a negligent or reckless manner so as to endanger life or cause damage to the property of others.
- Small unmanned aircraft shall give way to manned aircraft.
- The authority may define areas within Air Traffic Services airspace, where small unmanned aircraft activity may take place without permission from the Authority.

- A person who has charge of the operation of a small unmanned aircraft which has a mass of less than 25 kilograms, without fuel but including any articles or equipment installed in or attached to the aircraft and including cargo at the commencement of its flight shall not allow such an aircraft to be flown, unless otherwise permitted by the Authority and subject to such conditions as are required by such permission:
- within a prohibited area, a restricted area, or controlled airspace;
- in Air Traffic Services airspace, other than controlled airspace, within 5km of an aerodrome during periods of aircraft operations, unless the aerodrome operator has given permission;
- at a distance of less than 30 metres from a person, vessel, vehicle or structure not under the direct control of the operator;
- at a distance of less than 120 metres from an assembly of 12 or more persons not under the direct control of the operator;
- beyond direct unaided visual line of sight and not farther than 300 metres from the point of operation;
- at a height of more than 120 metres above the ground or water;
- permitting or attempting to permit, any article or animal, whether or not attached to a parachute to be released from that aircraft.
- A person who has charge of the operation of a small unmanned aircraft shall not permit such aircraft to be operated from any place unless the aircraft may take-off and land without undue hazard to persons or property and nothing in this order shall affect the rights and interests of the owner or occupier of that place.
- A person who has charge of the operation of a small unmanned aircraft, which has a mass of 4 kilograms or more and less than 25 kilograms, without fuel but including any articles or equipment installed in or attached to the aircraft and including cargo at the commencement of its flight, or as otherwise directed by the Authority, shall not allow such an aircraft to be flown unless that person has successfully undertaken a course of safety training accepted by the Authority.
- A person who has charge of the operation of a small unmanned aircraft which has a mass of 25 kilograms, or more and less than 150 kilograms, without fuel but including any articles or equipment installed in or attached to the aircraft and including cargo at the commencement of its flight, shall not allow such an aircraft to be flown without the permission of the Authority and subject to such conditions as are required by such permission.
- Permissions issued in accordance with this order may take the form of Specific Operating Permission.

In Japan the following UAS rules and Operational Limitations apply:

Any person who intends to operate a UA/Drone is required to follow the operational conditions listed below, unless approved by the Minister of Land, Infrastructure, Transport and Tourism.

I. Operation of UAs/Drone in the daytime.
II. Operation of UAs/Drone within Visual Line of Sight (VLOS).
III. Maintenance of 30m operating distance between UAs/Drone and persons or properties on the ground/ water surface.

IV. Do not operate UAs/Drone over event sites where many people gather.
V. Do not transport hazardous materials such as explosives by UA/Drone.
VI. Do not drop any objects from UAs/Drone

Source: http://www.mlit.go.jp/en/koku/uas.html

The following link to the website provides UAS laws and rules around the world. The information available on this website should be used for reference only. For most updated rules and regulation, please visit the governing Authority's website.

http://www.uavsystemsinternational.com/drone-laws-by-country/

International Perspectives

Countries around the world have taken action to address the use of sUAS (Small UAS) within their borders. Concerns have been expressed that overregulation of the UAS industry in the United States could lead companies to take UAS-related work abroad. Some examples follow of approaches taken by several other countries.

Canada

Canada regulates UAS use within its borders through Transport Canada, the department responsible for regulating transportation, similar to the U.S. Department of Transportation. If the UAS is being operated for personal hobby use and weighs less than 35 kilograms (approximately 77 pounds), the operator need not obtain permission to fly it. Any user of a UAS that weighs more than 35 kg must apply for a Special Flight Operations Certificate from Transport Canada.

In addition, any UAS being used for work or research that weighs more than 25 kg (approximately 55 pounds) must apply for the certificate. This also applies to any UAS that weighs less than 25 kg if the operator cannot meet certain exemption conditions. The government agency provides a diagram to help individuals determine whether they need permission to operate their UAS in Canada.

In 2016, Transport Canada plans to introduce regulatory requirements for UAS that weigh less than 25 kg and are operated within visual line of sight. The regulations will likely include aircraft marking and registration requirements, personnel licensing and training requirements, and flight rules.

European Union

Rules related to UAS vary across the European Union, according to the European Aviation Safety Agency. A formal Technical Opinion on the operation of UAS was released in December 2015, and rules are expected to be developed and amended based on the contents of the opinion in the next two years. The opinion includes 27 proposals for a regulatory framework. Among the proposals are establishing categories for the operation of UAS, "taking into account the nature and risk of the particular activity;" requiring manufacturers and importers to provide information to customers on operational limitations; and limiting where UAS can be operated, with no-fly zones over areas such as city centers, parks and airports.

France regulates UAS operation by hobbyists, prohibiting UAS operation over people, operation higher than 150 meters (approximately 492 feet), and operation out of line of sight. Notably, France does allow commercial UAS to be operated beyond visual line of sight. Ireland requires drone registration and limits where UAS can be operated. Italy also has UAS regulations.

Other Countries

Russia enacted a law requiring individuals who own UAS that weigh more than 250 grams (approximately 0.55 pounds) to register the aircraft with the Federal Air Transport Agency. In addition, UAS operators must have a team—the pilot and an observer—responsible for flight safety and must develop and submit flight plans to the regional body responsible for air traffic control.

In China, the Civil Aviation Administration issued regulations for UAS that weigh less than 116 kg (approximately 255 pounds) that were effective at the end of 2015, according to the law firm Hogan

Lovells. These rules create categories of UAS based on weight and use. A "real-time supervision system" is included, which seems to function similarly to geo-fencing. The regulations also require insurance coverage and specific rules for flight.

A number of other countries, including Australia and Mexico, also regulate UAS operation within their borders. Many similarities—such as registration and line of sight requirements—exist between UAS regulation in other countries and the United States.

Source: Taking Off: State Unmanned Aircraft Systems Policies; National Conference of State Legislatures

Hyperlinks:

Special Flight Operations Certificate: http://www.tc.gc.ca/eng/civilaviation/standards/general-recavi-uav-4161.html

provides a diagram: http://www.tc.gc.ca/media/documents/ca-standards/Info_graphic_-_Flying_an_umanned_aircraft_-_Find_out_if_you_need_permission_from_TC.pdf

according to the European Aviation Safety Agency: https://easa.europa.eu/easa-and-you/civil-drones-rpas

Technicalopinion:https://www.easa.europa.eu/system/files/dfu/Introduction%20of%20a%20regulatory%20framework%20for%20the%20operation%20of%20unmanned%20aircraft.pdf

regulates UAS operation: http://www.developpement-durable.gouv.fr/IMG/pdf/Drone-_Notice_securite-2.pdf

requires drone registration: https://www.iaa.ie/general-aviation/drones

UAS regulations: http://www.enac.gov.it/repository/ContentManagement/information/N1220929004/Reg%20SAPR%20english_022014.pdf

Russia enacted a law: https://www.popsci.com/russias-new-drone-rules-look-lot-like-americas

issued regulations: https://www.hlregulation.com/2016/01/20/china-launches-first-operational-rules-for-civil-unmanned-aircraft/

Australia: https://www.casa.gov.au/operations/standard-page/remotely-piloted-aircraft-rpa?WCMS%3ASTANDARD%3A%3Apc=PC_100374

Mexico: http://www.sct.gob.mx/fileadmin/DireccionesGrales/DGAC/00%20Aeronautica/CO_AV_23_10_R2.pdf

RECOMMENDATION: National regulations for the use of UAS are evolving very quickly in different countries. During this study of a few months, even some of them changed in the meantime. Therefore, we strongly recommend consulting the relevant updated regulation before and during each project involving UAS.

3. CASE STUDIES

The case studies presented in this section were collected after an extensive literature research. After reviewing, some of the case studies were curtailed to serve the purpose of this report. Relevant Parts and portions of other case studies has been used throughout this report.

Permission was obtained from the respective agencies to re-use their research work. A special reference is being made at the beginning of each case study to the original report. The audience reading this report is encouraged to refer to these original case studies for more information.

Lot of work and efforts has been put by the respective authors and the sponsoring agencies in these research projects. Therefore, all credit goes to them for their hard work. World Road Association and Rednoa do not claim any credit, except for the efforts in collecting, reviewing the literature and compiling them into this report.

At the end of each case study there is a “Conclusions and Recommendations” section that can be the particular interest for technicians and decision makers.

1.3. Case Study – Highway Construction, Inspection and Asset Monitoring

1.3.3. Case Study 1: Utah DOT's Use of Geospatial Technology$ for Design and Construction of State Route 20 (SR20)

Scope of this study is limited to use of UAS, therefore portions of the case study related to UAS are mentioned in this report. Other geospatial technologies used in this study were Global Navigation Satellite Systems (GNSS), Automated Machine Guidance (AMG) along with UAS.

Reference: FHWA contract #DTFH61-15-C-00042, final report (In publication) "Effective Use of Geospatial Tools in Highway Construction".

Introduction

This case study focuses on common highway construction applications, including the following:

- 3D Highway Modeling.
- Data collection for corridor mapping (e.g., topographic mapping).
- 3D modeling to support construction automation (e.g., AMG).
- Calculation of quantities (e.g., earthwork).
- Construction Engineering and Inspection.
- Real-time verification.
- Site or progress monitoring.
- Measurement of quantities.
- As-built records

Application / Methodology

Workflow

The workflow for using the appropriate geospatial tool is heavily dependent on the function for which the data is being collected. The guidance presented herein is based on the findings of the literature review and the documented case studies. The information is offered as a general guide to help DOTs deploy geospatial tools effectively. The areas covered in this section include Design, Construction Engineering and Inspection, and Asset Management. The workflow for using geospatial tools for highway construction projects is illustrated in Figure 4.1.1.1.

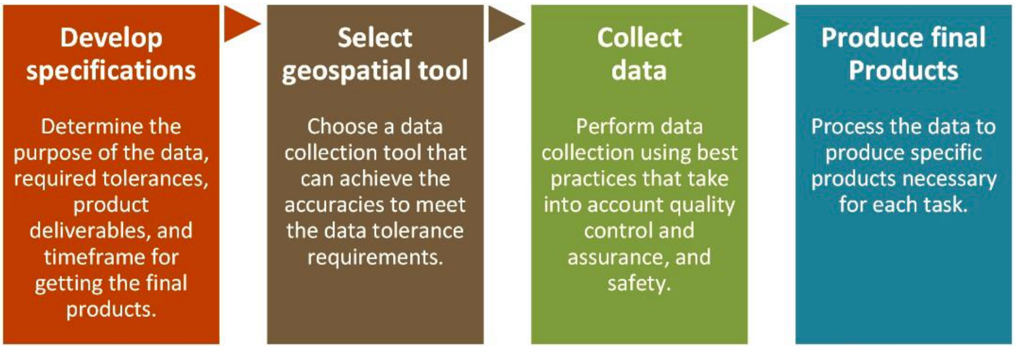


Figure 4.1.1.1. Flowchart. General guidance for effective use of geospatial in highway construction projects. Source: FHWA

The mission planning starts followed by the actual mission to produce the final deliverables. Figure 4.1.1.2 illustrates the mission planning workflow.

Figure 4.1.1.2. Flowchart. Mission planning workflow. Source: FHWA

Pre-mission: This task consists of preparing for the mission, location of targets and control points, safety considerations, and QA/QC plans for the operation. All these sub-tasks should be clearly documented in a pre-mission plan to share with the data owner. Diagrams are particularly helpful for communicating the target and survey control plan and trajectory of the mission (Figure 4.1.1.3). Note that the recommended number and spatial distribution of ground targets varies as a function of spatial extent, terrain, cover types, project accuracy requirements, and other variables. Ground control points were placed as target for a UAS flight (the flight plan is illustrated in Figure 4.1.1.4).

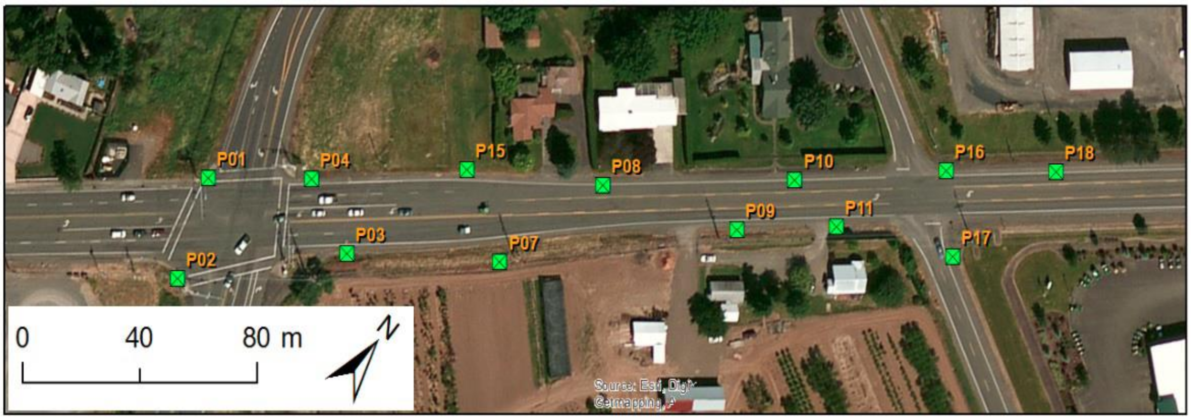


Figure 4.1.1.3. Photo. Example of ground control point layout plan for a UAS flight mission. Source: FHWA

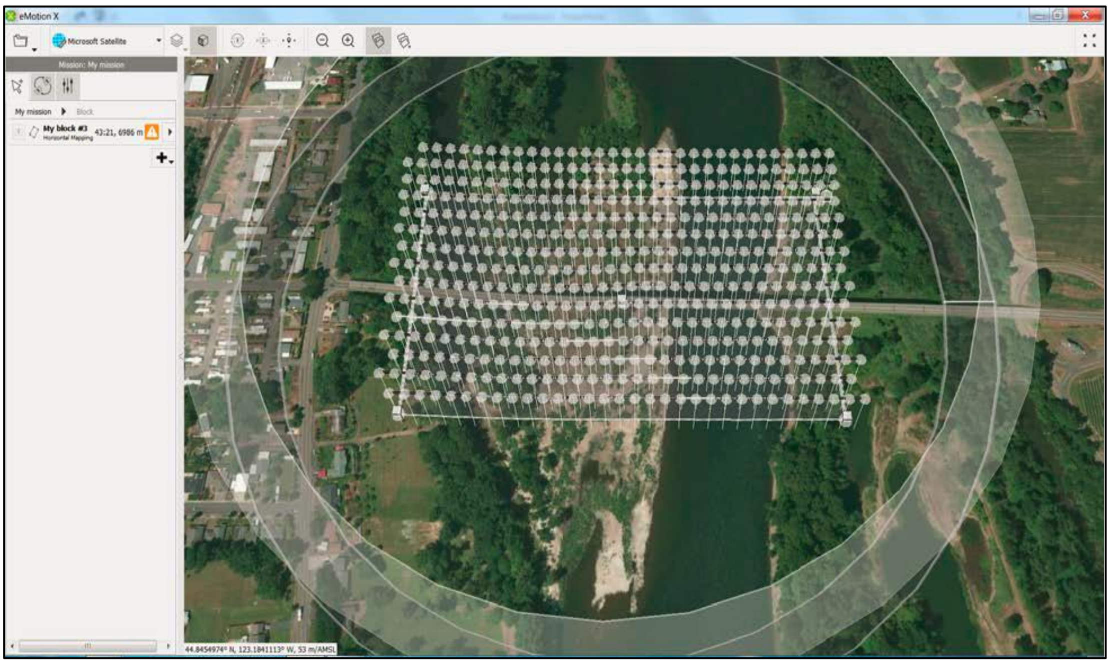


Figure 4.1.1.4. Photo. Flight plan for horizontal mapping mission. Circles denote planned photo centers.

The mission: This task is the actual collection of the data using the geospatial tools previously selected. Figure 4.1.1.5 presents the mission workflow. It includes setting the safety work zone (as applicable), targets and survey control points, instrument locations, and operating equipment. In addition, the quality control measures previously established are used to ensure the data are being collected in accordance with the requirements.

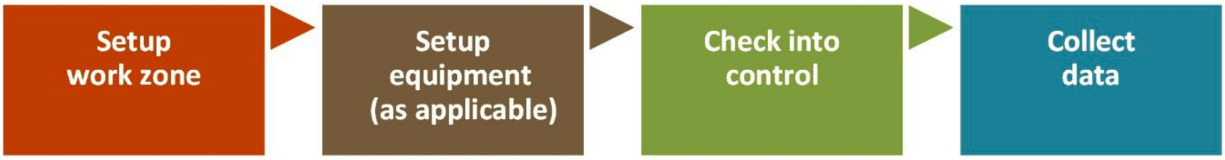


Figure 4.1.1.5. Flowchart. Data collection mission workflow. Source: FHWA

Post-mission: This task occurs immediately after the data collection ends. Figure 4.1.1.6 presents the post-mission workflow. It includes final quality assurance of the collected data and uploading datasets to external hard-drives or cloud-based storage for post-processing.

Figure 4.1.1.6. Flowchart. Post-mission workflow. Source: FHWA

Produce Final Products

The last step is to post-process the data to create the final deliverables in accordance with the specifications. Figure 4.1.1.7 presents the production workflow. Post-processing of the data depends on the collection approach and instruments used, and each of the workflows for producing the final products are dictated by proprietary software that is compatible with the hardware.

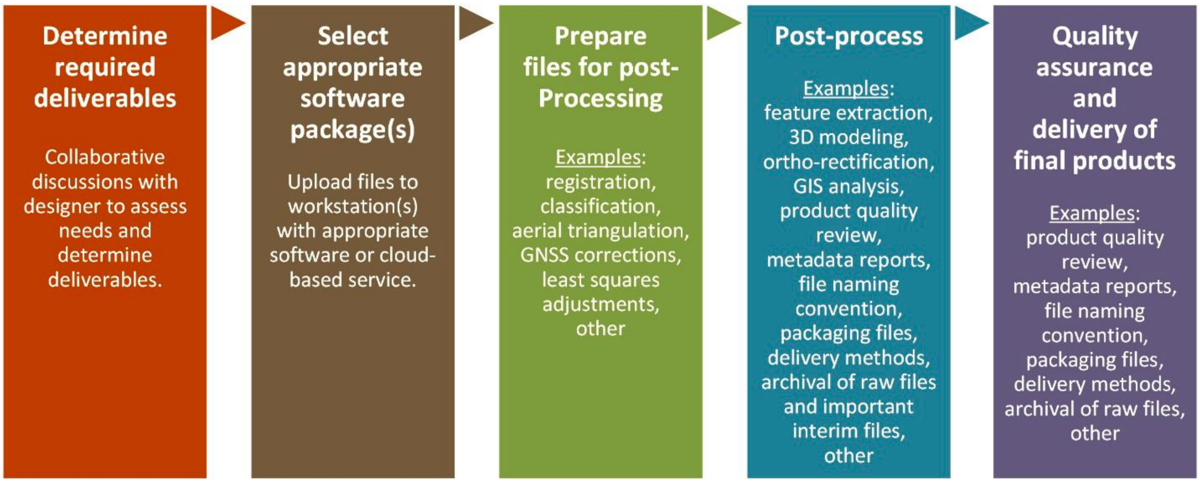


Figure 4.1.1.7. Flowchart. Workflow to produce final products to support design. Source: FHWA

UAS Data Processing

Figure 4.1.1.8 illustrates the semi-automated workflow of processing UAS imagery and related products. A number of cloud-based, server-based, and computer-based COTS platforms follow this general process.

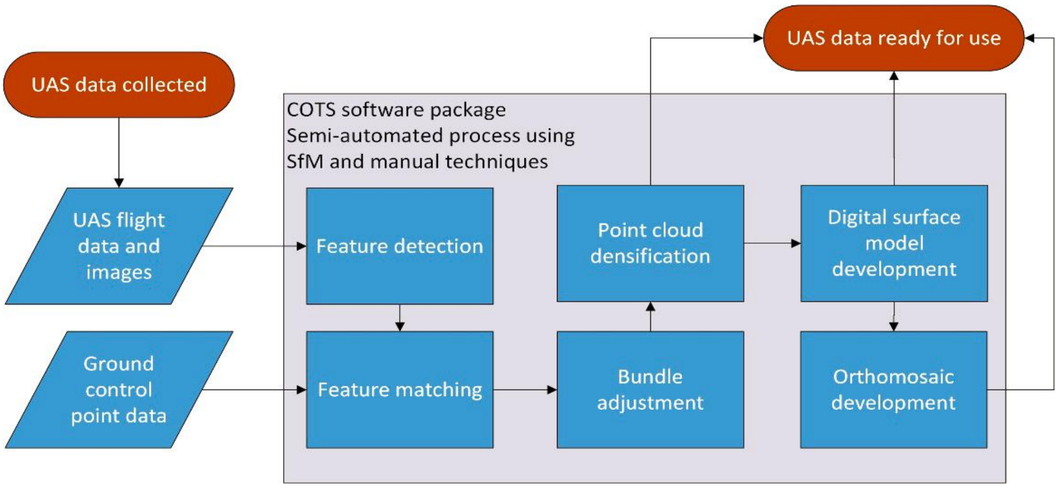


Figure 4.1.1.8. Flowchart. UAS imagery processing workflow. Source: FHWA

Site Overview

UDOT used a roadway project on SR20 as a pilot to evaluate multiple innovations that rely on geospatial technology. The scope of the project was to add climbing lanes on a steep hillside with significant geometric complexity. The following innovations were evaluated:

- 3D model as contractual "document".
- Topographic mapping using Small UAS (sUAS) for calculating earthwork quantities during construction.
- Use of sUAS for monitoring construction progress.
- Real-time verification and quantity measurements with GNSS rovers.

The project delivery method for this pilot project was Construction Management/General Contractor to allow flexibility during the evaluation of innovative technologies. The contract was awarded a medium-sized contractor with vast experience using geospatial technologies.

The Project

Highway Design

The original topographic mapping was created using a variety of technologies and workflows to develop a model used as the foundation for developing the design that met UDOT's standards, as required by the department's Survey and Geomatics Manual. The initial survey control network was established by UDOT in accordance with this manual.

Upon receiving the contract award, the contractor conducted a topographic survey using additional points to validate the existing ground surface in the model. This new existing ground model was provided to the design team to update the design with the most accurate existing ground model available. The contractor also established the construction survey network that would be used for AMG construction activities.

Construction Engineering and Inspection

All existing and proposed surfaces were provided to the construction inspection team to be used during real-time verification and quantity measurements using GNSS rovers. The survey equipment used for construction inspection was provided by the contractor, but operated by UDOT's construction staff.

Inspectors were able to check grades against tolerances specified in the contract requirements in real-time and measure quantities quickly by comparing the actual measurements to the original design values. This new process drastically reduced the time spent on this particular task. It also

Data Collection, Workflows, and Products

The case study also investigated the use of sUAS for data collection to create surfaces that inspectors could use for real-time verification and measuring quantities, as well as for monitoring progress. Although UDOT used the sUAS purchased for the pilot for collecting data, it was not used for production because the contractor was responsible for providing all data collection for production work. The workflow used for post-processing data collected using the sUAS is illustrated in Figure 4.1.1.9. The final deliverables are listed in Table 4.1.1.1.

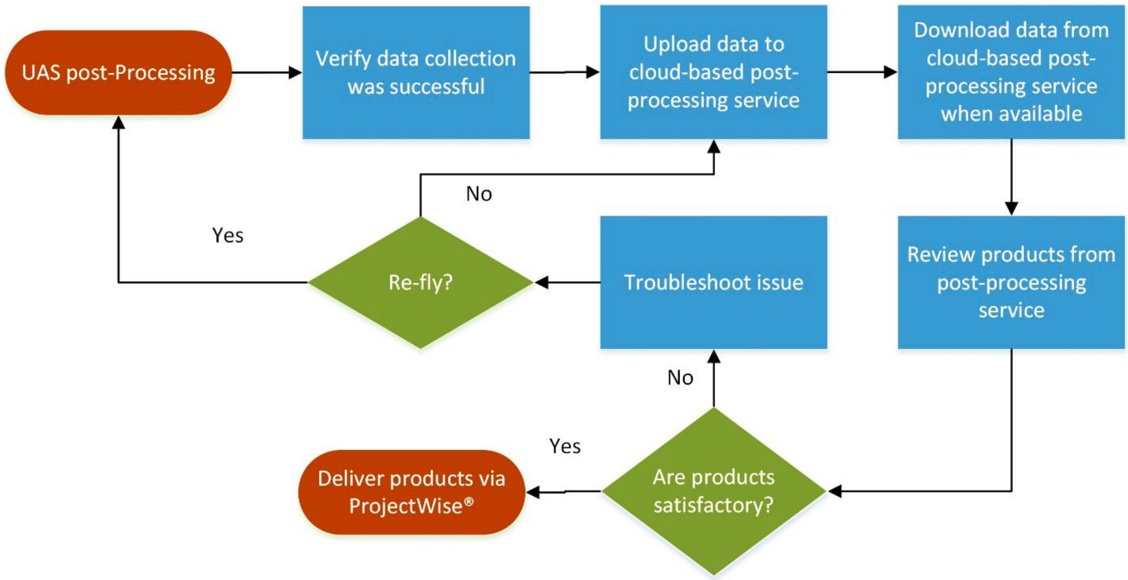


Figure 4.1.1.9. Flowchart. Workflow to post-process data collected by sUAS. Source: FHWA

Final Products Delivered	**Format Delivered**
Point clouds of interim and final surfaces	LAS
Final 3D models (as-built conditions)	3D PDF, InRoads DTM, MicroStation CAD drawing

Table 4.1.1.1. Final deliverables from data collection using sUAS.

Conclusions and Recommendations

The use of UAS and GNSS technology for construction engineering and inspection has resulted in a positive ROI for UDOT. It is important to note that UDOT introduced a new pay item for construction survey never used before for construction projects, thus the real benefits realized for using this technology are potentially much greater. The benefits realized by UDOT's use of geospatial technology are far greater than those documented in this case study.

Lessons Learned and Future Direction

The following challenges were encountered during construction inspection:

- The proprietary nature of the software programs prevented the team from seamlessly transferring the models from design to construction; thus, requiring vendors, UDOT, and the contractor to work together to develop workarounds to make the process work.
- The design models were too complex for construction applications and had to be simplified to be consumed by downstream users (e.g., contractor and inspector).
- There was no guidance for conducting inspection tasks with geospatial technology$, which identified the need for updating specifications to be more in line with using modern technology and techniques.

RECOMMENDATION: We invite road administrations and relevant organizations to update asset inspection specifications with geospatial technology and include them in their guidelines in order to foster and ensure a proper use of UAS in construction and asset inspections. An UAS has an important potential to increase the efficiency of construction and asset inspections.

The level of development was not sufficiently accurate in certain areas of the model, which required addressing discrepancies between design and actual construction quantities.

Overall, the pilot project was considered a success. The collaboration among UDOT, the contractor, and vendors was a key success factor for this project. Other success factors included agency support for taking risks, the availability of technical resources, and buy-in from the construction staff. The project was completed nearly 25 days ahead of schedule, which was attributed to the use of intelligent design and construction methods that rely on geospatial technology.

UDOT plans to implement intelligent design and construction methods and use geospatial tools on other highway construction projects as well as investigate the use of these technologies in asset management applications, specifically bridge inspection and maintenance.

Benefits and Costs

Estimates for both benefits and costs were provided by UDOT based on their knowledge of the use of GNSS rovers for real-time verification and sUAS data collection, post-processing workflows, and the efficiencies of using digital data during construction. It is difficult to isolate the use of one geospatial tool as the indicator for all the benefits gathered during this case study given the combined use of geospatial technologies used during this pilot project that resulted in the overall benefits. Additionally, it is important to note that UDOT purchased multiple sUAS for the purpose of testing numerous projects and applications. While this investment was not tied directly to the SR20 project, the BCA shows that technology was purchased and tested as part of UDOT's pre-implementation planning efforts. The technology is relatively inexpensive compared to the numerous applications and benefits that can be realized.

Overall saving for this project was $82,672 (2.58%) as reported in this case study by Utah DOT. Table 4.1.1.2 shows the cost for using UAS and GNSS rovers in this case study.

Table 4.1.1.2 Costs for using sUAS and GNSS rovers in UDOT's SR20 project.

Costs	**Measure**	**Data Needed**	**Data Input**	**Confidence Score**	**Comments**
UAS- Albris SenseFly	Dollars	One-time cost	$34,990	1	UAS (three-year replacement cycle)
UAS- DGI Phantom 4	Dollars	One-time cost	$2,500	1	UDOT has plans to procure more devices in the future. Intended use: photogrammetric surveys.
UAS- 3DR Solo	Dollars	One-time cost	$2,000	1	Additional antennas will be purchased to fix range of live video feed limitation.
Training (all-inclusive)	Dollars	One-time cost	$4,000	1	None
1-year product support (UAS)	Dollars	Annual cost	$1,500	1	None
UAS spare parts and labor warranty	Dollars	Annual cost	$979	1	None
Pix4D Mapper Pro	Dollars	One-time cost	$4,990	1	Software for UAS
Software annual maintenance	Dollars	Annual cost	$0	1	Chose not to purchase now; upgrades are additional costs, which are unknown
Survey contract pay item	Dollars	Contract bid cost	$62,000	2	Contractor provides 3D as-built surfaces and GNSS rovers for inspection
Technical support staff	FTE	Loaded rate/hr.	$48	1	Dedicated staff for technical support of geospatial technologies $30/hour. Loaded rate = 1.6 x $30

1.3.4. Case Study 2: Evaluating the Use of Unmanned Aerial Vehicles for Bridge Inspection

Note: This case study only focuses the lab test are not discussed in this report, refer to actual report for more details.

Reference: Author(s) C.Brooks, R.Dobson, D.Banach, D. Dean, T.Oommen, R.Wolf, T. Havens, T. Ahlborn, B.Hart; "Evaluating the Use of Unmanned Aerial Vehicles for Transportation Purposes".

Introduction

The final work plan for this project stated that advancements in remote sensing technology using an UAS would provide "the opportunity to take this technology to the next level by providing ready, rapidly deployable access in locations that are potentially challenging to inspect at higher resolutions than current methods are capable of." The main hypothesis was that these remote sensing techniques can provide objective non-destructive testing of critical components of transportation infrastructure. The objectives and resulting scope of the study were defined in the work plan as:

Develop, test, and demonstrate how UAS technology can help provide visual inspections from above for a variety of structures and locations of interest to Michigan Department of Transportation (MDOT), such as pump stations, roadway assets, and entrances to sewers and culverts.

Investigate non-destructive evaluation techniques using remote sensors on a UAS platform to evaluate the surface and structural integrity of bridge elements, including using thermal infrared and 3-D optical non-destructive evaluation (NDE) methods.

Provide a review of the current state-of-the-practice with a focus on practical UAS deployments by other transportation agencies including through up-to-date academic research projects.

Provide recommendations and an implementation plan on utilizing the UAS technology for MDOT infrastructure inspections and asset management data collection.

UAS Platforms – Technology Overview

The following sections describe the various aerial platforms used to accomplish the project research tasks and are included to give a detailed overview of their characteristics. The following table (4.1.2.1) provides a summary of these details, organized by platform (rows) and sensors (columns), with a description of the MDOT job function they can support, based on this project's study results.

Platform/ Sensor	Sensor Nikon	Camera Hokuyo UTM-30LX-EW LiDAR	Tau 2 FLIR thermal camera	Integrated Camera	D800 GoPro camera	Samsung 4G Camera
Bergen Hexacopter	Bridge Deck Inspection through 3D modeling	Roadway assets	Delamination detection			
DJI Phantom Vision 2				Bridge structure imaging, construction site monitoring		
Blackout Mini H Quadcopter				Bridge structure imaging, Confined space assessment, Culvert Inspection		

Table 4.1.2.1: Comparison table displaying platforms with which sensors they carry and the MDOT job functions they can support, based on study results.

Application / Methodology

Optical (i.e. visible) imagery use for NDE applications pertaining to bridge decks has been the focus of previous funding from the United States Department of Transportation (US DOT) Office of the Assistant Secretary for Research and Technology (OST-R) (formerly the Research and Innovative Technology Administration, RITA). Using the principles of photogrammetry, the project team successfully inspected bridge elements and calculated bridge distress quantities (e.g. percent spall and crack width). The project team's use of 3-D optics/photogrammetry was a technology demonstration to apply a potentially low-cost remote sensing method not typically yet seen in transportation applications. At the distance used in these previous projects, the deployment can be described as an implementation of close range photogrammetry (Luhmann et al. 2007). As compared to the standard methodology of measuring and mapping bridge distresses, which include hammer sounding or chain drag techniques and closure of the bridge for inspector safety, the remote sensing technologies and platforms provided faster data collection, without the necessity of closing the bridge.

For the purposes of this analysis, similar sensors were used to analyze bridge elements of two separate bridges in Livonia, Michigan, but operated from a UAS for wider-area data collection. The optical camera placed on the Bergen hexacopter was a 36 megapixel Nikon D800 camera. The optical system is being evaluated to create sub-centimeter 3-D models of bridge decks to help locate problems such as spalls (potholes). Optical imagery area reconstructed in Agisoft PhotoScan and processed to produce a DEM.

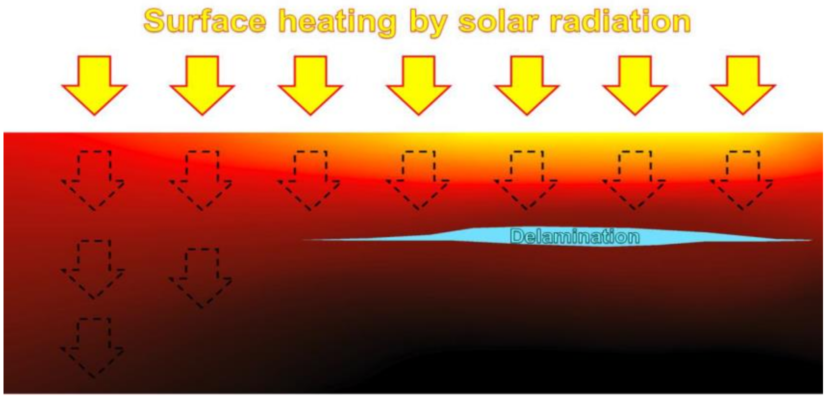
Applications of thermal remote sensing to monitor concrete surfaces are mainly aimed to detect anomalies associated to delamination and similar structural defects (Maser and Roddis 1990; Washer et al. 2009 and 2010; ASTM 2007; and ACI 2001). Detection of such defects, e.g. delamination, can help infrastructure inspectors to identify damaged areas before they develop from delamination into spalls (Ahlborn et al. 2012). The basic idea behind such approach is that the concrete surface changes temperature due to changes in the environmental conditions, either due to natural variation, e.g. the diurnal temperature and insolation changes, or due to artificial heat sources, e.g. heaters deployed for testing purposes.

The temperature changes affect differently areas with defects (e.g. delamination) from intact areas, resulting in temperature differences that can be detected with the thermal remote sensing methods. The areas with defects can be inferred and mapped from the radiance or temperature differences, even if they would otherwise (e.g. via visual inspection) not be noticed.

The spatial distribution of temperatures can be analyzed as a raw radiance map produce by the thermal remote sensing instrument, or it can be further processed to obtain a calibrated surface temperature map; for most purposes a raw radiance map will suffice, as the main goal is to see relative differences in temperature, which will be revealed by either the radiance or true temperature image. Thermal remote sensing instruments usually consist of an array of thermal sensor similar to the CCD or CMOS sensor used in common photographic or video cameras, but sensitive to the thermal infrared part of the spectrum. Such thermal cameras produce digital images of the surface being monitored, with each pixel of the image representing a radiance or a temperature.

The temperature and associated radiance differences seen in a thermal image arise from the way heat is transferred in and out of the concrete surface, following the fundamental laws of thermodynamics. A concrete surface at a different temperature than the surrounding environment will tend to equilibrate with that environments temperature; if the concrete surface is at a lower temperature than the ambient air (e.g. during the morning as the air is quickly heated by solar radiation), it will start to heat up, raising its temperature in a tendency to equilibrate thermally with the environment. Conversely, if the concrete surface is at a higher temperature than the ambient air (e.g. after sunset as the air quickly cools down), it will start to cool down, lowering its temperature again in a tendency to equilibrate thermally with the environment. In the case just discussed the thermal energy is being transferred by conduction with the air in contact with the concrete (and by convection of the air), but an analogous situation can be considered for the case of thermal energy being transferred by radiation of electromagnetic energy. A surface being exposed to electromagnetic radiation will absorb part of that radiation (e.g. by the direct exposure to solar radiation), increasing its temperature, but it will also radiate energy according to the principles discussed in the previous section, losing energy and tending to cool down (e.g. after sunset). The balance between incident and radiated energy, and the thermal exchange with the surrounding air will determine whether the surface will tend to heat or cool down.

Structural defects and imperfections alter the heat transfer patters (Maldague, 1993; Starnes, 2002; Washer, 2009). A delamination, which is basically a void in the concrete filled either with air or water, will conduct heat differently from the rest of the concrete structure. As the concrete temperature increases from the surface inwards (e.g. after sunrise), a delamination will act as a barrier slowing down heat transfer into the deeper parts of the concrete structure, this slowdown in heat transfer will result in an increase of the temperature of the concrete above the delamination. This is illustrated in Figure 4.1.2.1, where the area above the delamination



accumulates the heat that cannot be transferred to the deeper parts of the concrete body, resulting in a higher surface temperature.

Figure 4.1.2.1: Cross section illustration of heat flow through solid (left side) and delaminated (right) concrete. For a concrete body heated from its surface (e.g. through solar radiation) the heat flow will start to move away from the surface and through the body's interior. In the presence of a delamination the heat flow is interrupted or slowed down, leading to an increase of temperature right above the delamination.

When applied to concrete surfaces, the principles of thermal remote sensing follows the discussion from the previous section, and the values of the concrete emissivity and atmospheric absorption become critical in calculating radiance, temperature, and emissive power. Thermal remote sensing instruments usually work in the "thermal infrared atmospheric windows", where the absorption is minimal, and can be modeled by taking into account and modeling the absorption of the most critical gases present in the atmosphere (e.g. water vapor). The absorption will depend on the amount of atmosphere (and therefore absorbing gases) between the emitting surface and the sensor: the longer the distance the stronger the absorption, applying the remote sensing technique over longer distances produces higher absorption and lower quality data. Working in high humidity environments also reduces the data quality, and obviously the quality and even feasibility of obtaining data depends as well on the presence of other potential atmospheric blocking conditions (e.g. fog, dust, smoke, etc.). On-site applications of thermal monitoring to concrete surfaces are usually affected only little by atmospheric absorption if atmospheric conditions are good, due to the short distance (usually from meters to tens of meters) between the concrete surface and monitoring instrument, and these effects are often taken into account when calculating the emitted radiance from the surface. Longer distance applications of the thermal monitoring methods may face more challenges in that respect.

Practical applications of thermal remote sensing include both passive and active heat sources (Alqennah, 2000). Passive thermal remote sensing uses natural heat source, mainly solar heating, whereas active methods use artificial sources, like heat lamps and other heating devices. In both cases it is necessary to have variations of the heating over time to allow for differences in heat transfer to highlight the anomalies (e.g. associated to delamination); in the passive case the diurnal variation associated to insolation (from sunrise to sunset) provides that temperature change, and in the active case it depends on the time and mode of exposure to the heat source.

Asphalt and concrete pavement emissivity is usually assumed to be high (> 0.9), but this value can vary depending on the specific properties of the asphalt or concrete surface (e.g. how rough or smooth it is). More importantly from a practical standpoint is the possibility that other substances covering the concrete can dramatically change the surface emissivity, leading to very large differences in the calculated temperature (e.g. Clark et al. 2003). Although it may have an important impact on temperature measurements, emissivity may not be a critical variable in some cases where only relative differences of temperature (and therefore of radiance) are important, as long as the whole surface being measured has the same emissivity. Also important are other environmental variables that also control the heat transfer, like wind speed, which enhances convective and advective heat transfer (Washer et al. 2009; ASTM 2007).

Besides the characteristics of the concrete, surface material covering the concrete, and atmosphere, it is also important to consider the conditions of the potential defects that are attempted to be detected by the monitoring. The substance filling a delamination can have a large effect on heat transfer and therefore on potential detectability by thermal remotes sensing; for instance water will conduct heat much better than air (even at a similar rate than concrete), and therefore a water filled delamination may be much harder to detect by thermal methods (Maser and Roddis, 1990). The depth and width of the delamination also play a key role in how heat is transferred to the surface, with deeper and thinner delamination being harder to detect (Alqennah, 2000; Vaghefi et al. 2013). Finally, for passive thermal remote sensing the time of the day when the monitoring is done, and the relationship to the insolation (the amount of solar radiation received by the surface) are also important. For instance, the highest thermal contrast will be achieved at different times for delamination at different depths, with deeper delamination taking as much seven hours to achieve maximum contrast (Washer et al. 2009).

Thermal remote sensing is seen as advantageous because it is a relatively fast and undisruptive monitoring technique that translates in shorter inspection and lane closure times (Maser and Roddis, 1990). The digital format of the thermal remote sensing instruments output allows to easily combine and integrate the monitoring information with other data platforms, including standard GIS software packages, allowing to store the monitoring data in a georeferenced database (Ahlborn et al. 2012).

In order to conduct tests of UAS systems and technologies, example study bridges near southeast Michigan were searched for. In-the-field test flights of any UAS system are currently best conducted where public interaction and disruption can be kept minimal, and where safety can be maximized. The ideal location and bridge will include a site with minimal traffic on the bridge and the surroundings, and minimal to complete absence of nearby overhead electrical wiring or obstacles. Through coordination with MDOT and with project team members’ firsthand knowledge of the construction project and area, example study bridges, which were included in the I-96 Fix 37 bridge group scheduled for either repair or complete replacement, were selected for field data collections. Two overpass bridges in Livonia, Merriman (East U-turn) (Structure: 11515) (Figure 4.1.2.2) and Stark roads (Structure: 11491) (Figure 4.1.2.3) were selected for further analysis due to the fact that both bridges showed signs of significant distress (i.e. spalling and cracking), reconstruction efforts had not started on either bridge, and traffic below each bridge was limited to construction equipment. Additionally, MDOT Engineer Sean Kerley was successfully able to coordinate short-

term traffic closures on these bridges. Therefore, all of the desired conditions were met and UAS

data collections were able to be conducted.

Figure 4.1.2.2: Merriman East U-turn Bridge selected for a UAS assessment.
Figure 4.1.2.3: Stark Road Bridge selected for UAS assessment.

Results / Integration / Analysis

On June 6, 2014, the Merriman East U-turn Bridge was assessed. During this assessment, multiple types of technologies and UASs were used to detect different types of distress features (i.e. spalls and delaminations) on the bridge deck and underneath the bridge, and to better understand the condition of the bridge. The optical system, which uses an off-the-shelf digital single-lens reflex Nikon D800 camera system, was flown over the bridge and collected overlapping imagery at a frame rate of two images per second (Figure 4.1.2.4). The collected optical imagery was placed into a three-dimensional imagery reconstruction program, Agisoft Photoscan, to create sub-centimeter 3-D models of the bridge deck to help locate distress features such as spalls (potholes). The merged product is a high-resolution (2.5 millimeters or 1/10 inch resolution) orthorectified image, with visible spalls and patchwork. Additionally, a bridge deck 3D surface model (i.e., DEM) was also produced by Agisoft Photoscan and was used for the spall algorithm. The DEM is processed through the spall algorithm to detect minor (defined) differences in elevation, which was created to automatically detect and quantify the amount of spalling on the bridge deck. For the Merriman East U-turn Bridge, it was determined that a total area of 150.0 square feet of the bridge deck was spalled, which equates to 4.4 percent (Figure 4.1.2.5). The algorithm does not detect all of the patching on the bridge's surface, resulting in a lower spalled area than if this was included – but as patched areas are not usually included in spalling amounts, this is the correct result. Lastly, the DEM also aided in the creation of a hillshade image, or a surface with a 3-D "look" familiar to most people.

This creates a visual height difference output that aids in quick differentiation between the bridge

deck and spalls.

Figure 4.1.2.4: High-resolution image of Merriman Road East U-turn Bridge.

Figure 4.1.2.5: Automatically detected spalls on the Merriman Road East U-turn Bridge. These totaled 150.0 square feet of the bridge deck, or 4.4 percent of the total deck area.

On June 9, 2014, the bridge on Stark Road was assessed. This test incorporated the same UAS platforms, sensors, technologies, and methodologies as used during field tests conducted at the Merriman Road location except the LiDAR sensor was not flown during this assessment. After processing the collected optical imagery in Agisoft Photoscan, a high-resolution orthorectified image was produced, with clearly visible spalls and patchwork. Lastly, the DEM also aided in the creation of a hillshade image. This created a visual height difference output that aids in quick differentiation between the bridge deck and spalls.

The Tau2 plus ThermalCapture camera was mounted on the UAS, pointing in a nadir (vertical downward) direction, and flown over the bridge deck at an elevation of ~ 10 meters (33 feet) above the bridge level. This produced images with a ground pixel sizes between 1.3 and 1.4 centimeter (1/2 inch), and a total area coverage per image of ~ 3.3 x 4.7 meter (11 feetx 15 feet). The UAS flew back and forth at that elevation, along the orientation of the bridge, several times in an attempt to acquire a fully overlapping thermal imagery set of the bridge deck. Images in the native ThermalCapture 14 bit binary format were converted to standard 16 bit TIFF (tagged image file format) images and stored for further processing.

The high resolution and georeferenced orthophotography was used as the base layer to georeference the individual thermal image frames, captured by the Tau2 camera during the UAS flight. Georeferencing of the thermal images was done in ArcGIS, using reflective duct tape marks located on the bridge deck for that purpose. This enabled the thermal data to be laid directly on top of the optical bridge photos, enhancing image interpretation and usefulness of the data. The reflective tape marks are easily distinguishable in both the visible and the thermal images, and therefore can be used as tie-points between both datasets. Other distinctive and naturally occurring features that could be identified in both datasets were used in addition as tie-points for the georeferencing process.

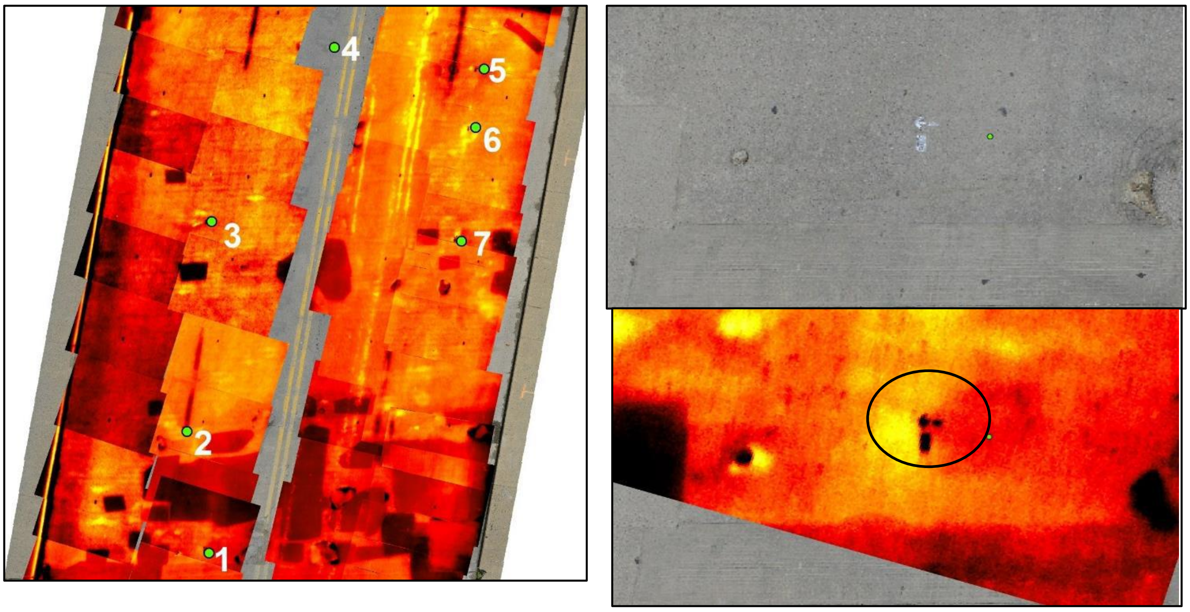


Figure 4.1.2.6: Delamination areas that were confirmed in the field through hammer sounding tests.

A View of the delamination locations (green dots) with their respective number labeled in white. B and C show a close-up view of delamination area 1, in the visible and thermal bands, respectively. Notice the absence of any noticeable signs of the delamination in the visible band (B), in contrast to the clearly visible area of higher temperature shown in the thermal band (C), and indicated by the blue circle.

The thermal imagery shows the complex and patchy structure of the bridge deck surface, caused in part by the many patches of repaired pavement and by pot holes and other surface discontinuities. Differences in patching material are reflected as differences in radiance values at the sensor, and although some may correspond to actual differences in temperature (some materials will absorb more radiation and heat up more by the solar radiation), some of the differences are likely to be mainly due to differences in the surface emissivity (e.g. Jensen, 2007). This complexity provides a challenging testing ground for the delamination classification methods, as will be explored further.

In addition to the remotely sensed data collection at the field sites, a series of seven hammer soundings were also performed over delamination areas at the Stark Rd bridge deck (see Figure 4.1.2.6).

Potential delamination sites were first spotted using the handheld FLIR ® SC 640 thermal camera, and were later tested with a hammer to confirm the presence of delamination. The approximate extent of the delamination was directly marked on the concrete. Other than the abnormally high thermal signals and the hollow sound produced by the hammer soundings, the seven areas did not show any visible signs of delamination, and would otherwise remained unnoticed. Of the seven areas with delamination confirmed with the hammer soundings, six were covered by thermal imagery acquired from the UAS platform. The georeferencing process was further refined for thermal images covering these areas, as these images were selected for further and more in depth analysis, described in detail in the following section.

The added complexity of the bridge deck surface, with a wide range of temperature and emissivity variations and combinations, presents a realistic challenge for any delamination mapping algorithm based on thermal remote sensing. Ideally we would test the performance of the thermal remote sensing method by comparing it to another independent delamination mapping method (e.g. hammer sounding or chain dragging). The extent of our hammer soundings is limited to only a few sites, preventing us to do a full quantitative evaluation of classification algorithm similar to what was done with the lab data. However we can still compare the performance of automatic mapping and classification algorithms described in the previous section, with the visual inspection method. Moreover, we can calibrate the visual observation method with the delamination identification done through hammer soundings.

Taking the areas mapped with the visual inspection methods as our reference, we can test how well the automated method (sliding window with local percentile threshold) reproduces what we generated by hand. ROC curves and related parameters were calculated for the six test areas, resulting in very similar classifications (see Table 4.1.2.2). The areas for these tests were chosen because of the available hammer soundings, but they are relatively simple, and this may explain in part the very good correlation between both methods.

Point	AUC	FPR50	TPR50	Acc50	FPR90	TPR90	Acc90
1	0.97	0.39	0.99	0.62	0.03	0.79	0.97
2	0.96	0.40	1.00	0.61	0.04	0.68	0.95
3	0.98	0.40	1.00	0.60	0.05	0.91	0.95
5	0.98	0.45	1.00	0.55	0.06	0.97	0.94
6	0.97	0.45	1.00	0.55	0.04	0.79	0.95
7	0.96	0.43	0.99	0.58	0.05	0.82	0.95

Table 4.1.2.2: ROC curve parameters for the test site delamination points. AUC is the area under the ROC curve. FPR50, TPR50 and Accu50 are the false positive rate, true positive rate, and overall accuracy at a threshold of 50th percentile. FPR90, TPR90 and Accu90 are the false positive rate, true positive rate, and overall accuracy at a threshold of 90th percentile. Note that these ROC curves only compare the local percentile threshold with visual inspection methods, the latter being used as the "true" reference.

All the study cases presented so far have only dealt with thermal imagery as the input for the delamination classification and mapping, but as mentioned previously in this section, high resolution photography in the visible range is available in a spatially co-registered format for the same areas covered by the thermal imagery. The information contained in this visible imagery can be used for the classification process as well, besides its use for georeferencing.

Visible imagery was collected from the same UAS platform using the Nikon D800 camera. The sensor array on the camera responds to electromagnetic radiation in the visible (red through blue) part of the spectrum. Three different spectra are separated by a filtering system during image acquisition, resulting in separate pixel arrays for red, green and blue (RGB) color bands. Each band is recorded and stored in the camera files system in a single, eight bit, three band .jpg file. The RGB bands can be read separately from this file and used in multiband analysis. However, the materials commonly used in bridge deck surface , and roads in general, tend to be gray colored, ranging from very dark (almost black) asphalt, to very light (almost white) concrete. This color range is influenced by the ambient lighting and camera aperture conditions at the time of the data acquisition, but tends to be close to the gray tones of the surface material. The tendency to record the gray colors of the bridge deck surface is reflected as a high correlation of the RGB color values across the three bands for each pixel position, varying mainly in the recorded intensity of the luminosity, from values near zero representing darker hues (closer to black), to values near saturation (255 counts in the eight bit digital image), representing the lighter and brighter tones (closer to white). This high correlation of the RGB bands can be appreciated in the value distribution plots shown in Figure 4.1.2.7.

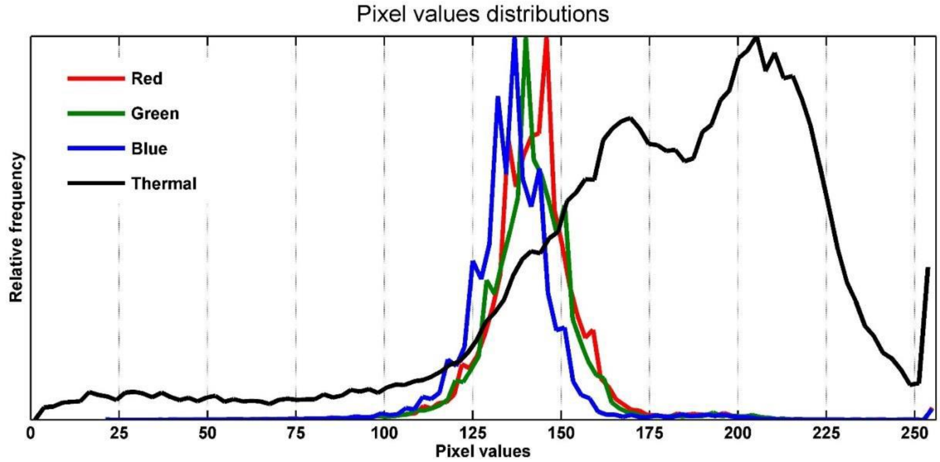


Figure 4.1.2.7: Distribution of pixel values for an eight bit multiband image of the bridge deck surface. Visible bans (red, green, and blue) are all grouped in a relatively narrow and coinciding band, corresponding to gray tones, while the thermal band values are extended over a broader and not very correlated range.

From the perspective of the multispectral analysis, the high correlation between the RGB bands implies a high redundancy of the data, such that each additional band provides little extra information. Standard multiband analysis, like principal component analysis (e.g. Jensen, 2007) would therefore benefit little from those extra bands. From a practical perspective only one of the visible bands could be used, discarding the other two, or the three bands could be combined (e.g. via a pixel-by-pixel averaging) into a single merged band. This last option is the one we implemented in our analysis, leaving us with two usable bands, the thermal IR and the combined visible (averaged RGB) bands.

Delaminations underneath the concrete surface usually do not produce visible signs at the surface. For that reason, the visible band will be of little help in trying to detect actual delaminations; instead, the value of the information contained in the visual band is in minimizing false positives. False positives in our case correspond to pixels that are classified under the category of "delamination", when in reality they are not. In a thresholding algorithm method like the one we use, the classification of a pixel in the delamination category happens when the pixel is above some level of radiance with respect to its neighbors, as explained in the previous section. However, the assumption behind this criterion is that those higher radiance areas correspond to hotter regions on the concrete surface, caused by the presence of sub-surface delaminations (as also explained in the previous section). In reality there may be other reasons for pixels on the surface to show higher radiances than the surrounding background.

Differences in the surface emissivity due to changes in the material (e.g. patches of different concrete or even asphalt) can lead to large changes in the recorded radiance, which translate in changes in the apparent brightness temperature (calculated assuming a constant emissivity). The changes in apparent brightness temperature can be caused by a change in surface emissivity (without an actual change in the surface kinetic temperature), a change in the temperature associated to the change in surface emissivity (because the surface will absorb more of the incident radiation and heat up), or in general, because of a combination of both.

In either case, this effect can mislead the algorithm into classifying areas where the surface material changes, into the delamination category, without real evidence for such a classification. However, such surface changes may easily be identified in the visible bands. In addition presence of foreign material (e.g. paint, shades, and leaves) on the bridge deck would produce thermal anomalies that are similar to delaminations (Del Grande 1996). This sets the rational for using the visible band to control for false positives: areas that show up as hotter than the surrounding background are first checked to see if they are significantly different to the background also in the visible, e.g. areas with a different surface appearance in the visible band.

If an area shows up as a thermal anomaly, but not as significantly different in the visible band, it is classified as a delamination; as there is no evidence for surface changes that could explain the apparent higher temperature. If an area shows up as a thermal anomaly, but the same area shows up as significantly different than the surrounding background in the visible band, it is not classified as a delamination; as the change in apparent surface temperature is likely caused by the change in the surface characteristics. Figure 4.1.2.8 shows the application of this algorithm to an area on the Stark Road test site, in this case changes in the surface material are the likely cause for what appears as a hot anomaly area in the thermal band, and could otherwise be mistaken for a delamination area.

Finally, after the application of any or a combination of the methods described in the last two sections, it is possible to classify and map all the delamination areas, within certain margins of error. Knowing the spatial characteristics of the images, particularly the ground pixel size, the calculation of the total delamination areas becomes straightforward. Figure 4.1.2.9 shows the application of such methods to one of the field test sites, the Stark Road Bridge. The total area of delaminations mapped through this method is 14.3 square meters (151 square feet) out of a total area covered by thermal imagery of 967.9 square meters (10,420 square feet) acquired over the bridge, resulting in a 1.5 percent of delamination area.

Figure 4.1.2.7 was generated applying also some additional post-processing techniques (e.g. low pass, adjacency connectedness, and minimum area filtering) that are not described in detail in this report. This highlights the preliminary nature of our results and the need for more research to test more extensively and refine the methods that we presented here.

Conclusions and Recommendations

Based on the findings of this case study, UAS capable of taking images in thermal and visible band can be used for bridge inspection. The data showed bridge deck surface and subsurface condition issues using UAS-collected imagery. Together, these research efforts have shown that UASs can help with many transportation issues, helping with needed bridge element inspection data including identifying spalls with optical images and likely delaminations with thermal data.

The following recommendations from the author should be taken into consideration before evaluating the use of UAS for any project.

Exhaustive delamination probing and testing though other methods in a real field setting are necessary to further validate our techniques. With the exception of one post-processing technique (minimum area filtering) that was used in generating the results shown in Figure 4.1.2.9, all the methods explored and applied in project are “pixel based” and have the disadvantage of only marginally taking into account the spatial context (e.g. shape and size) of the mapped delaminations in the classification process. Methods based on feature recognition that use such a spatially contextual information may produce better results.

Although visible and thermal IR bands were combined to control for false positives in the classification process, other ways to integrate the different bands are also possible, especially if this can be extended to other datasets. One such datasets is the DEM produced from the close range photogrammetry that was conducted as part of the project; the elevation information, or probably more usefully, a surface roughness metric derived from it could also be used to characterize the surface properties and help in the classification process, similarly to what was done with the visible bands.

Comparisons with other sensors (e.g. larger pixel array Tau2) and improvements in the UAS platform interface, e.g. including a real-time thermal video feed to provide a first person view of the thermal sensor imagery as it's being captured, would also improve the navigation and in that way the coverage of images over the target, minimizing data gaps. Integrating GPS locations with the sensor would also simplify the data processing. These ideas are proposed for a follow up phase to this project.

RECOMMENDATION: UAS can be successfully used for concrete bridge inspection for identifying the concrete delaminations. There are some areas for improvement such as better thermal sensor that may produce better results should be used.

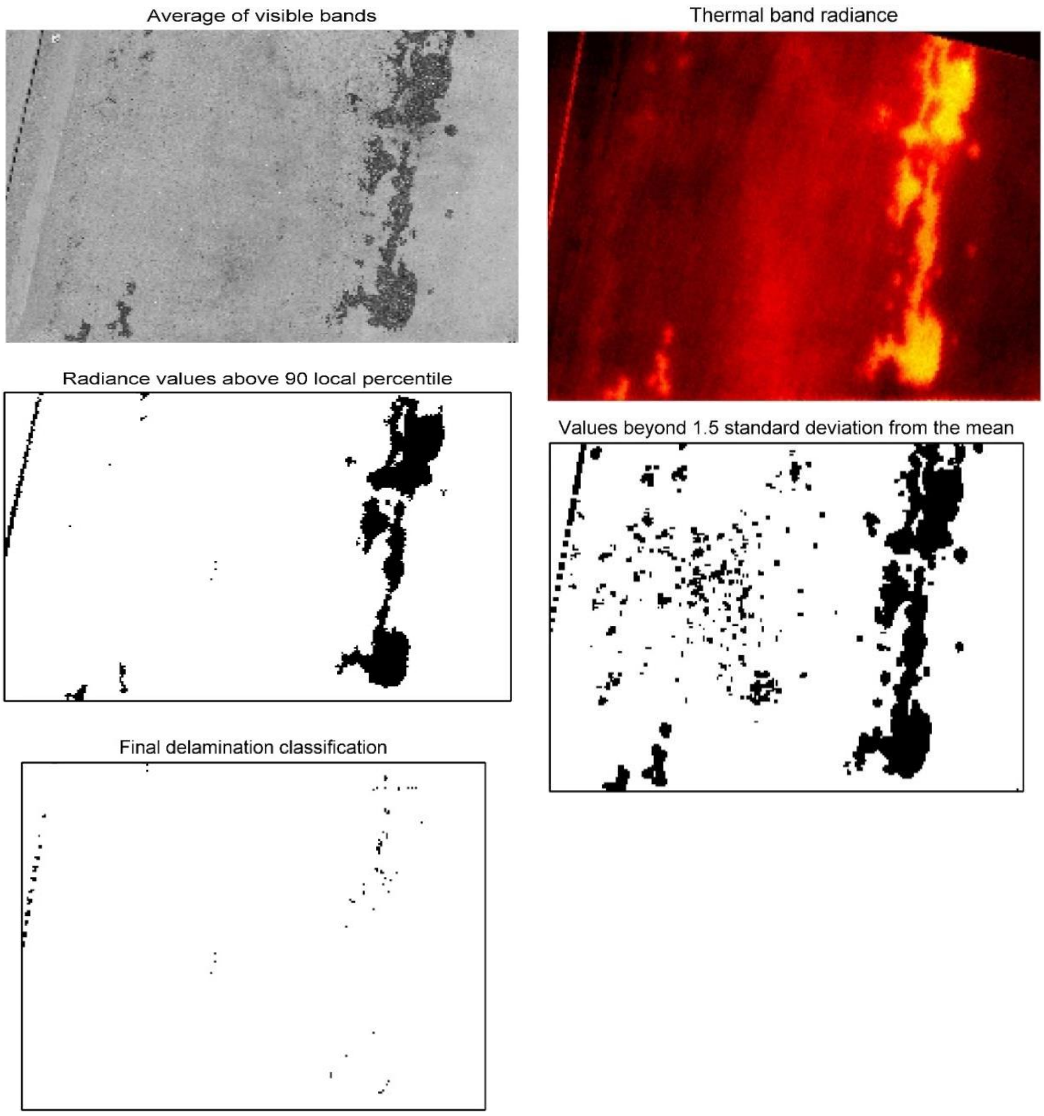


Figure 4.1.2.8: Combination of thermal (A) and visible (B) bands to control for false positives in the delamination classification and mapping process. Threshold classification of high temperature areas produces the map in C, but from inspecting the visible image (B) it becomes apparent that such areas show up as "hot" probably due to changes in the surface material. A map of pixels outside with values beyond 1.5 standard deviations from the local mean for the visible band is produced in D, and is used to control for the false positives: i. e. only pixels that show radiance values above the local background and do not deviate much from the local mean in the visible band are classified as delamination pixels in E. This virtually eliminates all the pixels that originally were classified as delamination pixels based only on the thermal band threshold information.

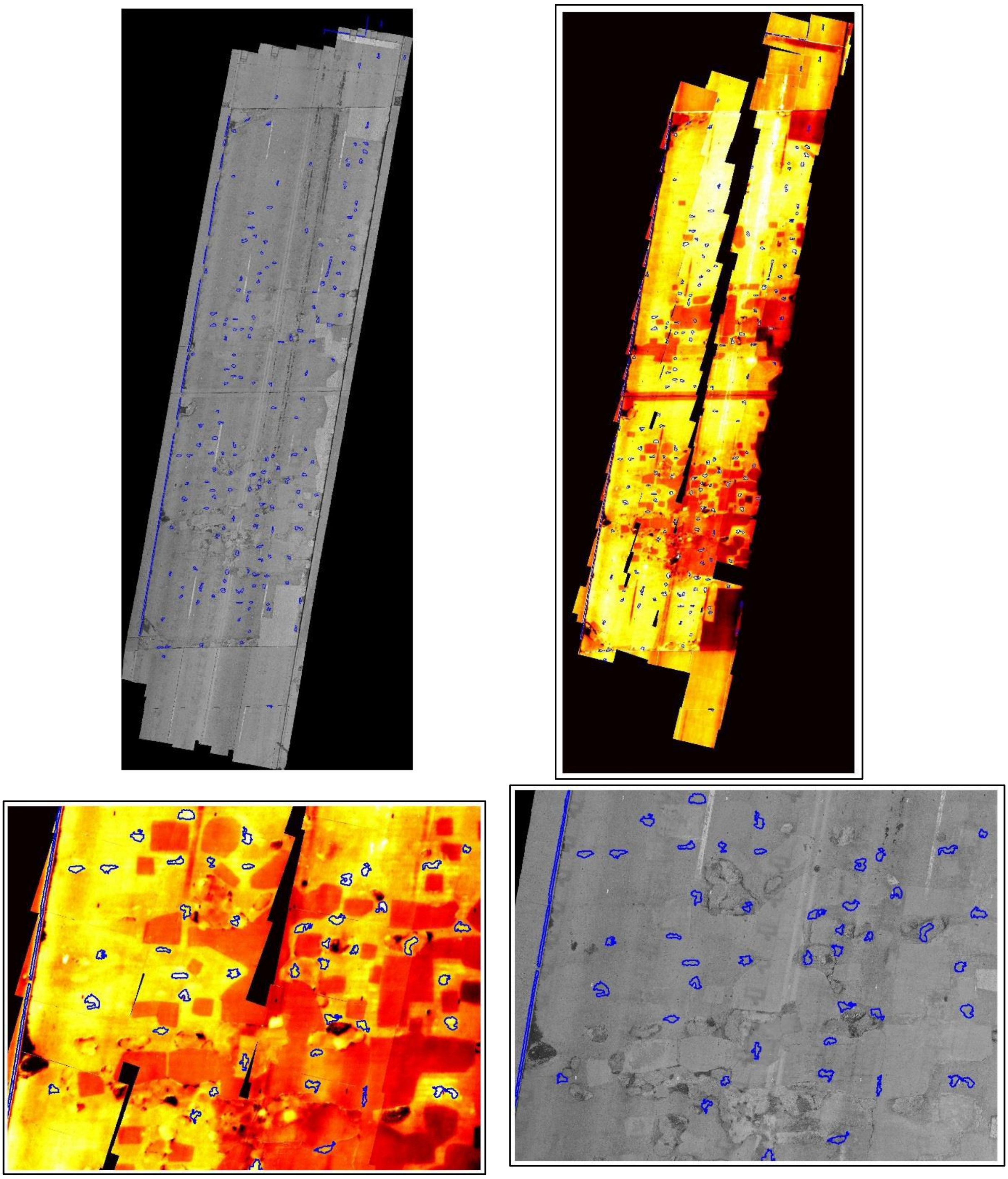


Figure 4.1.2.9: Overview of the entire bridge-deck in the visible (A) and thermal (B) bands, with delamination areas shown by the blue polygons. A close-up view of a section of the deck is also presented in C (visible) and D (thermal), with delamination areas also shown by the blue polygons.

1.3.5. Bridge Component Inspection Using UAS

Reference: Author(s) Jennifer Zink, Barritt Lovelace; "Unmanned Aerial Vehicle Bridge Inspection Demonstration Project", http://www.lrrb.org/pdf/201540.pdf

Introduction

This demonstration project involved using UAV technology to view four bridges at various locations throughout Minnesota. The project investigated the technology's effectiveness as compared to other access methods, for improving inspections, and use as a tool for interim and special inspections. Current and proposed Federal Aviation Administration (FAA) rules were investigated to determine how they relate to bridge safety inspection use. Different UAV technologies were investigated to evaluate current and future capabilities as they relate to bridge inspection.

Four bridges of varying sizes and types were selected throughout Minnesota, and the bridges were studied using a UAV after a detailed field work plan was prepared for each bridge. The plan addressed safety, FAA rules, and inspection methods. Several imaging devices were tested including still image, video and infrared cameras. Various data were collected in the field including still images, video, infrared images, site maps and 3D models of bridge elements.

Four bridges were selected based on the following factors:

- Cooperation of Local Agency
- Safety
- Varied bridge types and sizes
- Location
- Requirements of FAA

The following bridges were selected for the study after extensive coordination and evaluation:

1. Bridge 13509, Chisago County, MN – Prestressed Beam Bridge
2. Bridge 448, Oronoco, MN – Concrete Arch
3. Bridge 49553, Little Falls, MN - Pedestrian Steel Deck Truss
4. Arcola RR Bridge, Stillwater, MN – High Steel Arch Railroad Bridge

Note: Out of the above four bridges selected for study, only one bridge i.e. Arcola RR Bridge is mentioned in this particular case study. The readers are encouraged to refer to the original report, mentioned above.

Alternate: Bridge 6544, Duluth, MN – Oliver Bridge Steel Truss and Plate Girders

The Arcola Bridge is located north of downtown Stillwater, Minnesota and carries the CN Railway across the St. Croix River. The Arcola Railway Bridge was constructed in 1909, and is 2,682 feet long and located approximately 185 feet above the St. Croix River. The bridge consists of five truss arch spans each 350 feet long. There are seven steel bents on the west approach and four steel bents on the east approach.

Figure 4.1.3.1 Arcola Bridge Overall Map

Figure 4.1.3.2 Arcola Bridge Overall View

Application / Methodology

The bridge was accessed from the river by boat under the first arch span on the west side of the bridge. Each fascia of the arch span was flown from one end to the other to investigate the sides of the steel members. The bridge was also flown from the underside to investigate the substructures and the bottom of the steel members. The top of the bridge was be flown at a distance of 10 feet laterally from the track to meet CN requirements. CN Railway had a representative on site providing track clearance for the duration of the inspection.

The bridge was viewed with the use of UAV technology to determine its effectiveness as a tool for bridge safety inspection. A previous inspection report was not available at the time of inspection. Without a previous inspection report, this site provided an opportunity for a fresh perspective without prior knowledge of any defects.

The bridge accommodates railway train traffic, and the UAV was be flown in accordance with Unmanned Experts Operations Manual and the FAA Section 333 Exemption. Maritime traffic under the bridge was monitored in order to ensure the safety of the public. Spotters were used to communicate the presence of boaters to the operator to avoid conflicts.

The Arcola Bridge represented a large complex steel bridge in our study. This bridge is typically inspected using rope access because of the 185 foot height. The level of detail needed to detect defects was provided by the UAV. The elements that were traditionally difficult to access were readily visible using the UAV with very good detail. The zoom lens provided quality detail without having to position the UAV too close to the bridge. This bridge is an ideal candidate for a UAV technology when arm's length inspection is not required.

To view video of the Arcola Bridge Investigation visit the following link:

https://youtu.be/T5Y7On-yWWw

The figures below show the level of detail obtained from the UAV.

Figure 4.1.3.3 Photograph of Arcola Bridge Pin Detail Photo 1.

Figure 4.1.3.4 Photograph of Arcola Bridge Pin Detail. *Figure 4.1.3.5 Photograph of Arcola Bridge Pin Detail*

Figure 4.1.3.6 Close up Photograph of Arcola Bridge Pin Detail.

Three Dimensional Mapping

3D rendering of bridge components was explored using the UAV. Images were taken as the

UAV is flown around the bridge foundation. These images are then processed using software to create a 3D model of the foundation. This model is “coordinate correct” and contains a point cloud generated from the photographs and telemetry data. This feature can be enhanced with a variety of additional sensor if deflections or other movement needs to be monitored.

Figure 4.1.3.7 3D Orthographic Model of Bridge Foundation.

Conclusions and Recommendations

Based on our observations in the field and extensive literature research, the following conclusions were made:

RECOMMENDATION: Regarding the inspection of different component of existing assets such as bridges and other structures, it is stated that:

- UAVs can be used in the field during bridge inspections safely. Based on the UAVs size, weight, controllability and built-in fail safes, the risk to inspection personnel and public is very low.
- UAVs are more suitable as a tool for inspections of larger bridges, but there can also be some advantages for smaller bridge inspections. (i.e. short span bridges and culverts)
- UAVs themselves cannot perform inspections independently but can be used as a tool for bridge inspectors to view and assess bridge element conditions.
- Defects can be identified and viewed with a level of detail equivalent to a close-up photo.
- Measurements can be estimated from images, but tactile functions (e.g., cleaning, sounding, measuring, and testing) equivalent to a hands-on inspection cannot be replicated using UAVs.
- UAVs with the ability to direct cameras upward and the ability to fly without a GPS signal are important features when using this technology as an inspection tool.

- In some types of inspections, a UAV has the capabilities to be used in lieu of an under bridge inspection vehicle and would provide significant savings. These savings would come in the form of reduced or eliminated traffic control and reduced use of under bridge inspection vehicles and lifts.
- Infrared images of bridge decks and elements are already a common and accepted way to obtain information on concrete delaminations. UAVs can provide a very efficient way to collect infrared images of bridge decks and elements as they can be equipped with an infrared camera.
- Safety risks associated traffic control, working at height and in traffic could be minimized with the use of UAVs.
- UAVs can be utilized as an effective method to determine stream or river bank conditions upstream or downstream of the bridge as well as capture large overall aerial maps of dynamic bank erosion and lateral scour conditions.
- UAVs can provide important pre-inspection information for planning large-scale inspections. Information such as clearances, rope access anchor points and general conditions can easily be obtained with a UAV and would aid in the planning of an inspection.

Based on the information presented in this report, the following recommendations are made:

RECOMMENDATION: Regarding the use of UAS for bridge inspections, they should be considered as/for:

- The use of UAVs to aid bridge inspection should be considered as a tool to a qualified team Leader when a hands-on inspection is not required.
- The use of UAVs to aid bridge inspections should be considered for routine inspections to improve the quality of the inspection by obtaining information and detail that may not be readily obtained without expensive access methods. They should also be considered where they can increase safety for inspection personnel and the traveling public.

RECOMMENDATION: In order to further analyse the use of UAS for bridge inspection we should consider that due to the schedule and funding limitations of this project, an additional study phase could be considered. Topics for investigations in a future phase include:

- Cost comparison with Aerial Work Platforms and traffic control.
- Explore inspection-specific UAV technology.
- Compile a best practices document.
- Incorporate UAV technology into an actual inspection.
- Explore using UAV technology to perform culvert inspections which does not require FAA approval since culverts are an enclosed space.
- Explore using UAV technology to perform box girder inspections which does not require FAA approval since culverts are an enclosed space

1.3.6. An Automated Asphalt Pavement Inspection using UAS

Reference: Authors: H. Zakeri, Fereidoon Moghadas Nejad, Ahmad Fahimifar, Dep. of Civil and Environmental Engineering, Amirkabir University of Technology (AUT), Hafez Ave, Tehran, Iran; "Rahbin: A quadcopter unmanned aerial vehicle based on a systematic image processing approach toward an automated asphalt pavement inspection".

Introduction

Evaluation of pavement conditions is an essential mission in many road and transportation organizations. In the simplest method of detecting and classifying asphalt pavement cracking, the individual experts visually inspect and evaluate the pavement surface. This approach involves high labor costs and generates unreliable and inconsistent results [37]. In addition, it exposes inspectors to dangerous working conditions on highways. To collect high quality data in a consistent and uniform way, cost-effective automated systems and modified algorithms are proposed [36,37,80]. Most pavement cracking analyzer systems employ machine vision and image processing models to automate the process and minimize the problems involved [7,10,58,88,98–100]. However, due to irregularities of pavement surfaces, there has been limited success in accurately detecting cracks and classifying crack types. In addition, most systems require complex algorithms with high levels of computing power. Although many attempts have been made to automatically collect pavement crack data, more efficient approaches are required to evaluate these automated crack measurement systems [19,26,64,78,98–100,102]. Implementation costs, processing speed, repeatability, and accuracy are among the most important controlling factors in these systems [95].

In the present study, three primary contributions are made: First, a Quadcopter Unmanned Aerial Vehicle (QUAV) -based robot platform is implemented for inspection and image acquisition. Second, a set of new methods is developed for the adaptive thresholding and feature extraction. Third, a new form of the classifier is developed to extract some rules for distress classification. By the advent of UAV technology, further attention is paid to robotic inspection and automatic assessment of pavement surfaces, as they provide a faster, more sophisticated, and safer procedure. The proposed methodology for image interpretation will enable a more efficient distress detection and evaluation with the given classification rules.

The advantages of UAV systems are their low cost, fast speed, high maneuverability, and high safety for collecting images [67]. UAVs are already replaced over satellites and manned vehicles. Moreover, they overcome the low flexibility and high cost involved in applying aerial imagery. Compared to other existing UAV approaches, QUAV platforms have distinct advantages such as their low cost of manufacturing and maintenance, flexibility and maneuverability to work in very hard and complex surveying missions, the controllability in both autonomous and pilot mode, and manageability in abnormal stormy, windy, snowy, and rainy weather circumstances. The main objective of this work is to use a Quadcopter UAV instrument to capture pavement images.

Data acquisition system QUAV Specifications and Components

The automatic pavement inspection system developed in the present work is a quadcopter unmanned aerial vehicle (QUAV). The QUAV was selected because of its low cost and high flexibility to operate in very complicated missions. The hardware architecture of the system is shown in Figure 4.1.4.1. The developed quadcopter system, RAHBIN, is assembled with:

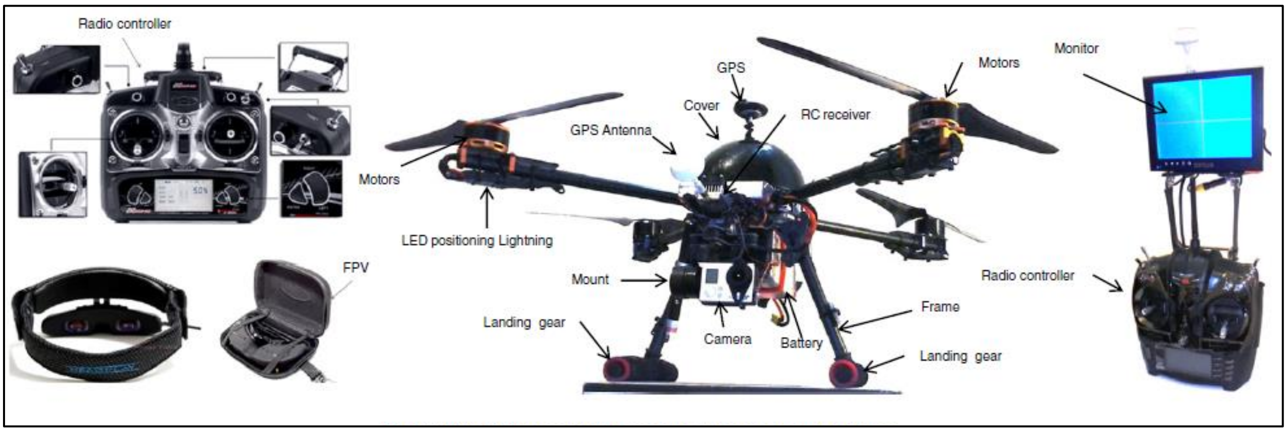


Figure 4.1.4.1 QUAV Platform used for the recording of pavement surface distress

- Four sets of Tarot 4114 320KV Out runner brushless motors,
- 4 sets of 40 Amp OPTO brushless motors,
- ESC speed controller,
- Carbon fiber quadcopter frame,
- Main controller,
- Power management unit (PMU),
- GPS,
- LED,
- Flight control,
- Telemetry system,
- GoPro 2Axis Brushless Gimbal
- All Multi-Rotor,
- Head track video goggles and LCD for monitoring,
- 5.8GHz 8CH FPV transmitter for sending data,
- AV receiver,
- LCD, and
- 2 sets of radio controllers.

The total size of this system is 100 cm in diameter. The QUAV is able to produce an absolute thrust of 3 kg. Its net (without battery and camera) and gross weights are 500 and 1000 g, respectively. The flight control system service both aided and programmed the flight mode.

An autopilot software (Grand Station NAZA-M V2) is utilized on the main computer system. The software GUI enables the user to define a mission plan according to the Google Map service and sets the height, speed, mission, and resolution of distress. Additionally, 3DMapDisplay, Real-time Flight Monitoring, One Key Takeoff, Joystick/Keyboard Mode, One Key Go Home, Click Go Mode, Waypoints Editing, Automatic Takeoff & Landing, F Channel Controller, General Purpose Servo Action, and Photogrammetry Tool can be used. The Gopro Camera has a wide range of resolutions

(5, 7, 12, and 14 MP). As the central part of the QUAV, the flight control unit (FCU) is able to apply autonomous inspection based on predefined scenarios. The inertial measurement unit (IMU) is used to identify the additional information data (such as alignment, acceleration, and altitude). The four brushless sets of motor controllers receive their orders from the FCU to adjust the rotational speed of the motors. The FCU is connected with a GPS receiver and a compass to increase navigational capabilities.

Due to its maneuverability, 'location hold', 'coming start point', and 'flight according to pre-identified waypoints', this system could be useful in many situations and positions dangerous for surveillance. An expert can generate the new waypoints based on the footprint of regions of interest.

For example, it can fly in circular, network, polyhedral, zigzag, curved, or other more complex patterns. QUAV also is able to stay in the air for 45 min and a distance of nearly 7 km at the speed of 4 m/s.

The QUAV used in this work is required to travel above 2000mand variable operating altitudes ranging from 1 to 100 m. The pavement surface information of the lane is collected and sent via a transmitter device to the host computer, where the proposed method for classification of pavement distress algorithms is implemented. The positioning information, indicating where the images are taken, was obtained from a global positioning system and saved. The existing similar systems have shown a good performance to collect new forms of pavement surface images.

A set of useful images is collected using the proposed instrument. This system is appropriate for an automatic remote sensing pavement surface with the adequate quality of systematic universal conditions evaluation.

Application / Methodology

In this study, distress images obtained from a QUAV instrument are investigated. The discrete wavelet transform (DWT) is applied to a set of pavement distress images after their preprocessing (enhancement), followed by applying the Radon transform (RT). Statistical and geometric features are extracted by applying a flexible threshold (a heuristic method) rather than a static or dynamic threshold for three-dimensional RT (3DRT). Overall, the structure of the proposed method consists of six steps in three stages:

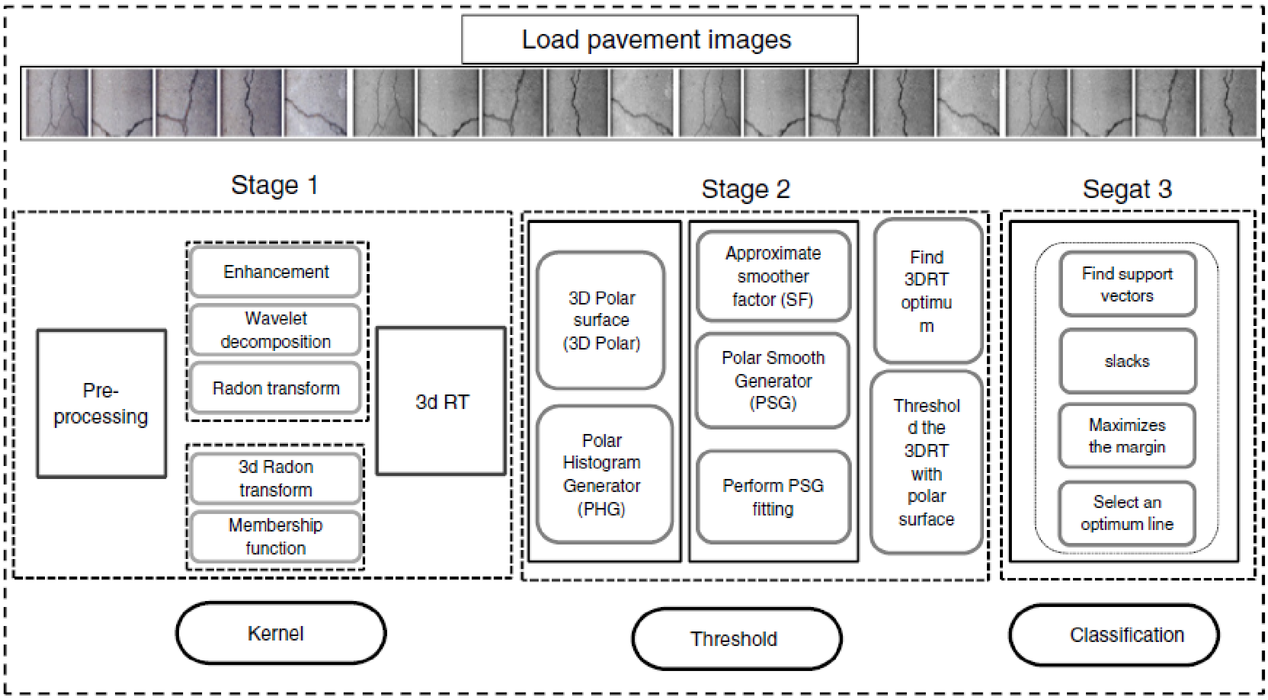
- Stage1 - image processing
    1) Image enhancement
    2) Wavelet decomposition
    3) 3DRT
- Stage2 - thresholding
    4) Threshold Selection,
- Stage3 - interpretation
    5) Polar Support Vector Machine (PSVM) to knowledge extraction
    6) Expert system for classification.

The test results show that the success rate is significantly improved when applying this method compared with the traditional methods.

Figure 4.1.4.2 shows the proposed Multi Stage System (MSS) block chart. It consists of three stages and six steps: Stage1 - image processing including (1) pre-processing: image enhancement, (2) decomposition: wavelet decomposition, and (3) transform: the 3DRT; Stage 2 - the threshold selection, (4) optimum surface generator: threshold selection; and Stage3- interpretation, (5) knowledge extraction: polar SVM to knowledge extraction and (6) the expert system for classification (Figure 4.1.4.2).

A mission strategy is arranged on the autopilot software (DJI Ground Station 4.0) to set the mission parameters. After a take-off, the QUAV hovered along the defined path with the steady state speed of around 5m/s and at a predefined elevation of 10m above the road surface, capturing images with the scale of around 100 and the crack resolution of approximately 1 mm. The behavior of Rahbin can be customized by programming its hover and information collection pattern from the pavement surface in real time.

Overall, the performance for the PSVM based on basic measures, Ratios of Ratios measures, and Additional Indexes was higher in almost all distress values, implying that the proposed method yields fair performance among the other methods. However, more extensive testing is required because of the uncertain effects of the spalling inside the edge of main cracking. Although this was not an exhaustive comparison of all classifiers, we used more Neutral Network (NN) and Support



Vector Machine (SVM) for the classification step. More notably, the PSVM and SVM confirm to be better than NN.

Figure 4.1.4.2 The block chart of the proposed developed method

Conclusions and Recommendations

The results showed the potentiality of QUAV as a device equipped with a set of automatic digital imaging systems for automated asphalt distress detection with a high precision. This system is possibly implemented in field conditions and can be developed in the network of roads as a surveillance agent robot.

Moreover, an MSS for QUAV image analysis is developed. The MSS is a new flexible method used to define a new kernel. This method consists of image processing, a threshold selection, and a classifier stage. The PSVM is introduced for classification and detection of pavement distress. A Mixture of Wavelet modulus and 3DPRTwere used for data generation. A novel segmentation method in the polar domain was proposed to handle the variable. The features and parameters of the peaks were finally employed to make the rules.

Results were compared with those of SVM and NN and it was detected that the method proposed in this work outperformed these methods in terms of detection and classification tasks.

The authors of this work showed that the PSVM method can be successfully applied to classify cracks and is capable of generating new features for cracking distress threshold selection and classification. In order to show the applicability and efficiency of the proposed system and the proposed method, a test was conducted with a variety of pavement distresses. The experiment results demonstrate that the applied system provides reliable results. The comparison of the derived information with the on-site manual quantifications revealed the potentiality of the QUAV and multi-stage system for future practices. Several parameters influencing performance of the main and basic measures of MSS were defined and discussed. The results demonstrated the improvement provided by this method compared to other ones.

As a result, the integrity of a QUAV together with the MSS would make this computer-aided procedure a reliable method to assess the pavement surface. The system would enable professional experts to work fast and safely, without the need for field visit. Although cracks are more complicated than other pavement distress, the focus of the present study is on the classification of Single Cracking (SC) and Multiple Cracking (MC). In future tasks, we would review the peripheral effects of other types of distress (e.g., spalling, etc.). Developing a new criterion and separating and combining the cracks and spalls are the objectives of our next work.

Finally, developing a new technique based on analyzing the severity and extent of cracks concerning the main and/or the secondary ones, would seem interesting enough for the further studies.

Following are the recommendations in terms of advantages and disadvantages of using an UAS compared to an Automatic Road Analyzer (ARAN) vehicle equipped to perform the asphalt pavement distress survey.

In Urban areas asphalt pavement distress survey using van will be safer and is a preferred method, although using a UAS will be more cost effective and faster but can pose a potential risk to public life and property. An UAS should be a preferred method for inspection in rural and less dense areas.

RECOMMENDATION: Advantages of using an UAS:

- Equipment Cost - UAS equipped with laser sensors, RTK GPS and high resolution camera is close to hundred thousand dollars compared to an ARAN vehicle that can cost few million dollars.
- Speed - UAS can perform the distress survey much faster than a van, as they have the ability to scan large and wide areas in a single pass.
- Survey Cost – As UAS can collect data faster, the survey cost is significantly lower.
- Safe - in rural areas it is safer to use UAS as there is no interference with traffic.

Advantages of using an ARAN vehicle:

- Rules and restriction – ARAN vehicle has no restriction and need to follow the driving rules, whereas an UAS is restricted by national and local government laws in urban areas with some exceptions.
- Distress survey in high traffic areas – As an ARAN vehicle follows the driving rules and follows the traffic, the data collected is clear from obstructions, and whereas data collected using UAS may capture the vehicles on the road instead of the distress.

1.3.7. Monitoring the Condition of Gravel/Unpaved roads with UAS

Reference: Principal Investigator: Dr. Chunsun Zhang; "Monitoring the condition of unpaved roads with remote sensing and other technology" Final Report for US DOT DTPH56-06-BAA-0002.

Introduction

More than half of all US roads (and more than 90% of roads globally) are unpaved (Skorseth and Selim, 2000). They serve remote areas and a few vehicles. On the other hand, gravel roads serve agriculture, logging and recreational areas with fairly high volume of traffic.

These roads tend to experience marked seasonal variations in traffic volumes with significantly higher flows occurring around harvest time each year. If periods of wet weather and high traffic volumes coincide, damage to unpaved roads can be very severe. Such roads are also susceptible to damage because of the kind of vehicles that traverse them. Heavy farm machinery and trucks laden with farm produce can do more damage to a road than a series of smaller vehicles of equal net mass.

We explore the use of an Unmanned Aerial Vehicle (UAV) as a road data collection platform, and develop efficient methods and systems to process UAV images and identify and quantify road condition parameters such as rutting, potholes, and road surface roughness. The research 8 necessary includes development of methods for UAV sensor calibration and orientation, and accurate geopositioning, and development of efficient image processing algorithms for automated 3D reconstruction of road surface and measurement of surface distresses.

Unpaved roads demonstrate a variety of conditions. A newly constructed or well-maintained road should have excellent surface condition and provides smooth and safety traffic. However, the unpaved roads can be deteriorated very quickly due to traffic, weather, bad habit of driving etc.

These damaged roads, if not promptly repaired, tend to be degraded more quickly with severe weather and traffic. In general, distresses on roads create difficulty to local community in day-to-day commune, transport of goods, and seasonal farming practice. In addition, the deteriorated roads pose a major challenge in traffic safety. Some typical unpaved road conditions are shown below in Figure 4.1.5.1.

Figure 4.1.5.1. Unpaved roads and road condition. The images of top row show two roads in good condition. The roads shown in the images of the two middle rows demonstrate significant surface distresses, such as potholes, loss of crown, resulting water trapped on surface after rainfall which in turn further deteriorating roads in they are not properly repaired. The last row gives examples of roads with corrugation effects and severe rutting.

Due to the nature of gravel roads and their variability, evaluation and rating gravel roads requires a different perspective than similar evaluations of asphalt or concrete pavements. Unpaved road condition is related to several factors, including structural integrity, structural capacity, roughness and rate of deterioration (Eaton and Beaucham, 1992). Direct measurement of all of these factors requires expensive equipment and highly trained personnel. However, these factors can be assessed by observing and measuring the distress of the surface.

Condition survey of unpaved roads is conducted by ground measurements. Usually, a two-person team is required. While the equipments needed to do a survey are simple and just a hand odometer used to measure distress lengths and areas, a straight edge, and a ruler to measure the depths of potholes, ruts, or loose aggregate, however, the measurement can be very time consuming and labor extensive. Figure 3 shows examples of ground measurement of ruts, pothole and cross section slope. Typically, it takes around 20~40 minutes for measurement on a single spot. The passing traffic and extreme weather condition can further stress the difficulty of the work, requiring even longer time for each measurement.

Measurement of ruts *Measurement of pothole depth*

Figure 4.1.5.2. Examples of ground measurement of surface distress.

Due to the high cost and difficulty of ground measurement, such survey is not affordable to most of the local road management authorities, and is conducted only occasionally. Local transportation management agencies largely rely on simple windshield inspection, or even no survey at all in many regions. The maintenances of the damaged roads are then performed based on the local authority discussions or even complaints of local residences.

Motivated by rapidly advancement of remote sensing and information technology, we explore the use of UAV based remote sensing and image processing technologies for the assessment of unpaved roads.

High resolution image data is essential in order to efficiently detect and measure features on unpaved roads for road condition monitoring. Aerial imagery can be a choice, but the limited maneuverability of the platform to acquire the image data and the associated high costs are shortcomings. In contrast, UAVs are highly flexible. UAVs can be programmed off-line and controlled in real time to navigate and to collect transportation data using a variety of multiple and interchangeable imaging devices and other sensors (NCRST, 2003c).

Our developed UAV-based remote sensing system acquires road imagery with high resolution from an UAV helicopter, and assesses roads based on the condition parameters derived through the development of sophisticated algorithms for image processing and analysis. In contrast to convention ground survey, this new approach performs distress measurement from UAV acquired imagery, therefore, improving the evaluation accuracy and reliability. This approach is faster, safer, and more consistent. In addition, the acquired imagery and developed algorithms may also be useful for the extraction and measurement of other road properties, such as road way width, curvatures, etc. which are also important components in road way management.

In addition to the operation of UAV for road image collection, the research includes development of the processing methods for accurate positioning and measurement from imagery, automated extraction of accurate digital surface model, and generation of high resolution orthoimages, and measurement of distresses. The measured parameters facilitate derivation of information about road quality to enable advanced warning of road deterioration. System tests are conducted, and the performance of system is compared with detailed ground survey to determine the measurement quality.

UAV System

The UAV-based imaging system for unpaved road image acquisition consists of a UAV helicopter, digital camera, on-board flight control system and ground control station (GCS). The system overview is shown in Figure 4.1.5.3.

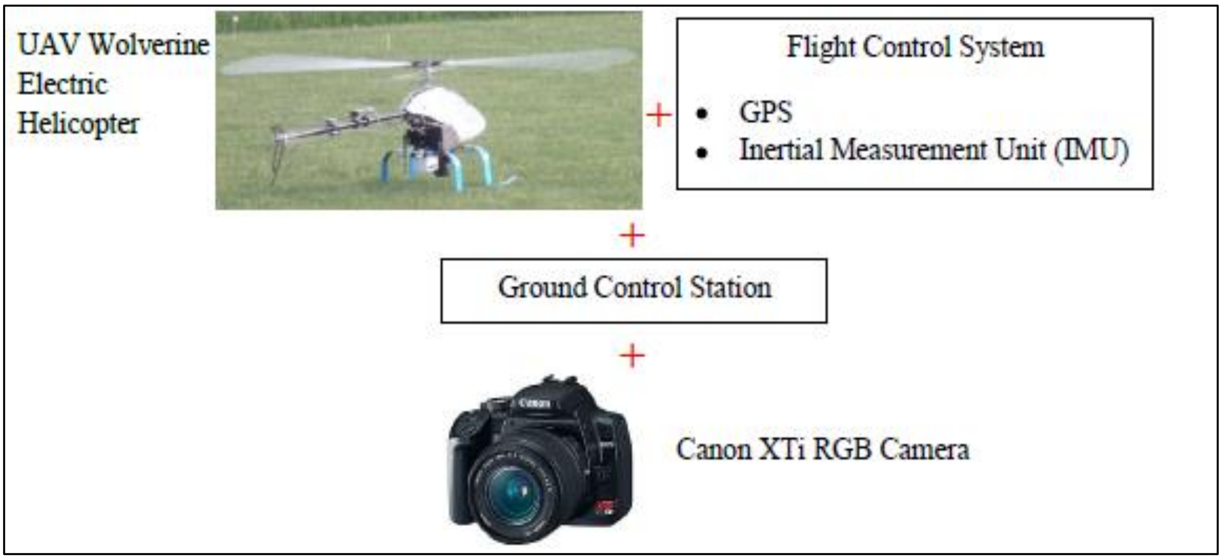


Figure 4.1.5.3 System overview.

The weGCS software (Figure 7) from weControl Inc. is installed on the GCS computer. The software features an interface for mission plan allowing for setting of mission parameters. A raster map can be loaded and displayed on the graphic user interface for operator to interactively define flight path and waypoints, set flight height and travel speed.

Application / methodology

Town Brookings, a small community locates in an agricultural area. It has a few farms and consists of eleven roads. These roads experience heavy traffic during late spring, summer and early fall, and connect farms to local towns and outside markets. While small, the site represents a typical farming community in agricultural regions. The roads are usually completely covered by snow and ice during winter. The conditions are generally bad after snow thaws in spring. Extensive maintenances are usually required in planting and harvest seasons. However, evaluation of road condition is rarely performed. Thus, maintenance is conducted based on the very limited windshield surveys or complaints of the local residences. Based on discussions with farmers and local road maintenance teams, this site is typical and representative, and thus is well suited as a test and validation site in our project. Figure 4.1.5.4 presents several examples of road images in this community taken in middle of May 2009. The surface distresses are clearly presented in the images.

Figure 4.1.5.4. Examples of road image in the selected test site.

Flight plan is performed on the weGCS on ground control station. A georeferenced raster map of the mission site is loaded in the software. The mission parameters can be set interactively on screen. The results of flight plan are flight route, definition and locations of waypoints, flying parameters such as flight height, speed in the course of the journey.

The UAV helicopter can be navigated both by weGCS and a human pilot. Usually take-off and landing were controlled by the pilot in so-call assisted mode, while the actual flight mission was navigated by weGCS in fully automatic mode following the planned flight mission. Based on the plan, the UAV traveled along the defined route passing through designed waypoints after assisted take-off. During the course, the camera was automatically triggered to capture road image with defined overlap from the first waypoint to the end of the mission. The system status was presented on GCS, allowing for system monitoring and intervention wherever necessary.

In tests, the UAV flew at an altitude of about 45m above ground, capturing details of the road surface with image scale of ~900. The ground resolution is about 5mm. The UAV travelled at 4m/s, acquiring road images with 60% overlap along the path. Figure 4.1.5.5 is an example of the road imagery collected over a road segment with ruts. This road segment was imaged four times in a single mission, providing highly redundant information for the evaluation of road condition, and also allowing for precise 3D measurement of road surface features. Thanks to the very high spatial resolution, the fine details of the road surface distresses are clearly presented in the image, allowing for detailed evaluation of the road surface condition.

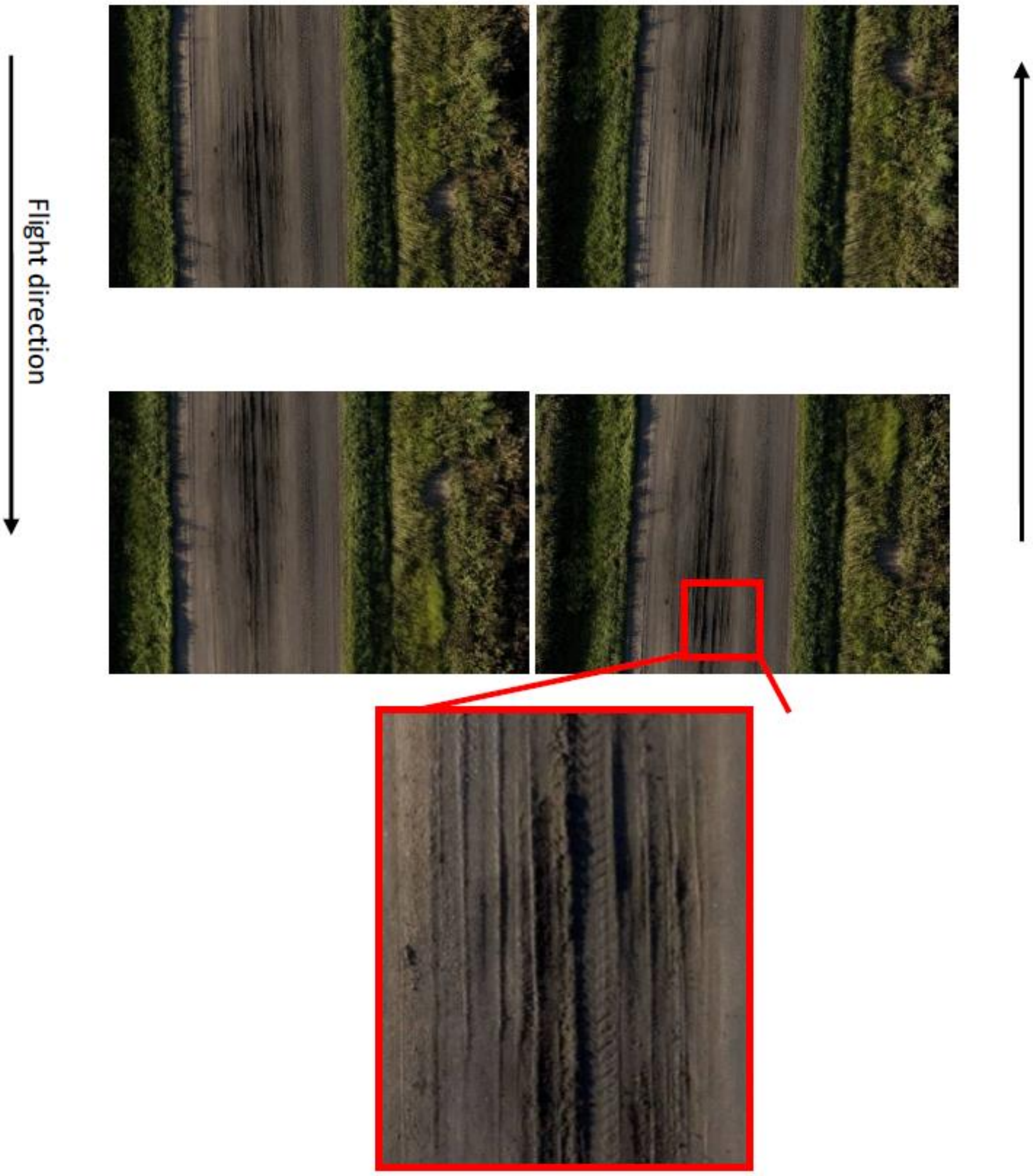


Figure 4.1.5.5. Example of road images acquired by UAV over a road segment. The segment was captured 4 times in a single mission. The flight directions are indicated by arrow lines. The bottom image shows the fine details of road feature (ruts) in original resolution.

Figure 4.1.5.6 is another imagery collected by UAV allowing for evaluation of culvert.

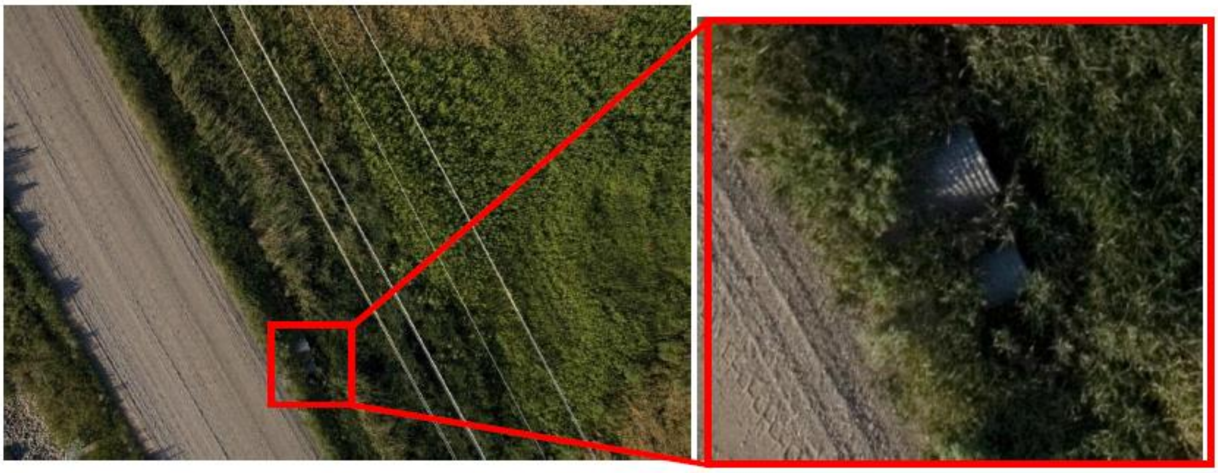


Figure 4.1.5.6 UAV acquired image allows for evaluation of culvert. Left: road image in reduced resolution. Right: culvert in original resolution.

Figure 4.1.5.7 Road image acquired by UAV showing severe ruts. Note the marks are designed for ground measurements and for relating ground measurements with image measurements.

Road shown in Figure 4.1.5.7 demonstrate severe ruts. Note we have designed some marks to facilitate ground survey and relate the ground measurements with image measurements. The system also recorded flight data, such as GPS, INS observations. We observed that the helicopter UAV did not follow exactly the predefined path during the missions. The actual route varies as a result disturbances such as air resistance, wind, vibration etc. Poor along-track overlap (~20%) has been observed. This has posed challenges for image orientation and 3D reconstruction.

3D Reconstruction of Ruts and Potholes

The developed 3D reconstruction algorithms were applied to the acquired imagery for 3D measurement of surface distresses, such as ruts and potholes. Figure 4.1.5.8 (left) shows an image patch of rut on a road section. Field survey with tape shows the distress is very mild with the depth of the hole around 2 inches. After manual identification of the rut in images, a regular grid was generated. With the determined image orientation parameters, the 3D positions of the road points were computed. This resulted in dense 3D points allowing for precise description of the shape and size of the rut as shown on the right of Figure 4.1.5.8.

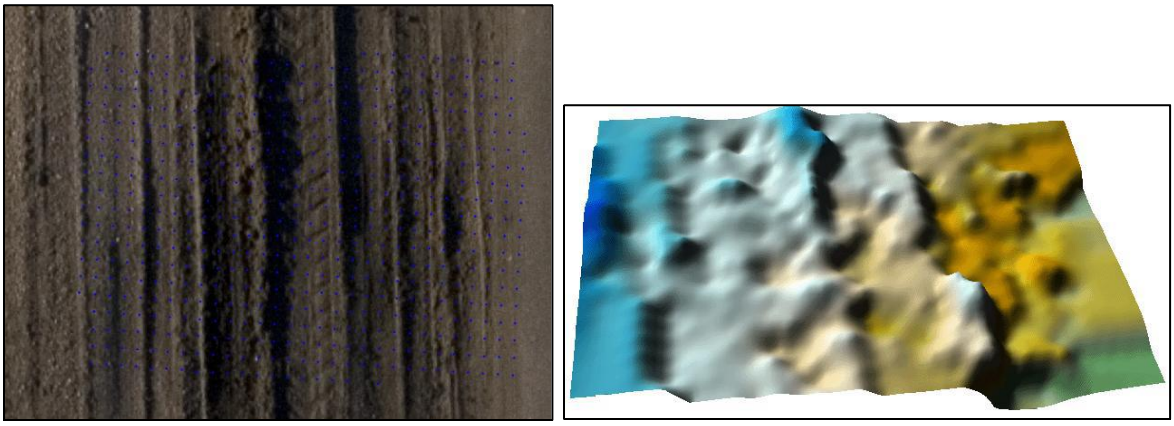


Figure 4.1.5.8. 3D reconstruction of rut. Left: an image patch of rut on a road. The blue dots represent grid points. Right: reconstructed 3D model of the rut area.

The similar procedures were applied to a road segment with mild potholes. An example is given in Figure 4.1.5.9. It shows the ground shot of the pothole and the field measurement of the depth using a tape. It is clear this is a mild distress with the depth less than 2 inches. However, the developed approach has successfully generated the 3D shape (bottom row, right) from the UAV acquired images.

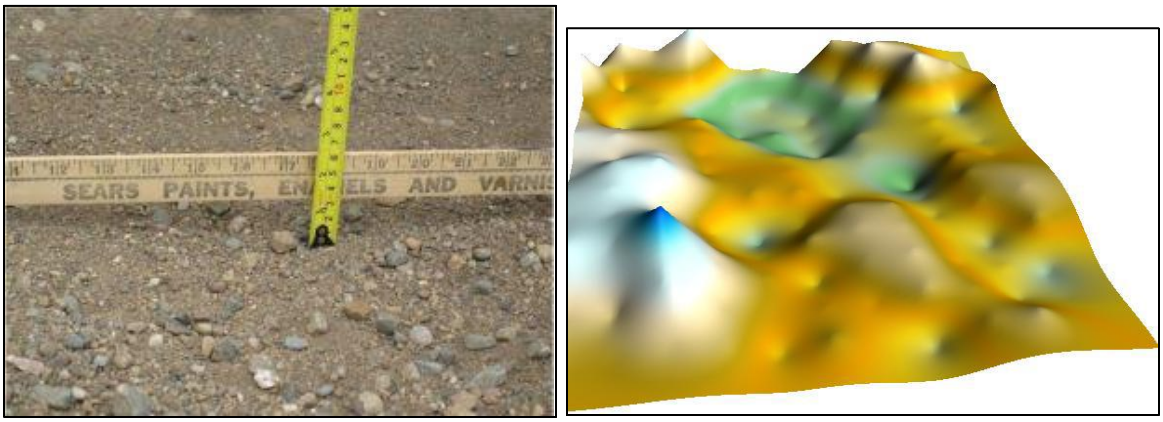


Figure 4.1.5.9. 3D reconstruction of pothole from UAV-acquired imagery; (Left) ground shot of pothole and field measurement. (Right) 3D model produced from imagery.

Generation of 3D Images

With the determined orientation parameters of images and the reconstructed 3D surface, the orthoimages and 3D road images can be generated. Orthoimages can be used for precise measurement in two-dimension space. Orthoimage and 3D images are particularly useful for visualization. For production of orthoimages, a regular grid is generated in ground space. The coordinates for each grid point can be derived from the reconstructed 3D surface. Each grid is then back projected to image space using the image orientation parameters. The color information at the projection point is taken to paint the grid and thus producing orthoimage. To generate 3D image of road surface, the 2D image is draped onto the reconstructed surface again using the orientation parameters. Since 3D image is a virtual representation of object, it is more attractive for visualization. The 3D images can be further treated to generate video product which provides virtual tour of the roads. This allows for more detailed visual inspection of roads on computer. Examples of the generated 3D road images with different perspectives are shown in Figure 4.1.5.10.

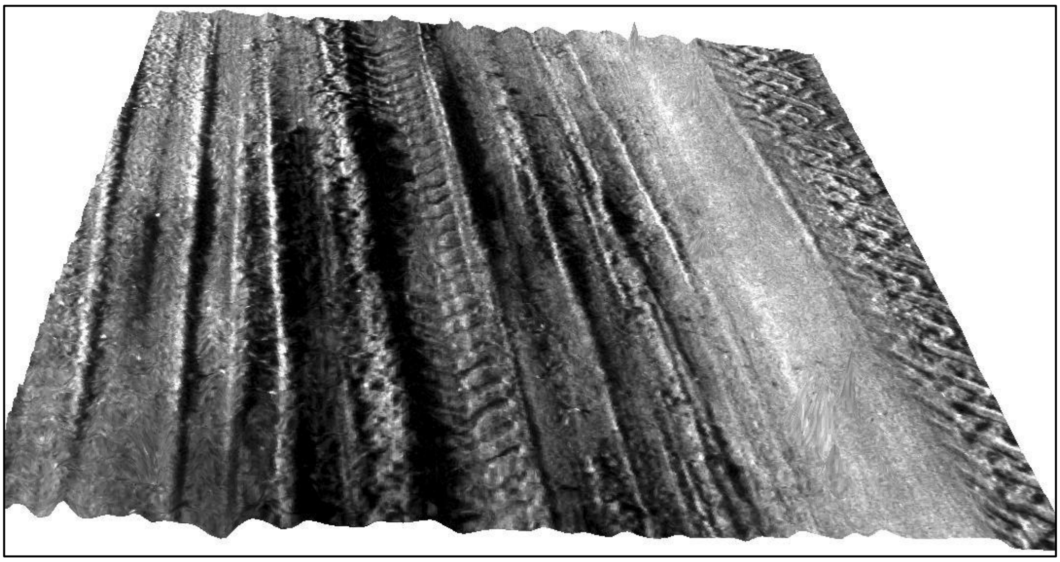
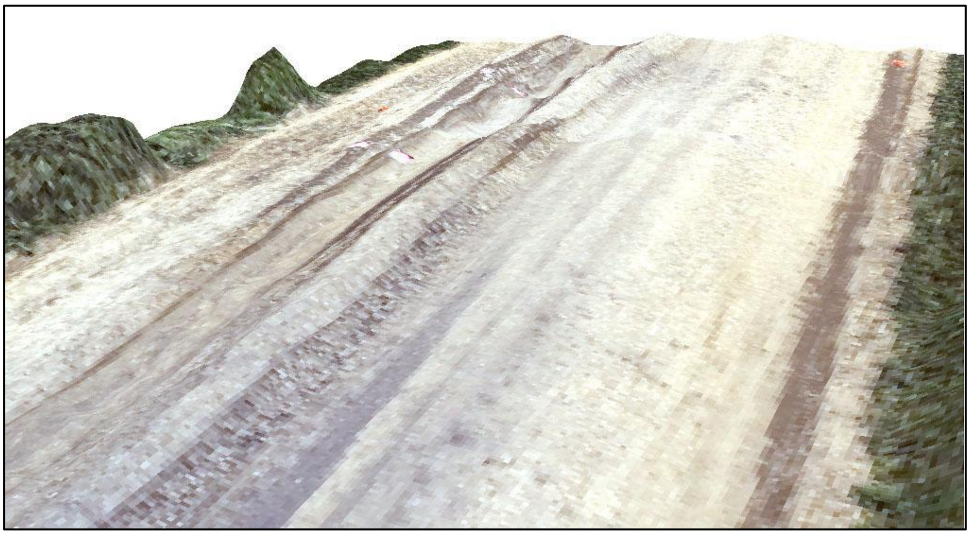


Figure 4.1.5.10. Reproduce of 3D image of road with severe distress from UAV-acquired imagery.

Based on the 3D models and orthoimages of ruts and potholes, the distress properties, such as depth and size can be measured. This is done in GIS software Arcmap. The maximum depths of the ruts and potholes in Figure 4.1.5.8 and Figure 4.1.5.9 are 6.5 cm and 3.5 cm respectively. Comparison with field survey with tape was also conducted. The differences between image-based measurement and field survey are within the range of 1 cm, demonstrating good performance of the system. In addition to depth, other important parameters in road condition assessment, such as the size and extension of potholes and ruts can also be easily measured with a few mouse clicks.

Conclusions and Recommendations

Rural road network is the lifeline of agricultural activities and link agricultural communities to nearby towns and markets. Thus, road condition data is important in local transportation management, and road condition is also critical to safety and farming activities. At present, essential information about the existence, locations, dimensions, and condition of roads is typically



collected in slow, dangerous, and expensive manual processes. This significant cost-in both time and money- has caused many local agencies to rely on visual inspection, intuition and occasional spot measurement in their assessment. Yet, the importance of timely identification and rectification of road deformation cannot be overstated.

The research part of this case study, developed a UAV-based remote sensing system for road condition data acquisition. This low-cost flexible system is easy to operate, and can efficiently capture road imagery fully automatically. Developed image processing algorithms then analyze the acquired images for image orientation, generation of 3D models of road surface and ortho-rectified road images which allows for extraction of road surface distresses (potholes, ruts etc) with more details. Quantitative measurements are conducted in office with computer-aided techniques. Thus, in contrast to conventional road condition data collection approaches, this system does not require field work. Even field visit is not needed. Therefore, it enables local agencies more quickly, efficiently and safely collect data needed for rural road condition assessment. Since the road data are documented in digital imagery, re-measurement is possible whenever is necessary. The generated 3D road images enable better visualization and inspection of road features. They can be easily integrated as video products for virtual roads. In addition, the acquired digital imagery of roads, together with the extracted road condition data, and the derived products can be directly integrated into road management system.

The proposed system has been tested over a number of rural roads with various surface conditions. Road images has been acquired with ground resolution as high as 5 mm, allowing for identification and detailed evaluation of road surface condition including distress type, severity and extent. The developed 3D surface reconstruction approach has been applied to the acquired imagery, and the 3D shapes of surface distresses such as potholes, ruts have been generated. A semi-automatic approach then allows for accurate measurement of extent of the distresses three-dimensionally on computer. Meanwhile, manual field measurements were conducted during flight mission to establish ground truth for testing the accuracy of the proposed system. The results show that the image processing algorithms works well on the UAV-acquired road imagery to measure the road surface distresses.

In conclusion, this research has demonstrated the capability of UAV-based remote sensing for rural road condition data collection. The developed system can provide detailed and accurate measurements of road surface distresses, and thus improving the efficiency of road condition data collection.

Recommendations

To make the developed system serve transportation agencies, further research may be directed:

Extensively test the developed systems over a diversity of regions to validate the performance in terms of accuracy and efficiency. Due to limited data collection in this phase, the time and cost associated with image-based condition data collection were not adequately documented. From the limited experience, the field work required for UAV flight is significantly low compared to ground survey. However, the save of time and cost is not fully clear yet.

Further development of automated methods for distress measurement. Currently, the image orientation and surface model production are carried out by computer with high quality. However, the measurements for length, depth and area are performed semi-automatically on computer. Further research will focus on new robust approaches to automatically identify various distresses on roads.

With the advancement of UAV and sensor technologies, more powerful and safer inexpensive UAVs will emerge onto market. Such UAVs will supply longer endurance in mission to serve larger community. Innovative sensors, such as infrared cameras, Lidar can be integrated to the current system. This will allow for more efficient road condition assessment in fully automatic mode.

In addition to collect surface distress data, the developed UAV-based remote sensing system can be also used to collect other transportation asset. One of the further researches submitted to USDOT by us recently has been documented in a white paper in response to US DOT DTOS59-08-RA-00002. That white paper has been accepted by USDOT in which we propose to further develop our system to collect road images and quantify other road condition parameters including length, width, slope, radii, curvatures of unpaved roads, geolocation of roadside features (trees, utility poles, buildings), drainage features (culverts, bridges), and other small structures, and their distance to the edge of roadway. Such information, together with surface condition data, constitute the critical component of rural road management system which allows state DOTs and local authorities to manage their road networks more efficiently.

RECOMMENDATION: There is a potential increase of efficiency in the use of UAS for monitoring surface characteristics of unpaved roads compared to visual inspections although further research should be done in a variety of regions to validate results. UAS can help in identifying the following:

- Potholes
- Loss of crown
- Corrugation
- Rutting

Data collected through UAS can be used for generating 3D models for rut and potholes depth measurement.

In contrast to conventional road condition data collection approaches, UAS does not require field work. Even field visit is not needed. Therefore, it enables local agencies more quickly, efficiently and safely collect data needed for rural road condition assessment. Since the road data are documented in digital imagery, re-measurement is possible whenever is necessary.

RECOMMENDATION: Use of UAS is very efficient when the objective is to collect data in the surrounding of the infrastructure: trees, utility poles, building… and their distance to the edge of the roadway.

1.4. Case Study – Emergency Response

1.4.3. The Use of Small UAS by the Washington State DOT for Avalanche Monitoring

Reference: Author Edward D. McCormack; "The Use of Small Unmanned Aircraft by the Washington State Department of Transportation".

Introduction

The test was applied to avalanche control because there was an obvious and immediate need for it, as well as support from WSDOT's maintenance personnel.

WSDOT estimates that a 2-hour avalanche closure can cost the state economy over a million dollars. Current WSDOT efforts involve the use of surplus military equipment to shoot explosives into areas that are in range of the roadside and the dispatching of skiers with handheld charges, plus the occasional use of helicopters to drop explosive charges into inaccessible areas. The project test flights explored whether, in the longer term, UASs may provide a less expensive and safer option for triggering avalanches than shooting explosives from howitzers or dropping explosives from manned aircraft, and also explored the UAS's ability as a tool to provide enhanced information about the terrain and conditions in the area.

Because the FAA application process is aircraft specific, the first step required finding a suitable UAS. A review of others' studies of UASs, as well as discussion with WSDOT staff, suggested the following parameters:

- The tests should use smaller tactical or man-portable UASs that could be operated on or near a state highway.
- To avoid training costs, the actual flights would be completed under contract with the aircraft owners but following WSDOT test requirements.
- The test would use a system (aircraft as well as the ground control station) that would potentially be affordable to a state DOT. For this effort it was decided the UAS systems should cost no more than $500,000. In addition, the UAS should be operable and maintainable by WSDOT maintenance personnel with appropriate training.
- Both a fixed wing and rotary wing system would be considered.

Given that certification and other institutional issues could be a major roadblock, this test also focused on reducing potential FAA concerns. The researchers decided to complete the test in a rural, lightly populated area with minimal air traffic. The application process and test were closely coordinated with WSDOT's aviation division. This ensured that proper air traffic pre-flight notification was completed and that project staff were conversant with the specialized aviation and air traffic control terminology necessary for the application process.

Application / Methodology

The First Test

The selected test area was centered on State Route 20 in the Cascade Mountains of north-central Washington State (approximately between mileposts 160 and 168). The UAS operating test area was a square roughly 9 miles by 9 miles, with steep terrain. The test area focused on a narrow valley with SR 20 on the north side and with 3000-ft walls and a 30-degree slope on either side.

The aircraft selected for the first test was the MLB BAT. This 25-pound UAS had a 72-inch wingspan and carried both a pan-tilt video camera and a digital camera (Figure 4.2.1.1). The aircraft could be disassembled and placed in a car trunk. The aircraft could be launched from a vehicle and landed on a 100-ft stretch of roadway. The ground station consisted of a portable computer and a video screen that was temporarily located in the back compartment of a van, plus an external antenna on a tri-pod.

Figure 4.2.1.1: MLB BAT

MLB BAT Test

The test of the UAS occurred in April 2006 along a snowy, avalanche-prone section of SR 20 that had been closed for the winter. WSDOT maintenance staff were in the midst of a month-long effort to reopen the road and were conducting avalanche control operations by using a 105-mm military howitzer. The test flight was designed to evaluate the ability of the UAS to use an on-board video camera to:

- • view a roadway
- • operate off a highway
- • survey the surrounding terrain.

In terms of avalanche control, of interest was the ability of the UAS and camera to identify avalanche trigger zones, verify that the targets for the howitzer were free of skiers and other hazards, and generally evaluate snow pack conditions.

The flying conditions during the test were difficult, with visibility ranging from poor (clouds and snow) to a 1500-foot ceiling, with temperatures around 35 degrees F. At times, wind speeds above the surrounding peaks were 30 mph.

The MLB operator climbed the plane to 600 feet and turned on the autopilot to circle a re-set GPS waypoint at 1000 feet above the roadway. The plane was then commanded to climb to 2500 feet above the road to obtain flying space away from ridges. Video of various snow gullies and the roadway were taken, but in some cases clouds obstructed the view, so the aircraft was brought down to 1000 feet above the ground. The plane then shot some videos of avalanche-prone snow chutes.

The next task was to fly the plane at 1500 feet above and along the highway. While flying above the road, the plane encountered strong turbulence, and the operator decided to land it before the weather got worse. The aircraft was manually landed on the closed highway after 22 minutes. The resulting videos provided a clear view of the roadway, and individual vehicles could easily be identified. Post flight interviews with the WSDOT avalanche control staff indicated that they thought the concept had potential.

They reviewed the aerial video and determined that the views captured by the camera also had value and that such video would be worth further exploration. The test also highlighted some issues that may affect a transportation agency's use of a fixed wing aircraft. The aircraft required a 100-foot-long flat stretch of roadway. This need for a miniature airstrip could limit the use of these aircraft in urban areas. The aircraft also has operational limitations related to difficult terrain and weather. The aircraft owner was understandably reluctant to push the aircraft to some areas in which WSDOT was interested.

The Second Test

Given the difficulties with terrain and weather encountered in the first test, a more mobile, vertical takeoff and landing UAS was selected for the second test. The aircraft selected was the R-Max made by Yamaha. This rotary wing (helicopter) aircraft weighed 150 pounds and had a rotor span of 10 feet (Figure 4.2.1.2). The aircraft was developed in Japan and is used for crop spraying in Asia, but a few are in the United States for research purposes.

The process was new, initially complex, and required some detailed information about the aircraft as well as an airworthiness certification. As a public agency, WSDOT had an advantage in that it could certify the airworthiness of each UAS in the test. This certification was mainly based on the fact that the aircraft would be operated over an unpopulated area.

Figure 4.2.1.2: Yamaha R-Max

Yamaha R-Max Test

The second test occurred in September 2007. The R-Max contracted for this project was owned and operated by Georgia Technical University and was equipped with pan-tilt cameras. The ground station for this aircraft was considerably larger and more complex than that for the BAT. The station was set up in the back of a specially equipped van that doubled as a transporter for the aircraft. The van was equipped with spare parts, generators, portable computers with several aircraft controls screens, and a number of external antennae on tri-pods.

The weather was warm, with light winds and good visibility. During this two-day test, nine flights, varying from two to forty minutes long, were completed.

Conclusions and Recommendations

The aircraft and the on-board sensor demonstrated the ability to follow a road with predetermined waypoints. This exercise was designed to simulate a survey before the start of snow clearing operations on the road, but it was also a successful test of the UAS's ability to fly along a road center-line to record traffic or conditions. The ability of the aircraft to hover provided a stable platform on which camera use was effective. Other test flights demonstrated the ability of the UAS to accurately drop packages at pre-determined GPS locations and heights. Such missions could be used to drop explosive charges at predetermined avalanche trigger zones.

RECOMMENDATION: When road infrastructure faces snow avalanches the UAS of drones has been proved very efficient at least for two applications:

- To provoke controlled avalanches by dropping explosive charges at predetermined avalanche trigger zones.
- To provide current condition of the infrastructure right after an avalanche occurred, in order to better organize the snow clearing works.
- However, when UAS are used in a high mountainous area, particular attention should be given to flight conditions because of lower air pressure and climate conditions (potential strong wings, changes of air temperatures, etc.)

This test also demonstrated the R-Max's ability to survey terrain alongside a roadway. This capability could easily be used for construction site surveys, security checks, and numerous other transportation tasks that require an aerial view.

Several issues arose that affected the R-Max flights. The day was warm, and the resulting thinner air, combined with the altitude, degraded the ability of the R-Max, which was heavier than the production model because of the number of research sensors installed, to operate in the afternoon. In addition, the GPS system devices that the aircraft used to navigate demonstrated some inaccuracy, possibly because of signal bounce (possible multiplexing). In addition, as a safety precaution, the flight crew restricted the flight range of the aircraft to no more than a mile from the ground control station, limiting the potential effectiveness of the aircraft.

Both aircraft systems showed considerable potential for aerial roadway surveillance and avalanche control. They were able to obtain clear and usable videos of the roadway at a height that allowed for efficient viewing of roadway conditions and traffic. At times, however, the mountainous terrain provided operational challenges related to both altitude and weather (hot and cold).

RECOMMENDATION: UAS have showed considerable potential for aerial roadway surveillance when the infrastructure was not easily accessible for road vehicles. They have proofed to be able to obtain clear and usable videos of the roadway at a height that allows an efficient viewing of roadway conditions and traffic. This opens a series of potential use of UAS on the road sector when the road is not accessible:

- Monitoring of a blocked road after a landslide.
- Monitoring of road infrastructure after a natural disaster: floods, hurricanes, earthquakes…
- First monitoring of an accident under traffic congested road.
- Etc.

1.5. CASE STUDY – TRAFFIC MONITORING

1.5.3. Monitoring Driver Adaptation to a Two-Lane Roundabout with UAS

Reference: Authors Eric Hildebrand, Caitlin Sowers; "Monitoring Driver Adaptation to a Two-Lane Roundabout with Drones: A Case Study".

Introduction

The first two-lane roundabout in New Brunswick, Canada was proposed in 2013 to create a connection between two of Fredericton's busiest urban collectors (Smythe Street and Bishop Drive). A unique aspect of the roundabout is that it included Route 8, a 4-lane divided provincial arterial highway posted at 90 km/h (shown in Figure 4.3.1.1). Concern was expressed by the design team that the unfamiliarity of drivers with this type of facility compounded by the incorporation of high-speed approaches could be problematic. The development of this roundabout provided a unique opportunity to study driver behaviour and adaptation since the vast majority of drivers would not have been exposed to this configuration. The study goal was to document the types of driver errors and how quickly the error rates change as motorists become more familiar with the facility.

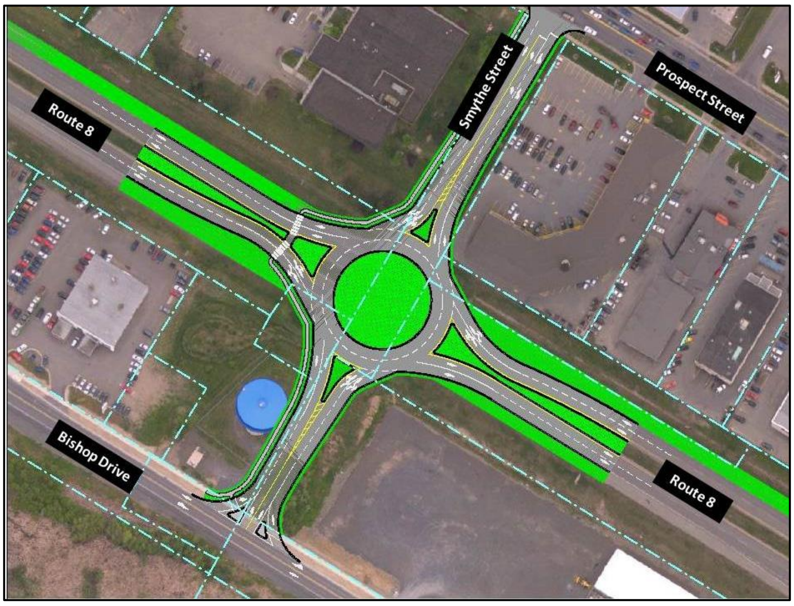


Figure 4.3.1.1 Smythe Street/ Route 8 Roundabout [City of Fredericton, NB]

The two-lane roundabout opened in September 2015 and included many safety features to reduce driver speeds on the approaches. These safety features included mounded medians with landscaping, removal of shoulders, introduction of curbs, reverse curves, oversized guide signs, short mast lighting, and overhead pedestrian crossing signs. An extensive public education campaign was also undertaken by the City of Fredericton to help drivers become more comfortable with how the facility is to be properly driven.

The use of both an Unmanned Aerial Vehicle (UAV) and a GoPro camera installed on a nearby water tower provided overhead video of drivers as they navigated through the roundabout. The UAS provided such high quality footage that early on it was decided to rely on this collection method solely and abandon the perspective given by the water tower. Using the video footage, driver error was investigated from the opening of the roundabout when drivers were most unfamiliar, continuing throughout a full year to capture the rate at which drivers adapted to the operation of the facility. Determining what common driving errors were being made within the roundabout and how they change over time provided a proxy for driver adaptation rates and improved safety levels. Results can be used to modify current and future designs and help focus driver education programs.

Traffic capacity is an important measurement to predict how many vehicles can traverse a two-lane roundabout. It also provides the foundation to permit level of service (LOS) analysis used to evaluate the operational performance of a facility. Given that saturated conditions at two lane roundabouts are rarely observed in Canada, the Smythe Street/Route 8 roundabout provided a unique opportunity in the summer of 2016 when an adjacent arterial route (Regent Street) was closed for rehabilitation. Traffic from Regent Street was redirected to the two-lane roundabout, allowing for saturated observations to be made. It was hypothesized that detoured volumes would exceed peak hour capacities, and allow measurement of critical and follow-up gaps. It was unknown how resulting capacities would compare to default values used in current LOS software developed on the basis of U.S. and European observation. Estimating the critical and follow-up headways accepted by drivers will provide more accurate default values to be used in LOS software analysis in Eastern Canada.

The use of Unmanned Aerial Vehicles (UAVs), commonly known as drones, for traffic monitoring is a valuable transportation-monitoring tool, particularly for traffic surveillance at complicated junctures. Roadway networks can be difficult to monitor on the ground as they require fixed infrastructure and are labour intensive (Coifman et al. 2006). UAVs equipped with a video camera, geo-positioning sensors, and communications hardware to relay the data to the ground are now readily available on the commercial market.

Local critical and follow-up headways dictate capacity in a roundabout. The critical headway is defined as the minimum time interval in the major-street traffic stream that allows intersection entry for one minor-street vehicle (HCM 2010). Follow-up headway is defined as the time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same gap under a condition of continuous queuing (HCM 2010). A variety of estimation theories exist to determine the critical headway, all of which use the rejected and accepted gaps observed. Raff's method states that the number of rejected headways larger than the critical headway is equal to the number of accepted headways smaller than the critical headway (Guo 2010). A newer method for determining the critical headway is presented by Wu (2006) based on the equilibrium of probabilities. Probability density functions (PDFs) were estimated through the newer model presented by Wu (2006) and provided similar results to past theories.

Application / Methodology

Data Collection

Video Footage

Data collection for the Route 8/Smythe Street roundabout began in September 2015 and continued to September 2016, resulting in a full year of data collection. A water tower near the roundabout presented a unique vantage point to capture video footage. A GoPro camera was installed on the Water Tower by city workers, capturing approximately two hours of oblique footage in both

September and October 2015. A magnetic tripod mount was used to secure the GoPro to the edge of the water tower.

An unmanned aerial vehicle model DJI Phantom 3 Professional was also flown for a one-hour period in conjunction with GoPro footage during the months of September and October 2015. Upon reviewing the footage, it was determined that quality of footage captured by the UAS was of significantly higher quality compared to that of the mounted Water Tower camera. The UAS provided a perfectly centered aerial image (rather than orthogonal) which afforded the ability to monitor vehicle off-tracking throughout the roundabout.

Since the UAS also requires no installation, it was decided that the UAS would thereafter become the sole means of data collection for remainder of the project. Data were collected once a month by the drone for duration of approximately one hour at non-peak hours throughout the year to normalize for potentially aggressive driving during peak periods. The drone battery life was a limiting factor as each battery held approximately 15 minutes of charge, requiring four batteries to collect an hour of data.

A typical frame capture is shown in Figure 4.3.1.4. The rectangular-shaped frame of the footage

was selected intentionally to allow a greater view of the Route 8 approaches. This allowed for queuing to be shown for the purpose of capacity investigations, as well as speed investigations as vehicles transition from a rural two-lane divided highway into an urban two lane roundabout.

Figure 4.3.1.4 Aerial view of roundabout captured by drone from 150m

Figure 4.3.1.5 Follow-up headway data collection

Approval to Use UAS

The use of the UAS required approval from Transport Canada. Transport Canada is the federal governing body responsible for the regulation of UASs in Canadian Airspace. A formal application was required since it was not possible for this project to "stay at least 30 metres away from people, animals, buildings, structures, and vehicles not involved in the operation", which is required for an unmanned aerial vehicle of 2kg or less.

Transport Canada states that there are two main types of applications, a Compliant Operation Application and a Restricted Operator Application, which has three sub methodologies: Complex Application, Simplified Application, and a Model Aeronautics Association of Canada/Academy of Model Aeronautics Application (MAAC/AMA). For the application of this project a Restricted Operator – Simplified Application was appropriate after discussion with the Atlantic Regional Civil Aviation Inspector.

Collision Data

Motor vehicle collision data at the roundabout location were collected by the Fredericton police department from the opening of the roundabout in September 2015 through to September 2016. For the purpose of this research, reported collisions were assumed to represent all collisions that occurred at the roundabout which is consistent for comparison with established collision rates or Safety Performance Functions.

Critical and Follow-up Headways Data

Accepted and rejected headways were recorded for all vehicles in the northbound and southbound approaches, as these approaches were observed to be operating at saturated levels during the nearby construction detour. Figure 4.3.1.5 depicts the areas where time stamps were collected, using the northbound approach as illustration. For each approach lane analyzed, the time at which a vehicle came to a stop and entered the roundabout at line 2, shown in Figure 4.3.1.5, was recorded. The time when circulating vehicles in either the inside or outside lane crossed line 1 was also recorded. Using these three recordings, the accepted and rejected gaps by each entering driver was determined. The follow-up headway was also determined when two consecutive vehicles entered at line 2 using the same gap in circulating traffic, provided there were queuing conditions.

The mean of the follow-up headway observations was assumed to be an accurate value due to the large number of observations. The critical headway cannot be directly observed in the field thereby requiring additional analyses. Raff and Wu's method were both used and the values provided by both are compared in this study. Raff's method states that the number of rejected gaps larger than the critical headway is equal to the number of accepted gaps smaller than the critical headway (Guo 2010). Wu's method is established by determining probability distribution functions (PDFs) for the accepted and rejected PDFs.

Driver Error Analysis

The error observation period was intended to be undertaken from September 2015 to September 2016, resulting in a full year of data; however, construction began on a major nearby connection in June 2016. The construction influenced drivers to redirect their route to the roundabout who otherwise may have avoided the roundabout. The disturbance caused by the construction altered the "normal" environment in which driver behaviour was being documented; therefore, vehicle errors were not observed during the construction period which ended in early September 2016. Error observations were therefore made from September 2015 to September 2016, excluding June, July, and August.

Results and Discussion

Driver Error Results

Errors peaked at the onset during September, the first month of operation, and subsequently declined at a fairly steep rate for the first few months. The percent reduction of each error and the percent total of each error as of September 2016 are presented in Table 4.3.1.1.

Total driver errors are plotted in Figure 4.3.1.6 where it is seen that overall rates have fallen by approximately 74% in the 12 months since the roundabout first opened. The findings found in Oregon by The Federal Highway Administration (2007) indicated that the driver errors associated with an urban multi-lane roundabout followed a "learning curve" pattern which leveled off approximately six months after opening; Figure 6 confirms this pattern, with total driver errors levelling off at approximately 24 weeks (six months).

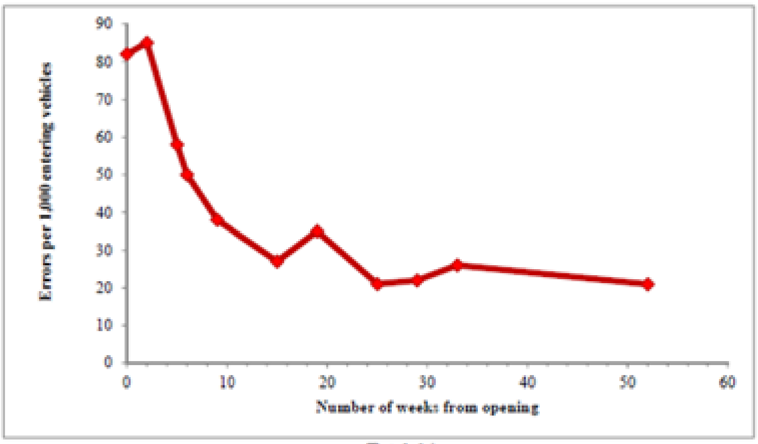


FIGURE 4.3.1.6 Total driver errors

	% Reduction (Sept/15 to Sept/16)	% of Total Errors (Sept/16)
Changing lanes within roundabout	81	60
Not yielding to traffic already in roundabout	59	16
Improper lane usage	15	16
Stopping within roundabout	39	5
Not giving ROW to trucks	0	5
Left-turn (wrong way)	100	0
Total	74	100

Table 4.3.1.1 Percent Error Reduction and Percent of Total Errors

Changing lanes within the roundabout was initially observed at 68.6 (the average of 53.5 and 83.6) errors per 1,000 entering vehicles and as of September 2016 it had declined to 2.7 shown in Table 4.3.1.2, an 81% reduction. The roundabout lane line being broken (which would typically indicate a lane change is allowed) may be a contributing factor to vehicles making lane changes within the roundabout. There is a discrepancy on pavement marking guidelines for multi-lane roundabouts; TAC indicates that pavement markings should be broken, whereas, other jurisdictions such as British Columbia indicate a solid line should be used. The error data (shown in Figure 4.3.1.7) appears to support that a solid line might be preferred to improve safety.

The errors that were expected to decline to the lowest rates included vehicles not giving ROW to trucks, left-turns (wrong-way), and stopping within the roundabout. With very low error occurrences, they were not shown to be a significant safety concern. Stopping within the roundabout to allow approach vehicles to enter was attributed to the friendly nature of Fredericton drivers. Left-turns into the roundabout were expected to diminish after the initial confusion of unfamiliar drivers to the roundabout.

An unusual spike can be seen in the second data collection point (early October) in Figures 4.3.1.6, 4.3.1.7, and 4.3.1.8. This spike may be attributed to the day of collection which was a Sunday. It is quite possible that this early Sunday period saw a disproportionate percentage of cautious first time users of the two-lane roundabout. Following this experience, all further data were collected at similar times during mid-week.

Collision Results

The Region of Waterloo presents an empirical collision prediction model which uses the AADT for all movements to estimate the total daily conflicts (TDC) at each approach for roundabouts (Region of Waterloo 2014). The total annual collisions are determined by:

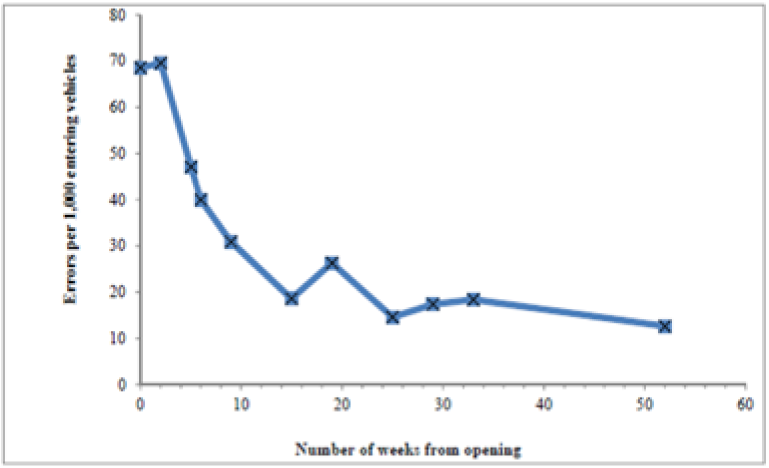


FIGURE 4.3.1.7 Drivers who changed lanes within the roundabout

$$Estimated\ Annual\ Collisions = (0.0004 \times Total\ Daily\ Conflicts) + 1.8122 \qquad \text{[Eq. 1]}$$

The total daily conflicts for the eastbound (EB) approach, by way of illustration, can be described as:

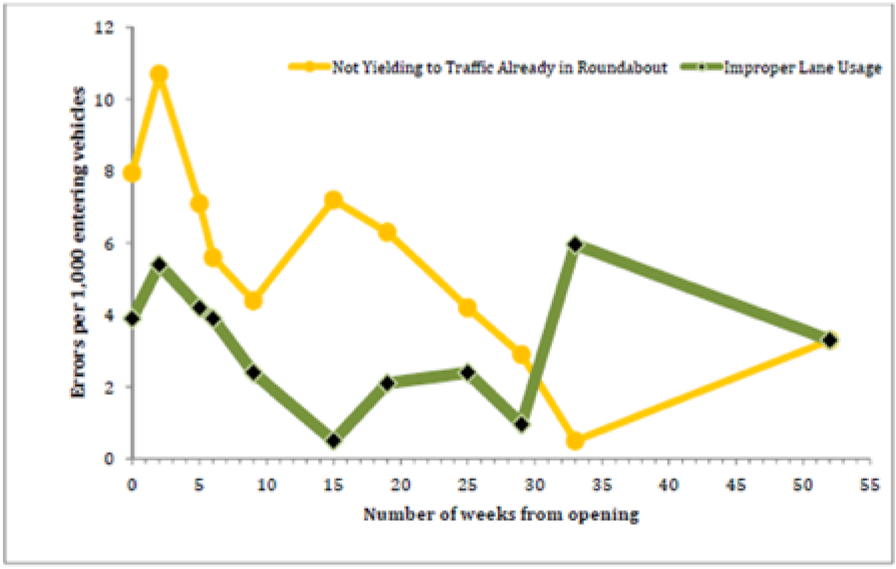


FIGURE 4.3.1.8 Drivers not yielding and improper lane usage

TABLE 4.3.1.3 Potential for Improvement

	Expected Collisions (per 15 months)	Observed Collisions (per 15 months) Sept/15 – Dec/16	Annual PFI
PDO	32	42	+8
Injury	3.5	3	-0.4

[ADT = 25,200]

$$EB\ Conflicting\ Volume = min(EBL, SBT) + min(EBL, SBL) + min(EBL, NBL) + min(EBL, NBT) + min(EBL, WBL) + min(EBL, WBT) + min(EBT, SBL) + min(EBT, SBT) + min(EBT, NBL) + min(EBT, NBT) + min(EBT, NBR) + min(EBR, SBT) \quad \text{[Eq. 2]}$$

The number of injury collisions is considered to be 10% of the total estimated annual collisions (Region of Waterloo 2014). A comparison between the expected collisions (based on the Waterloo model) and observed collisions is presented in Table 4.3.1.3.

Given the approximate ADT, the Smythe Street roundabout is expected to experience 25.6 Property Damage Only (PDO) collisions per year (with another 2.8 collisions resulting in injury) based on these Safety Performance Functions (SPFs). After a 15 month observation period (September 2015-December 2016), 42 collisions have occurred within the roundabout, 3 of which caused injury. While there is an annual PDO PFI (potential For Improvement) of 8 collisions, it is important to note that 59% of the observed collisions occurred over a three month span during which the presence of a work zone downstream may have negatively impacted the observed collisions, shown in Figure 4.3.1.9 (construction months are denoted in red stripes). The roundabout was used as a detour during this construction which may have negatively impacted the observed collisions as well. If the months during which construction occurred are eliminated, 21 PDO collisions occurred over a 12-month period, which is in fact better than the 25.6 PDO PFI over a 12-month period predicted using the same safety performance functions.

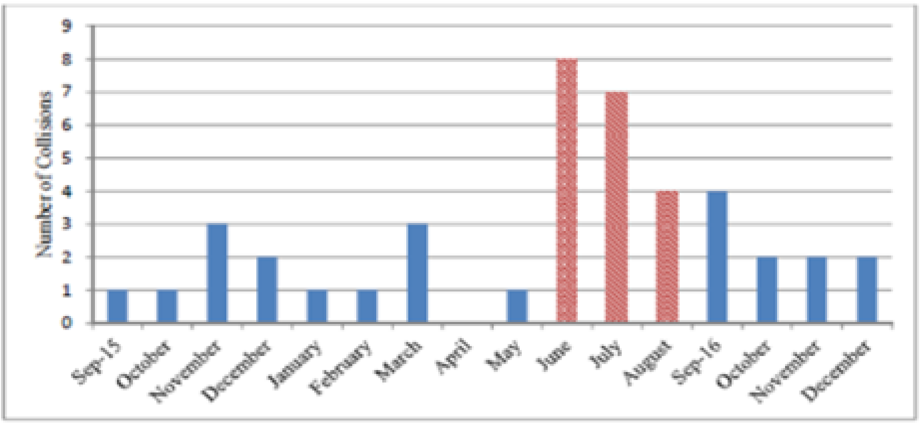


FIGURE 4.3.1.9 Observed collisions by month

Critical and Follow-up Headways

The evening peak hour of video footage (during the summer of 2016 when an adjacent arterial route was closed for rehabilitation) yielded 55 minutes where the north and southbound lanes were operating at capacity. From the video footage, 612 critical headway times and 460 follow up times were observed for the right and left approach lanes. LOS analyses results based on critical/follow-up headways from Raff's Method, Wu's method, and HCM default values are presented in Table 4.3.1.4.

TABLE 4.3.1.4 Comparison of Raff, Wu, and HCS

Method	Follow-up Headway (sec)	Critical Headway (sec)		Intersection Delay (sec)	LOS
		Right	Left		
HCM 2010	4.29	4.11	4.29	56.1	F
HCM 6	3.19	4.32	4.65	--	--
Raff	3.02	3.20-3.50	3.50-3.80	27.1	C
Wu	3.02	3.21	3.35	21.4	C

The roundabout intersection delay using the default HCS values indicated a level of service F, while both Raff and Wu's method indicate a level of service C. The difference in indicating that a facility is failing (LOS F) rather than at, or near, free flow (LOS C), is significant. The video footage during the peak hour supported the LOS estimated by Wu's and Raff's method. Both Raff and Wu's method provide values which indicate that the default values currently used by HCM 6 are not accurate for this jurisdiction.

Conclusions and Recommendations

Driver errors were evaluated first to determine how they changed over time as drivers became more familiar with the operation of a two-lane roundabout. The majority of observed errors began to level-off at 15-20 weeks, which is consistent with findings from a FHWA study (2007). An observed reduction in total errors of 74% was found over a 12 month period. The most commonly observed error was drivers changing lanes within the roundabout; however, the error causing the most collisions was drivers not yielding to traffic already in the roundabout. Driver errors were categorized into six types, all of which saw a reduction throughout the year (excluding ROW to trucks, given that this error was observed so rarely, reduction estimates could not be developed): changing lanes within roundabout (81% reduction), not yielding to traffic already in roundabout (59%), stopping within roundabout to allow approach vehicles to enter (39% reduction), left-turn into roundabout (100%), and improper lane usage (15%).

Collisions within the roundabout can be delineated into three categories: yield violations (56%), turning violations (41%), and rear-end (3%). After a full year of observations 32 collisions occurred within the roundabout, 30 of which were property damage only. It is important to note that 59% of the collisions occurred over a three-month span during which the presence of a work zone downstream likely had a significant impact on observed collisions. A comparison between the expected collisions (based on the Region of Waterloo (2014) SPF model) and observed collisions provides a potential for improvement of 8.0 property damage only and -0.4 injury collisions per year. This means that the roundabout has performed slightly worse from a PDO standpoint, but better than expected from an injury perspective.

A secondary objective of the study was to observe the roundabout during a period of over-saturated demand to quantify the facility's overall capacity. An analysis of critical and follow-up headway default values was then undertaken to determine if the HCS 2010 default values are accurate representations of what was observed. Two methods were used: Wu's method and Raff's method, both of which indicated the default values for critical and follow-up headways are too conservative and do not reflect local driver characteristics. More appropriate estimates for critical and follow-up headways were developed.

It can be concluded from this case study that an UAS can help in monitoring and analyzing the driver's behavior. As human errors are an important aspect of road safety, UAS can be used at strategic locations (ex. locations with high number of incidents) to monitor driver's behavior and to analyze any existing patterns.

RECOMMENDATION: UAS can be used to monitor high incident locations. Further analysis can be done to identify the root causes such as human errors, improper geometric design of the roadway, any elements obstructing the driver's view etc. and implementing the solution to resolve the root cause.

1.5.4. Surface Transportation Surveillance from Unmanned Aerial Vehicles

Reference: Benjamin Coifman (coifman.1@osu.edu), Mark McCord (mccord.2@osu.edu), Rabi G. Mishalani (mishalani.1@osu.edu), Keith Redmill (redmill.1@osu.edu); "Surface Transportation Surveillance from Unmanned Aerial Vehicles".

Introduction

As congestion continues to grow on roadway networks it becomes increasingly important to collect precise and timely information about the traffic state for improved control and response. The need for faster assessment and response to incidents is just one example of this need. Faster response can lead to reduced traveler delay, as well as improved health status of injury victims through faster medical attention. At any given instant, the biggest value from monitoring only a small portion of the network. Unfortunately, the specific portion that would provide this largest value is constantly changing and often is not known a priori. For example, the points where queuing will form as a result of an incident depend on where the unpredictable incidents occur. Conventional traffic surveillance uses a set of detectors (including cameras) deployed at fixed locations, requiring a high density of detectors to ensure the ability to respond rapidly under changing conditions throughout the network. When information is needed from beyond the range of these fixed detectors a person may be deployed to assess conditions. For example, a highway patrol officer may be directed to the scene of an incident to prescribe remedial measures. Often this first responder would have to travel through prevailing queues before reaching his or her destination.

Technological advances in electronics and communication have recently enabled an alternative to an inflexible fixed network of sensors or labor-intensive and potentially slow deployment of personnel. Unmanned Aerial Vehicles (UAVs) capable of carrying a video camera, geo-positioning sensors and communications hardware to relay data to the ground are becoming available on the commercial market. Examples include the MLB-BAT [1] and GeoData Systems-Airborne Data Acquisition System (ADAS) [2]. These aircraft have capabilities ranging from conventional model aircraft control to sophisticated autonomous flight. Various models have different payload and data collection capabilities. Most transmit video data to the ground in real-time, and some are capable of storing higher quality video or images on-board.

While the various companies have developed the technology and demonstrated the capability of such aircraft, researchers at the National Consortium for Remote Sensing in Transportation-Flows (NCRST-F) have recognized the potential of UASs to provide a low cost means to achieve a "bird's eye view" and a rapid response for a wide array of transportation operations and planning applications. The focus is on how these technologies can be used for surface transportation applications, identifying benefits and determining barriers to deployment, as discussed in the following sections. The paper also mentions applications NCRST-F researchers have been developing that could possibly benefit from UAS-based traffic surveillance.

Application / Methodology

To further explore the benefits of UAS applications to transportation surveillance and understand the barriers to reaping these benefits, it is critical to conduct field experiments with UASs. Field experiments would also allow UAS operators to compile a track record of safe operations and practitioners to join in shaping the evolution of the technology for useful applications. As a first step in this direction, on July 22, 2003 a set of experiments were conducted on the campus of The Ohio State University in Columbus using the BAT III technology [1] carrying a payload of two video cameras. Four distinct experiments were conducted.

1. Freeway conditions: The UAS flew over a freeway for the purpose of observing flows, speeds, densities, off-ramp weaving, and vehicle trajectories. Figure 4.3.2.1 shows four sample video frames captured during this experiment.
2. Intersection movements: The UAS circled an intersection for the purpose of observing flows, turning movements, and queue lengths. Figure 4.3.2.2 shows two sample video frames captured during this experiment.
3. Network paths: The UAS traversed an urban street network consisting of seven intersections for the purpose of observing path flows, speeds, densities, queue lengths, and vehicle trajectories. Figure 4.3.2.3 shows two sample video frames captured during this experiment.
4. Parking lot monitoring: The UAS made a tour of surface parking lots for the purpose of assessing their utilization. Figure 4.3.2.4 shows a sample video frame captured during this experiment.

Each of these experiments can relate to real-time transportation management and off-line transportation planning applications. The choice of experiments resulted from discussions among transportation researchers, the UAS operator, and several regional operating agencies. The UAS was flying at an altitude of 500 ft and an air speed of 30 mph while transmitting the video images collected by its on-board camera to the ground station in real-time.

What follows are qualitatively encouraging conclusions and observations:

1. The Federal Aviation Administration official and the representatives of the helicopter unit of the Columbus Police Department, after ground- and air-based inspections, approved the operation of the UAS in an area close to the Columbus international airport, and the regional Don Scott airport, as well as several police and hospital heliports. They attended the first flight from preflight planning, through take-off, to landing, and left apparently satisfied.
2. The UAS followed its pre-programmed flight plan covering the locations of interest accurately.
3. Flows, speeds, densities, weaving, intersection turning movements, queues, and parking utilization were observed directly from the video images. Most of these variables are readily evident in Figures 4.3.2.1 through 4.3.2.4. Although it is not clear from these figures, speeds can be computed from a sequence of images.
4. One of our flights occurred on an overcast day, and the FAA ordered other aircraft to operate under Instrument Flight Rules (IFR). Because the UAS normally operates below the controlled airspace, we were able to fly. Moreover, any other manned aircraft would have needed to fly above the low cloud ceiling and not have been able to image the ground. As a result of this experiment, it is evident that flying low may be advantageous in providing aerial surveillance when manned aircraft would be unable to do so.

What follows are issues that require further investigation or refinements:

1. Identifying distinguishing characteristics in individual vehicles did not seem possible given the resolution and, therefore, observing vehicle trajectories when a vehicle leaves the field of view and reappears would not have been possible with the data collected. This challenge may be overcome by improving the resolution of the on-board camera.
2. Beyond a distance of 1 mile there was some radio interference corrupting the images transmitted to the ground over sporadic periods of up to a few seconds in duration. This problem was thought to be due to the urban nature of the environment. Such interference can be addressed by utilizing a dedicated communication channel.

The turning radius of the fixed wing UAS is such that changing directions at waypoints can take some time and space until the vehicle regains its course. When traversing roadway links of lengths less than 400 ft, large portions of the links went unobserved. This can be addressed by utilizing a clover-leaf type flight plans when sharp turns are required to maintain a good view of an urban street network or further development of the UAS.

Clearly, the above discussion is preliminary and qualitative in nature as the collected data has yet to be quantitatively analyzed. Such analyses are expected to be valuable for reaching firmer conclusions regarding specific potential benefits and barriers. Nevertheless, the conducted field experiments provide good indications that the application of the UAS technology to surface transportation surveillance seems viable and potentially valuable.

In addition, these experiments clearly point to the need for continued experimentation and refinement in order to achieve further advancements in this area.

Conclusions and Recommendations

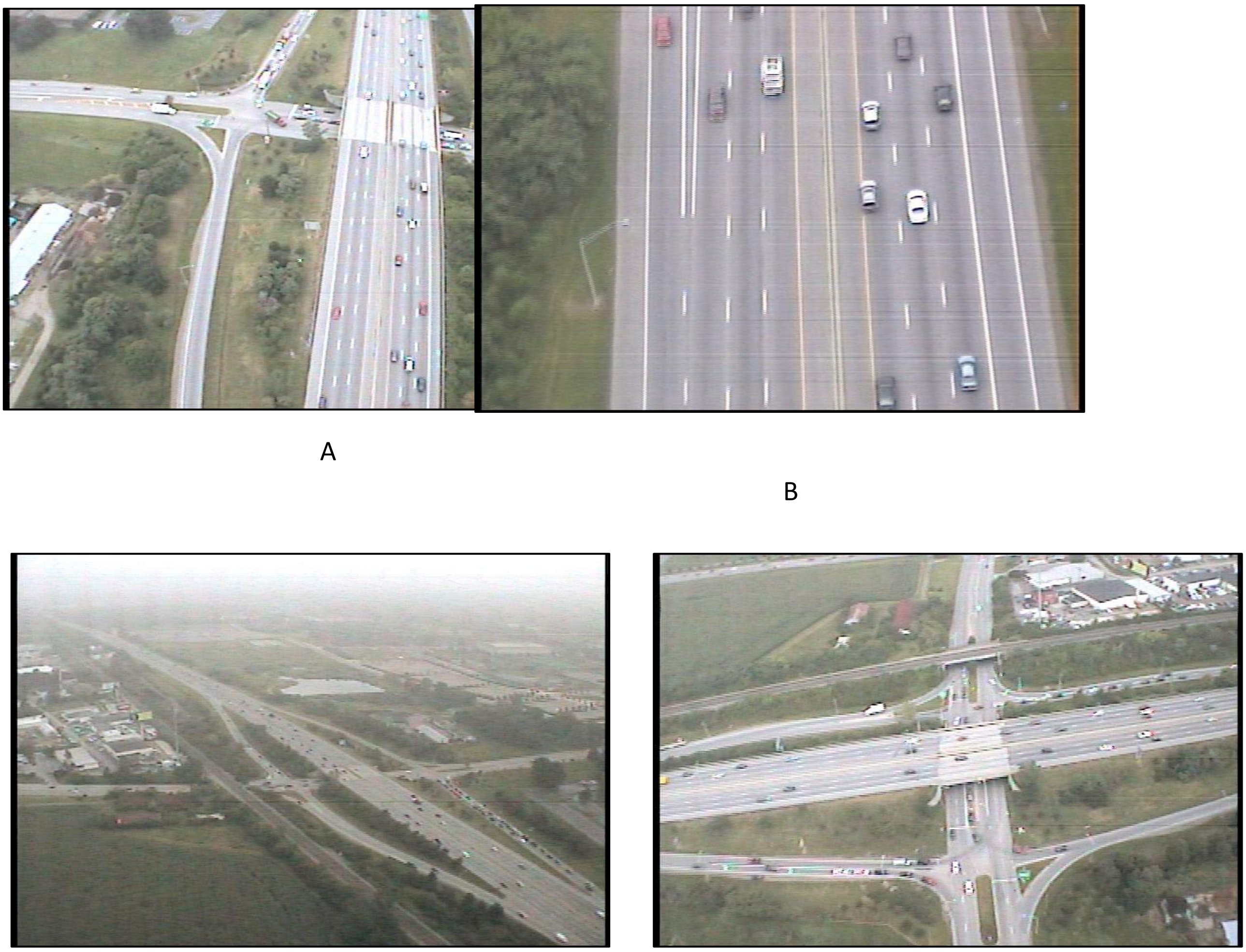
Airborne cameras offer many benefits over ground-based detectors. They offer mobility to cover a large area and potentially greater speed than surface vehicles. The bird's eye view could enable new measures and new surface transportation studies. UASs promise to be the lowest cost aircraft to operate. As a result of their characteristics, UASs have changed the cost/benefit relationship for airborne data collection. A UAS has a rapid launch compared to manned aircraft, where the pilots must get to the vehicle and potentially taxi before takeoff. UASs are both fast and highly maneuverable compared to ground vehicles, with the speed coming not only from velocity but also the simple fact that a UAS can travel in almost a straight line and avoid congestion on the road network. While the lower cost of operation compares favorably to conventional aircraft.

RECOMMENDATION: It is recommended to analyze the possibility of using UASs for transportation studies where data from airborne cameras can be useful. UASs offer mobility to cover a large area and potentially greater speed than surface vehicles. The bird's eye view could enable new measures and new surface transportation studies. UASs promise to be the lowest cost aircraft to operate. As a result of their characteristics, UASs have changed the cost/benefit relationship for airborne data collection.

UASs could potentially be justified on the basis of primary, emergency-related applications, e.g., incident response and verification. Once in possession of the aircraft for these low frequency emergency-related applications, marginal cost of operations would be low, and the aircraft could prove cost-effective for non-emergency traffic surveillance applications, such as measuring network usage or quantifying turning movement at intersections. This paper has described several of these applications, as well as barriers to the use of UASs for traffic data collection.

RECOMMENDATION: It is recommended to analyze the complementary use of the same UASs for different applications. For instance, UASs deployed to provide primary, emergency-related applications, e.g., incident response and verification; could be used in between these low frequency emergency-related applications, for non-emergency traffic surveillance applications, such as measuring network usage or quantifying turning movement at intersections, with a reduced added marginal cost.

To further understand the potential applications and barriers, four experiments were conducted. The set of experiments have led to encouraging conclusions and identification of issues requiring further attention.



A B C D

Figure 4.3.2.1, Four views of the SR 315 freeway interchange with Lane Ave extracted from video captured in real-time, remotely from a UAS. (A) Wide angle view looking south while flying along the freeway, (B) telephoto view looking south while flying along the freeway, (C) distant view looking northeast while circling a network of arterial streets, (D), closer view looking west while circling the same network.

A B

Figure 4.3.2.2, An example of circling a facility with the UAS, (A) looking west at the intersection of the Kenny Rd and Lane Ave, (B) a second view looking east at the same intersection illustrating the changing perspective when circling a facility. Note that the queue lengths and turning movements are visible in these images.

A

B

Figure 4.3.2.3, An example of circling a network with the UAS, (A) looking east at the eastern leg of the network, Fife Rd running from Lane Ave on the left to Woody Hays on the right. Note the long queue backed up from Woody Hays, (B) looking west at the northwest intersection of the network, Kenny Rd and Lane Ave.

Figure 4.3.2.4, A sample view from the UAS showing the utilization of three parking lots.

1.6. Case Study – Mapping

1.6.3. Using UAS (senseFly) for urban mapping & flood prevention in Dar es Salaam (Tanzania)

Introduction

Dar es Salaam, Tanzania's largest city, The World Bank (TWB) is working with government departments on a range of development projects. These include: transportation projects, flood mitigation schemes, and other preparedness and assessment projects.

The challenge the organizations faces on the ground is a lack of accurate, up-to-date geographic data of the city. TWB's team wants to improve its understanding and identification of flood risk areas, largely driven by the devastating effect floods can have on the City's informal settlements.

The problem is that satellite imagery of the region is expensive and doesn't offer full coverage. The cost of using a manned aircraft is also extremely high. This is why, in 2015, TWB decided to look into how drones could help – the idea being to use them to collect high-resolution geospatial data, cost effectively.

RECOMMENDATION: Fixed wing UAS can be used for collecting accurate geographic data (ortho imagery, elevation model) in areas where satellite imagery is not available or is expensive. The cost of using a manned aircraft is also extremely high.

RECOMMENDATION: Elevation model created from UAS data helps in identifying the road infrastructure in low lying areas that are susceptible to flooding.

Thus TWB turned to Drone Adventures, a non-profit group that uses senseFly eBee mapping drones, and the team at Humanitarian Open Street Map (HOSM).

Application / Methodology

The Dar es Salaam project involved two missions, one month apart.

Accoridng to Adam Klaptocz, co-founder of Drone Adventures "The first trip to Daar es Salaam was mainly a feasibility analysis and preparation for the second mission, where the majority of the data collection was carried out.

The project's target ground resolution was highly precise, just 5 cm (2 inches) per pixel. The area to map was huge, and a large chunk of downtown Dar es Salaam is mostly an informal communities made up of shelters and shacks. The total mapping coverage area was over 88 km2 (55 mi2).

The team flew two senseFly eBee drones during the first mission, and three during the second, managing these flights via the drones' eMotion ground station software. Since landing zones were sparse in such a built-up urban environment, the team used a school yard as the project's primary takeoff and landing location.

Managing the data

One of the biggest challenges was keeping track of the drone-collected data and the team's image processing work.

"We flew multiple flights over several days in different conditions (…) so that we could pack in as much data collection as possible during our trip," Klaptocz explains. "The changing weather meant lots of differences in image lighting, so we needed to prune the data a little afterwards."

TWB's team liaised with each ward's officer about the work taking place. They explained what was happening with the drones, what data was being collected and how outputs such as orthophotos and digital surface models would be used.

The local leaders were enthusiastic. "They liked the new technology, but aside from the cool factor they understood the potential impact of the data—they were aware of the need and value of up-to-date geospatial information," Klaptocz says.

Conclusions and Recommendations

The dataset the mission produced was huge and detailed; and is now proving of great value to many organizations and government departments. The dataset comprises ten orthophotos, produced by processing over 20,000 aerial images. This dataset was delivered to TWB, whose team used it to generate accurate 3D elevation models as shown in image below. This 3D elevation models were used, in turn, to run flood simulations that help identify at-risk areas.

This drone-derived elevation model, produced using InaSAFE software, shows the varying vulnerability of buildings and roads to flooding in Dar es Salaam's Tandale Ward. Edward Anderson of TWB, who was involved on the ground, said about the mission: "The novelty value of the drones increased interest and participation in the project, and engaged our government clients. The main orthophoto the drone data produced is already being used for roof print digitisation, and we're planning to use the digital model for inundation mapping. I see drones as having great cross-sectoral potential."

https://www.sensefly.com/fileadmin/user_upload/sensefly/user-cases/2016/senseFly-Case-Study-Dar-es-Salaam.pdf

1.7. CASE STUDY – LAW ENFORCEMENT

1.7.3. Evaluating the Use of UAS for Transportation Purposes – Crash Scene Reconstruction Technologies

Reference: Author - Colin Brooks, Michigan Tech Research Institute, "Evaluating the Use of Unmanned Aerial Vehicles for Transportation Purposes – Crash Scene Reconstruction Technologies".

Introduction

Whenever a traffic accident happens, police have the responsibility to secure the site and gather all the evidence and clues as accurately as possible before cleaning up the site and opening it to the traffic. All the information gathered from the accident scene and surrounding area is used to reconstruct the crash scene. This helps in answering many questions such as what was the cause of the accident?

Michigan Tech Research institute (MTRI) has performed variety of studies for the use of UAS in many areas. They have worked with local, state, and federal agencies in the use of UASs for data collection and assessment such as:

- Michigan Department of Transportation
- United States Department of Transportation
- USDA Forest Service
- Utility companies
- Class I Railroad
- Pipeline service company

This case study briefly discusses the potential use of UAS for crash scene reconstruction based on the outcome of a demonstration by MTRI to Michigan State Police (MSP) and Bloomfield Township Police Department.

Application / Methodology

The first ddemonstration was for Michigan State Police (MSP) at MTRI using small DJI Phantom 2 quadcopter and GoPro-Hero 3. This demonstration highlighted rapid collection of aerial imagery of a crash scene investigation using low-cost (~$1,000), commercial off the shelf technologies.

Imagery outputs provide a good overview of crash scene, but due to the lower resolution of GoPro imagery, these should not be used to make measurements. Therefore, measurements were collected by MSP officer for use by crash scene investigators in tandem with aerial imagery.

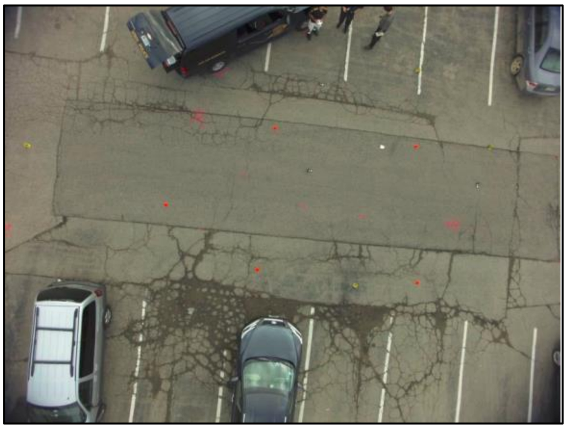


Figure 4.5.1.1: Demonstration at MTRI

The second Demonstrations at the Bloomfield Township Police Department using a Bergen Hexacopter (Figure 4.5.1.2) (flights up to 20 minutes; $5,400) and Nikon D800 digital camera ($3,800 with lens).

A mock traffic incident was set up, with tire marks left by police cruiser, and crash scene markers placed by crash scene investigators from local police. Due to the high resolution, 36 megapixel images, quantitative measurements could be made using the UAS collected aerial imagery which was not possible in the earlier demonstration due to low resolution camera.

Each crash scene marker was about 20x20 pixels per flat rectangular area, with a pixel equal to 1/11 inch (0.0875 inches) or 2.2 mm.

Figure 4.5.1.2 – Bergen Hexacopter

Figure 4.5.1.3 – A mock incident traffic set up.

Conclusions and Recommendations

As demonstrated in the second test, the high resolution imagery obtained through UAS can be used for reconstructing the crash scene using the quantitative measurements.

- The overhead images from the UAS helps in looking at a broader picture and helps in capturing the information that can sometimes be missed by the police staff.
- UAV technology can be implemented and be useful – daytime is currently more practical to implement.
- UAVs can be implemented into crash scene investigations to provide both qualitative and quantitative information concerning the incident.
    - Lower resolution imagery can quickly provide an overview
    - High resolution imagery can provide measurements concerning how fast vehicles were moving at the time of impact can be calculated.
    - Can potentially reduce time spent measuring data (increase safety, reduce traffic impact)

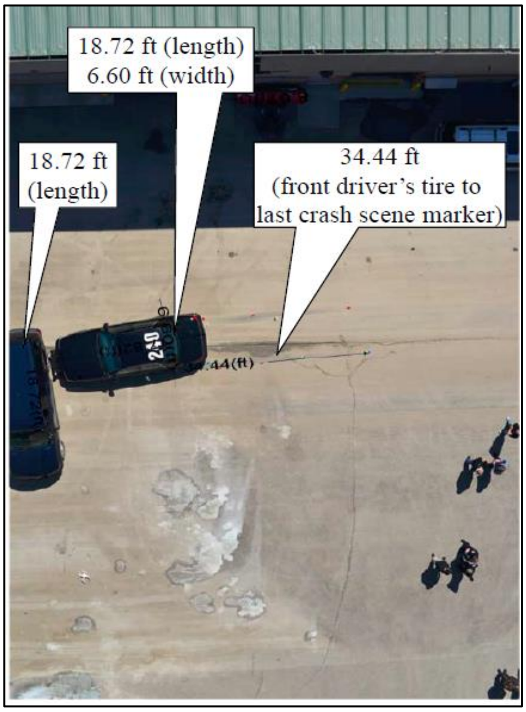


Figure 4.5.1.4 – Mock incident reconstruction

"By using known distances and an approximated drag factor for the road surface, with 15-20 minutes of work, I was able to estimate the speed of the vehicle at 28 mph through imagery captured by the UAS. In training environments, we will test skids at 30 mph, so everything seems to be in line with reality." – St. Clair County Officer, Crash scene investigation team.

RECOMMENDATION: UAS can be used for reconstructing the crash scenes by using the quantitative measurements.

- The overhead images from the UAS helps in looking at a broader picture and helps in capturing the information that can sometimes be missed from a land perspective
- UAVs can be implemented into crash scene investigations to provide both qualitative and quantitative information concerning the incident.
- Lower resolution imagery can quickly provide an overview
- High resolution imagery can provide measurements concerning how fast vehicles were moving at the time of impact can be calculated.
- Can potentially reduce time spent measuring data (increase safety, reduce traffic impact)

According to **Crash Investigation and Reconstruction Technologies and Best Practices - US DOT**:

- There is no one-size-fits-all solution in traffic crash reconstruction.
- Each agency should examine their activities and resources to decide what is best for their environment.
- Each agency will have a different traffic environment, organizational structure, political establishment, and funding constraints.

- It is recommended that an agency familiarize themselves with the practices and technologies presented in this report and identify those that best match their organizational practices, requirements, and needs.
- The benefits and budgetary information provided for each technology can be used to justify expenditures or negotiate budget for purchase, training, operation and maintenance of the system.
- This report collects crash reconstruction technology and best practices data to inform those decisions.

4. UAS SURVEY

1.8. Road Administrations, Consultants / Contractors Survey

A survey was carried out for Road Administrations, Consultants and Contractors to gather the information for the use of UAS. This survey was distributed in early October and most of the responses were received by the end of October.

Thirty five (35) responses were received from different parts of the world, mostly from North America. Twenty five responses were from the Road Administrations and remaining from Consultants and contractors. These responses are briefly shown I the table below.

	Road Organization	Consultants and Contractors
Number of response	25	10
Has your organization used UAS (Unmanned Aerial System, Drone) for any project related to road sector (including construction, maintenance or other)?	Yes - 14 No -11	Yes - 6 No -4
If Yes, How have you applied UAS technology? Select multiple as applicable.		
a. Pre-Construction Surveys (Design-to-Construction)	5	3
b. Construction Engineering & Inspection	7	5
c. Asset Inventory/ Maintenance	4	5
d. Traffic management	5	1
e. Traffic accident management	0	0
f. Natural disaster response	4	3
g. Other emergency situations	0	1
h. Law enforcement	0	0
i. Wild life management	0	0
j. Infrastructure security	1	1
k. Other (please specify) _______________	4	0

As shown in above table majority of the UAS use is in Construction Engineering and Inspection areas followed by Asset Inventory/ Maintenance and Pre-Construction Surveys (Design-to-Construction). UAS has not been used in Law enforcement, Wild life management and other emergency situations.

Those who answered NO to the use of UAS, were asked if their organization is thinking about using UAS. The answers are summarized below.

	Road Organization	Consultants and Contractors
If NO, Is your organization thinking about using this technology?	8	4
If YES, What kind of data will be collected?		
a. Pre-Construction Surveys (Design-to-Construction)	3	2
b. Construction Engineering & Inspection	8	3
c. Asset Inventory/ Maintenance	8	4
d. Traffic management	4	1
e. Traffic accident management	3	0
f. Natural disaster response	4	2
g. Other emergency situations	2	1
h. Law enforcement	1	0
i. Wild life management	1	0
j. Infrastructure security	1	0
k. Other (please specify) _______________	0	0

Organizations that are thinking of using UAS are mostly interested in again Asset Inventory/ Maintenance and Construction Engineering & Inspection, followed by Natural disaster response, Traffic management and Pre-Construction Surveys (Design-to-Construction).

The survey questionnaire and summary of the responses is (will be) attached as an appendix.

5. CONCLUSIONS

Based on the authors observation in the field and extensive literature research, the following conclusions were made:

Bridge Inspection:

UAS can be used in the field during bridge inspections safely. Based on the UAS size, weight, controllability and built-in fail safes, the risk to inspection personnel and public is very low.

UAS are more suitable as a tool for inspections of larger bridges, but there can also be some advantages for smaller bridge inspections. (i.e. short span bridges and culverts)

UAS themselves cannot perform inspections independently but can be used as a tool for bridge inspectors to view and assess bridge element conditions.

Defects can be identified and viewed with a level of detail equivalent to a close-up photo.

Measurements can be estimated from images, but tactile functions (e.g., cleaning, sounding, measuring, and testing) equivalent to a hands-on inspection cannot be replicated using UAS.

UAS with the ability to direct cameras upward and the ability to fly without a GPS signal are important features when using this technology as an inspection tool.

UAS technology is evolving rapidly and inspection-specific UAS features are just coming into the marketplace that will increase their effectiveness as it relates to bridge safety inspection.

In some types of inspections, a UAS has the capabilities to be used in lieu of an under bridge inspection vehicle and would provide significant savings. These savings would come in the form of reduced or eliminated traffic control and reduced use of under bridge inspection vehicles and lifts.

UAS can provide a cost effective way to obtain detailed information that may not normally be obtained during routine inspections.

UAS can provide a very efficient way to collect infrared images of bridge decks and elements as they can be equipped with an infrared camera.

Safety risks associated traffic control, working at height and in traffic could be minimized with the use of UAS.

Automated Asphalt Pavement Inspection:

The results showed the potentiality of QUAS as a device equipped with a set of automatic digital imaging systems for automated asphalt distress detection with a high precision. This system is possibly implemented in field conditions and can be developed in the network of roads as a surveillance agent robot.

PSVM method can be successfully applied to classify cracks and is capable of generating new features for cracking distress threshold selection and classification.

Gravel road Inspection:

The research has demonstrated the capability of UAV-based remote sensing for rural road condition data collection. The developed system can provide detailed and accurate measurements of road surface distresses, and thus improving the efficiency of road condition data collection.

The developed 3D surface reconstruction approach has been applied to the acquired imagery, and the 3D shapes of surface distresses such as potholes, ruts have been generated.

With the advancement of UAV and sensor technologies, more powerful and safer inexpensive UAVs will emerge onto market. Such UAVs will supply longer endurance in mission to serve larger community. Innovative sensors, such as infrared cameras, Lidar can be integrated to the current system. This will allow for more efficient road condition assessment in fully automatic mode.

Avalanche Monitoring:

Other test flights demonstrated the ability of the UAS to accurately drop packages at pre-determined GPS locations and heights. Such missions could be used to drop explosive charges at predetermined avalanche trigger zones.

During warm days, the air is thinner, when combined with the altitude, it can degrade the ability of the heavier UAS to operate in the afternoon.

UAS showed considerable potential for aerial roadway surveillance and avalanche control.

Traffic - Driver Behavior Monitoring and Crash Scene Investigation:

Using the video footage collected from UAS, driver error was investigated throughout a full year, determining what common driving errors were being made within the roundabout and how they change over time provided a proxy for driver adaptation rates and improved safety levels.

A UAS has a rapid launch compared to manned aircraft, where the pilots must get to the vehicle and potentially taxi before takeoff.

UASs are both fast and highly maneuverable compared to ground vehicles, with the speed coming not only from velocity but also the simple fact that a UAS can travel in almost a straight line and avoid congestion on the road network.

UAS can be implemented into crash scene investigations to provide both qualitative and quantitative information concerning the incident.

General Conclusions:

There is no one-size-fits-all solution, each agency should examine their activities and resources to decide what is best for their environment. As each agency will have a different traffic environment, organizational structure, political establishment, and funding constraints.

It is recommended that an agency familiarize themselves with the practices and technologies presented in this report and identify those that best match their organizational practices, requirements, and needs.

The benefits and budgetary information provided for each technology can be used to justify expenditures or negotiate budget for purchase, training, operation and maintenance of the system.

1.9. Overall Success

All the case studies presented in section 4 of this report are considered as a success by the respective authors and the project team, although some limitations to each of the different uses were noted. The UAS has been successfully used in monitoring Highway Construction, Evaluation of delamination on concrete bridges, Inspection of bridge components, Asphalt pavement distress survey, Monitoring the condition of gravel roads, Avalanche monitoring, Monitoring driver behavior, Mapping for flood prevention and for Reconstructing crash scene. Although most of the case studies were conducted in High Income Countries, success was also achieved in Low Middle Income Countries, and most of the different uses presented in this report are useful to all countries once they adapt to the national and local context.

Based on the survey results conducted as part of this report, 25 organizations have used UAS for various projects. Majority of them have expressed satisfaction and no concerns for UAS projects they were involved in. Over 90% respondent are planning for more projects and are expanding the use and scope of UAS.

Considering the above facts and figures, it is safe to conclude that the use of UAS is a success. There are numerous benefits in using this technology safely and effectively and it is foreseen that more applications will be growing in the following years.

1.10. Areas of Improvement

Data storage - The amount of data collected from UAS is huge (in Giga Bytes), some organization have expressed concern with storing this data, anticipating more data to be collected in future.

Lack of standards and specifications in current guidelines within road administrations - also need to be addressed in order to use UAS to its full potential.

Safety – One of the biggest concern from regulatory authorities is the safe use of UAS in public areas. Although current generation of UAS has Obstacle Avoidance system to prevent crashing in to structures, a system that is capable of preventing a crash in a situation where UAS loses control can greatly reduce the risk to public.

Battery life – Some low end UAS has limited flight time, varying from 15 to 30 minutes, this reduces the efficiency. A longer battery life will certainly improve the overall efficiency.
More extensive studies need to be done over a diverse region to validate the performance in terms of accuracy and efficiency.

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