III. Applicable Platforms

3.1. Single Rotor Helicopters

Single rotor unmanned aerial vehicles (UAVs) are commonly available designs. With a large selection of manufacturers and models, single rotor UAVs offer a wide range of applications for remote sensing. Considering the variety of models available, it would be easy to categorize the potential application based on the specifications of each model. With UAVs ranging from a total length of 2 feet and a payload capacity 0.2 lbs and up to 5 feet in length with payloads of 10 lbs, any application can be suited with the appropriate aircraft. In addition, some manufacturers specialize in aerial imaging and offer custom packages designed for specific observations. While these more advanced packages can be expensive, several capable single rotor UAV platforms range from $700 up to $5,000. Depending on the scope of the observations to be made, an acceptable model can be chosen to maximize data collection and minimize total investments. Table 1 is a sample of single rotor UAVs currently available.

Manufacturer	Model	Length (in)	Height (in)	Main Rotor (diam. in)	Weight (lbs)	Payload (lbs)	Power Source	Cost
Rotomotion	5R5	26	10	31	4	0.2	Battery	unavailable
Rotomotion	5R20	60	22.5	75	16.5	3.3	Battery	unavailable
Rotomotion	5R30	66	24.5	78	15.4	15.4	Gasoline	unavailable
Rotomotion	5R100	58	27	19	35	6	Battery	unavailable
Advanced UAVs	AT-10	52	14.5	67	10.5	3.3	Battery	unavailable
Advanced UAVs	AT-20	61	22.5	75	15.4	10	Battery	unavailable
Advanced UAVs	AT-30	64.5	24.5	78	15.4	11	Gasoline	unavailable
Advanced UAVs	AT-100	58	27	79	35	17.6	Battery	unavailable
Bergen	44-Mag	54	18	29.5	unavailable	unavailable	Battery	$5,450
Bergen	e-observer	52	17.5	31.5	19.8	8	Battery	$3,000
Bergen	Intrepid-Tazer	54	18	27.5	11.5	10	Battery	$1,170
Bergen	Intrepid-90	53	17	28	10	unavailable	Battery	$1,299
Align RC	T-REX 550E	45.5	13	47	4	unavailable	Battery	$750
Align RC	T-REX 700E	53	14	61.5	4	unavailable	Battery	$1,200

Table 1. A sample of single rotor UAVs available commercially.

Single rotor helicopters come with two engine options, battery powered and gas/nitro powered. While gas powered models have the advantage of extended flight times, battery powered models can be better suited to collecting remote sensing data. The internal combustion engine for remote controlled devices generates extra vibrations as it runs which could lead to a less stable platform on which to mount a camera. These engines are also two-cycle and require oil to be mixed into the fuel. This oil is typically not burned in the engine and is expelled through the exhaust pipe. This leads to smoke being generated which can obstruct the view of the surface being sensed depending on the wind direction and viewing angles. The unburned oil also poses an issue as it tends to be deposited on objects as its expelled from the exhaust pipe. Cameras, lenses, and other equipment can become covered in the oil which leads to a reduction in the image quality or equipment malfunction.

Battery powered models do not have the issue with oil coating equipment and, since internal combustion does not occur, very little vibration is produced. This leads to a more stable platform that is better suited to capturing high quality remotely sensed data. The disadvantage of having a reduced flight time (typically less than 20 minutes) restricts the usage of these systems to small areas or short flights with regular battery replacements. This would include short sections of roads (100 - 600 ft sections of unpaved roads as shown by Brooks et al.) or a single bridge inspection at a time. Figure 12 shows a Bergen Tazer 800 being deployed on an unpaved road to collect

imagery to perform distress detection. Most single rotor helicopters are not suitable for confined spaces as they tend to be too large.

Figure 12. Bergen Tazer 800 being deployed over an unpaved road to collect road distress data. Similar data could be collected for bridge deck condition.

Current transportation-related uses of single rotor UAVs have been limited, but some projects have been well documented. The Washington State Department of Transportation (WSDOT) utilized a Yamaha R-Max UAV. This UAV has a 10 foot rotor span and weighs approximately 150 pounds (which does not qualify it to be a small-UAV, i.e., a total weight of < 55 lbs.). While this vehicle is primarily used in Japan for crop dusting, there are a few in the United States that are being used for research purposes (McCormack, 2008). Figure 13 shows this UAV, which was operated by Georgia Tech University, equipped with pan-tilt cameras.

Figure 13. The Yamaha R-Max UAV used by the WSDOT in 2008.

The goals of this project was to demonstrate that the on-board sensor could follow a predetermined path, set with waypoints, and provide surveys for snow clearing operations and

traffic monitoring applications. This test also proved to be an effective method to survey roadside terrain for construction and security purposes. Another research project has focused designing a network of single rotor UAVs to carry loads to unique locations or work together to track moving, ground based objects (Maza et al.).

3.2. Multi-rotor Helicopters

Multi-rotor helicopters are helicopters that have multiple rotors that help with stable flight. Currently available models includes quadcopters (four propellers or rotors), hexacopters (six rotors), and octocopters (eight rotors). Table 2 provides a representative example of state-of-the-art multi-rotor platforms. The examples range from micro-UAVs (e.g., Crazyflie) to small-medium sized UAVs (e.g., DJI Phantom, Aeryon Scout, Bergen Hexacopter, etc.) (Figure 14). From the available information, such small platforms can cost between $175 and $480, but pricing is higher for the more complex UAVs, such as the Bergen and Aeryon platforms. Complete pricing for these platforms is typically only available via quotes; as a representative price, the Bergen hexacopter cost our team $5,400 including spare batteries.

Figure 14. The Crazyflie (left) DJI Phantom (left-center), Aeryon Scout (right-center), and Bergen Hexacopter (right).

Payloads and flight time also differ between each platform but are generally less than those of similarly sized single rotor helicopters. The advantage that multi-rotor models have over single-rotors is that they are more stable and therefore are easier to fly and provides an easier to use platform for collecting remote sensing data. These systems are also safer to operate than single-rotor systems.

Like single rotor helicopters, multi-rotor helicopters can incorporate multiple types of payloads. The representative examples are able to fly thermal remote sensors, gas and liquid detectors, and video/still cameras. Additionally, the Aeryon and DJI Phantom Vision feature gyroscopic sensors that adjust the camera's orientation to help it remain on-target. Flight time varies and is dependent on the weight and capacity of each platform. The examples from Table 2 have flight times that range from 5-20 minutes, with the Aeryon platforms providing the most flight time. Some models have the capability to fly programmed waypoints which would be useful for imaging larger areas. Most multi-rotor helicopters, however, are limited to flight times of less than 20 minutes.

Manufacturer	Model	Type	Length (in)	Height (in)	Weight (lbs)	Payload (lbs)	Cost	Flight Time (min)
Dragonfly	X6	Hexacopter	34.25	12.6	2.20	1.1	-	15-20
Aeryon	Scout	Quadcopter		8.5	3.00	-	-	25
Aeryon	Skyranger	Quadcopter		9.3	5.30	-	-	50
DJI	Phantom	Quadcopter	13.77	7.48	-	-	$479	10-15
Blade	350QX	Quadcopter	18.3	5.43	-	-	$470	5-14
Crazyflie	-	Quadcopter	3.54	-	0.04	0.02	$180	7
Bergen	-	Hexacopter	-	-	8.81	11.02	-	16
DJI	Vision	Quadcopter	Specifications available end of 2013				$1,200	15
Spiri	-	Quadcopter	-	-	-	0.22	-	10-15
Steadi Drone	QU4D RTF	Quadcopter	22.83	4.3	2.64	<1.75	$1,640	25
Aibot	X6	Hexacopter	40.8	18	4.40	4.4	-	30
Microdrone	md4-200	Quadcopter	21.4	-	1.76	0.44	-	35
3DR	Iris	Quadcopter	21.65	4	2.82	0.8	$730	9-14

Table 2. Representative example of multi-rotor helicopters and their specifications.

MTRI has used multi-rotor technology in the analysis of unpaved road distresses and this related research can be applied to sensing of transportation infrastructure such as bridges. The DJI Phantom has collected imagery concerning potholes, washboarding, and improper drainage for unpaved roads. Imagery is reconstructed as a 3D model, which aids in the analysis of such distresses (Figure 15). DJI is releasing an updated quadcopter, called the DJI Vision. Due to the success of the Phantom, MTRI recommends the purchase of the Vision, which will be available by the end of the 2013. Upgrades include an on/off switch, larger battery compartment, longer flight time (up to 15 minutes), and integration with a built in first person viewer (FPV) for Apple's and Android's phone or tablets. Apple's tablet and phone integration with the FPV will indicate the speed, altitude, direction, battery status, and distance up to 300m from the pilot. Furthermore, the pilot will be able to control the on-board payload device by moving the tablet or phone during flight.

Figure 15. Unpaved road imagery collected by a multi-rotor platform, which has been reconstructed as a 3D model.

In addition, the Aibot X6 hexacopter also has the capability to inspect infrastructure. Although the Aibot X6 platform is the biggest in size as compared to the other platforms in Table 2, it has completed a structural inspection of a dam in Italy. The imagery was reconstructed as a 3D model, where distress features are visible. This hexacopter also has the capability to hosts a variety of payloads that can collect data, such as thermal, LiDAR, air/gas sensor, and multispectral imagery. Depending on the payload, flight time is estimated to last 30 minutes. Similar in size and quality to the DJI Phantom is the Blade 350QX. Using the GoPro Hero

payload, this platform is also capable of collecting imagery pertaining to a wide variety of interests. The technology also includes a smart mode, which minimalizes the amount of work the pilot must do in order to keep the platform flying.

Micro-UAVs have attracted significant interest for a wide range of applications, from surveillance (Croom et al., 2004, Kim et al., 2003), search and rescue (Bourgault and Durrant-Whyte, 2004), culvert inspection (Serrano, 2011), 3-dimensional mapping (Jutzi et al., 2013), atmospheric measurement (Rogers, 2013), and forest inventory (Wallace et al., 2012).

For infrastructure inspection and, more specifically, transportation infrastructure, there has been some research into using multi-rotor micro-UAVs. Lin and Saripalli (2012) developed a method to detect and track roads from imagery taken from a micro-UAV. Serrano (2011) developed a quadcopter platform for inspecting culverts. Jiang et al. (2013) developed a UAV-based system for power line inspection. Russ et al. (2012) developed a system for detecting car-like objects in an earth-fixed point cloud measured via LIDAR on a micro-UAV.

3.3. Fixed Wing

Fixed wing UAVs are typically powered by a single electric motor. This UAV design has the advantage of extended flight times, with many systems capable of autonomous flight. The extended flight times are due to less energy needed to keep a plane flying than a helicopter. A helicopter platform has to constantly use its motors to create down force as well as provide directional stability and movement while an airplane just needs to create forward momentum to stay aloft. The reduced energy consumption allows for significantly greater flight times over helicopter platforms (up to 60 minutes in affordable <$25k systems vs. 20 minutes for helicopters).

The disadvantage for fixed wing platforms however is that they need space to be launched and recovered. Helicopter platforms have the ability to take off and land vertically so they only need a space that is large enough for their rotor(s) to operate without striking nearby objects. Fixed wing platforms can be launched by hand (for smaller systems) or by a launch catapult (for the larger systems) to get airborne. For landing, instead of landing back in the same space that they took off from, they need to have a short runway. The size of the runway depends on the size of the of the aircraft. Another disadvantage is that only the larger and more expensive (>$20k systems) would be able to fly a DSLR camera that single or multi rotor helicopters are capable of. One design that keeps costs reasonable (about $6k) is the LA 300 from Lehman Aviation which flies the Nokia Lumia cell phone camera with a resolution of 41 MP (Figure 16).

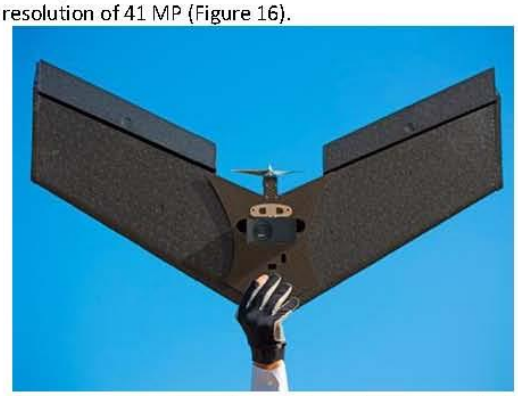

Figure 16. Lehman Aviation LA 300 showing the Nokia Lumia cell phone camera.

Company	Model	Wingspan	Length (in)	Weight (lb	Engine Type	Cruise Speed	Max Speed	Wind Tolerance	Range (mi)	Endurance	Payload (lbs)	Camera	Price
Altavian	Nova Block III	108	67	15	Electric	35	70		50	90		Various	
Sensefly	Swinglet Cam	31.5		1.5	Electric	22	22	16	2	30		16 MP	
Sensefly	eBee	38		1.5	Electric	22	35	28	2	45		16 MP	
AeroVironment	Puma	110	55	13	Electric	23	51		9	60		Various	
AeroVironment	Raven	54	36	4.2	Electric	20	50		6	90		Various	
AeroVironment	Wasp	28.3	15	0.95	Electric	25	40		3	45		Various	
AeroVironment	Wasp AE	39.6	30	2.85	Electric	23	52		3	50		Various	
MarcusUAV	Zephyr 2	54		4	Electric	30	90	40	25	60		Various	
Aurora	Skate	24	19	2.2	Electric	3	31		3	60		Various	
Lehmann Aviation	LA 100	36	17.7	1.9	Electric	12	50	22	0.3	5	GoPro	12 MP	1356.00
Lehmann Aviation	LA 200	36	17.7	2	Electric	12	50	22	2	30	GoPro	12 MP	3411.00
Lehmann Aviation	LA 300	36	17.7	2	Electric	12	50	22	9	30	Nokia Lumia	41 MP	6836.00
Lehmann Aviation	LM450	36	17.7	2	Electric	12	50	29	2	30	GoPro	12 MP	8206.00
Lehmann Aviation	LP960	36	17.7	2.75	Electric	12	50	29	2	25		16 MP	9576.00
Lehmann Aviation	LV580	36	17.1	2	Electric	12	50	29	2	40	Integrated Camera		13686.00
Falcon UAV	Falcon	96	50	9	Electric	25	55		6	90	Integrated Camera	24.1 MP	55000.00
Trimble	UX5	39.4	26	5.5	Electric	50		40	3	50	Integrated Camera	16.1 MP	
Trimble	X100	39.4	23.6	5	Electric	50		40	3	45	Integrated Camera	10 MP	
ARA Force Protection	Nighthawk	26		1.9	Electric	25	40		6	60	Integrated Camera and IR		35000.00

Table 3. Table of available fixed wing UAVs.

Fixed wing UAVs work best for wide area coverage of features. This is due to their extended flight times and waypoint software (Table 3). Typical software for these systems allow you to program in waypoints and/or designate an area of interest to collect overlapping imagery for enabling 3D data creation. The Sensefly UAVs (Figure 17) come with software that will automatically plan out missions (set waypoints, speed and altitude for the UAV) based on the area that is drawn within the software.

Figure 17. The Sensefly fixed wing UAV.

3.4. Blimp/ balloon/ aerostat

A blimp or aerostat is a different kind of UAV than those reviewed so far. They consist of an envelope made of a gas impermeable material and can be shaped in what is commonly considered to be a "blimp". Stabilizing fins are generally added to the back of the envelope for a more hemispherical / spheroid shape. This addition helps to keep the aerostat stable and pointed into the wind. Figures 18 and 19 show examples of small blimps capable of deploying the types of digital cameras described earlier in this report that could be used for traffic monitoring.

Figure 18. An Allsopp Helikite small aerostat. Note the keel and wing assembly that keeps the aerostat stable and pointed into the wind and the camera below the keel and behind the tether. In this case, the keel/wing assembly also provides some lift as wind increases. Source: www.allsopp.co.uk

Figure 19. A Kingfisher aerostat. Note the sail under the aerostat that helps keep the aerostat from rotating in the wind. The sail also provides some lift in windy conditions. Source: http://www.aerialproducts.com/surveillance-systems/kingfisher-wind-capable-aerostat.html

Aerostats/blimps are useful for traffic monitoring installations that require a temporary installation but persistent observation of an area on the ground without the need for permanent infrastructure. Aerostats provide a traffic monitoring option that can remain on station for several days at a time, much longer than fixed or rotary wing UAV systems.

Multiple aerostat options are available at different price points. Our September and October 2013 review of various aerostate vendor options finds that most systems seem to be tailored toward military/homeland security applications and are priced accordingly (i.e., very expensive). Several vendors have offerings that appear to be aimed at the civilian aerial photography market – commercial property and high end residential photography would appear be the target market for

these systems. These systems may be a better fit for traffic monitoring. Several companies seem to use the same Aerial Products Kingfisher aerostat for their systems; others use the Allsopp Helikite aerostat to fly their cameras/sensors.

Options are pre-configured systems that require us to provide a camera (~$6,100) and a-la-carte systems where the elements of a complete system to accomplish traffic monitoring goals can be completed. An a-la-carte system using an inexpensive advertising blimp and an inexpensive point and shoot can be put together for around $1,200 - $1,500. This system would use an advertising blimp from Aerial Systems, who also produce the Kingfisher Aerostat, instead of a larger aerostat. Going this route would also require fabrication of a camera mount and video downlink.

Most aerostat systems are too large for our purposes or are targeted at the larger military/homeland security market. However there are a few which may work well for our intended application. Allsopp is an English company which appears focused on aerial photography from aerostats. Their aerostats, including the Allsopp Helikite, have the capability to deploy and operate in high winds and rain. Although based in England, the company (Allsopp) has a US distributor in North Carolina
http://www.carolinaunmanned.com/ or http://www.allsopp.co.uk/index.php?mod=page&id_pag=33.

The aerostats sold by Sky Sentry have a wide range of sizes and payloads. The systems seem to be useful for many different purposes. They use the Allsopp Helikite Aerostat as the basis for some of their smaller systems while the larger systems use a more typical blimp configuration. However, their target market seems to be military/law enforcement/homeland security (see http://www.skysentry.net/tactically-expedient-aerostat-tea).

Aerial Products has aerial photography aerostat systems that seem to meet the requirements for this project. The aerial photography systems use the Kingfisher aerostat to loft the payload. The Kingfisher aerostat seems to be similar in design to the Allsopp Helikite aerostat. However, the Helikite can operate in higher winds (up to 70 mph) than the Kingfisher (30+mph). Multiple aerostats are available in different sizes depending on the size of the camera selected.

Our team recently met with representatives of Ohio DOT (Fred Judson and Ben Cordes) who are working with UAVs, and they gave us some information on a possible additional vendor for an aerostat. They are looking at Blimp in a Box, which has Global Telesat Corp as a vendor; however, following the www.blimpinabox.com link takes you to Lighter Than Air Systems (http://www.ltascorp.com/aerostats.html), which is part of Aerial Products Corp, and the Kingfisher aerostat.

IV. Application of Remote Sensors on UAV Platforms

4.1. Confined Spaces

As UAV technology has improved, the creation of micro-UAVs (MAVs) has become possible. Since the mid 1990s, micro and nano UAVs (NAVs) have undergone major developments in their design and application (Watts et al., 2012; Min et al., 2009). Practical uses for MAVs and NAVs have been tested in confined and inaccessible spaces. While these technologies are relatively new, commercially available platforms and experimental platforms have promising capability. Research into MAVs and NAVs have led to the conclusion that quad-rotor aircraft are capable of stable flight and hovering abilities, which is essential for confined space monitoring (Min et al., 2009). An example of this is recent testing conducted by MTRI using a DJI Phantom quadcopter in MDOT pump stations (Figure 20). This platform proved that it is possible to operate in this environment but in practice a smaller system would be needed as the UAV would need to fly into the pump station though access entryways.

Figure 20. DJI Phantom flying in an MDOT pump station. A First Person Viewer (FPV) camera is attached and is sending a live video feed to an MDOT employee.

A major concern for using MAVs and NAVs is navigation. Many different systems have been designed to overcome this obstacle. One solution is to install a network of sensors in the space which is to be examined. These sensor networks can utilize radio transmitters, ultrasonic receivers, and GPS systems (Hightower and Borriello, 2001; Ward et al., 1997; Yedavalli et al., 2005; Pahlavan et al., 2002). While these applications are useful, these types of MAVs and NAVs cannot be deployed in environments that do not have an existing navigational infrastructure. To address this, systems have been designed that utilize infrared transmitters and 3-dimensional receiver architectures to detect their location in a space. This type of navigational system was tested to be

accurate at distances as great as 30 meters and can "lock" the aircraft to within 1 cm of its desired location (Kirchner and Furukawa, 2005). Alternative to the high accuracy infrared system, many MAV and NAV are equipped with cameras that communicate back to a monitor, which the operator can use to navigate through the space. One such example of this technology has been documented by the Detroit Aircraft Corporation (www.detroitaircraft.com). In a joint exercise with the Wayne County Sheriff's Office (WCSO), the Detroit Aircraft Corporation used one of their MAVs to conduct an indoor search and seizure of a suspect. Figure 21 is an image captured during this demonstration. Documentation of this process can be seen at www.detroitaircraft.com.

Figure 21. Action shot of the Wayne County Sheriff's office use of UAV to find suspects.

Other applications of MAVs and NAVs include the inspection of vessels such as ships, industrial facilities, wildlife habitats, and culvert inspection (Ortiz et al.; Nickolic et al., 2013; Watts et al., 2012; Serrano, 2010). These applications involve the use of cameras and LiDAR mounted systems to observe for physical defects such as cracks, corrosion, infrastructure stability, and safety issues. The use of MAVs and NAVs for these inspections substantially reduces time and cost, and increases safety.

4.2. Traffic Monitoring

Current traffic monitoring practices involve using inductive loop detectors, video cameras located at fixed positions within the road network, and temporary pneumatic hoses stretched across a road attached to a counting device. While effective at providing information about traffic flow at a particular location over time, with the exception of the pneumatic hose counter, these monitoring systems are not mobile or able to easily provide a synoptic view of conditions at an intersection or interchange (Puri, 2008).

UAVs of various configurations (rotary wing, multi rotor, fixed wing, aerostat/blimp) can be effective tools for traffic monitoring. Each configuration has advantages and disadvantages that should be considered when evaluating an unmanned system for traffic monitoring applications. For short duration flights, small fixed wing systems have loitering capabilities that can last as long as 10 hours or more. Rotary wing UAVs require less space to operate but generally have shorter operating times than fixed wing systems, at generally less than an half an hour.

For missions requiring longer continuous monitoring, an aerostat/blimp mounted system can provide observation times from three to ten days, depending on the size of the aerostat and the materials from which it is constructed. An advantage of aerostats is the relative simplicity of obtaining permission from the FAA to place the aerostat, significantly easier than untethered UAVs.

Generally, launching an aerostat requires the operator to contact the FAA within a few days before flight so that a Notice to Airmen (NOTAM) can be issued to alert pilots to the presence of the aerostat.

Ro et al. (2007) discussed the potential for UAVs to provide useful input to an Intelligent Transportation System. The paper describes research done in conjunction with the Michigan Department of Transportation to evaluate the feasibility of integrating UAVs into a traffic monitoring system in urban areas. Ultimately, the field experiment envisioned for the project "is still in a pending status due to safety concerns and regulatory issues."

Only a few studies have actually been able to obtain permission to fly a UAV to demonstrate the utility of small unmanned systems for traffic monitoring applications. Coifman et al. described their 2003 experience using a small UAV (a BAT III) for different traffic related applications such as observing traffic flow, speed, density, intersection movements, network paths, and parking lots. Results of this study were promising, even though the challenges involved with integration of data derived from UAV operations into a larger traffic monitoring system were not directly addressed. Although this experiment took place in 2003, the barriers to deployment that are in place today were also a concern of the researchers when they conducted their experiment.

Puri's review of UAVs for Traffic Surveillance lists a dozen or so projects developing unmanned systems for traffic monitoring. Some focused on developing control systems, others on airframe development. Of the projects described by Puri, the European Commission's COMETS Project, Ohio State/Ohio DOT, Bridgewater State College/UMass – Boston and Virginia DOT actually flew data collection missions using UAVs. The University of Arizona did fly data collection missions but used a manned helicopter rather than a UAV.

Other research has explored the potential to use UAVs to monitor traffic flow, estimate origin-destination time, coordinate traffic signals, monitor rural areas, reconstruct vehicle accidents, monitor hazardous environments, and assess material releases (Coifman et al. 2004, and Srinivasan et al., 2004). Companies such as Barnard Microsystems Limited have UAV systems that can provide real time and day to day monitoring of traffic flow conditions, web based route planning, identification of stranded motorist, and support for police and rescue personnel (www.barnardmicrosystems.com). Current research into traffic monitoring applications of UAVs is becoming more prevalent with systems being testing by multiple research groups. Currently, the Georgia Department of Transportation and the Federal Highway Administration's Priority Technology Program are developing a traffic surveillance UAV. The goal of this project will be to have the ability to relay live video to Georgia's Advanced Traffic Management System (ATMS) via a spread spectrum link (Puri, accessed October 28, 2009). Other research groups, such as those at the University of California, Berkeley, have been developing UAVs to identify and track a ground vehicles through autonomous controls (Huang et al, 2003). The European Commission's COMETS project was designed to develop UAV sensor networks to provide traffic monitoring, vehicle identification, episodic traffic behavior, road network use, and emergency service assistance data, among many other objectives (comets-uavs.org). Figure 22 is an image acquired from the COMETS project.

Figure 22. Live shot taken from an UAV platform deployed during the COMETS project.

In addition to traffic monitoring, groups are working on using remotely sensed imagery to calculate standard roadway statistics. Common traffic measurements such as annual average daily traffic (AADT) have traditionally been measured using ground-based traffic recorders. Early studies have shown that supplementing ground-based recorders with satellite and aerial imagery can produce AADT estimates that are accurate within 85% of traditional ground-based recorders (McCord et al., 2003). The benefit to using UAVs as opposed to satellite and manned aircraft is the reduced cost of operation and acquisition of imagery. Also, UAV imagery can be used in place of ground-based sensors which have their own costs and challenges (Coifman et al., 2004).

4.3. Infrastructure assessment

Remote sensors on UAV platforms are also capable producing infrastructure assessments (Figure 23). Due to the shrinking number of experienced inspectors and rising costs of necessary improvements, the use of such platforms can enhance the monitoring of infrastructure conditions (Ahlborn et al., 2013). Typical infrastructure assessments consist of visual inspection and measurements pertaining to, among other distresses, cracks and spalls (Ahlborn et al., 2013; Metni and Hamel, 2007). This process can be time consuming and labor intensive depending on the condition of the infrastructure and often requires a complete shutdown of traffic. However, with the advancement of remote sensing, there are new technologies that are allowing the assessment of infrastructure to become less time consuming, safer, and more accurate. One of these technologies includes using UAVs that are equipped with remote sensing payloads/cameras.

Figure 23. A UAV assessing a bridge in Saint Cloud, France.

Using a UAV to assess infrastructure has many advantages over manual inspections. Manned assessments often involve safety issues pertaining to the complete shutdown of traffic flow within the area of study, potential traffic crashes, and natural hazards such as elevation changes and weather conditions (Hart and Gharaibeh, 2010; Metni and Hamel, 2007; Coifman et al., 2004). In addition, reanalysis of infrastructure sites are often difficult to complete due to costs and having to travel back to the same site (Hart and Gharaibeh, 2010). Incorporating UAV assessments cancel out many of these inconveniences. For example, flying payload technologies allow for a quicker collection of data since restrictions due to traveling on a road network are not in place, such as gaining access to an area of concentration, rather it be a roadway or bridge (Puri, 2008). In fact, by using a UAV platform instead of manual labor, analysis into multiple road networks is possible due to the reduced amount of time needed per assessment. Additionally, the need for closure of the road network on or near such infrastructure is reduced since manual inspection is not needed, therefore making the working environment much safer for the analysts and motorists (Puri, 2008; Metni and Hamel, 2007).

Another benefit of using a UAV includes their ability to fly in situations or environments where manned flight would be deemed too dangerous. Such situations would include inclement weather conditions (to a certain extreme), evacuations, and areas where there are electrical wires or confined spaces (Li et al., 2008; McCormack, 2008; Puri, 2008; Coifman et al., 2004). Upon completion of data collection in these unsafe environments, assessments of digital imagery and videos can be analyzed in safer and less stressful environments (Hart and Gharaibeh, 2010).

Even with the number of benefits that UAVs possess when it comes to infrastructure assessments, there are disadvantages that limit this method of analysis. One of the biggest obstacles with any UAV analysis pertains to regulations set forth by the FAA. As noted, current FAA regulations require all (untethered) UAV flights, including infrastructure assessments, to apply for a project specific Certificate of Authorization (COA) or an experimental airworthiness certificate (FAA, 2013; McCormack, 2008; Puri 2008). Experimental airworthiness certificates permit flying for research and development, training, and flight demonstration purposes (FAA, 2013). The certification process has recently been restructured and the processing of experimental certificates is estimated to take 2-3 months (FAA, 2013).

Weather conditions must be taken into consideration before the collection of infrastructure assessment data. Previous studies such as those by Hart and Gharaibeh (2010), McCormack (2008), and Puri (2008) have mentioned that weather factors have limited the flight time and, in some instances, canceled any data collection. The most limiting weather condition is wind, especially for micro-UAVs, with winds of 5 miles per hour proving to reduce the quality of data collected. Winds greater than 15 miles per hour have completely stalled micro-UAV flights (Hart and Gharaibeh, 2010), although not necessarily for small UAVs such as the DJI Phantom and Bergen hexacopter. An additional obstruction to the use of UAVs stems from concerns about liability and privacy. This issue was addressed by the Washington State Department of Transportation (WSDOT) when traffic cameras were installed near residential areas (McCormack, 2008). Even though there are a variety of UAV applications represented in the literature, few have been applied towards transportation analyses due to the obstacles previously mentioned (McCormack, 2008).

Depending on the type and capacity of the UAV, different sensors/cameras can be used in the analysis of distresses on the infrastructure. As demonstrated by Ahlborn et al.'s (2013) ground based assessment of bridges in Michigan, there is not a single technology or sensor that serves as an overall solution to assess infrastructure conditions, but through the integration of multiple types of sensors (i.e., thermal infrared, ground penetrating radar, light detection and ranging (LiDAR), synthetic aperture radar (SAR), and three dimensional optics) the technologies and their outputs prove to be beneficial (Figure 24). Therefore, it is ideal to use a UAV that has the capacity to

incorporate different types of payloads. Current UAVs have incorporated interchangeable sensors that collect high resolution near- and thermal infrared, LiDAR, mutli- and hyperspectal, and chemical sensors (Puri, 2008). Sensor technology is being developed at a quick rate, with payloads advancing to higher resolutions and becoming smaller in size. These advancements not only create a smaller, lighter payload, but have also helped create smaller UAVs, which result in a safer and more agile system (McCormack, 2008; Puri, 2008). However, careful consideration into the size and use of such a system must be taken into account when deciding what type of payload is necessary when remotely monitoring infrastructure (McCormack, 2008).

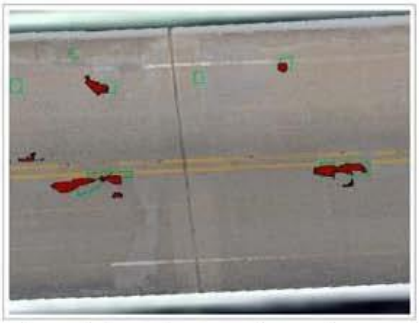

Figure 24. A thermal (red polygons), three dimensional optical imagery (background), and ground truth (green polygons) analysis of delaminations within a bridge located in southeast Michigan.

Limited amounts of research have explored the practicability of using UAVs in infrastructure assessment pertaining to bridge and pavement conditions (Hart and Gharabieh, 2010). There have been UAV studies concerning traffic flow (Feng et al., 2009; Puri, 2008; Coifman et al., 2004), natural hazards (e.g. avalanches) and their effect on transportation (McCormack, 2008), and bridge conditions (Metni and Hamel, 2007). Metni and Hamel's (2007) bridge condition study was conducted in France, where nearly half of the bridges are at least 40 years old. The typical bridge condition assessments they had experience with involved heavy machinery, closing of the bridge to traffic, and difficult working conditions. With the incorporation of UAVs and nondestructive techniques, work accidents and budgets have decreased, and traffic closures have become unnecessary. Through a process of creating a UAV control model, which helps keep distresses of interest in the field of view, results indicated that features such as cracks on the order of 1/10mm were able to be detected and reconstructed (Figure 25).

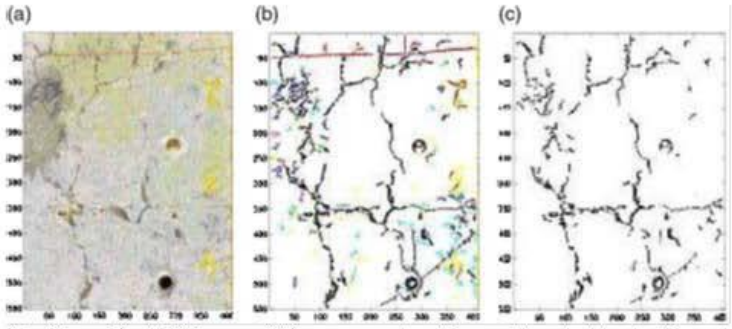

Figure 25. The original RGB image (a) is processed and given a threshold value for each color (b). Black pixels are then further extracted and represent cracks within infrastructure (c).

Although a UAV was not used in Ahlborn et al.'s (2013) analysis of bridge condition, the study still serves as a model for what could potentially be completed with UAV assessments of bridges and other infrastructure. As previously mentioned, there were multiple technologies incorporated into Ahlborn et al.'s (2013) analysis. Thermal data aided in determining the locations of delaminations within the bridge deck. Three dimensional optical (3DOBS) and GigaPan imagery mapped the bridge deck, producing digital elevation models indicating the locations of spalls. LiDAR imagery and multiple other technologies also aided in the building of digital models of the bridge and bridge deck. The data collected and analyzed were compared against professional visual inspection reports and ground truth measurements. Sample products from Ahlborn et al. (2013) can be seen in Figure 26.

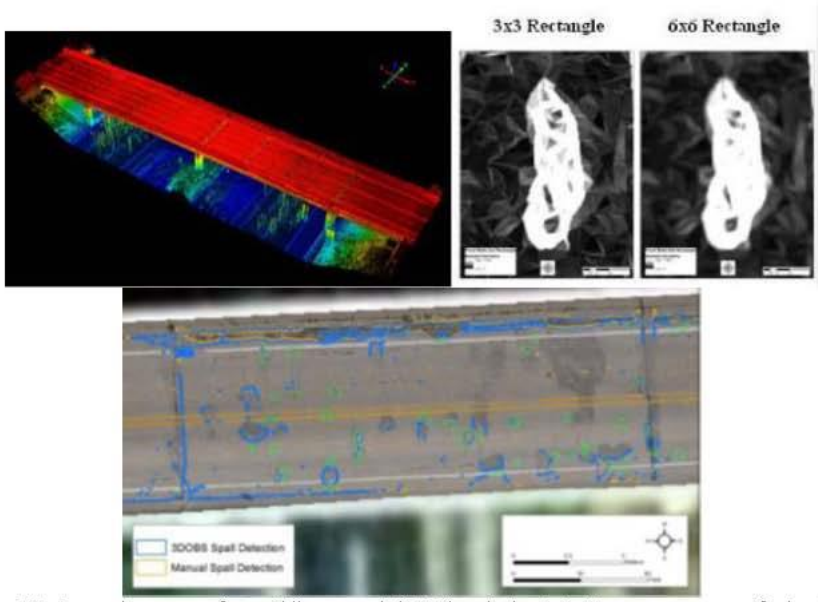

Figure 26. Example outputs from Ahlborn et al. (2013) include a LiDAR representation of a bridge in southeast Michigan (top left), a digital elevation model of a spall (top right), and a geographic information system layout of manual versus automated detection of spalls (bottom). Collecting these types of data should be possible with UAVs as well.

Based on the types of payloads available, similar infrastructure assessments to Metni and Hamble (2007) and Ahlborn et al. (2013) should be plausible when using UAVs. Although Metni and Hamble (2007) have already indicated the potential of UAVs when it comes to infrastructure assessments, the study did not provide as in-depth analyses as did Ahlborn et al. (2013). The potential to collect in-depth data concerning infrastructure assessments using a UAV is high, especially since studies have already shown how different technologies, when combined together, can provide a detailed analysis. As compared to manual inspections, studies concerning UAV based assessments reported more detailed condition ratings of roadways and also improved safety and time-efficiency (Hart and Gharabieh, 2010).

V. Current Use of UAVs for Transportation

UAV technologies have been used for many different applications in various departments of transportation across the country. Such applications include avalanche control, crash reconstructions, traffic monitoring, disaster relief, and surveying (McCormack, 2008; PB Farradyne, 2005). Because of the immediate need, the Washington State Department of Transportation (WSDOT) has tested UAVs to aid in avalanche control and to help develop the department's policies on the long-term use of such technologies. Specifically, avalanche analysis using UAVs was conducted near state highways, with an overall goal of understanding how to reduce highway hazards and closure times since estimates had shown that a 2-hour state highways closure could cost the state over a million dollars (McCormack, 2008). Using a test area that was 81 sq. miles with steep terrain and a 30-degree slope, a MLB BAT (Figure 27) carrying a video and digital camera was flown in April 2006, which allowed WSDOT to evaluate the UAV's and payload's ability to view the roadway, operate near a highway, and survey terrain (McCormack, 2008). In addition, the UAV also helped identify avalanche trigger zones and snow pack conditions. A second UAV test using the Yamaha R-Max was conducted in September 2007. The test used predetermined waypoints to help guide the UAV, and also collected traffic information. In addition, the Yamaha R-Max is a larger vehicle and is able to carry packages containing explosives, which can aid in avalanche control (McCormick, 2008). While both vehicles were effective in the collection of the desired data, concerns pertaining to replacement costs and FAA procedures have challenged the use of UAVs by WSDOT (McCormick, 2008).

Figure 27. WSDOT's MLB BAT, which collected data concerning avalanche control.

Florida's rapid growth in population, commerce, and tourist destination necessitates the need for a more in-depth analysis into the transportation network throughout the state (PB Farradyne, 2005). The Florida Department of Transportation (FDOT) conducted preliminary analysis into the applications that UAV imagery could provide. Such examples include traffic management, forest fire detection, coast guard and immigration surveillance, and the collection of meteorological data for major events such as hurricanes (PB Farradyne, 2005). A pilot based study had attempted to integrate remote sensing techniques and data with intelligent transportation systems (ITS). However, due to FAA regulations, all fights were grounded and efforts into the development of a UAV-ITS were halted as FDOT ended all funding. Although UAV test flights were never conducted, the concept of airborne data collection and distribution of real-time data were proven to work in theory. Working more closely with the FAA, and pending new regulations should enable newer projects to move beyond these limitations.

The Hawaii Department of Transportation (HDOT), like WSDOT and FDOT, also experienced issues pertaining to FAA regulations. In an attempt to conduct an analysis on harbor activities in Honolulu Harbor, HDOT spent $75,000 on a UAV, which never took flight (Kerr, 2012). HDOT failed to receive permission to fly over Honolulu Harbor from the FAA, which grounded all UAV flights due to the close proximity to Honolulu International Airport. The only solutions for such an issue were for HDOT to enter a collaborative agreement with another state or county, or to sell the drone (Kerr, 2012). UAV operations will continue to be challenged by such regulations, which are one of the largest barriers to any UAV data collection (NCHRP, 2013; McCormack, 2008). However, the FAA has also been known to collaborate with UAV analyses, as such the case in New Jersey. Although it is not directly related to transportation, the New Jersey Department of Transportation (NJDOT) has used UAVs to help implement a plan to map the removal of trees that obstruct airport approaches by aircraft (NCHRP, 2013). The UAV of choice was equipped with a camera and GPS unit, and has successfully proven in effectively locating trees near airports that fail to meet FAA regulations.

Restrictions on the operation of UAVs without a Certificate of Authorization (COA) issued by the Federal Aviation Administration (FAA) continue to limit development of applications for UAVs. However, the State of Ohio Department of Transportation has been successful in obtaining COAs for various sites around the state of Ohio, having 13 active COAs and 5 pending COA applications. The COAs have been mostly for rural bridge and culvert projects, although one COA in Muscatatuck, Indiana was granted to support an urban emergency response exercise.

VI. Conclusion

This report has provided a review of different sensors capable of being flown on UAVs, the current suite of available platforms, and specific applications of UAVs with a focus on those by transportation departments. It is clear to the authors that there is a strong potential to apply UAVs to meet transportation infrastructure assessment needs, including confined spaces, bridge inspections, traffic monitoring, and other applications. As of October 2013, FAA regulations do limit day-to-day operations, but pending new regulations for small UAVs and for commercial integration of UAVs in the national airspace are poised to enable significantly more widespread use of these advanced sensing platforms. We recommend revisiting this issue as technology and regulations develop to continue understanding the potential and practical applications of Unmanned Aerial Vehicles.

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9.3 Comparison of uncalibrated Digital Number output from Tau 2 with calibrated temperature data from the SC640 cameras

The Tau2 sensor is not temperature or radiance calibrated, however the sensor output voltage should scale linearly with radiant power (Φ). The output voltage is instead linearly digitized in a 14 bit format, and therefore the resulting digital numbers (DN) should also scale linearly with radiance. This is shown in Equation 9.3 A:

$$\Phi = a1*DN+b1 \; ; \qquad \text{Equation 9.3 A}$$

Where:
Φ is the radiant flux (watts)
DN is the digital numbers
a_1 and b_1 are constants dependent on calibration

If we further assume a gray body radiance with a Lambertian surface emission model, we can relate the radiance (L) to the temperature (T), according to the following Equation 9.3 B:

$$L = \Phi/[\Omega A\cos(\theta)] = (\sigma/\pi)*T4 \; ; \qquad \text{Equation 9.3 B}$$

Where:
Ω is the solid angle "seen" by the sensor (through the optical focusing system)
A is the sensor area
θ is the angle with respect to the surface normal
σ is the Stefan-Botzman constant
T is the temperature of the emitting surface

Combining equations I and II and solving for T, we can see that the relationship between the digital numbers (DN) output should scale linearly with the fourth power of the surface temperature, as shown in Equation 9.3 C:

$$T^4 = a_2*DN+b_2 \; ; \qquad \text{Equation 9.3 C}$$

Where:
a_2 and b_2 are constants dependent on calibration

To test how well the sensor fits to this model, an intercalibration experiment between a FLIR SC640 and the Tau2 sensors was performed. Two hotplates were imaged simultaneously with both cameras at different temperatures, from ambient (~ 22 degrees Celsius) to the Tau2 saturation temperature (~ 200 degrees Celsius). The simultaneous images were then corregistered and the respective pixel-by-pixel values of calibrated temperature (for the SC 640) and digital numbers (for the Tau 2), were compared, to test the fit to the model predicted in

Equation 9.3 C. Figure 9.3 A shows the digital numbers plotted against the fourth power of the temperature, and the point dispersion shows a predominantly linear relationship, as expected.

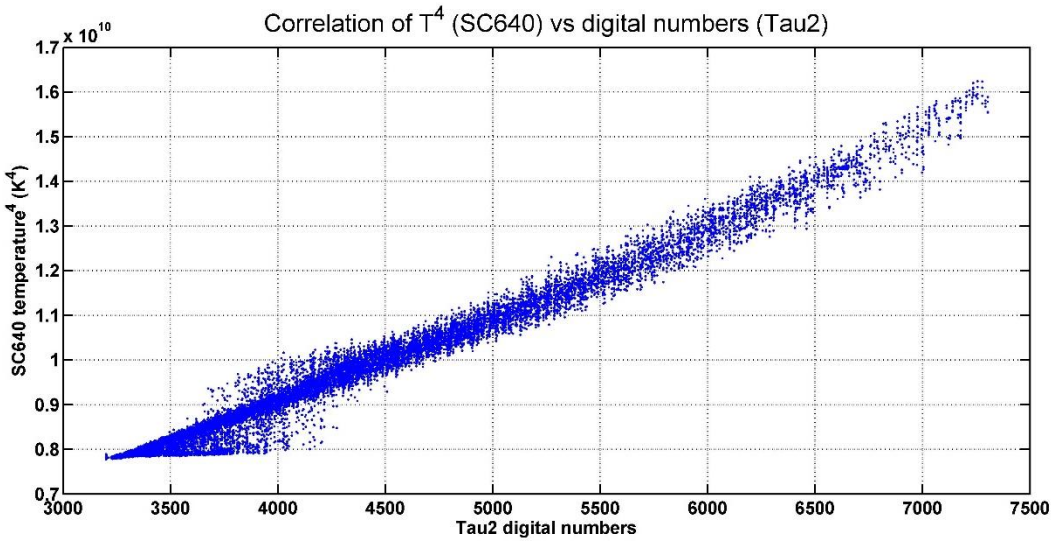

Figure 9.3 A. Dispersion plot of paired pixel digital number and temperature^4 values, for one of the hot plate intercalibration experiments.

Larger noise levels at low temperatures are most likely cause by pixel misregistration near the edge of the hot plates. General noise (point dispersion around the linear trend) are most likely caused by the high frequency noise in the Tau 2 dataset. Despite the noise, the correlation is overall very good.

Although a general calibration (i. e. finding a_2 and b_2 in Equation 9.3 C) could be attempted from this empirical intercalibration test, this constants would change from scene to scene, and would be dependent on environmental variables like air temperature and humidity, as well as distance to the target and the target's surface emissivity, all of which were controlled for the hot plates experiment, and would have to be estimated in each case for a similar calibration.

For such reasons we do not attempt to provide a general calibration for the sensor, but only to show that the sensor performs as expected, and if needed a calibration could be possible.