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16. Abstract

Micro unmanned aerial vehicles (MUAVs) that are equipped with digital imaging systems and global positioning systems provide a potential opportunity for improving the effectiveness and safety of roadside condition and inventory surveys. This study provides an assessment of the effectiveness of MUAVs as a tool for collecting condition data for roadside infrastructure assets using three field experiments. The field experiments entail performing a level of service condition assessment on roadway sample units on IH-20 near Tyler, Texas; IH-35 near Dallas, Texas; and local streets at the Riverside Campus of Texas A&M University. The conditions of these sample units were assessed twice: on-site (i.e., ground truth) and by observing digital images (still and video) collected via a MUAV. The results of this study will help transportation agencies decide if MUAV technology can be adopted for inventory and condition surveys of roadside assets and maintenance activities.

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USE OF MICRO UNMANNED AERIAL VEHICLES FOR ROADSIDE CONDITION ASSESSMENT

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EXECUTIVE SUMMARY

This study provides an assessment of the effectiveness of micro unmanned aerial vehicles (MUAVs) as a tool for collecting condition data for roadside infrastructure assets. The motivation for this study was to improve the safety, accuracy, and time efficiency of roadway condition assessment surveys, and to identify technologies that can provide visual digital records of these condition surveys. The cost-effectiveness of this approach is not addressed in this study, since it is likely to change as MUAV technology matures.

The study conducted three field experiments. The field experiments entailed performing a level of service (LOS) condition assessment on ten roadside sample units on IH-20 near Tyler, Texas (rural area with medium traffic volume); two roadside sample units on IH-35 near Dallas, Texas (urban area with heavy traffic volume); and five roadside sample units located within the Riverside Campus of Texas A&M University (urban area with low traffic volume). The conditions of these sample units were assessed twice: on-site (i.e., ground truth) and by observing digital images (still and video) collected via the MUAV. In the IH-20 and Riverside experiments, the MUAV was easy to control and produced high-quality images. For both experiments, the condition ratings assigned by the MUAV video rater matched those assigned by the field raters 72-95 percent of the time, with an average of 84 percent of the time. In the IH-35 experiment, the MUAV was difficult to operate and produced poor-quality images for estimating roadside condition due to high wind speed and heavy traffic volume.

While the MUAV was not flown in rainy weather, wind was found to be the most restricting weather condition encountered. The MUAV was easy to control and produced the highest-quality images in 0-5 mile per hour winds. The MUAV was not operational (could not be controlled) in 15 mile per hour (or higher) winds. In favorable site conditions (low traffic volume and low wind speed), the MUAV survey was faster and safer than manual surveys. MUAV-based inspection, in most cases, produced higher condition ratings for roadway surveys than on-site inspections.

The authors suggest that the use of MUAVs as a screening survey tool prior to conducting full on-site condition surveys should be investigated. In this manner, MUAV images can help delineate roadway segments that require detailed on-site inspection from those that are in good condition and do not require on-site inspection. Additional areas of future work include

investigating the effect of flight altitude on the quality of MUAV-captured images, and evaluation of the MUAV's global positioning system and live data feed capabilities.

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CHAPTER 1. INTRODUCTION AND RESEARCH SIGNIFICANCE

BACKGROUND

The majority of state departments of transportation (DOTs) collect roadway inventory and condition data for asset management and maintenance quality assurance (MQA) purposes (Pantelias et al. 2009). These programs require periodic and systematic inventory and condition surveys of all roadway assets (culverts, ditches, signs, pavement, guard rails, vegetation, etc.) to determine the roadway's level of service (LOS), set maintenance priorities, and make funding tradeoff decisions.

Current methods for assessing roadside condition involve manual field inspections that tend to be time consuming, labor intensive, and lack adequate visual digital recording of condition information. Digital inspection can potentially address these shortcomings. While vehicle-mounted digital imaging systems are commonly used for pavement condition and roadway inventory surveys, roadside condition surveys are typically performed manually due to limited accessibility. "Roadside" can be defined as the areas between the outside edges of the shoulders and the right-of-way (ROW) boundaries (TxDOT 2005). On multi-lane highways, the median and/or outer separations are included. Diverse maintenance activities are performed on roadsides, such as litter pickup, vegetation management, roadside drainage maintenance, culvert and storm drain maintenance and repair, barrier maintenance, and guard rail repair.

Micro unmanned aerial vehicles (MUAVs) that are equipped with digital imaging systems (still and video cameras) and global positioning systems (GPS) provide a potential opportunity for improving the effectiveness and safety of roadside condition and inventory surveys. These MUAV systems are commercially available and have been used in areas such as crime scene investigation, cinematography, rescue operations, and building inspection.

The primary objective of the research effort documented in this report was to evaluate the effectiveness of using MUAV systems for roadside condition assessment.

PROJECT ACTIVITIES AND REPORT ORGANIZATION

To achieve the research objective, three field experiments were performed. The field experiments entailed performing level of service condition assessment surveys on several sample units at three different roadways in Texas (IH-20 near Tyler, IH-35 near Dallas, and local streets at the Riverside Campus of Texas A&M University). The results of these experiments are compared and analyzed statistically to reveal possible inferences about the effectiveness of MUAVs as a data collection technology for transportation infrastructure.

This report is organized into five chapters. This chapter has defined the research problem and the objective of the research effort. Chapter 2 provides a literature review of current practices in roadside condition assessment methods and the MUAV technology. Chapter 3 describes the methods and sites of the field experiments. Chapter 4 discusses the results of the field experiments. Finally, Chapter 5 presents the conclusions and recommendations of this study.

CHAPTER 2. LITERATURE REVIEW

This chapter provides a review of the literature in two relevant areas: roadway condition assessment methods and MUAV technologies.

ROADWAY CONDITION ASSESSMENT METHODS

As part of maintenance quality assurance, the condition of highway assets and maintenance activities are evaluated regularly. Many highway agencies have implemented MQA processes for monitoring the quality of maintenance on their highway systems. A survey of 39 highway agencies in the United States and Canada (located in 36 states and 3 Canadian provinces) found that 83 percent of these agencies have an MQA program (Schmitt et al. 2006). Examples of these programs include the Texas Department of Transportation (TxDOT) Maintenance Assessment Program (TxMAP), Florida DOT Maintenance Rating Program (MRP), Tennessee DOT Maintenance Rating Program, North Carolina DOT Maintenance Condition Assessment Program, California DOT (Caltrans) Level of Service Program, Washington State DOT Maintenance Accountability Process (MAP), and Wisconsin DOT Compass Program. Florida DOT's MRP process was refined under the National Cooperative Highway Research Program (NCHRP) Project 12-12 by Stivers et al. (1999).

The MQA process uses the level of service concept as an overall performance measure for roadway assets and maintenance activities. LOS is measured in the field using visual condition assessment of randomly selected sample units. For each sample unit, each asset type (e.g., culverts, drain inlets, etc.) is inspected against a set of performance standards to assign either a passing or failing grade or to assign a numerical score (typically 0–5, with 5 being a perfect score). Performance standards are short descriptive statements of the physical condition required for each roadway asset type. Stankevich et al. (2005) suggested that performance standards should be measured using indicators that are SMART (Specific, Measurable, Achievable, Realistic, and Timely to schedule). Different highway agencies have established their own performance standards.

The American Association of State and Highway Transportation Officials (AASHTO) has developed national performance standards for highway assets and maintenance activities. Below are relevant assets to this study for which AASHTO has developed performance standards (AASHTO 2006):

- Roadsides: vegetation and aesthetics, trees, shrubs and brush, historic markers, and right-of-way fence.
- Drainage structures: cross pipes and box culverts, entrance pipes, curb and gutter, paved ditches, unpaved ditches, edgedrains and underdrains, stormwater ponds, and drop inlets.
- Traffic: attenuators, guard rail, pavement striping, pavement markings, raised pavement markers, delineators, signs, and highway lighting.

The performance ratings of inspected sample units are analyzed using statistical methods to determine the roadway's overall LOS. The LOS method allows for the use of weighting to represent the agency's priorities. Weighting factors can be assigned for asset types and maintenance features based on their level of importance to the highway agency and the traveling public (i.e., the customer). Techniques such as customer surveys and focus groups can be used to obtain input from the traveling public. Wilson Orndoff (2005) developed customer survey instruments for highway asset valuation based on input from three affected groups (decision makers, businesses, and the general public). The Texas Transportation Institute (TTI) conducted a series of focus groups in 2009 to assess the public's priorities and to investigate issues relating to mobility, connectivity, pavement quality, funding, and general perceptions of TxDOT operations (Geiselbrecht et al. 2009).

Since sampling the entire length of a roadway network to determine LOS is labor intensive, statistical procedures are often used to determine an appropriate sample size to estimate the performance of a roadway segment or network. For ease of computation, some highway agencies use a fixed sampling rate (i.e., percentage of the roadway to be inspected). Typically, this percentage ranges between 5 percent and 15 percent. Schmitt et al. (2006) suggested that a sampling rate of 2–5 percent is adequate to determine the average condition of a highway network; however, they recommended a sampling rate of 10–15 percent for determining the distribution of condition and the percentage of the network below (or above) a given target condition score.

While this approach for determining sample size is relatively simple, it may not be justified statistically. In order to correctly define a sampling procedure, de la Garza et al. (2008) suggested that the characteristics of the “overall population, sample units, asset items within each sample unit, and acceptable quality levels must be understood.” Several methods have been proposed in the literature for computing the number of sample units needed to be inspected (i.e., sample size). For a given precision and confidence level, the necessary sample size should be a function of size of roadway segment or network (i.e., population size), estimates of the population variance, desired precision, and desired confidence level (Medina et al. 2009, Kardian and Woodward 1990, de la Garza et al. 2008). This approach for determining sample size is founded on basic statistics theory. Virginia DOT has implemented this approach for determining sample size for its statewide MQA program (Kardian and Woodward 1990, de la Garza et al. 2008).

AUTOMATED DATA COLLECTION METHODS FOR ROADWAY CONDITION ASSESSMENT

While advances have been made in developing automated inventory and condition surveys of pavement assets, roadside assets are not as accessible and therefore currently require manual inspection methods. Vehicle-mounted sensors (digital imaging systems, laser, acoustic, etc.) are able to capture accurate pavement surface condition data; however, these technologies are not applicable to roadside condition assessment due to limited accessibility. A recent survey of 48 transportation agencies from 40 different states in the U.S. showed that 34 agencies use manual methods for collecting roadside and drainage condition data (Pantelias et al. 2009). The same survey showed that only three agencies use manual methods for collecting pavement condition data.

Manual methods for conducting roadside condition and inventory surveys involve certain safety issues, ranging from traffic crashes to natural hazards such as washouts, sharp changes in elevation, or hidden objects. Additionally, these manual inspection methods lack an accurate record of the roadside’s true condition. Inadequate data records make it virtually impossible to re-evaluate previously inspected roadside sections without having to travel back to the same site. MUAV systems can potentially fill this gap in automated roadside condition assessment. MUAVs outfitted with digital imaging systems and GPS technology can capture digital videos and still-frame images of roadside assets. These digital images can later be analyzed in a safe, non-stressful work environment and stored for later visualization. The following section provides an overview of the MUAV technology.

UNMANNED AERIAL VEHICLE SYSTEMS

Unmanned aerial vehicles (UAVs) were first designed to act as decoys to distract opposing military forces from what was occurring on the ground. Later, UAVs were modified to perform surveillance missions. After the Vietnam War, military science agencies set out to find a more “soldier safe” method for reconnaissance (Levinson 2010). This led to the development of UAVs that could be flown unmanned, but have the functionality of a manned aircraft. Remote sensing combined with computer and GPS technologies led to the development of the present omniscient UAV. Current military UAVs are fully autonomous and can perform multiple tasks, such as seek and destroy, pre-determined flight, and supply and reinforcement (Taylor 2004).

To improve mobility of UAVs, smaller UAVs that can be carried and operated by a single person were developed and are currently known as micro unmanned aerial vehicles, or MUAVs. This advancement has opened many doors for civilian applications to take advantage of this state-of-the-art technology. MUAVs are currently being used in civilian applications such as firefighting, search and rescue, law enforcement, monitoring of oil and gas pipelines, monitoring of rivers and canals, and private surveillance. Limited research efforts have begun to explore the feasibility of using UAV systems in infrastructure management such as bridge condition inspection (Metni and Hamel 2007), pavement condition inspection (Herold et al. 2004, Zhang 2008a, Zhang 2008b, Jengo et al. 2005), and collection of roadway traffic data (Coifman et al. 2006, Srinivasan and Latchman 2004). Rathinam et al. (2008) developed a detection algorithm that enables UAVs to identify and localize linear infrastructures such as canals, roads, and pipelines.

Generally, there are two major types of MUAVs: plane-configured and helicopter-configured. Examples of these MUAV types are shown in Figure 2-1.

Figure 2-1. Helicopter-configured (Left) and Plane-configured (Right) MUAVs.

A plane-configured MUAV mimics a single-propeller aircraft. These MUAVs have the ability to fly in a straight-line path and must be designed to obey the same laws of aerodynamics that apply to regular aircrafts. The wingspan on this type of MUAV can vary from 12 inches up to 4 feet, depending on application. A helicopter-configured MUAV utilizes upward thrust induced by a single or multiple propellers to maneuver in flight. The typical size for helicopter-configured MUAV is approximately 2-3 feet diametrically. However, recent research projects have used nanotechnology to produce an insect-sized helicopter-configured MUAV (Newcome 2004). Advantages of plane-configured over helicopter-configured MUAVs include:

- greater speed,
- ability to carry larger payloads, and
- ability to glide while in flight (which reduces fuel or battery consumption).

Advantages of helicopter-configured over plane-configured MUAVs include:

- greater maneuverability (enabling immediate and sharp changes in flight direction),
- ability to loiter in place (which, when coupled with GPS, allows for programming the MUAV to hover at predetermined coordinates),
- smaller size, and
- ability to takeoff from a standing position.

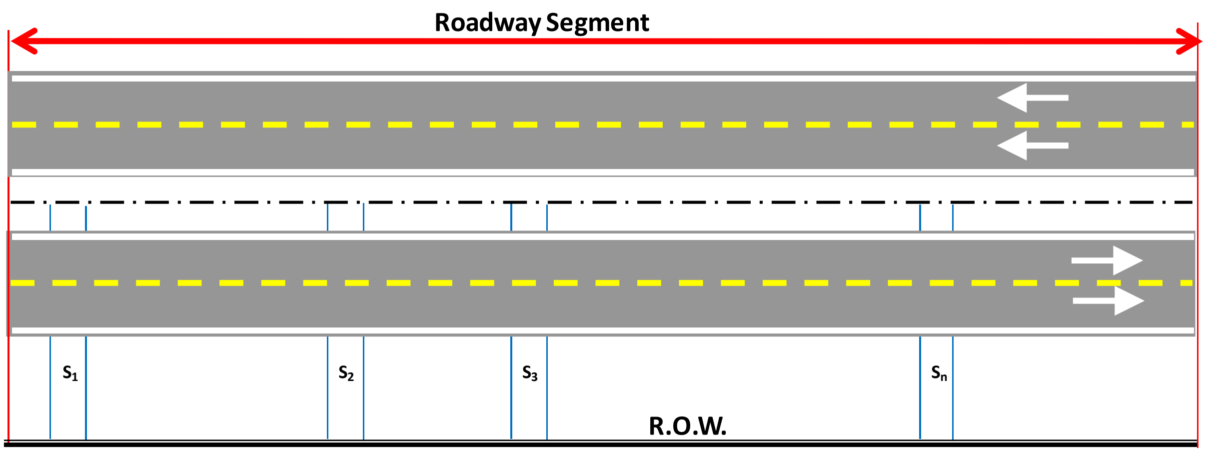
CHAPTER 3. FIELD EXPERIMENTS

This chapter discusses a set of field experiments where roadside LOS condition assessment was performed twice: on-site (i.e., ground truth) and by observing digital images (still and video) collected via an MUAV. The results of these field surveys were then analyzed to assess the effectiveness of MUAVs as a data collection technology for roadside assets.

ROADSIDE CONDITION ASSESSMENT METHOD

Figure 3-1 illustrates the roadside LOS assessment method used in the field experiments. This method was recently developed for the Texas Department of Transportation (Gharaibeh et al. 2010). The process begins by dividing the roadside segment or network into sections and then performing visual field inspections (using predefined performance standards) on a randomly selected sample of these sections. The LOS of each sample unit is computed and then aggregated to determine the LOS for the entire segment or network. The roadside asset types and maintenance activities included in this methodology are grouped as follows:

- Vegetation-related: mowing and roadside grass; landscaped areas; trees, shrubs, and vines.
- Safety-related: attenuators; guard rails; chain link fence.
- Drainage-related: ditches and front slopes; culvert and cross-drain pipes; drain inlets.
- Cleanness-related: removal of litter and debris; removal of graffiti.



Divide Project Length into *N* 0.1-mi Sample Units

Compute Required Sample Size (*n*)

Perform Condition Inspection on *n* Randomly Selected Sample Units (S_1 to S_n)

- Compute Sample Units Scores
- Compute Overall Project Level of Service (LOS)

Figure 3-1. Illustration of Roadside LOS Assessment Method.

The sampling process and LOS computations consist of the following steps:

1. The roadway segment or network is divided into *N* sample units (each is 0.1- to 0.2-mi long).
2. *n* sample units are selected randomly for field survey. The sample size (*n*) is computed as follows:

$$n = \frac{s^2 N}{s^2 + \frac{(N-1)e^2}{Z^2}} \tag{3-1}$$

where *e* = Sampling error, which is the maximum acceptable difference between the true average and the sample average (to be specified by the highway agency); *Z* = Z-statistic associated with a desired confidence level so that the error does not exceed *e; N* = population size (i.e., total number of sample units in the roadway segment); and *s* = estimate of the population's standard deviation. If no historical data exist to estimate *s*, an *s* value of 6-11 can be used (Gharaibeh et al. 2010).

3. The randomly selected sample units are inspected and rated on a "Pass/Fail/Not Applicable" basis using the inspection form shown in Figure 3-2. The form includes a total of 57 performance standards for 11 roadside elements (i.e., asset types and maintenance activities).
4. A 0-100 sample unit score (SUS) is computed as a weighted average score for all elements within the sample unit, as follows:

$$SUS = \frac{\sum_{i=1}^{k} \frac{PS_i}{AS_i} \times PM_i}{\sum_{i=1}^{k} 100 \times PM_i} \qquad (3\text{-}2)$$

where *PS* is the number of passing performance standards; *AS* is the number of applicable performance standards; *PM* is an agency-specified priority multiplier (or weight) for each roadside element; and *k* is the total number of roadside elements within the sample unit. A set of priority multipliers was developed based on feedback from TxDOT's districts and is discussed later in this report.

5. A roadside average LOS for the roadway segment or network is computed as follows:

$$LOS = \overline{SUS} = \frac{\sum_{j=1}^{n} SUS_j}{n} \qquad (3\text{-}3)$$

where SUS_j is the sample score for sample unit *j* and *n* is the total number of inspected sample units (i.e., sample size).

6. **Optional Step:** Because the LOS is computed based on a random sample, it is recommended that a confidence interval be computed for the LOS. However, to compute a confidence interval for LOS (CI_{LOS}), the probability distribution of SUS must be determined. Data gathered from multiple field trials showed that the SUS follows a Beta probability distribution (Gharaibeh et al. 2010). The Beta distribution density function is implemented in many statistical software tools. For example, it can be solved using Microsoft Excel's function *BetaDist*, as follows:

   $PD = BetaDist(x, \alpha, \beta, A, B)$, where *BetaDist* returns cumulative Beta probability density function; *x* is the SUS variable; α and β define the shape of the curve; *A* is the

SUS lower limit (i.e., zero); and *B* is the SUS upper limit as a fraction (i.e., 1.0). α and β are computed as functions of the average SUS ($\overline{SUS}$) and the variance of SUS (v_{SUS}) as follows:

$$v_{SUS} = \frac{\sum_{j=1}^{n}(SUS_j - \overline{SUS})^2}{n} \tag{3-4}$$

$$\alpha = \overline{SUS}\left(\frac{\overline{SUS}(1-\overline{SUS})}{v_{SUS}} - 1\right) \tag{3-5}$$

$$\beta = (1-\overline{SUS})\left(\frac{\overline{SUS}(1-\overline{SUS})}{v_{SUS}} - 1\right) \tag{3-6}$$

The confidence interval for any desired confidence level can be determined using the inverse of the Beta distribution. The inverse Beta distribution density function is implemented in many statistical software tools. For example, it can be solved using Microsoft Excel's function *BetaInv,* as follows:

SUS_P = *BetaInv(P,α, β, 0, 1)*, where *BetaDist* returns the SUS that corresponds to probability *P*. For example, the 95 percent confidence interval can be determined as follows:

Lower Bound = $SUS_{2.5\%}$ = *BetaInv(0.025,α, β, 0, 1)* (3-7)

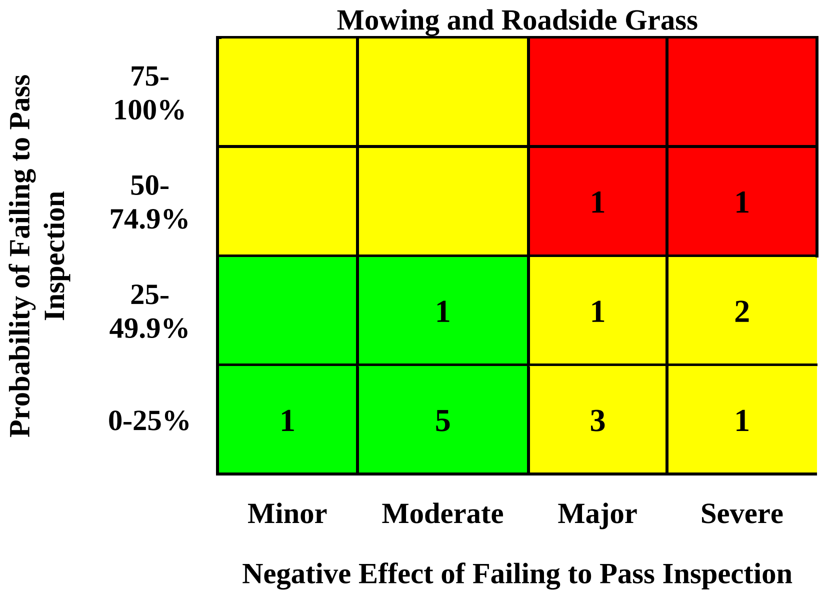
Upper Bound = $SUS_{97.5\%}$ = *BetaInv(0.975,α, β, 0, 1)* (3-8)

Inspector's Name:		**Inspection Date:** **Time:**	
District:		**Highway:** **Milepoint:** **Sample Unit No.:** **Urban/Rural:**	

Roadside Asset Type/Mainten	**No.**	**Performance Standard**	**Grade (Pass, Fail, NA)**
Mowing and Roadside Grass	1	Any use of herbicide requires advance approval of the Engineer.	
	2	Paved areas (shoulders, medians, islands, slope, and edge of pavement) shall be free of grass	
	3	Unpaved areas (shoulders, slopes, and ditch lines) shall be free of bare or weedy areas	
	4	Roadside vegetation in the mowing area shall be at least 85% free of noxious weeds (undesired vegetation)	
	5	In rural areas, roadside grass height shall be maintained below 24 inches and shall not be cut to below 7 inches.	
	6	In urban areas, roadside grass height shall be maintained below 18 inches and shall not be cut to below 7 inches.	
Landscaped Areas	7	Any use of herbicide requires advance approval of the Engineer.	
	8	Landscaped areas shall be maintained to be 90 percent free of weeds and dead or dying plants.	
	9	Grass height in landscaped areas shall be maintained at a maximum height of 12 inches.	
Trees, shrubs and Vines	10	No trees or other vegetation shall obscure the message of a roadway sign.	
	11	No leaning trees presenting a hazard shall remain on the roadside.	
	12	Vertical clearance over sidewalks and bike paths shall be maintained at 10 feet or more.	
	13	Vertical clearance over roadways and shoulders shall be maintained at 18 feet or more.	
	14	Clear horizontal distance behind guardrail shall be at least 5 ft for trees	
	15	No dead trees shall remain on the roadside.	
Ditches and Front Slopes	16	Ditches and front slopes shall be maintained free of eroded areas, washouts, or sediment buildup that adversely affects water flow.	
	17	Erosion shall not endanger stability of the front slope, creating an unsafe recovery area.	
	18	Front slopes shall not have washouts or ruts greater than 3 inches deep and 2 feet wide.	
	19	No part of the ditch can have sediment or blockage covering more than 10% of the depth and width of the ditch	
	20	Concrete ditches shall not be separated at the joints, misaligned, or undermined.	
	21	Front slopes shall not have holes or mounds greater than 6 inches in depth or height.	
Culvert and Cross-Drain Pipes	22	A minimum of 75% of pipe cross sectional area shall be unobstructed and function as designed. There shall be no evidence of flooding if the pipe is obstructed to any degree	
	23	Grates shall be of correct type and size, unbroken, and in place.	
	24	Installations shall not allow pavement or shoulder failures or settlement from water infiltration.	
	25	Culverts and cross-drain pipes shall not be cracked, have joint failures, or show erosion.	
Drain Inlets	26	Grates shall be of correct size and unbroken. Manhole lids shall be properly fastened.	
	27	Installation shall not present a hazard from exposed steel or deformation.	
	28	Boxes shall show no erosion, settlement, or have sediment accumulation.	
	29	Outlets shall not be damaged and shall function properly.	
	30	Inlet opening areas shall be a minimum of 85% unobstructed.	
	31	Installations shall have no surface damage greater than 0.5 square feet.	
Chain Link Fence	32	Installations shall have no open gates.	
	33	Installations shall have no openings in the fence fabric greater than 1.0 square feet.	
	34	Installations shall have no openings in the fence fabric with a dimension greater than 1.0 feet.	
Guard Rails	35	Installations shall be free of missing posts, offset blocks, panels or connection hardware.	
	36	End sections shall not be damaged.	
	37	Rails shall not be penetrated.	
	38	Panels shall be lapped correctly.	
	39	No more than 10% of guard rail blocks in any continuous section shall be twisted.	
	40	No 25-foot continuous section shall be more than 3 inches above or 1 inch below the specified elevation.	
	41	No more than 10% of wooden posts or blocks in any continuous section shall be rotten or deteriorated.	
Cable Median Barrier	42	Installations shall be free of missing or damaged post, cable, or connections	
	43	Installations shall be free of missing or damaged end sections	
	44	Installations shall be free of loose cable or cable with incorrect weave	
Attenuators	45	Each device shall be maintained to function as designed.	
	46	Installations shall have no visually observable malfunctions (examples – split sand or water containers, compression dent of the device, misalignment, etc.)	
	47	Installations shall have no missing parts.	
Litter and Debris	48	1. No litter or debris that creates a hazard to motorists, bicyclists, or pedestrians is allowed.	
	49	2. No 0.1 mile roadway section shall have more than 50 pieces of fist-size or larger litter or debris on either side of the centerline of the highway.	
	50	Litter volume shall not exceed 3.0 cubic feet per 0.1 mile roadway section on both sides of the pavement.	
	51	In rural areas, traffic lanes shall be free of dead large animals.	
	52	In urban areas, traffic lanes and right of way shall be free of dead animals.	
Graffiti	53	No graffiti is allowed	
	54	Surfaces and coatings shall not be damaged by graffiti removal.	
	55	Surfaces from which graffiti has been removed shall be restored to an appearance similar to adjoining surfaces.	

Figure 3-2. Field Inspection Form.

Based on the responses received from 17 TxDOT districts regarding the designation of performance risk for each roadside element, a priority multiplier was computed for each one of these elements (Gharaibeh et al. 2010). Figure 3-3 is a visual representation of the risk matrix for "Mowing and Roadside Grass" with risk assessed by TxDOT's districts. The vertical axis is the probability that the element will fail inspection and the horizontal axis is an adjective describing the negative consequences of failing to pass inspection (minor, moderate, major, and severe). The numbers in the boxes represent the number of TxDOT districts that agree with that risk position. The priority multiplier is calculated as a weighted average of the responses for each consequence classification (minor, moderate, major, and severe) where the Minor classification is given a consequence value of 1, Moderate 2, Major 3, and Severe is given a value of 4.



$$\boldsymbol{Priority\ Multiplier\ (PM) = \frac{(1*1)+(2*6)+(3*5)+(4*4)}{16} = 2.8}$$

Figure 3-3. Example Risk Matrix for Mowing and Roadside Grass.

Table 3-1 shows the calculated priority multipliers for each roadside element. The original survey of TxDOT's districts did not include the roadside element "cable median barrier" so the priority multiplier for this element is taken as an average of the safety-related assets as related to traffic (guard rails and attenuators). Table 3-2 shows an example of how to calculate the sample unit score.

Table 3-1. Priority Multipliers.

Roadside Element	Priority Multipliers (1-4 scale)
Mowing and Roadside Grass	2.8
Landscaped Areas	1.6
Trees, Shrubs, and Vines	2.1
Ditches and Front Slopes	2.7
Culvert and Cross-Drain Pipes	2.9
Drain Inlets	2.9
Chain-Link Fence	1.7
Guard Rails	3.3
Cable Median Barrier	3.5
Attenuators	3.7
Litter and Debris	1.7
Graffiti	1.6

Table 3-2. Sample Unit Score Computation Example.

Roadside Element	No. of Applicable Standards	No. of Passed Standards	Priority Multiplier	Element Score (0–100)
Mowing and Roadside Grass	6	5	2.75	83.33
Landscaped Areas	3	NA	1.63	
Trees, Shrubs, and Vines	5	NA	2.07	
Ditches and Front Slopes	6	NA	2.70	
Culvert and Cross-Drain Pipes	4	2	2.86	50.00
Drain Inlets	6	NA	2.87	
Chain-Link Fence	3	NA	1.73	
Guard Rails	8	6	3.33	75.00
Cable Median Barrier	3	NA	3.52	
Attenuators	4	NA	3.71	
Litter and Debris	5	3	1.69	60.00
Graffiti	4	NA	1.60	
			Total	723.27
			Perfect Total	1062.8
			Sample Unit Score (SUS) = 727.83/1062.8 =	**68.5%**

MUAV USED IN THE FIELD EXPERIMENTS

As discussed earlier, the purpose of this study was to assess the effectiveness of MUAVs as a data collection tool for roadside assets. Since roadside assets are not always clear along the entire length of a sample unit (e.g., trees and debris can block the flight path), this study required an MUAV that could manipulate its flight path and maneuver in tight spaces. The MUAV had to be able to capture high-resolution video and still images for later analysis and editing. The selected MUAV had to be able to utilize GPS technology so that its flight path could be tracked and recorded for later use. With the known GPS coordinates of a sample unit, unique and complete databases can be created.

Several manufacturers were considered in the MUAV selection process for this study. Most MUAVs were eliminated as candidates based on unaffordable price. The selected MUAV model was the Dragan Fly X6 helicopter-configured MUAV(see Figures 3-4, 3-5, and 3-6). This model is produced by Dragan Fly Innovations, a company located in Saskatoon, Canada. Table 3-3 shows the helicopter's and imaging system's specifications in detail. The selection of this particular MUAV model was based on the following criteria:

- Loiter capabilities.
- Ability to takeoff/land in confined spaces.
- Use of state-of-the-art imaging devices.
- GPS capabilities.
- Onboard and satellite media storage devices.
- Ability to maintain continuous flight for at least 15 minutes.
- Reasonable price compared to other commercial MUAVs.
- Easily piloted.
- Compact, simple, and durable.

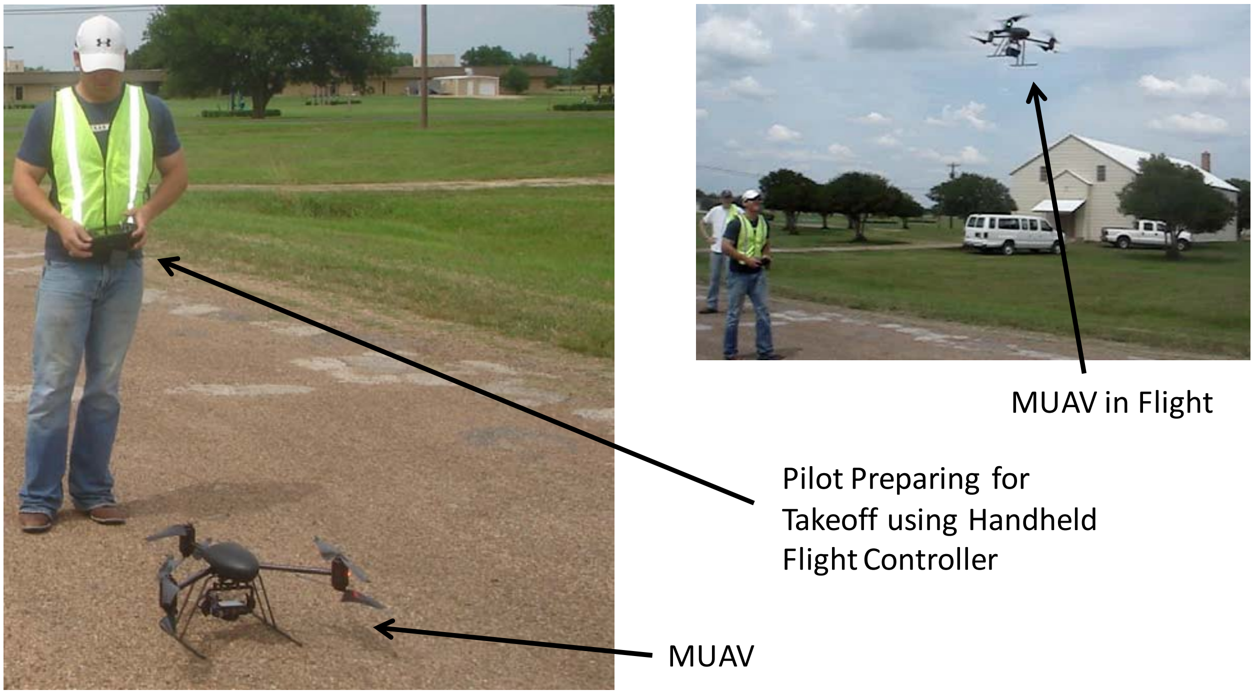


Figure 3-4. Operation of MUAV Used in Field Experiments.

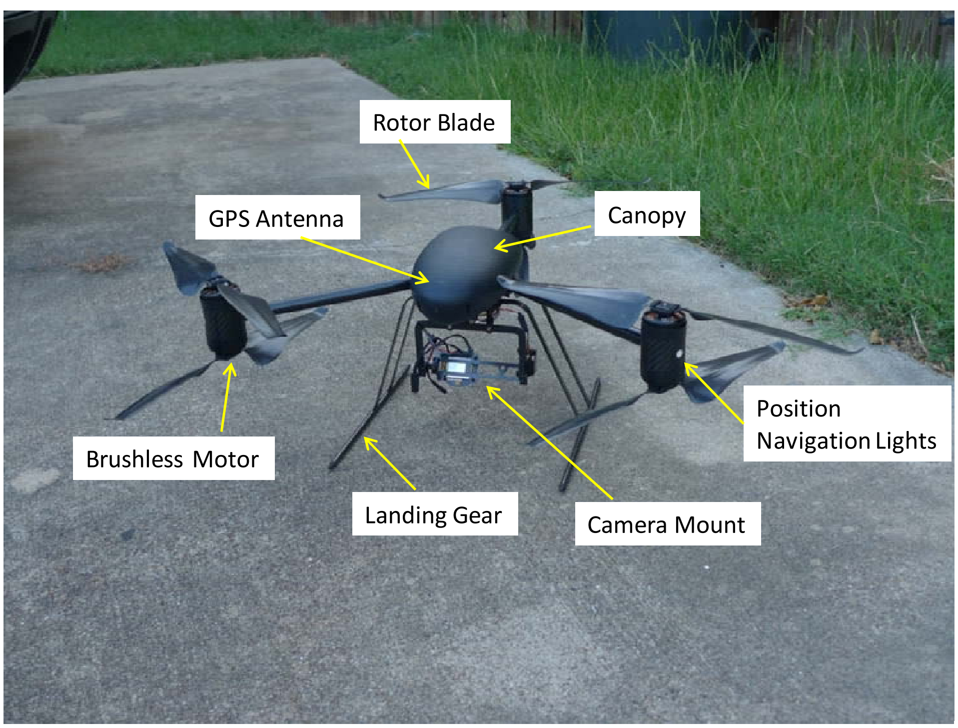


Figure 3-5. Main Components of MUAV Used in Field Experiments.

Figure 3-6. Handheld Flight Controller.

Table 3-3. Technical Specifications of Dragan Fly X6 MUAV.

Aspect	Characteristic	Value
Helicopter Size (Fully Assembled)	Width	36 in
	Length	33 in
	Height	10 in
Weight and Payload	Helicopter Weight	2.2 lbs.
	Payload Capacity	1.1 lbs.
	Maximum Gross Takeoff Weight	3.3 lbs.
Flight	Unassisted Visual Reference Required	Path Entered Flight Capabilities
	Max Climb Rate	23 ft/s
	Max Descent Rate	13 ft/s
	Max Turn Rate	90 ˚/s
	Approximate Max Speed	30 mph
	Minimum Speed	None
	Launch Type	Vertical Take Off and Landing
	Maximum Altitude	8,000 ft.
	Max Flight Time	25 min.
Camera Type	Still Camera	10 MP Digital Still
	Motion Camera	720p High-Definition
	Max Storage	2 GB
GPS	Satellites Used	16
	Position Update Rate	4 Hz
	GPS Capabilities	Position Hold, Location Data

SITE CHARACTERISTICS

The field experiments entailed performing roadside LOS condition assessment on three locations in Texas (IH-20 in Tyler, IH-35 near Dallas, and local streets at Texas A&M University's Riverside Campus). The characteristics of these sites are summarized as follows:

- **IH-20 near Tyler:** This 10-mi long segment of IH-20 was surveyed in April 2010. The site starts at Texas Reference Marker (TRM) 556 and ends at TRM 566 in Smith County (see map in Figure 3-7). This site is characterized as a rural area and was rated accordingly.
- **IH-35 near Dallas:** This 10-mi long segment of IH-35E was surveyed in May 2010. The site is located in the north side of the Dallas metropolitan area, between Lewisville and Denton (see map in Figure 3-7). The survey was conducted on the northbound direction only. The entire length was characterized as an urban area. Due to its proximity to a large city, this site has high traffic volume. The entire length is divided by a concrete barrier at the median. This highway has frontage roads on both sides.
- **Riverside:** This site consists of local streets at the Riverside Campus of Texas A&M University (see map in Figure 3-7). This site was surveyed in June 2010. These streets are 2-way 2-lane with very low traffic volume (average daily traffic of approximately 150 vehicles per day). This site is characterized as an urban area and was rated accordingly.

Each site was divided into multiple 0.1-mi sample units and the sample unit scores were assessed twice:

- On-site (i.e., ground truth): Inspectors rated the roadside assets and maintenance activities within each sample unit directly in the field.
- MUAV video: A separate inspector rated the same sample units by observing digital images (still and video) collected via the MUAV.

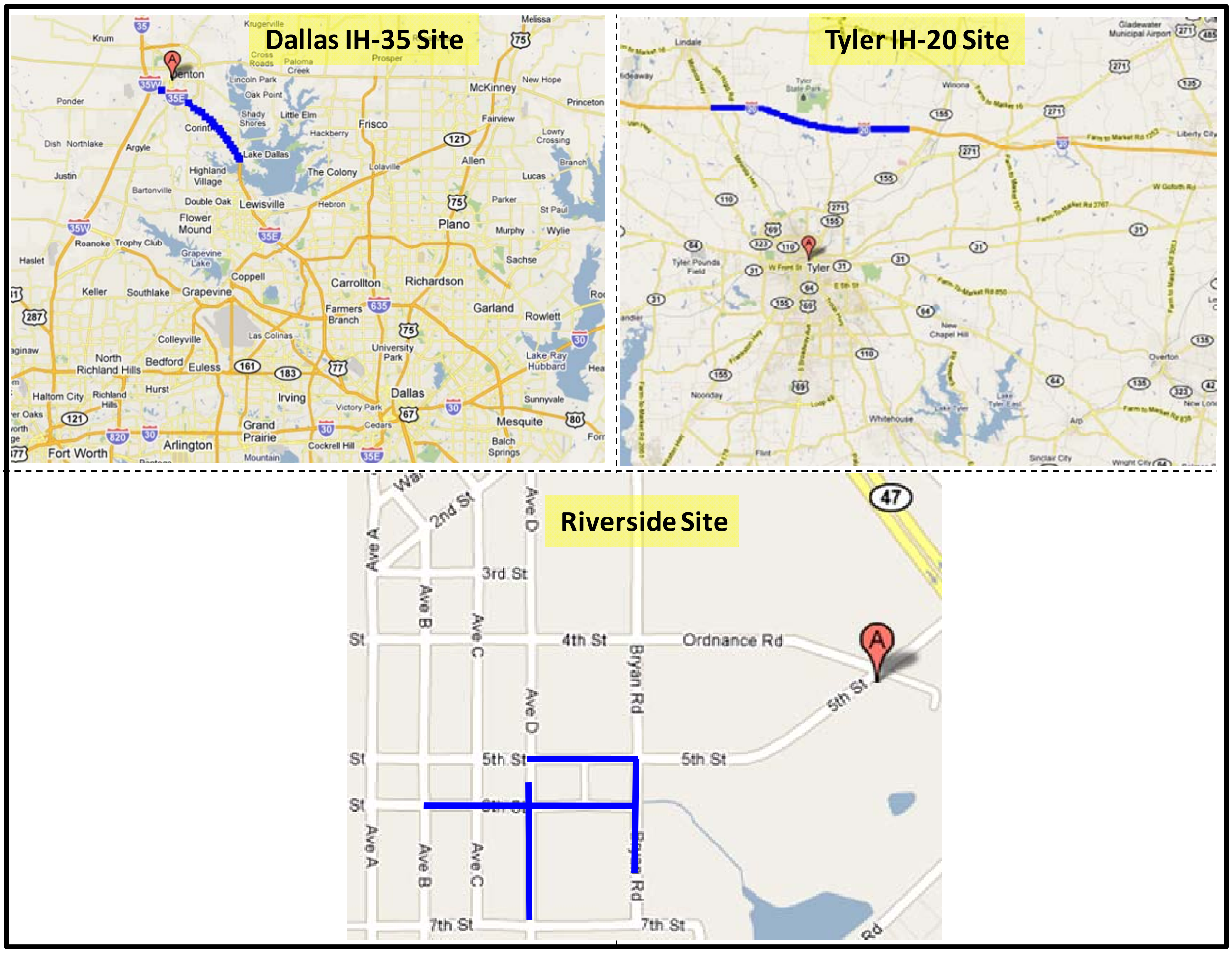


Figure 3-7. Locations of Field Experiments.

CHAPTER 4. RESULTS OF FIELD EXPERIMENTS

This chapter discusses a the results of the field experiments, on an experiment-by-experiment basis.

RESULTS OF THE IH-20 EXPERIMENT

The SUSs for the IH-20 experiment are summarized in Table 4-1. These SUS values were computed for each sample unit using Equation 3-2. The first two columns in the table represent the sample unit numbers used in this analysis and the sample unit numbers used in the on-site inspection. Figure 4-1 shows a side-by-side comparison of the MUAV scores and the on-site scores for each sample unit.

Table 4-1. SUS for the IH-20 Experiment.

Sample Unit No.	On-site Sample No.	Surveyor 1	Surveyor 2	Surveyor 3	MUAV
1	7	63	75	58	100
2	18	87	83	82	73
3	23	84	83	94	87
4	28	100	83	93	80
5	32	93	100	94	67
6	33	96	94	93	82
7	40	83	94	83	67
8	48	88	88	82	79
9	57	100	92	92	100
10	60	88	81	91	100

Two statistical tests were conducted on the SUS results. The first was a two-tailed t-test, in which the on-site SUS data sets were compared to the corresponding MUAV SUS data set, under the null hypothesis that true mean values are equal. The second statistical test was the F-test, which was conducted on the same data sets under the null hypothesis that the variances are equal. Table 4-2 shows the results of these two statistical tests. The results show that, at a 95 percent confidence level, there is no statistical evidence that the null hypothesis in either case is false.

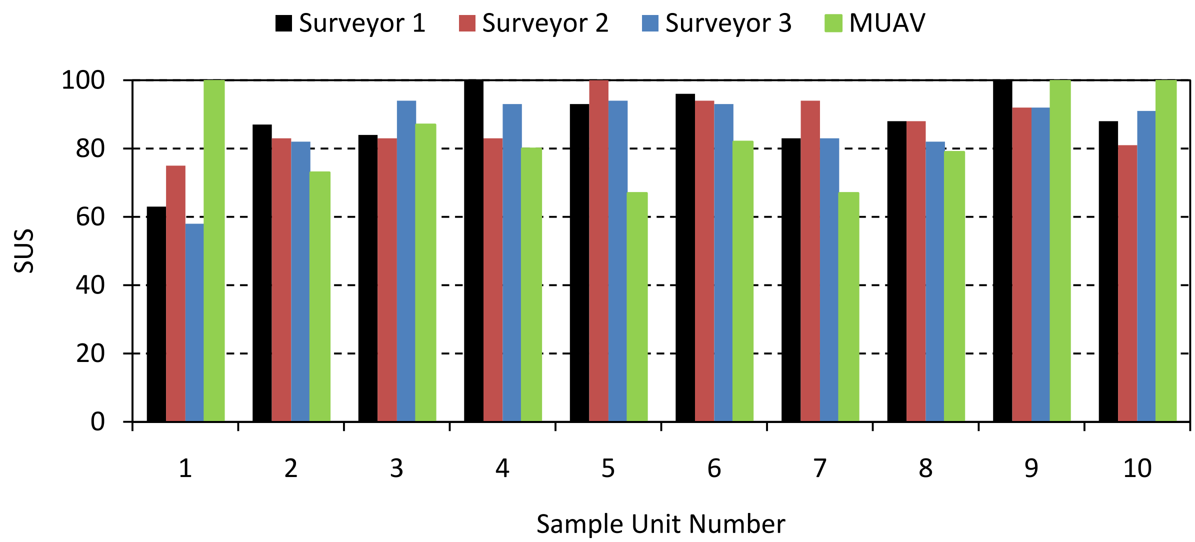


Figure 4-1. On-site vs. MUAV-based Sample Scores for the IH-20 Experiment (chart legend and columns are in the same left-to-right order).

Table 4-2. Statistical Results Comparing On-site vs. MUAV-based Sample Scores (95% Confidence Level) for the IH-20 Experiment.

Comparison	Sample Size (number of sample units)	T-Test p-value	F-Test p-value	Evidence of Difference in SUSs (Reject Null Hypothesis?)
Surveyor # 1 vs. MUAV	10	0.390	0.585	t-Test: No F-Test: No
Surveyor # 2 vs. MUAV	10	0.437	0.126	t-Test: No F-Test: No
Surveyor # 3 vs. MUAV	10	0.437	0.650	t-Test: No F-Test: No

Figure 4-2 shows the level of agreement between the performance standards ratings (Pass, Fail, or Not Applicable) obtained by monitoring MUAV videos and corresponding ratings obtained directly in the field by three different inspectors. Considering all performance standards, 72-95 percent of the time, the ratings assigned by the MUAV video rater matched those assigned by the field raters. On average, these ratings matched 81 percent of the time.

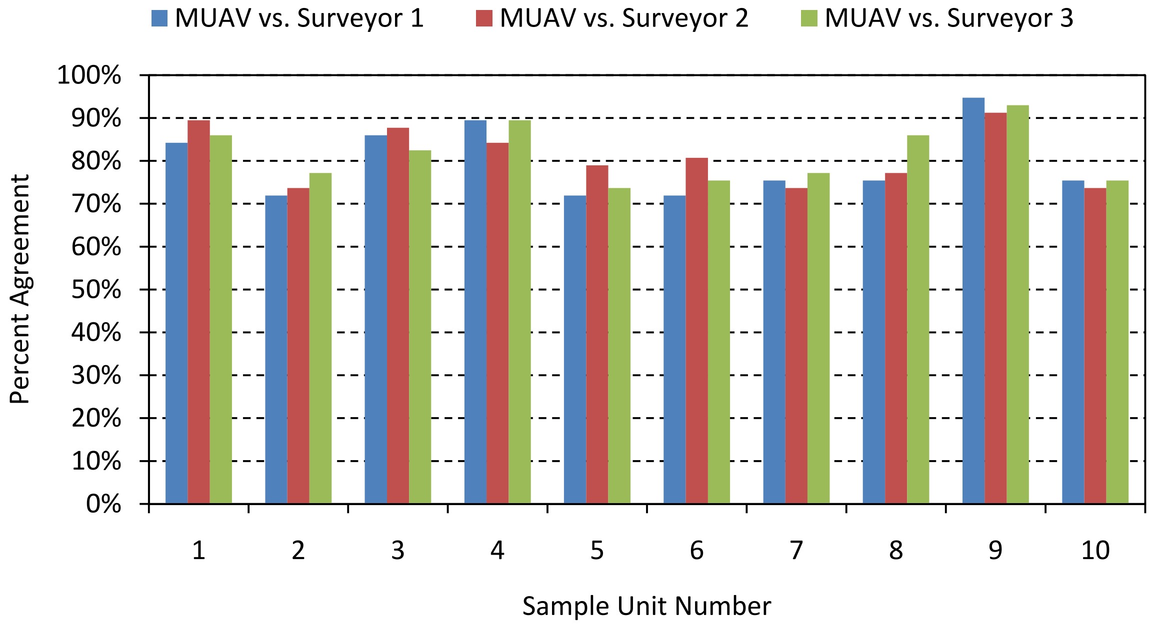


Figure 4-2. Agreement between MUAV and On-site Ratings for the IH-20 Experiment (chart legend and columns are in the same left-to-right order).

Figure 4-3 shows each of the sample unit scores grouped by surveyor. This figure helps reveal any patterns or tendencies between each of the four different surveyors and how they score roadside condition surveys. The figure reveals that, with the exception of sample units 1, 9, and 10, the scores given by the MUAV inspection are consistently lower than the other three on-site surveyors. This can be attributed to the false readings in sample units 1, 9, and 10, where certain failed assets could not be detected by the MUAV.

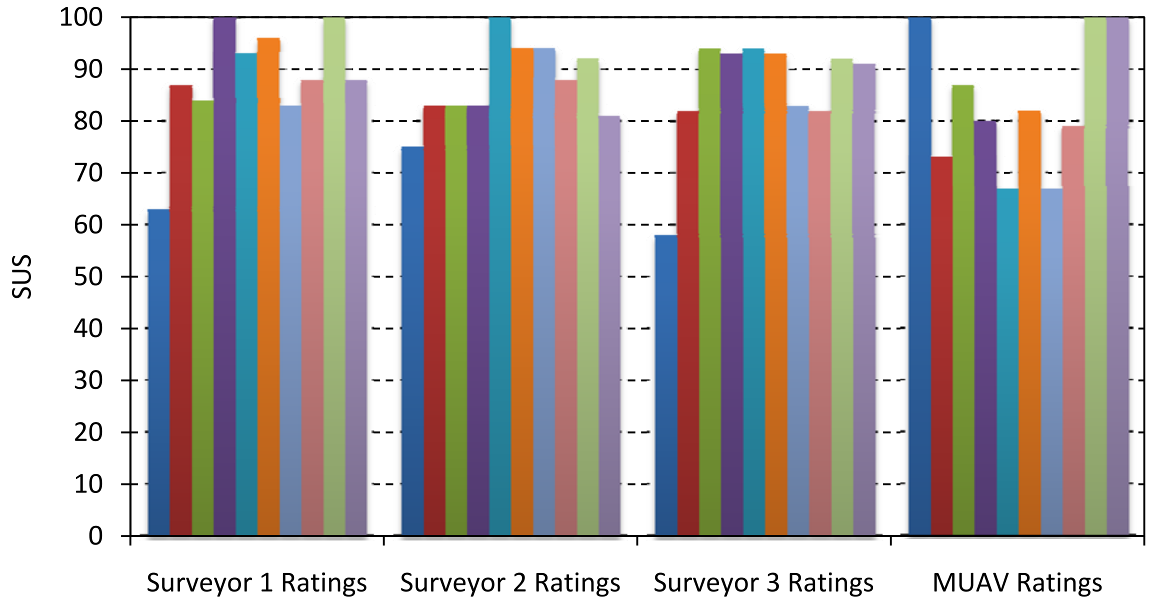


Figure 4-3. Sample Scores Grouped by Surveyor and MUAV for the IH-20 Experiment.

RESULTS OF THE IH-35 EXPERIMENT

This experiment was conducted to evaluate the performance of MUAV in adverse weather and field conditions. The roadway has a heavy traffic volume, with average daily traffic (ADT) of approximately 124,000 vehicles per day. The wind speed during the experiment was 15 to 20 mile per hour. Several attempts were made to fly the MUAV; however, the MUAV was unstable to fly in these adverse conditions. The experiment was stopped after collecting data from two sample units only (out of 10 sample units planned). The collected survey data for these two sample units are summarized in Table 4-3 and are shown graphically in Figure 4-4. No statistical tests were conducted on these data due to the small sample size.

Table 4-3. SUS Results for the IH-35 Experiment.

Sample Unit No.	On-site Sample No.	Surveyor 1	Surveyor 2	Surveyor 3	MUAV
1	5	79	81	76	100
2	38	70	67	50	100

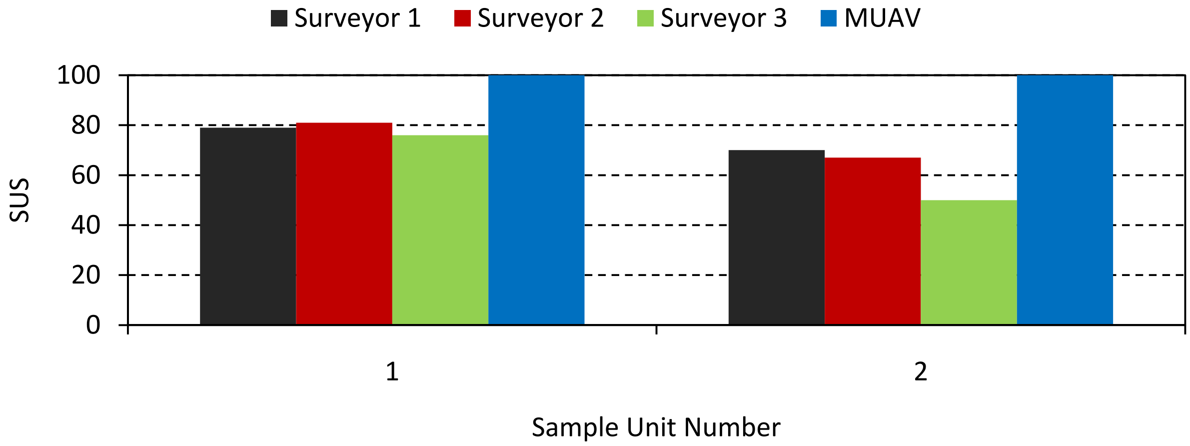


Figure 4-4. On-site vs. MUAV-based Sample Scores for the IH-35 Experiment (chart legend and columns are in the same left-to-right order).

Figure 4-5 shows the level of agreement between the performance standards ratings (Pass, Fail, or Not Applicable) obtained by observing the MUAV videos and corresponding ratings obtained directly in the field by three different inspectors. Considering all performance standards, 65-84 percent of the time, the ratings assigned by the MUAV video rater matched those assigned by the field raters. On average, these ratings matched 76 percent of the time.

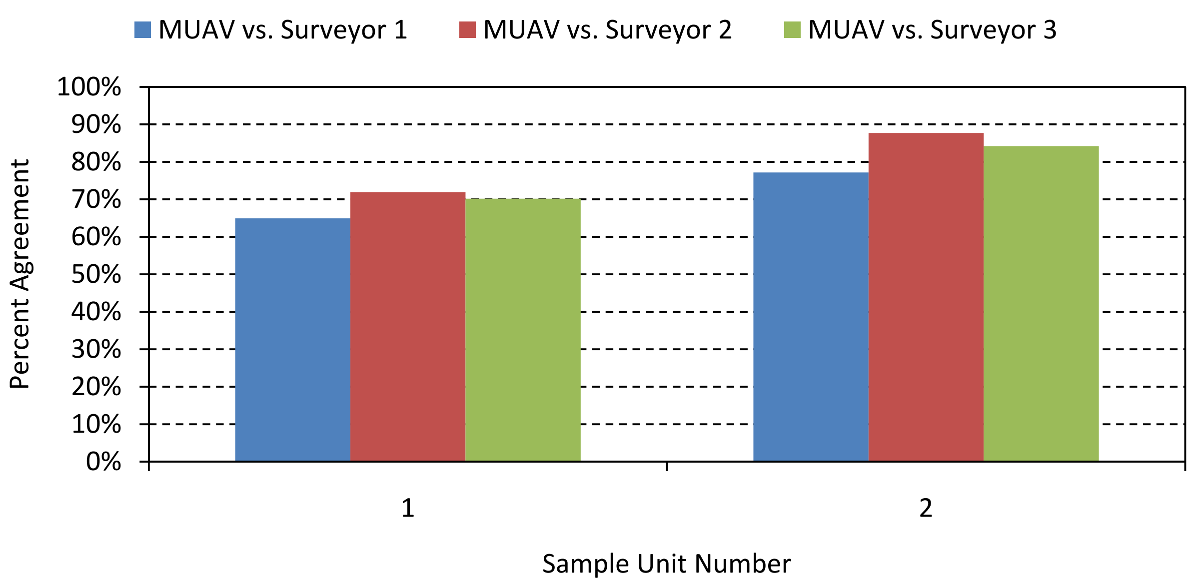


Figure 4-5. Percent Agreement between MUAV and On-site Ratings for the IH-35 Experiment (chart legend and columns are in the same left-to-right order).

Figure 4-6 shows that the MUAV consistently scored higher than the rest of the surveyors. Again, this can be attributed to the MUAV's poor-quality images, which missed certain assets or failed to detect that these assets did not meet the performance standards.

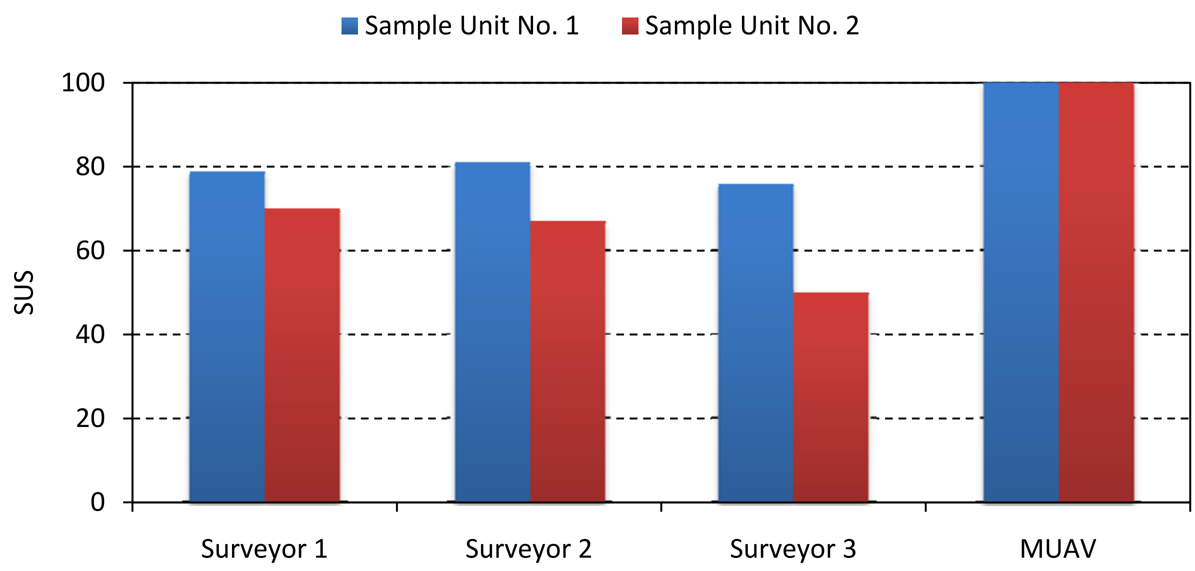


Figure 4-6. Sample Scores Grouped by Surveyor and MUAV for the IH-35 Experiment.

RESULTS OF THE RIVERSIDE EXPERIMENT

As discussed earlier, the sample units of this experiment are located on local streets at the Riverside Campus of Texas A&M University. These streets are 2-way 2-lane with very low traffic volume (ADT of approximately 150 vehicles per day). The collected survey data for the Riverside experiment location are summarized in Table 4-4 and are shown graphically in Figure 4-7. Similar to the other two experiments, Equation 3-2 was used to calculate the SUS for each sample unit. The first two columns in Table 4-4 represent the sample unit numbers used in this analysis and the sample unit numbers used in the on-site inspection. Only one field inspector conducted the on-site inspections in this experiment. This is the same Surveyor 1 in the IH-20 and IH-35 experiments. No statistical tests were conducted on these data due to the small sample size.

Table 4-4. SUS Results for the Riverside Experiment.

Sample Unit No.	On-site Sample No.	Surveyor 1	MUAV
1	1	96	100
2	2	91	96
3	3	86	92
4	4	83	96
5	5	78	100

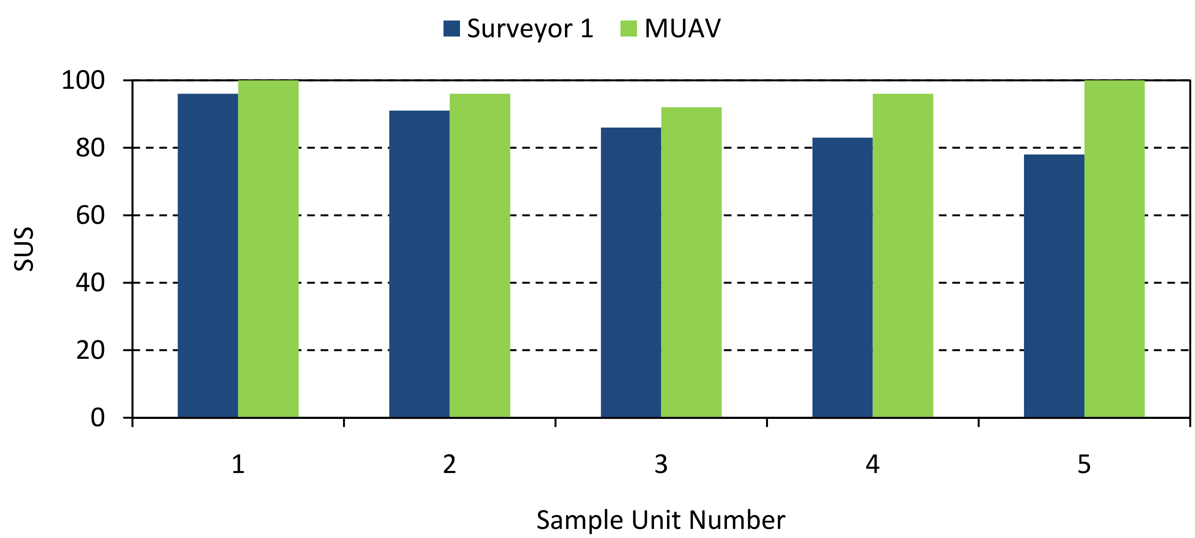


Figure 4-7. On-site vs. MUAV-based Sample Scores for the Riverside Experiment.

Figure 4-8 shows the level of agreement between the performance standards ratings (Pass, Fail, or Not Applicable) obtained by monitoring MUAV videos and corresponding ratings obtained directly in the field. Considering all performance standards, 75-93 percent of the time, the ratings assigned by the MUAV video rater matched those assigned by the field rater. On average, these ratings matched 86 percent of the time.

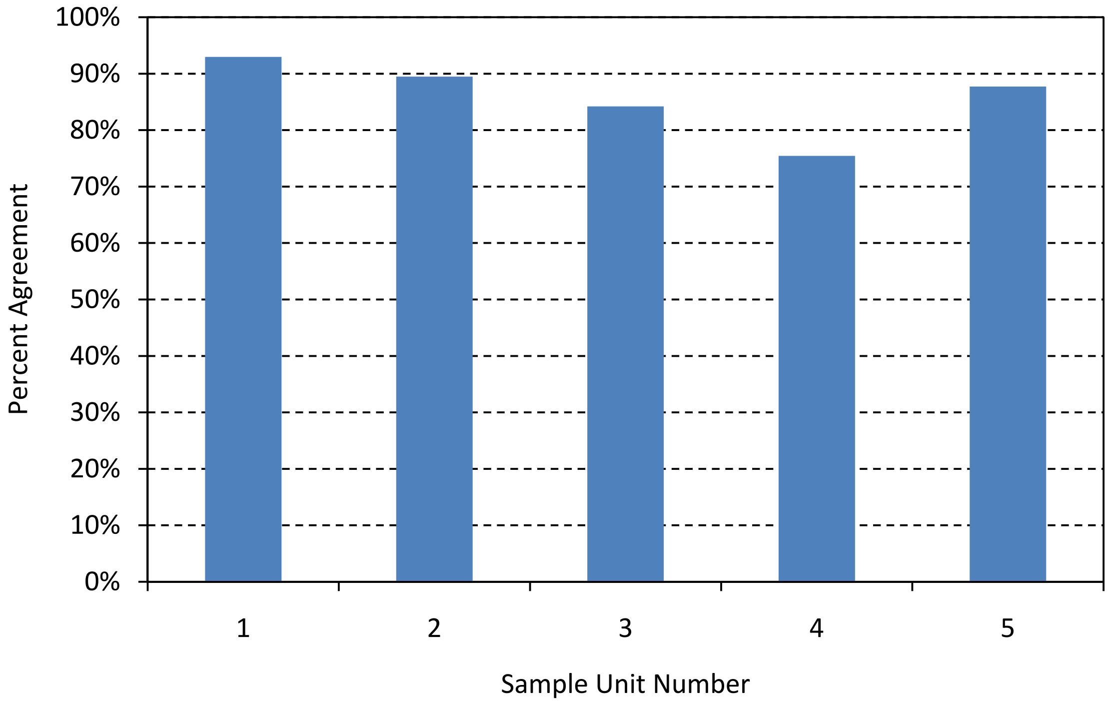


Figure 4-8. Percent Agreement between MUAV and On-site Ratings for the Riverside Experiment (Surveyor 1 vs. MUAV).

Figure 4-9 shows once again that the MUAV scores are consistently higher than the on-site surveyor's ratings. Similar to previous sites, this can be attributed to the false readings where certain failed assets could not be detected by the MUAV.

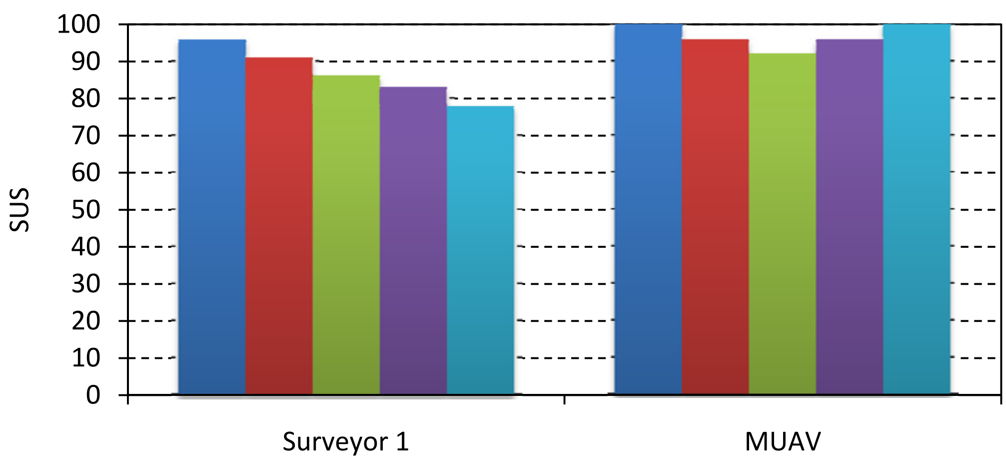


Figure 4-9. Sample Scores Grouped by Surveyor and MUAV for the Riverside Experiment.

ANALYSIS OF FALSE READINGS

For this study, a false reading is a case where an asset is rated incorrectly using the MUAV-captured images. There are two types of false reading that occurred in this study. The first type occurred when an asset in a sample unit was observed and rated in the visual inspection, but was missed in the MUAV inspection. The second type occurred when the MUAV captured an image of an asset, but it could not be properly rated due to lack of visibility or clarity of images.

The IH-20 experiment provided the most information with regard to these false readings. Each sample unit was closely analyzed to determine when the on-site survey differed from the MUAV-captured survey by three or more different standards for any given asset class or maintenance activity. For example, the Drain Inlet asset class has six standards measured in the roadside condition survey. If three or more of these standards were recorded differently for the two survey methods then it was considered a false reading. The threshold value of three standards was used because differences in one or two standards have very minor effect on the sample score. Table 4-5 shows all of the false readings that were identified in the IH-20 experiment.

Out of the 10 sample units that were surveyed, there were 14 total false readings that affected the outcome of the MUAV rating process. Fifty percent of these false readings occurred when rating ditches and front slopes. The remaining 50 percent of false readings occurred when the MUAV failed to capture a specific asset due to lack of visibility or clarity of images. Figure 4-10 shows an example false MUAV reading. This example was taken from the last image in the video that the MUAV captured for Sample Unit No. 2. The image taken on-site shows that the guard rail is included in the sample unit. The MUAV was unable to capture the image of the guard rail due to obstructions from trees and signage, coupled with uncontrollable winds that prevented the MUAV from maneuvering around these obstacles. Since the MUAV missed the guard rail (which met all performance standards), the other standards that received a failing rating carried larger impact on the overall condition of the sample unit, lowering the SUS rating obtained from the MUAV-captured images.

It is worth noting that the images shown in this analysis were taken using the same high-definition digital camera. However, the wind jostles the MUAV around, which results in poor-quality images. The quality of the images decreases as the wind speed increases.

Figure 4-11 shows an example false reading where the MUAV missed a drain inlet, whereas the on-site inspector was able to see and rate the same drain inlet.

Table 4-5. SUS Results for the Riverside Experiment Showing False Readings.

Sample Unit No.	Asset	False Reading	Effect on Score
1	Ditches and Front Slopes	On-site survey issued a failing score, MUAV captured a passing score.	Increased
2	Ditches and Front Slopes	On-site survey issued a passing score, MUAV captured a failing score.	Decreased
2	Guard Rail	On-site survey captured the asset, the MUAV missed the asset.	Decreased
3	Culvert and Cross-Drain Pipes	On-site survey captured the asset, the MUAV missed the asset.	Decreased
4	Ditches and Front Slopes	On-site survey issued a passing score, MUAV captured a failing score.	Decreased
5	Ditches and Front Slopes	On-site survey issued a passing score, MUAV captured a failing score.	Decreased
5	Culvert and Cross-Drain Pipes	Surveyor 1 rated the asset, the MUAV failed to capture it.	Decreased
6	Ditches and Front Slopes	On-site survey issued a passing score, MUAV captured a failing score.	Decreased
6	Drain Inlet	On-site survey captured the asset, the MUAV missed the asset.	Decreased
7	Guard Rail	On-site survey captured the asset, the MUAV missed the asset.	Decreased
7	Ditches and Front Slopes	On-site survey issued a passing score, MUAV captured a failing score.	Decreased
8	Ditches and Front Slopes	On-site survey issued a passing score, MUAV captured a failing score.	Decreased
10	Culvert and Cross-Drain Pipes	On-site survey captured the asset, the MUAV missed the asset.	Increased
10	Drain Inlet	On-site survey captured the asset, the MUAV missed the asset.	Increased

Figure 4-10. False Readings Example 1: MUAV-Captured Image Missed Guard Rail (Left Image); On-site Inspection Captured Guard Rail (Right Image).

Figure 4-11. False Readings Example 2: MUAV-Captured Image Missed Drain Inlet.

OPERATIONAL PERFORMANCE OF MUAV

The MUAV was flown at three different times throughout the day in order to find the optimum time window to collect best quality images. This is not truly a test of the MAUV's capabilities, but rather the capability of the camera mounted on the MUAV. The specific digital camera that was used in this study was a LUMIX DMC-LX3 manufactured by Panasonic. The camera captured 720 pixels high-definition video images at 24 frames per second and 10.2 megapixel still images. It was observed that the optimum time of day to capture images was between 8:00 a.m. and 12 noon. In the afternoon, there was excessive glare from adjacent pavement surfaces, which reduced the quality of the captured images.

Weather was the most restricting factor in the entire data collection process. While the MUAV was not flown in rainy weather, wind was found to be the most restricting weather condition encountered. Generally, the MUAV performed well and was easy to control in 0-5 mile per hour winds. In 5-10 mile per hour winds, the MUAV became more difficult to control, but with some training, data could be collected. Wind speeds greater than 10 miles per hour interfered with operating the MUAV and resulted in “shaky” video that was difficult to analyze. The MUAV was not operational (could not be controlled) in 15-mile per hour (or more) winds.

Flight speed affects the quality of video and images that the MUAV captures as well as endurance of the MUAV (i.e. maximum flight time). The slower the MUAV travels, the higher the quality of data becomes. However, slower flight speed (i.e., longer flight times per sample unit) reduces the number of sample units surveyed per battery. Approximately 1.5 minutes of flight time per 0.1 mile sample unit (allowing 4 sample units to be collected per battery) appears to be most practical.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This study provides an assessment of the effectiveness of MUAVs as a tool for collecting condition data for roadside infrastructure assets. The motivation for this study was to improve the safety, accuracy, and time efficiency of roadway condition assessment surveys, and to identify technologies that can provide visual digital records of these condition surveys. The cost-effectiveness of this approach was not addressed in this study, since it is likely to change as MUAV technology matures.

The study conducted three field experiments. The field experiments entailed performing a level of service condition assessment on ten roadside sample units on IH-20 near Tyler, Texas (rural area with medium traffic volume); two roadside sample units on IH-35 near Dallas, Texas (urban area with heavy traffic volume); and five roadside sample units located within the Riverside Campus of Texas A&M University (urban area with low traffic volume). The conditions of these sample units were assessed twice: on-site (i.e., ground truth) and by observing digital images (still and video) collected via the MUAV. Specific findings from each experiment are as follows:

- IH-20 experiment: The MUAV was easy to control and produced high-quality images. The condition ratings assigned by the MUAV video rater matched those assigned by the field raters 72-95 percent of the time. On average, these ratings matched 81 percent of the time. No significant statistical difference was found between the sample unit scores obtained from on-site inspection and those obtained by observing digital images collected via the MUAV.
- IH-35 experiment: The MUAV was difficult to operate and produced poor-quality images for estimating roadside condition due to high wind speed and heavy traffic volume.
- Riverside experiment: The MUAV was easy to control and produced high-quality images. The condition ratings assigned by the MUAV video rater matched those assigned by the field raters 75-93 percent of the time. On average, these ratings matched 86 percent of the time.

Based on the results of this study, the following conclusions can be made:

- Weather is the most restricting factor in the MUAV data collection process. While the MUAV was not flown in rainy weather, wind was found to be the most restricting weather condition encountered. The MUAV was easy to control and produced the highest quality images in 0-5 mile per hour winds. The MUAV was not operational (could not be controlled) in 15 mile per hour (or more) winds.
- For rural highways and local streets and wind speed less than 10 miles per hour, the MUAV produced adequate-quality images for estimating the LOS for roadside assets.
- For urban highways and wind speed greater than 10 miles per hour, the MUAV was difficult to operate and produced poor-quality images for estimating the LOS for roadside assets.
- In favorable site conditions (low traffic volume and low wind speed), the MUAV survey was faster and potentially safer than manual surveys.
- MUAV-based inspection, in most cases, produced higher condition ratings for roadway surveys than on-site inspections.

RECOMMENDATIONS

The authors offer the following recommendations for further research:

- Investigate the use of MUAVs as a screening survey tool prior to conducting full on-site condition surveys. In this manner, the MUAV images can help delineate roadway segments that require detailed on-site inspection from segments that are in good condition and do not require on-site inspection.
- Investigate the effect of flight altitude on the quality of MUAV-captured images.
- Evaluate the MUAV's GPS and live data feed capabilities.
- Evaluate the cost-effectives of MUAVs.

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