Georgia DOT Research Project 12-38

Final Report

Feasibility Study to Determine the Economic and Operational Benefits of Utilizing Unmanned Aerial Vehicles (UAVs)

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Contract with

Georgia Department of Transportation

May 6, 2014

1.Report No.: FHWA-GA-1H-12-38	2. Government Accession No.:	3. Recipient's Catalog No.:

4. Title and Subtitle: Feasibility Study to Determine the Economic and Operational Benefits of Utilizing Unmanned Aerial Vehicles (UAVs)	5. Report Date: April 2014
	6. Performing Organization Code: 12-38
7. Author(s): Javier Irizarry, Ph.D., P.E., CGP Eric N. Johnson, Ph.D.	8. Performing Organ. Report No.:
9. Performing Organization Name and Address: Georgia Institute of Technology 225 North Ave NW Atlanta, GA 30332	10. Work Unit No.:
	11. Contract or Grant No.: Georgia DOT Research Project 12-38
12. Sponsoring Agency Name and Address: Georgia Department of Transportation Office of Research 15 Kennedy Drive Forest Park, GA 30297-2534	13. Type of Report and Period Covered: Final; January 2013-April 2014
	14. Sponsoring Agency Code:

15. Supplementary Notes:

16. Abstract: This project explored the feasibility of using Unmanned Aerial Systems (UASs) in Georgia Department of Transportation (GDOT) operations. The research team conducted 24 interviews with personnel in four GDOT divisions. Interviews focused on (1) the basic goals of the operators in each division, (2) their major decisions for accomplishing those goals, and (3) the information requirements for each decision. Following an interview validation process, a set of UASs design characteristics that fulfill user requirements of each previously identified division was developed. A “House of Quality” viewgraph was chosen to capture the relationships between GDOT tasks and potential UAS aiding those operations. As a result, five reference systems are proposed. The UAS was broken into three components: vehicle, control station, and system. This study introduces a variety of UAS applications in traffic management, transportation and construction disciplines related to DOTs, such as the ability to get real time, digital photographs/videos of traffic scenes, providing a "bird’s eye view" that was previously only available with the assistance of a manned aircraft, integrating aerial data into GDOT drawing software programs, and dealing with restricted or complicated access issues when terrain, area, or the investigated object make it difficult for GDOT personnel to conduct a task. The results of this study could lead to further research on design, development, and field-testing of UAVs for applications identified as beneficial to the Department.

17. Key Words: Unmanned Aerial Vehicles, Unmanned Aerial Systems, Operational Requirements, Technical Requirements, Cost Analysis.	18. Distribution Statement:

19. Security Classification (of this report): Unclassified	20. Security Classification (of this page): Unclassified	21. Number of Pages: xiv + 144	22. Price: $74,984

Acknowledgements

The research team would like to acknowledge the Georgia Department of Transportation for their support of the research project and the following individuals for their direct involvement with the project.

- GDOT Technical Advisory Committee: Binh H. Bui, Georgene Geary, and Carla J. Sands
- H. Claus Christmann – Graduate Student, Georgia Institute of Technology
- Ebrahim P. Karan – Graduate Student, Georgia Institute of Technology
- Personnel from the following areas: Construction, Engineering, Intermodal, and Permits and Operations

Executive Summary

In April of 2013, a team from the Georgia Institute of Technology entered into a research project to explore the feasibility of using Unmanned Aerial Systems (UASs) in Georgia Department of Transportation (GDOT) operations and to determine the economic and operational benefits of this technology. Unmanned Aerial Systems are normally comprised of a control station for a human operator and one or more Unmanned Aerial Vehicles (UAVs). The utilized UAVs can be equipped with various sensors, such as video or still cameras, including far and near infrared, radar or laser based range finders, or specialized communication devices. The ground stations utilized by the human operators can vary from portable computer based systems to fixed installations in vehicles or dedicated control rooms.

The project lasted for a period of one year and the research team conducted several interview sessions with a variety of directors or administrators in different GDOT divisions and offices. The research team first studied all GDOT divisions and offices to identify those that have the potential for using UASs. This analysis was performed by investigating the operations, mission and sets of responsibilities that each division and their internal offices have. At the same time, previous uses of UASs across all DOTs as well as the current status of different civilian applications of UASs were investigated. The result of this phase led to identifying four GDOT divisions with the potential for using UASs as well as determining the potential uses of UASs across all GDOT divisions. Semi-structured interviews with Subject Matter Experts in each identified division were conducted and focused on (1) the basic goals of the operators in each division, (2) their major decisions for accomplishing those goals, and (3) the information requirements for each decision. All of the information was validated through feedback from the interviewees and further analyzed to identify the tasks with the greatest potential use of UASs.

Following the interview validation process, a set of UASs design characteristics that fulfill user requirements of each previously identified division was developed. Among them are the UAV platform (i.e. whether the vehicle is a fixed wing system or a rotary wing system), the sensor and other device requirements, the payload components, the sizing of the vehicle based on the required payload capacity in the context of the airframe choice, and the power consumption (i.e. electric or gasoline powered system). In an effort to visualize UASs specific interconnections, an adoption of a "House of Quality" viewgraph has been chosen to capture the relationships between GDOT tasks and potential UAS aiding those operations. As a result, five reference systems are proposed. These systems capture the majority of the tasks identified through the interview process and cover a wide spectrum of capabilities, expandability, but also availability. The UAS was broken into three components: vehicle, control station, and system. The vehicle component includes airframe hardware and its related requirements. The control station component includes the requirements related to the user interface of the control station, the control station's hardware that will be used outdoors, and transportation of the control station. Specific guidance, navigation, and control aspects that mainly contain capability features of the reference systems are grouped into the system component. This study introduces a variety of UAS applications in traffic management, transportation and construction disciplines related to DOTs, such as the ability to get real time, digital photographs/videos of traffic scenes, providing a "bird's eye view" that was previously only available with the assistance of a manned aircraft, integrating aerial data into GDOT drawing software programs, and dealing with restricted or complicated access issues when terrain, area, or the investigated object make it difficult for GDOT personnel to conduct a task. The results of this study could lead to further research on design, development, and field-testing of UAVs for applications identified as beneficial to the Department.

Keywords: Unmanned Aerial Vehicles, Unmanned Aerial Systems, Operational Requirements, Technical Requirements, Cost Analysis

Table of Contents

List of Figures

List of Tables

List of Acronyms

ADAS	Airborne Data Acquisition System
ADS-B	Automatic Dependent Surveillance-Broadcast
AEC	Architecture, Engineering, and Construction
ATC	Air Traffic Control
COTS	Commercial-Of-The-Shelf
DOT	Department of Transportation
FAA	Federal Aviation Administration
FDOT	Florida Department of Transportation
FPV	First-Person Video
GA	General Aviation
GDOT	Georgia Department of Transportation
GDTA	Goal Directed Task Analysis
GIS	Geographic Information Systems
GNC	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
GUST	Georgia Tech UAV Simulation Tool
HERO	Highway Emergency Response Operators
HoQ	House of Quality
HMMWV	High Mobility Multi-Purpose Wheeled Vehicles
INS	Inertial Navigation System
IRB	Institutional Review Board
LiDAR	Light Detection and Ranging system
MALE	Medium Altitude, Long Endurance
MANET	Mobile Ad-hoc NETwork

NCRST	National Consortium on Remote Sensing in Transportation
ODOT	Ohio Department of Transportation
P3	Public-Private Partnership
PF	Pilot-Flying
PNF	Pilot-Non-Flying
R/C	Radio controlled (flight)
R/F	Radio Frequency
ROM	Rough Order of Magnitude
SA	Situational Awareness
SAS	Stability Augmentation Systems
SLAM	Simultaneous Location And Mapping
SME	Subject Matter Expert
TAM	Transportation Asset Management
TIA	Transportation Investment Act
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
UDOT	Utah Department of Transportation
UUV	Unmanned Underwater Vehicles
VDOT	Virginia Department of Transportation
VFR	Visual Flight Rules
VTOL	Vertical Take-Off and Landing
WSDOT	Washington State Department of Transportation

1. CHAPTER I

1. Introduction

1.1. Overview

Unmanned Aerial Systems (UASs) are an emerging technology that can be widely used in various civil applications, ranging from monitoring tasks to simple item manipulation or cargo delivery scenarios. UASs are normally comprised of a portable control station for the human operator and one or more Unmanned Aerial Vehicles (UAVs). The utilized UAVs can be equipped with various sensors, such as video or still cameras, including far and near infrared, radar or laser based range finders, or specialized communication devices. Most UASs are capable of real-time data transfer between the UAV(s) and the control station; some have additional on-board data storage capabilities for enhanced data collection tasks. UASs can perform tasks similar to those that can be done by manned vehicles, but often faster, safer, and at a lower cost (Puri 2005).

Although an initial wide spread application of UAS was within military operations, having reached a permanent position in the military arsenals of many forces (Nisser and Westin 2006), peaceful applications of these systems are currently investigated in border patrol, search and rescue, damage investigations during or after natural disasters (e.g. hurricanes, earthquakes, tsunamis), locating forest fires or farmland frost conditions, monitoring criminal activities, mining activities, advertising, scientific surveys, and securing pipelines and offshore oil platforms (Anand 2007). Due to the ability to utilize various sensor devices and the potential to hover for a long period of time, UAS utilizing rotary wing aircraft (e.g. quad- and other multicopters, as well as traditional helicopters) are well suited as experimental platforms for different efforts investigating the application of unmanned systems, such as autonomous surveillance/navigation (Krajník et al. 2011), human-machine interaction (Ng and Sharlin 2011), or as sport training assistant providing athletes with external imagery of their actions (Higuchi et al. 2011).

As the continuous improvement in function and performance of UASs promotes the need for specific research to integrate this leading edge technology into various applications, Departments of Transportation (DOTs) of several states have started using UAS technology for different purposes from tracking highway construction projects and performing structure inventories to road maintenance, monitoring roadside environmental conditions as well as many other surveillance, traffic management or safety issues. Some examples of previous application of UASs by various DOTs across the country are listed in Table 1-1. Some examples of previous application of UAVs by various DOTs across the country are as following:

The *Florida Department of Transportation (FDOT)* in collaboration with University of Florida used surveillance video from UAV systems to monitor remote and rural areas of the State of Florida (Werner 2003). This project served as a case study on how UAV technology could be used for remote sensing in multimodal transportation applications. The *Virginia Department of Transportation (VDOT)* also cooperated with the National Consortium on Remote Sensing in Transportation (NCRST) to demonstrate the feasibility of an unmanned Airborne Data Acquisition System (ADAS) for real-time traffic surveillance, monitoring traffic incidents and signals, and environmental condition assessment of roadside areas (Carroll and Rathbone 2002).

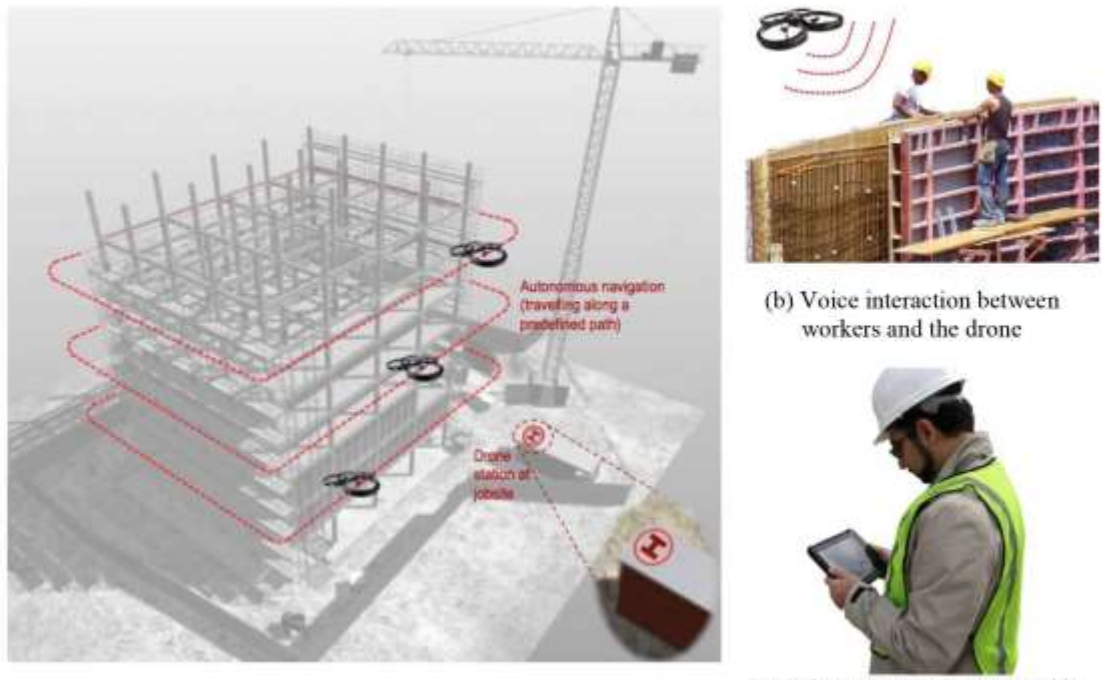
Table 1-1: Summary of previous UASs applications by DOTs

DOT	Application	Equipment
Virginia	real-time traffic surveillance, monitoring traffic incidents and signals, and environmental condition assessment of roadside areas (Carroll and Rathbone 2002)	video/digital camera
Florida	monitor remote and rural areas of the state of Florida (Werner 2003)	video/digital camera
Ohio	collect data about freeway conditions, intersection movement, network paths, and parking lot monitoring (Coifman et al. 2004)	Video/digital camera
Washington State	capturing aerial images for data collection and traffic surveillance purpose on mountain slopes above state highways (Coifman et al. 2004)	video/digital camera
Utah	take high-resolution pictures of highways to inventory their features and conditions at a very low cost and in short time (Barfuss et al. 2012)	video/digital camera

The *Ohio Department of Transportation (ODOT),* in collaboration with Ohio State University, performed field experiments in Columbus, OH, on the use of UAVs to collect data about freeway conditions, intersection movement, network paths, and parking lot monitoring. They were using the collected information for space planning and distribution as well as providing quasi real-time information to travelers (Coifman et al. 2004). The *Washington State Department of Transportation (WSDOT),* in collaboration with University of Washington and the Georgia Tech UAV Research Facility (involving co-PI Johnson), conducted several experiments including the evaluation of UAV use on mountain slopes above state highways to control avalanches or capturing aerial images for data collection and traffic surveillance purposes (McCormack 2008). Furthermore, the *Utah Department of Transportation (UDOT),* in collaboration with Utah State University Hydraulic Lab, used UAV systems to take high-resolution pictures of highways to inventory their features and conditions at a very low cost and in short time. The pictures taken by UAVs also helped to improve "UDOT geographic information systems (GIS) databases with photos of ongoing and recent highway construction, fish passage culvert locations, wetlands and noxious weeds along highway corridors, and highway structures and road maintenance issues" (TRB 2012).

Aligned with Federal Aviation Administration (FAA) goals of efficient integration of UASs into the nation's airspace, the presented work is performed to determine the potential applications of UASs within divisions and associated offices across the Georgia DOT (GDOT). The methodology for the identification of UASs requirements for potential applications within GDOT consists of three stages. The study started by analyzing the DOT divisions/offices through a series of semi-structured interviews. Then, the user requirements of each identified division/office were investigated. Finally, a UAS specifications matrix based on design characteristics that fulfill the identified requirements was developed. The results of this study will help GDOT prepare a platform for efficient and economical implementation of UASs to support the department's mission and goals.

Irizarry (PI) and his research team (2012) studied the initial application of UAV technology in the construction industry. In their study, a small-scale UAV was used as a tool for exploring potential benefits to safety managers within the construction jobsite. The UAV was an aerial quadrocopter which could be piloted remotely using a smart phone, a tablet device, or a computer. Since the UAV was equipped with video cameras, it could provide safety managers with fast access to aerial images as well as real-time videos from a range of locations around the jobsite. Figure 1-1 shows the experimental setup used in the study. The results of this study led to recommendations for the required features of an ideal safety inspection assistant UAV. Autonomous navigation, vocal interaction, high-resolution cameras, and collaborative user-interface environment are some examples of those features.



(b) Voice interaction between workers and the drone

(a) Autonomous navigation using predefined paths or locations

(c) Safety manager interacts with workers using the drone and through the iPad

Figure 1-1: UAV technology as safety inspection tool

Johnson (co-PI), and his research group within the UAV Research Facility in the School of Aerospace Engineering at Georgia Tech, have been doing guidance, navigation, and control work for unmanned system for nearly 20 years. An emphasis has been on small unmanned aircraft capable of vertical takeoff and landing (VTOL), with an extreme variety of different aircraft types utilized, some of which are shown in Figure 1-2. The type of work they do is indicative of the kinds of capabilities that UAVs have gained in that time period, including precision Global Positioning System (GPS)-based navigation, vision-aiding capabilities, automatic real-time video processing, and increased autonomy in general.

1.2. Research Objectives

It is envisioned that this feasibility study would ideally lead to further research on design, development, and field-testing of UAVs for applications identified as beneficial to the Department. It is also envisioned that this GDOT-based user-centered study for developing UAV design characteristics will provide a platform for appropriate data collection to facilitate FAA to accurately develop UAV integration policies and certification requirements.

(a) TwinStar (electric airplane) (b) 33% Yak (gas airplane) (c) GTQ (quad rotor)

(d) Yamaha RMAX (gas helicopter) (e) Logo (electric helicopter) (f) HeliSpy (ducted fan)

Figure 1-2: Some of the aircraft that have been utilized for research in the Georgia Tech UAV Research Facility, including a variety of configurations.

This study investigates various divisions and offices within GDOT and determines the user requirements for specific divisions that have the potential to implement UAV technology. This will lead to a set of UAV design characteristics that fulfill user requirements of each previously identified division. A cost benefit analysis will be finally performed to realize the financial feasibility of applying UAV technology in each selected division within GDOT. In summary the goals of the study include:

1. To identify user requirements for each division/office in GDOT that has the potential to benefit from UAVs.
2. To identify UAV design characteristics based on the user requirements for each GDOT division/office.
3. To perform a cost benefit analysis, comparing the UAV design and construction, maintenance, and operation cost against potential cost savings due to performance enhancement in specific GDOT department practices.

1.3. Research Methodology

Systems have traditionally been designed and developed through a technology-centered perspective (Endsley et al. 2003). In such a perspective the designers would accept the technology as is and would try to apply the very same technology in different domains without considering the very important element of the ultimate end-user (humans). In a technology-centered perspective, the end user and all its requirements would be considered improperly identical in different domains. In this research, a user-centered approach is employed. Unlike the technology-centered approach, the very first issue that should be resolved in a user-center perspective is whether the technology is usable considering the real users’ experience and their own requirements in a specific domain. This user-centered usability-based step would provide a grounded base for understanding the requirements for practical application of the technology in a domain. Having the UAV technology might seem very useful for most GDOT practices but the very first issue that should be resolved is whether this technology would be usable for different applications within GDOT divisions and offices. A usable UAV system should be designed firstly by investigating the user requirements across all divisions and offices of GDOT and then identifying and developing a set of design characteristics for the UAV based on the previously identified user requirements. Even when a real UAV is designed based on user requirements, it should be tested using real users of the system to evaluate its applicability and usability.

The work plan of this research has been illustrated in Figure 1-3 and the related activities are described next. The whole research encompasses four phases of;

1. Analysis of GDOT divisions/offices,
2. Identification of user's operational requirements in each identified division/office ,
3. Identification of UAV design characteristics for each identified division/office,
4. Cost-benefit analysis for each identified division/office based on the proposed UAV for that division/office.

Phase 1: Analysis of GDOT Divisions (Chapter III)

All divisions and offices of GDOT would be studied to identify those that have the potential for using UAVs. This analysis is performed by investigating the operations, mission and sets of responsibilities that each division and their internal offices might have. Furthermore, interviewing directors or administrators of each division or office would help build a clearer picture of what would be general goals and tasks of different divisions and offices.

A simultaneous study is conducted on investigating previous use of UAV across all DOTs together with determining the current status of different civil applications of UAV. A detailed review of various DOTs' materials and reports together with a study of up-to-date publications and research on UAV civil application is also performed. This will lead to a set of case studies and application areas and provide a good starting point for visualizing GDOT's roadmap for UAV implementation. Having a clear understating of what other DOTs have done and determining the current status of civilian application of UAVs would help when identifying different divisions of GDOT with potential of applying UAVs. Those case studies and application areas would help the directors and administrators of GDOT divisions and offices to build a clear picture of how UAVs have been previously utilized so they as experts in the division would provide more valid feedback in their interviews. The result of this phase would lead to identifying different GDOT divisions with the potential for using UAVs as well as determining the potential uses of UAV across all GDOT divisions.

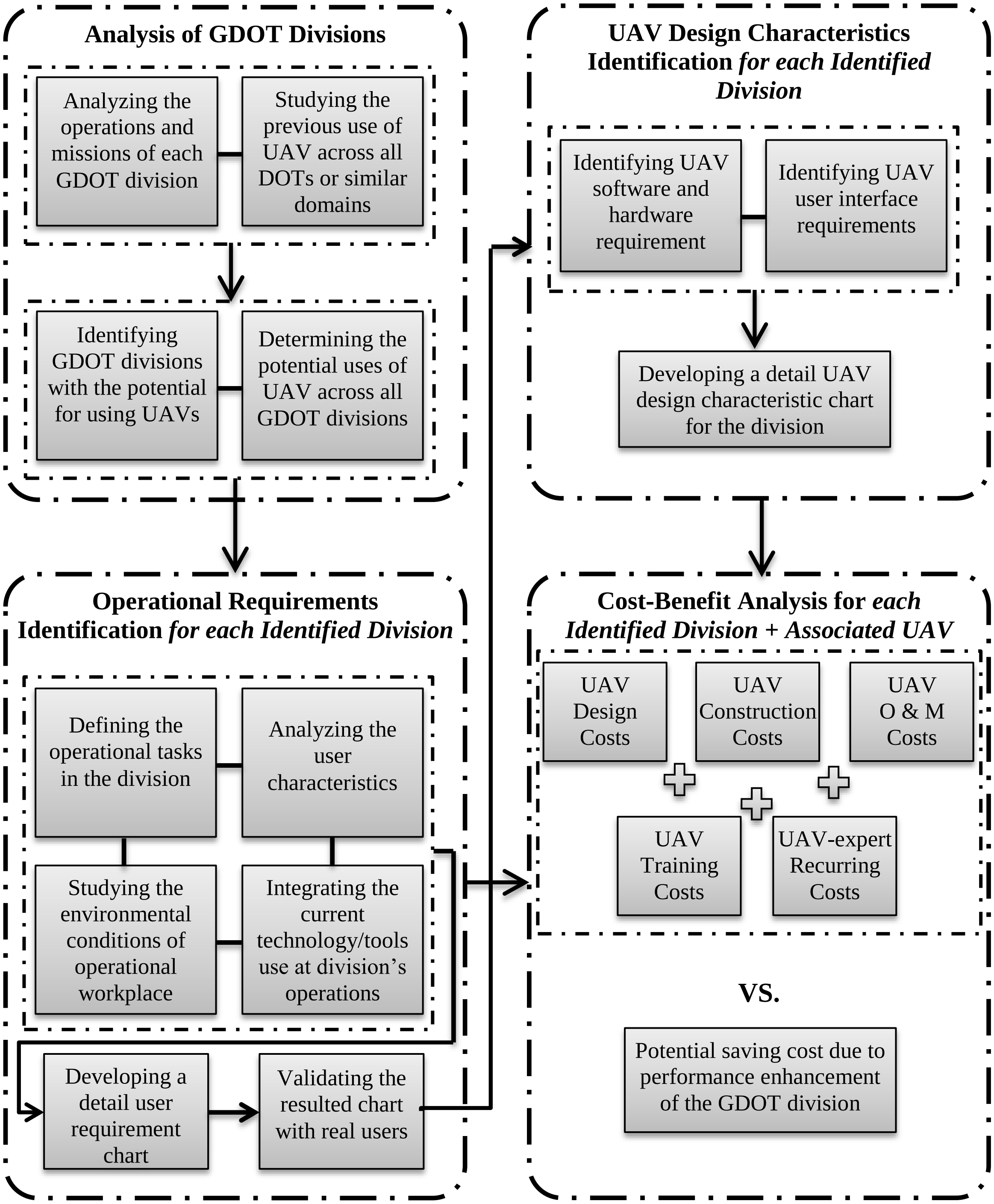


Figure 1-3: Work plan flowchart

Phase 2: Operational Requirement Identification for each identified division (Chapter IV)

In this phase, the broad goals and objectives of each identified division would be translated into a set of requirements that should be considered for designing a specific UAV for that division. This analysis will include four different considerations: (1) defining the operational tasks in the division, (2) studying the environmental conditions of operational workplace, (3) analyzing the user characteristics, and (4) investigating the current technologies/tools use at division's operations.

(1) Defining the operational tasks in the division: The very first and the most important issue in this phase is to study the tasks and operations performed in the identified division to develop exact definitions of those tasks and operations as well as their scope. In this research, an adapted form of cognitive task analysis, Goal Directed Task Analysis (GDTA), is used for this purpose (Bolstad et al. 2002). The GDTA is employed broadly for analysing the tasks and operations in the identified divisions and for determining requirements of individuals performing those tasks and operations (Endsley 1993; Endsley and Rodgers 1994). The GDTA follows a set of semi-structured interviews with Subject Matter Experts (SMEs) in each identified division and focuses on (1) the basic goals of the operators in each division, (2) their major decisions for accomplishing those goals, and (3) the information requirements for each decision.

The information obtained from the GDTA is organized into figures depicting a hierarchy of the three main components of the GDTA (i.e., goals/subgoals, decisions relevant to each subgoal, and the associated information requirements for each decision). The research team has worked with the proposed method for determining the information requirements of safety managers and well as those of facility managers in Architecture, Engineering, and Construction (AEC) organizations (Gheisari and Irizarry 2011; Gheisari et al. 2010; Gheisari et al. 2010) The broad goals and objectives of each identified division are taken from interviews with the SMEs identified by their respective supervisors at the respective division. Detailed information about each task can then be translated into a set of requirements that should be considered when designing a UAV for use in a division that has the potential to implement the technology to aid and supplement their daily operations.

(2) Studying the environmental conditions of operational workplace: The other important issue that should be studied together with operational requirements is the environmental conditions in which the tasks/operations occur in each identified GDOT division. These environmental conditions would affect the design requirement of the UAV. Ambient noise levels, lighting levels, susceptibility to weather and temperature variations, vibration, privacy, expected pace of operations, position of use (e.g., sitting, standing, while mobile), and frequency of use (e.g., occasional, intermittent, frequent, continuous), are some issues that should be considered as the environmental conditions (Endsley et al. 2003).

(3) Analyzing the user characteristics: The user characteristics are identified in this phase. The different types of users that this system would accommodate should be discussed considering issues such as gender (male, female, or both), anthropometric characteristics, including height and weight (percentile of the population to be accommodated), skill level, training, and background knowledge (including technical capability and experience with similar types of systems), age ranges (with special note of young or aging populations), visual acuity and hearing capabilities, languages to be accommodated, special clothing or other equipment to be accommodated (such as gloves, masks, or backpacks), any physical disabilities or special requirements, and the need to accommodate multiple users on the same system (Endsley et al. 2003).

(4) Investigating the current technologies/tools use at division's operations: Here all different technologies or tools that are being used by the identified division are evaluated for possible integration with the UAV platform. There might be a need for integrating hardware (e.g. sensors, radars, or different type of cameras) with the UAV hardware or software. Also, the user interface might be required to incorporate or be compatible with other technologies that are currently used by GDOT in the identified division (e.g. energy or traffic software).

This phase of the study will lead to a detail operational requirement matrix considering each division's operation, user characteristics, working environment, and technology use.

This matrix would be taken back to the SMEs who were interviewed in Part 1 of Phase 2 (Defining the operational tasks in the division).

Phase 3: UAV Design Characteristics Identification (Chapter V)

This phase entails determining requirements on the UAV system necessary to meet GDOT needs for each identified division. These requirements will entail software, hardware, and the user interface. Under this effort, off the shelf UAV systems will also be identified that partially or completely meets requirements. It is important not to limit this effort to existing vehicle systems, given how new this industry is. However, existing systems can be the basis to validate stated requirements as feasible and cost estimates described below. In addition, this is an important basis for identifying the risks associated with meeting stated requirements.

Phase4: Cost-Benefit Analysis (Chapter VI)

In this phase, a cost-benefit analysis is performed. On one side, the total cost of the UAV implementation and use in each identified GDOT division are studied. This total cost consists of design, construction, operation and maintenance costs of the UAV and the costs for training the users at the division for its efficient use and also the possible cost of recruiting UAV experts to work for GDOT. All these costs are compared against the potential cost savings due to performance enhancements in GDOT practices. The basis of UAV operation cost estimates are based on current Georgia Tech UAV Research Facility operations, information provided on currently available systems, and publically available information. Reporting will include an evaluation of the uncertainty in these cost estimates.

1.4. Expected Results

The expected results of the project are:

1. An in-depth understating of the current status of UAV application across various DOTs in the US and determining the current status of different civilian applications of UAV technology.

2. Determining the operational requirements for each identified GDOT division/office considering its operation, user characteristics, working environment, and technology use.
3. Determining the UAV design characteristic for each identified GDOT division/office which is mapped with operational requirements (result of Phase 2)
4. A cost-benefit analysis of the recommended UAV (result of Phase 3) for each identified GDOT division/office. The result would show whether UAV application in that division/office can be financially justified or not.

2. CHAPTER II

2. Literature Review

Innovative applications of UAS for improved mapping operations take advantage of several inherent characteristics of UAV systems. For instance, aerial video, collected by visible or infrared video cameras deployed on UAV platforms, is rapidly emerging as a low cost, widely used source of imagery for response to time-critical disaster applications (Wu and Zhou 2006) or for the purpose of fire surveillance (Wu et al. 2007). During the past decade, UASs have been applied in a wide range of transportation areas, including monitoring and controlling traffic on surface streets during and after emergency incidents, traffic data collection, monitoring bridges and overpasses during severe weather or general maintenance, day-to-day monitoring of roadways for preventative maintenance activities, and managing work zone and traffic congestion while enhancing the safety of workers. This chapter introduces a wide variety of UAS applications in traffic management, transportation and construction disciplines related to DOTs.

2.1. Traffic Surveillance

Traffic surveillance systems are systems that monitor the behavior of vehicles in the transportation network. Various traffic survey methods such as loop detectors and cameras are used to collect the needed traffic data. The increase in traffic volumes over the past decade has been especially large on the beltline and interstate route system and on radial arterials beyond this system that lead into urban areas. The need for faster assessment and response to incidents has consequently increased. Technological advances in communication can enhance the monitoring capabilities of traffic surveillance systems and alleviate some of the already existing problems of inflexible fixed network of sensors or labor intensive activities. UAVs capable of carrying a video camera and communication sensors to relay data to the ground can provide a low cost means to achieve a "bird's eye view" and a rapid response for a wide array of transportation operations .

UASs, compared to traditional traffic monitoring systems, can move (or fly) at higher speeds and have the ability to cover a larger area. Because they can potentially fly to a given destination, UAVs have the ability to operate in conditions that would be too dangerous or in areas that are inaccessible (e.g. evacuation conditions, urban and forest fire) to manned vehicles. To further explore the benefits of UAS applications to transportation surveillance and understand the barriers to deployment, Coifman et al. (2004) conducted four field experiments for freeway conditions, intersection movements, network paths, and parking lot monitoring. The UAV, equipped with an on-board camera, was flying low (i.e. at an altitude of 500 ft) and an air speed of 30 mph while transmitting the video images and providing aerial surveillance. They concluded that the UAS could eventually be airborne most of the time since the operator would be on duty for any emergency calls. However, power limitations and lack of experience with operations would limit flight time, but these limitations could likely be overcome if widespread deployment is targeted.

Similar study conducted by the University of Florida has also attempted to implement a system for aerial traffic surveillance using UASs (Srinivasan et al. 2004). First, the research team reviewed and compared six UAV vendors based on the features and characteristics of the UAVs as well as flight experience. Adroit Systems, along with their partner, Aerosonde Communications, was selected as the UAV vendor. After providing and purchasing the necessary telecommunication equipment (e.g. antenna, video receiver, transmission lines, transient voltage surge suppressors, and etc.), a field experiment was conducted. The UAV was flying over a small segment of a highway between two FDOT's microwave towers and capturing video as it flied along the highway. The UAV would transmit video of the highway throughout its journey and the video would be received and encoded at each of the two towers. The video captured by the UAV was received by the antenna that was installed at both the microwave towers. This signal was relayed to the ground station using a transmission line. This video signal was transmitted over FDOT's microwave network. The objective was to determine the feasibility of incorporating UAVs equipped with video cameras and/or other sensors in traffic surveillance.

Several other studies also suggest the usefulness of UAS in the traffic management to handle traffic and congestion on the main road network such as moving vehicle detection (Lin et al. 2008), autonomous ground vehicle following and providing local and "over-the-horizon" visual coverage (Lee et al. 2003), visualization and parameter estimation of traffic flows (Shastry and Schowengerdt 2002), and real-time video relay for traffic monitoring system (Chen et al. 2007). These applications are performed through a UAV that is equipped with a camera.

2.2. Traffic Simulation

Traffic simulation models are used to improve traffic control and better help plan, design and operate transportation systems. The simulation results can serve as a basis for predicting future traffic demands, optimizing signal timing and/or changing lane configuration. Traffic simulation models rely on routinely collected data in real-time and process such data to determine origin-destination flows and to evaluate traffic patterns for emergency response and. Puri et al. (2007) proposed to exploit the UAS application for real-time traffic data collection and use this data to generate statistical (mathematical) profiles to improve accuracy, parameter calibration and reliability of traffic simulation models, thus, improving traffic prediction. The UAV was a small unmanned vertical take-off and landing helicopters controlled by a dual on-board / on-the-ground processing system and equipped with a pan–and–tilt camera that collected visual data. Visual data are then converted to traffic statistical profiles that serve as input to the simulation models and are used to update, calibrate and optimize them. In fact, the role of UAS used in the study was to provide input visual data for the traffic statistical profiles that are used to run the traffic simulation models. To accomplish this, they used a specific camera (Sony block FCBEX980S) with a horizontal Field of View of 42.2^{o}. Also, the maximum altitude the helicopter has flown was 200 ft (approx. 66m) and the maximum area that could be observed was about 167 ft (50.9 m).

In a similar effort, Coifman et al. (2006) used UASs as an alternative for roadway traffic monitoring. They claimed that the captured data can be used to determine level of service, average annual daily traffic, intersection operations, origin–destination flows on a small network, and parking lot utilization.

2.3. Monitoring of Structures

Inspecting and monitoring linear infrastructures such as roads, pipelines, aqueducts, rivers, and canals are very important in ensuring the reliability and life expectancy of these structures. A UAV can stay or fly on top of the structures and transmit a precise image or video stream for inspecting and monitoring purposes. A study, sponsored by the Office of Naval Research's (ONR) Autonomous Intelligent Network and Systems (AINS) program, aimed to develop a control technology that can be used to produce infrastructure monitoring or inspection video using an autonomous UAV (Rathinam et al. 2008). While most UAVs are commanded to fly along a path defined by a sequence of GPS points (called waypoints), this study tried to improve the performance by putting an imaging sensor to detect the linear structure. Therefore, the UAV with a camera can navigate based on visual information rather than GPS information.

Using a semi-supervised learning algorithm, the vision-based system can detect many kinds of linear structures. The result is a cross-sectional profile of the target structure. Then, the UAV is commanded to direct the fixed wing to follow the detected profile. The vision-based control system was tested using a Sig Rascal model aircraft, which had a wingspan of 9.2 ft (2.8 m) and an empty weight of 12 lbs (5.5 kg). A camera was mounted at an angle of 30° with respect to the yaw axis of the aircraft. The image and video outputs were simulated using a real-time 3D visualization software package. Though a downward-looking camera on a UAV, flying UAVs based on vision and GPS is better than flying them purely based on GPS for these applications. It would be ideal to have an additional Gimbaled camera mounted on these vehicles. One of the problems in the developed system was to deal with the wind disturbances while flying small, light vehicles (e.g. path following for small UAVs in the presence of wind disturbance).

In another study which investigated computer vision sensors for UAVs operating, Frew et al. (2004) applied a vision-based system for tracking and following a road using a small autonomous UAV. They concluded that the performance of the control strategy is directly related to errors in the aircraft altitude.

2.4. Avalanche Control

It is estimated that a 2-hour avalanche closure can cost over a million dollars. Current efforts involve the use of surplus military equipment to shoot explosives into areas that are in range of the roadside and the dispatching of skiers with handheld charges, plus the occasional use of helicopters to drop explosive charges into inaccessible areas. The University of Washington and WSDOT conducted a test of two types of UAVs to explore whether, in the longer term, UAVs may provide a less expensive and safer option for triggering avalanches than shooting explosives from howitzers or dropping explosives from manned aircraft, and also explored the UAS's ability as a tool to provide enhanced information about the terrain and conditions in the area (McCormack and Trepanier 2008). In the first step, the criteria and parameters for finding a suitable UAS were determined. For instance, it was decided to complete the test in a rural, lightly populated area with minimal air traffic and with UAV systems that cost no more than $500,000. The aircraft selected for the first test was the MLB BAT with the following specifications:

- Weight: 24 pounds (maximum)
- Payload: 5 pounds
- Wingspan: 80 inches
- Flight duration: 5.0 hours (nominal); 8 hours (maximum)
- Flight speed: 40 to 60 mile/hour
- Altitude (maximum operating): 10,000 feet
- Engine: 1.25 cubic inch (26cc) 2-stroke
- Range: 10-mile radius (telemetry limited); 180-mile fuel range

The MLB Company was contracted for the flights, and the test of the UAV occurred in April 2006 along a snowy, avalanche-prone section of the highway that had been closed for the winter. The test flight was designed to evaluate the ability of the UAV to use an on-board video camera to view a roadway, operate off a highway, and survey the surrounding terrain. The resulting videos provided a clear view of the roadway, and individual vehicles could easily be identified. Given the difficulties with terrain and weather encountered in the first test, a more mobile, vertical takeoff and landing UAV (i.e. the R-Max made by Yamaha) was selected for the second test. Technical specifications of this rotary wing (helicopter) aircraft were as follows:

- Weight: 205 pounds
- Payload: 65 pounds
- Main Rotor Diameter: 12 feet
- Tail Rotor Diameter: 21 inches
- Overall Length: 11.9 feet
- Flight duration: One hour
- Flight Speed: 10 to 12 mile/hour
- Engine: Water-cooled, 2-stroke, horizontally opposed 2-cylinder (246 cc)

Both aircraft systems showed considerable potential for aerial roadway surveillance and avalanche control. They were able to obtain clear and usable videos of the roadway at a height that allowed for efficient viewing of roadway conditions and traffic.

2.5. Aerial Assessment of Road Surface Condition

The assessment of road surface distress is an essential part of a road management system for developing repair and maintenance strategies to ensure a good and an effective road network. Over the last decades, significant progress has been made and new approaches have been proposed for efficient collection of pavement condition data. Zhang and Elaksher (2012) introduced an innovative UAV-based digital imaging system for aerial assessment of surface condition data over rural roads. The system for unpaved road image acquisition consists of a UAV helicopter equipped with a digital camera, a GPS receiver, a ground control station, an Inertial Navigation System (INS), and a geomagnetic sensor. The UAV features an electric engine with a payload of 15 lbs (6.8 kg) and is capable of flying around 25 minutes with a fully charged battery. It can reach 650 ft (approx. 200 m) above the ground and travel at a maximum speed of 30 ft (approx. 10 m) per second.

The developed system has been tested over several rural roads near Brookings, South Dakota. During the data acquisition period, the roads demonstrated moderate distresses such as potholes or ruts. Flight plan was prepared on the autopilot software with a georeferenced raster map to set the mission parameters. After the assisted take-off by an operator, the UAV flew along the defined route at an altitude of about 150 ft (45 m) above the ground, capturing details of the road surface with the image scale of about 900 and the ground resolution of about 0.2 inch (5 mm). The UAV traveled at 13 ft/s (4 m/s), acquiring road images with 60% overlap along the path. The acquired images were then analyzed to determine the orientation parameters. Afterwards, the developed 3D reconstruction approaches were applied to generate 3D models of potholes and ruts.

2.6. Bridge Inspection

Field engineers and technicians working in infrastructure construction or inspection projects need to conduct regularly scheduled routine inspections of highway bridges in order to determine the physical and functional condition of a bridge and to identify changes compared to previous inspections. Furthermore, these inspections are conducted to ensure that a bridge continues to satisfy all applicable serviceability requirements. In LCPC-Paris (Laboratoire Central des Ponts et Chaussées), Metni and Hamel (2007) have started a project pertaining to civil applications of a UAV for bridge inspection and traffic surveillance. A UAV capable of quasi-stationary flights was used to inspect the bridge and detect the location of defects and cracks. The UAV was equipped with a camera, an image transmitter, and a vision system that included INS and GPS. It followed a predefined path and was controlled by visual servoing (vision-based robot control). The size and location of defects and cracks were detected through image treatment. In order to keep the object in the camera's view field, the research team presented a control strategy for the autonomous flight with orientation limits

In order to validate the concept of inspecting bridge defects by means of an image capture device mounted on a UAV, an on-site experiment was performed with a helicopter flying around a bridge and capturing video. It was also a test for the required security measures and applicable regulations. This road with particularly high traffic is located indeed in an urbanized zone subjected to the control of two airports. During the test, a video sequence was taken using the onboard camera. The images were presented to bridge inspection experts to provide useful information about the physical and functional condition of a bridge.

2.7. Safety Inspection at Construction Jobsites

One of the main concerns in the construction industry is related to safety issues. Technological advances in areas such as personal protective equipment, safety conscious design, focused safety training, and others have improved worker safety. However, even with such improvements, construction continues to be one of the most dangerous industries in the U.S. economy. One of the most important procedures for safety managers is conducting periodical inspections of the whole construction jobsite to evaluate site conditions based on safety criteria. Providing safety managers with a communication tool that can enable them to be present at any time in all different areas of the construction jobsite and to provide the workers with real time feedback would be extremely beneficial. Irizarry et al. (2012) used an aerial drone quadrotor helicopter (AR.Drone quadricopter) with the ability to fly all around the construction jobsite and provide the safety managers with real time information about what is happening on the jobsite.

The first step of this research was performing a Heuristic Evaluation of the AR.Drone interface that is considered as a prototype of a fully functioning safety inspection aerial drone. Then a within-subjects experiment was designed to test the AR.Drone with real subjects while performing a safety-manager-related-task under different conditions. In this experiment, the subjects would count the number of hardhats they could see in different images of the construction jobsite. Figure 2-1 shows FlightRecord User Interface while flying the UAV.

They concluded that the following three features are required and/or recommended for a safety inspection UAS:

(1) Autonomous navigation: The safety managers should be able to manually control the device as well as using the autonomous navigation feature. Having predefined paths or locations that the drone can automatically use, with or without minimum user interference, would be an ideal feature.

(2) Voice interaction: The safety managers should be able to have direct interaction with workers through the communication tools (video and voice transmitters).

(3) Improving the battery life: The battery life of the AR-Drone provides up to 13 minutes of continuous flight. This should be increased to allow longer flight time.

In terms of the challenges of using drone in the construction industry, the main one is endangering the safety of the workers in the jobsite. Issues such as workers being distracted or even hit by drones should be studied (and obviously avoided in any deployed system). Also there is a social challenge of applying this technology in the construction jobsite that should be considered as well. In summary, providing real time videos, being able to fly to all different parts of the jobsite, and voice interaction are some features that would make the drone an appropriate technology to be used in other sectors of the construction industry.

Figure 2-1: Example of UAV flight controller user interface – safety inspection experiment

3. CHAPTER III

3. Analysis of GDOT divisions/offices

All divisions and offices of the GDOT were studied to identify the divisions with the highest potential for benefitting from UAV technology. It should be noted that the GDOT website is the primary source of information provided in this chapter (GDOT 2013). The GDOT consists of 8 divisions; each relating to a major area of transportation concern as follows: administration, construction, engineering, finance, intermodal, local grants and field services, program delivery, and permits and operations. Also, each division consists of 1-5 offices that are briefly explained in Table 3-1.

Table 3-1: GDOT divisions and offices and summary of their responsibilities (adopted from GDOT website, access date: March 2013)

Division	Office	Responsibilities/Tasks
Administration/General Counsel	Construction Claims	Provide high-quality legal advice and services about construction claims and lawsuits filed by contractors. Reviewing, analyzing, negotiating, mediating and directing the Department's defense against construction claims.
	Equal Employment Opportunity	Ensuring the right of all persons to work and advance on the basis of merit, ability and potential, as well as providing equal employment and business opportunities. Assisting in the implementation and monitoring of GDOT’s Contractor Compliance and Labor Compliance. Providing training, consulting, and a vehicle for improving the skills and experience necessary to establish goals for the GDOT certified Disadvantaged Business Enterprises.
	Human Resources	Providing policy, strategic planning, and consultative services for all GDOT personnel, and developing and administering policies and programs to build and enhance a diverse, highly functioning workforce. Providing information about employment, recruitment, and job benefits to the public and the department's personnel.

Division	Office	Responsibilities/Tasks
Administration/ General Counsel	Legal	Responsible for the supervision, coordination and review of the legal work and services concerning recurring issues of interest to the Department.
Chief Engineer (Not a Division)	Engineering Services	Providing general engineering support and infrastructure planning for federally-funded projects. Directing project review process, managing standard specifications and providing project cost estimates as well as value engineering services for all construction projects with total combined costs of $10 million or more.
	Organizational Performance Management	Responsible for implementing and administering the Transportation Asset Management (TAM) Program. Preparing strategic plan update and annual "strategic implementation plan".
	Program Control	Monitoring project status with the aid of Project Scheduling Software and Project Status Reports. Providing training to raise awareness of the value of collaborative practices from project selection through project closing.
Commissioner	Audits	Responsible for the financial matters of all architectural and engineering consultants who work for the Department and audits of all third party consultant contracts. Planning and performing research grant audits of billings from state and local governments and educational institutions.
Construction	Bidding Administration	Responsible for preparing proposals and letting to contract all GDOT highway and bridge projects.
	Construction	Monitoring and inspection construction projects and assisting in timely problem resolutions. Reviewing and approving contract modifications and communicates with construction industry.

Division	Office	Responsibilities/Tasks
Construction	Materials	Testing materials used in construction and maintenance activities, maintaining qualified products lists and providing expertise in construction materials.
Deputy Commissioner (Not a Division)	Communications	Developing and managing the overall communications strategy for the Department. Providing services such as Constituency and Press Room, and advising the Commissioner and top management on public affair issues involving the Department.
	Information Technology	Managing Department's new and existing computer applications and computer network. Supervising Department's electronics processing budget, configuration and asset management. Developing information technology policy, standards and strategic planning functions.
	Procurement	Developing and directing all staff, strategic goals, and operational objectives for Department operations (e.g. operational purchasing, transportation services procurement for preconstruction, construction, maintenance initiatives).
Engineering	Bridge Design & Maintenance	Supervising the structural design of highway bridges, culverts and retaining walls as well as the hydraulic design of bridge structures.
	Design Policy and Support	Responsible for supporting and enhancing all aspects of program delivery through developing and maintaining Design Policy, Guidelines, and Standards and providing Engineering Technical Support. Responsible for reviewing the engineering literature, reducing it to a form that can be communicated, and deciding whether GDOT needs to implement it.
	Environmental Services	Coordinating reviews and evaluations for federally funded transportation projects, on behalf of the Federal Highway Administration. Obtaining environmental approvals for all constructions projects both on time and in accordance with numerous environmental laws.

Division	Office	Responsibilities/Tasks
Engineering	Right-of-Way	Responsible for the acquisition of properties necessary for transportation projects. This task includes plan design review and approval, appraisal, relocation assistance, condemnation, negotiation and property management. Both DOT acquisitions as well as local government acquisitions (if they include state or federal funds) are monitored by this office.
	Roadway Design	Responsible for project design and plan development. This includes the development and coordination of conceptual layouts, preliminary and final construction plans and right-of-way plans. Performing most of the analyses for design of a variety of urban and rural transportation projects throughout the State of Georgia, prepare reports and gain input from other Divisions.
Finance	Budget Services	Developing and managing the Department's annual operating budget. Serving as a financial advisor to the Treasurer and upper management staff
	Financial Management	Processing requests for authorization and preparing documents for billing for federal aid, bond and state funds. Preparing, submitting and tracking project expenditures through Department's project accounting system and project information system.
	General Accounting	Responsible for maintaining the general ledger, recording of revenue/receivables, expenditure/payables, processing payroll and disbursement of salary checks, processing/issuance of travel advances/checks, and the maintenance of capital asset/inventory records.

Division	Office	Responsibilities/Tasks
Intermodal	Intermodal	The main responsibility is to support and facilitate the development and implementation of intermodal policies, planning, and projects. Focusing on intermodal issues in the highway program and formulate, organize and administer all major statewide programs in support of the transit, rail, port, waterway and aviation systems.
Local Grants and Field Services	Field Districts Services	Responsible for operating and maintaining the transportation system at the local (district) level.
	Local Grants	Providing contracts to local governments to assist in the construction and reconstruction of their road and street systems
	Property and Equipment Management	Responsible for the administration and management of the Department's fleet, compromised of approximately 8,600 units. Directing and administering the program for statewide purchasing of vehicles and equipment. Determining vehicle and equipment replacement requirements, considering both budget and needs.
P3, TIA & Program Delivery	Innovative Program Delivery	Managing innovative programs in transportation system delivery, through Public Private Partnerships, Design-Build, and other alternative delivery methods. Handling major transportation projects, feasibility studies and special projects.
	Public-Private Partnership (P3)	Responsible for the development and implementation of the agency's Public-Private Partnership (P3) Program in coordination with the Department's leadership,
	Program Delivery	Coordinating project development and delivery with Department offices, local government, business and community stakeholders, and other state and federal agencies. Focusing on critical project delivery tasks that include scope, schedule, and budget development, resource management, and risk analysis.

Division	Office	Responsibilities/Tasks
P3, TIA & Program Delivery	Transportation Investment Act (TIA)	Handling transportation projects that fall under the Transportation Investment Act.
Permits and Operations	Maintenance	Coordinating all statewide maintenance activities such as bridge and sign maintenance, roadway striping, routine maintenance of state highway system, emergency response (both roadway and weather induced) and the Adopt-a-Highway Program. Developing contract documents for letting maintenance projects.
	Traffic Operations	Coordinating traffic engineering, traffic safety, traffic management and incident management statewide. Supervising programs that include vehicle crash analysis and reporting, traffic studies, traffic engineering, general operations, intelligent transportation systems, Highway Emergency Response Operators (HERO), and access management. Providing design services for safety improvements, pavement markings and traffic signals, signing, implementation of the intelligent transportation system.
	Transportation Data	Gathering data directly through automated means and field personnel or indirectly through other government entities in the areas of Road Inventory and Traffic Data Collection.
	Utility	Developing and administering reasonable utility and railroad policies, procedures, standards and regulations for the safe and efficient use of highway right-of-way. Providing expert technical assistance and functional guidance on utility and railroad encroachments, adjustments, relocations, agreements and billings to meet the diverse needs of our stakeholders.
Planning	Planning	Developing and coordinating balanced transportation policy and planning which are consistent with the social, economic and environmental goals of the State.

This analysis is performed by investigating the operations, mission and sets of responsibilities that each division and their internal offices might have. Having a clear understating of what other DOTs have done and determining the current status of civilian application of UAVs were utilized to identify different divisions of GDOT with potential of applying UAVs. Of the twelve overall divisions of GDOT, four divisions with the highest potential for benefitting from UAV technology were selected for further investigation (construction, engineering, intermodal, permits and operation).

Figure 3-1 shows some of the tasks and responsibilities associated with each of the selected GDOT divisions. Through a series of interviews with employees at the division and office level, the user requirements of each identified division/office were investigated. For a full presentation of the interview questions, the reader is referred to Appendix A. The following sections provide a brief description of these four divisions including their tasks and responsibilities. Some of the Construction and Permits and Operations employees are divided into seven districts in order to facilitate regional development. Each district is responsible for the traffic operation and construction of the state and federal highways in their region. The districts are further divided into several area offices, which are managed by area engineers. Figure 3-2 shows the geographical location of GDOT districts and their office areas.

3.1. Construction Division

The Construction Division is responsible for construction contract administration and overseeing construction projects and permitting in the State of Georgia. It conducts general construction oversight and also oversees project advertising, letting and awards, and testing of materials. Furthermore, it inspects and monitors contractual field work, specifies material requirements, and provides geotechnical services. Interviews were conducted with eight engineers at management and operational levels. Its goal is to provide the resources necessary to insure the quality of construction projects by improving decisions made in the field, making information available for training and to maintain statewide consistency.

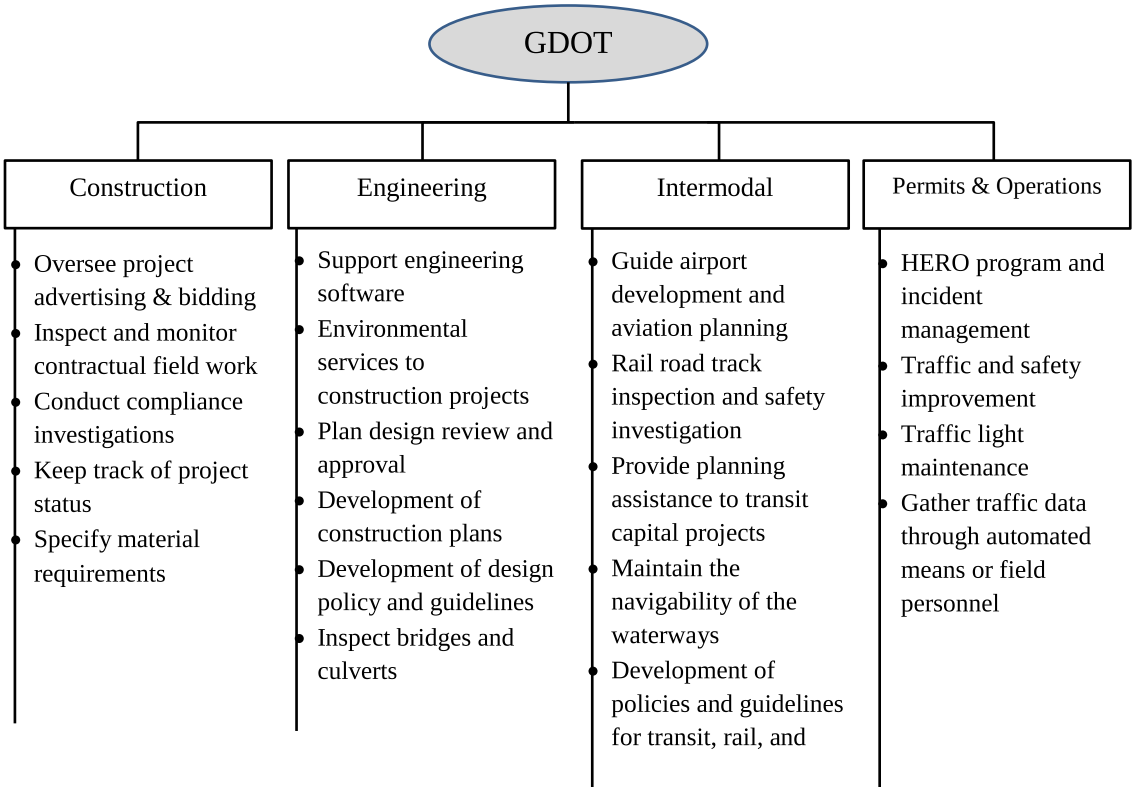


Figure 3-1: GDOT divisions with the highest potential for benefitting from UAV technology

At the district level, GDOT construction engineers are responsible to oversee, inspect, and monitor contractual field work. In this regard, they take field measurements of pay items. The task includes performing several linear, areas, and counting measurements in the construction site. Moreover, area engineers take field measurements of underground items (e.g. piping and utilities) during the construction stage. The task includes performing measurements and documenting for the items underground (e.g. pipes). For overseeing the work at the construction site, the task includes photo-documentation (ideally near real-time aerial photography) to see the project overview and also enhancing the project personnel's perception of the environment. Thus, they can ensure that projects are completed on schedule, within budget, and in a way that is safe and follows the GDOT codes and laws. All data, queries, commands, or responses must be entered into the GDOT server through a new software program called SiteManager. Information entered on series of computerized forms is stored in a central database, so when a user calls up a report or record, the program automatically transfers information from one form to all other forms and reports that use the same information.

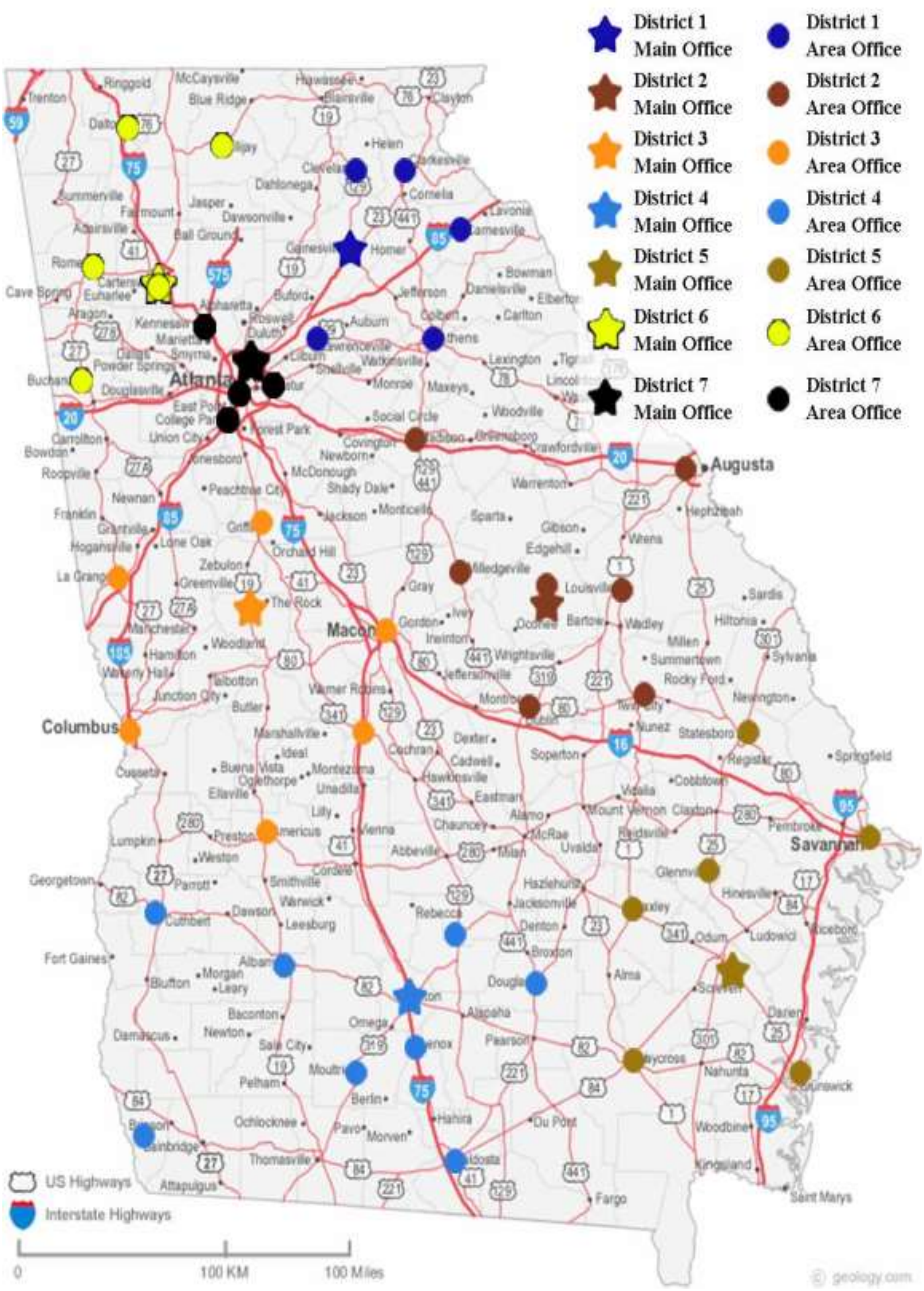


Figure 3-2: GDOT districts – main office and area offices (adopted from GDOT website, access date: March 2013)

This software automates and streamlines the management of highway construction contracts for everyone involved in the project (SiteManager 2008). To achieve their important objectives, GDOT construction engineers must communicate with many individuals at the construction jobsite as well as GDOT people in the office. Eight interviews were conducted with persons at the district main office and area office levels. Figure 3-3 shows the organizational chart for construction division and shows how interviews fit into the organizational chart.

3.2. Engineering Division

The Engineering Division develops environmental studies, right-of-way plans, construction plans and bid documents through a cooperative effort that results in project design and implementation. Moreover, the division is responsible for supporting and maintaining all engineering software, engineering document management, and state wide mapping. Four interviews were conducted with persons in charge of activities conducted by the engineering division.

The Engineering division consists of five offices: Environmental Services, Roadway Design, Bridge Design and Maintenance, Right of Way, and Design Policy and Support. Office of Environment Services is responsible for obtaining environmental approvals and all necessary regulatory permits for constructions projects. Roadway Design is responsible for the development and coordination of conceptual layouts, preliminary and final construction plans and right-of-way plans of a variety of urban and rural transportation projects throughout the State of Georgia. The Bridge Design office oversees the structural design of bridge walls, culverts, sign supports, and anything else requiring structural expertise. Also this office oversees the hydraulic design of bridge structures. Bridge maintenance is one of the main activities in the office. This office inspects all the bridges and bridge culverts in the State (including county bridges) every two years and evaluates bridges and determines if they must be “load limited.” The Right-of-Way office reviews process of right of way plans submission and is responsible for the acquisition of properties necessary for transportation projects. Design Policy and Support is responsible for supporting and maintaining all engineering software, statewide plotting, and engineering document management such as design guidelines and standards adopted by the GDOT for the design of roadways and related infrastructure.

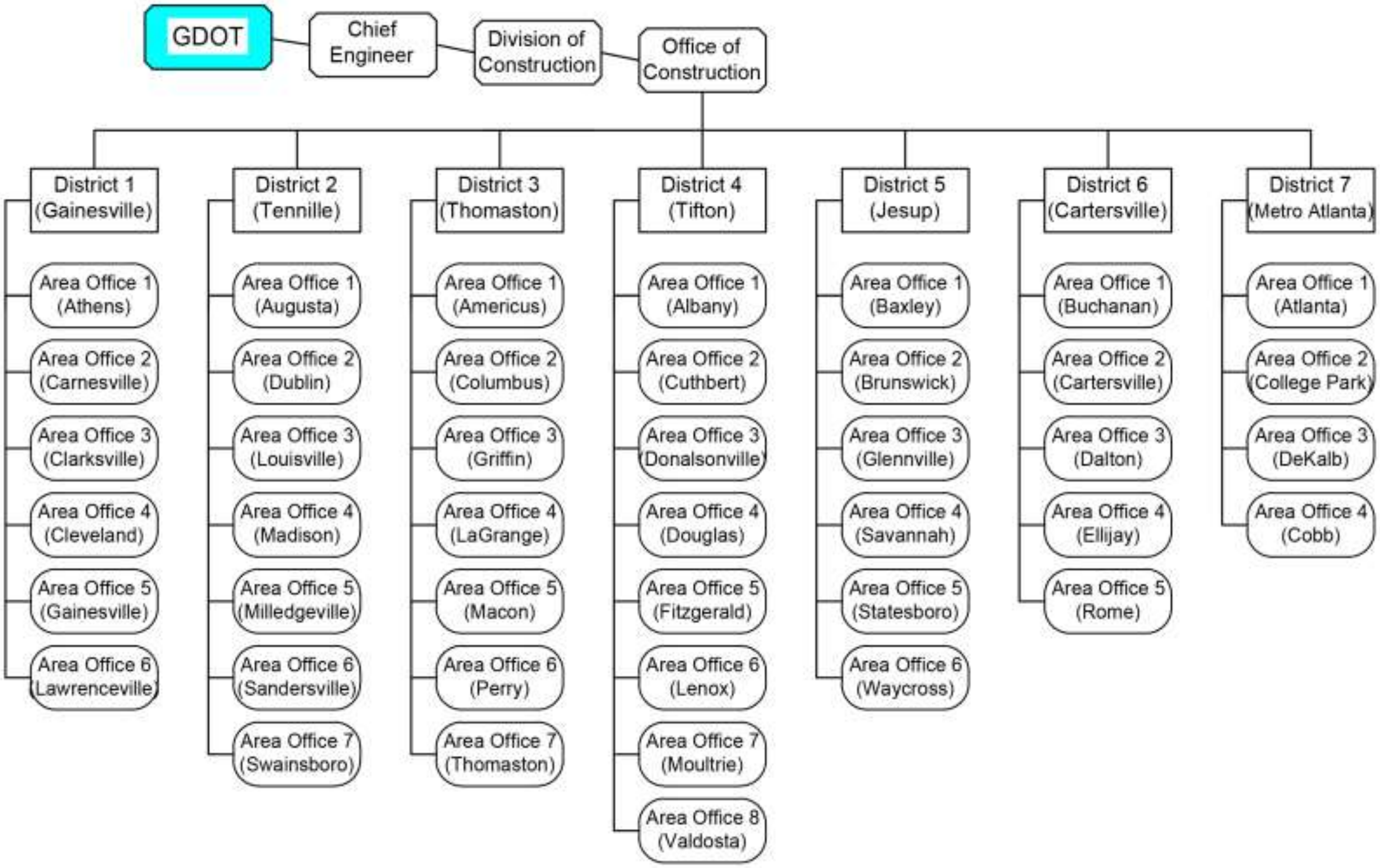


Figure 3-3: Organizational chart of GDOT construction division (adopted from GDOT website, access date: March 2013)

Considering the roles and responsibilities of the Engineering division, this project only focuses on “Bridge Design and Maintenance” and “Design Policy and Support” offices. GDOT bridge maintenance employees are tasked to conduct regularly scheduled routine inspections of conventional bridges in Georgia. The goal of this task is to determine the physical and functional condition of a bridge and to identify changes compared to previous inspections. Furthermore, these routine inspections are to ensure that a bridge continues to satisfy all applicable serviceability requirements. A Routine inspection is a regularly scheduled inspection to determine the physical and functional condition of a bridge and to identify any changes since previous inspections. These inspections are generally conducted from deck level, ground or water levels, or from permanent-access structures. An In-Depth inspection is a close-up, hands-on inspection of one or more members to identify deficiencies not normally detected during routine inspections. These types of inspections are generally completed at longer intervals than Routine inspections and may include the use of more advanced nondestructive examination techniques. A Specialized inspection is completed to assess structural damage resulting from environmental or human actions. The scope of each specialized inspection is unique, with the general goal of assessing the need for further action. Special inspections could also be warranted for complex bridge structures (major river bridges, movable, suspension, cable stayed, and other bridges with unusual characteristics) or inspections of underwater parts of a bridge.

Design Policy and Support is responsible for supporting and enhancing all aspects of program delivery through developing and maintaining Design Policy, Guidelines, and Standards and providing Engineering Technical Support. The GDOT Design Policy and Support office has recent and historical aerial imagery of the entire state of Georgia to assist in the design of highways and other transportation improvements. There is a need for aerial photography at conceptual and engineering level (i.e. elevation dependent). The task includes managing an archive of aerial photography procured by GDOT and other cooperating agencies. Figure 3-4 shows the organizational structure for the engineering division (only offices of interests to the present study are shown). Five interviews were conducted with personnel at management and operational levels.

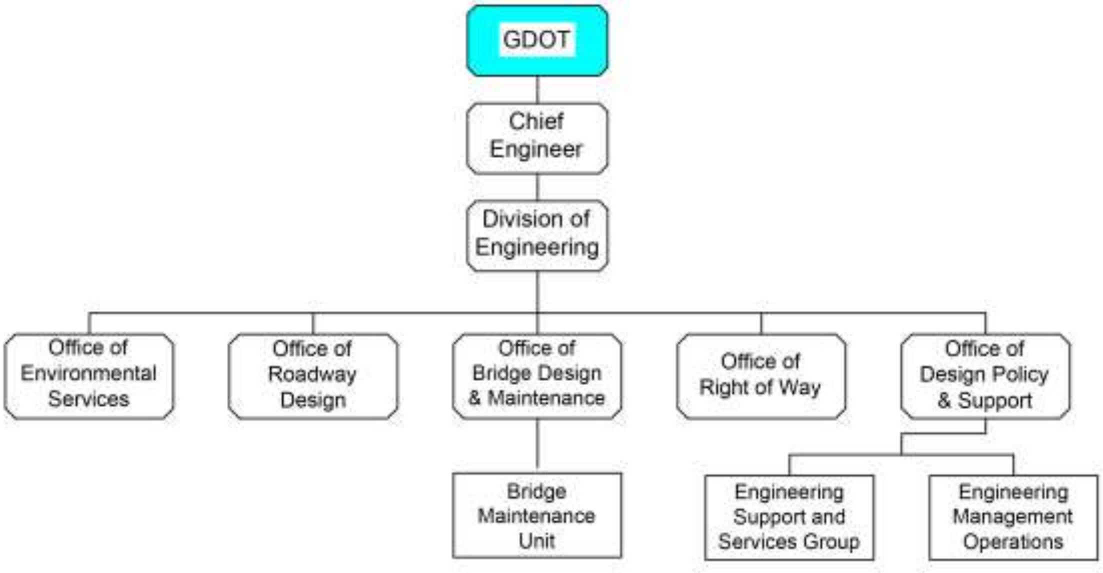


Figure 3-4: Organizational chart of GDOT engineering division (adopted from GDOT website, access date: March 2013)

3.3. Intermodal Division

The main responsibility of the Intermodal Division is to support and facilitate the development and implementation of intermodal policies, planning, and projects in the highway program and organize all major statewide non-highway programs for the development of a comprehensive transportation system. The intermodal division consists of four main programs: (1) aviation programs is tasked to guide airport development and to assure a safe and well-maintained system of public-use airports; (2) transit programs provide transit capital and operating assistance to the urban and all metropolitan planning organizations in Georgia; (3) rail programs include track inspection and safety investigation for the Georgia rail system in cooperation with the Federal Railroad Administration; (4) waterways programs maintain the navigability of the Atlantic Intracoastal waterway and Georgia's deep water ports in Savannah and Brunswick. Consequently, five interviews were conducted with members from the intermodal division, including at least one interviewee from each of the above programs.

The condition of airports is assessed by the Intermodal division through field investigation. The aviation program is responsible for airport investigation for compliance with relevant Georgia codes as well as the collection of data for federal agencies (mainly through the form "5010"), including assessing the location of trees, airport and runway geometry, lighting and wildlife and bird control/monitoring. The transit program provides funding to support urban areas in planning, developing, and improving public transportation systems and Federal resources to urbanized areas and for transit capital and operating assistance in urbanized areas (population of 50,000 or more) and for transportation-related planning. The railroad program includes track inspection and safety investigation in cooperation with the Federal Railroad Administration and preservation of railroad corridors for current and future use. The task includes having near real-time (aerial) photography that provides an overview of the railroads and also allows for assessing environmental conditions. The Port of Savannah handles 80% of the ship-borne cargo entering Georgia. The GDOT (waterways program in particular) is the local sponsor for the Savannah Harbor and is responsible for: (1) Providing easements and rights-of-way for upland disposal areas, and (2) Providing 35% of the cost required to raise the dikes at the upland disposal areas in the Savannah Harbor. The task includes conducting field surveys to determine the current height and capacity of disposal areas. Also, the GDOT waterways program is responsible to monitor wildlife along the intercostal waterways, such as monitoring bird nesting activities and all the nests located in flood-prone areas. Figure 3-5 shows the organizational chart for intermodal division.

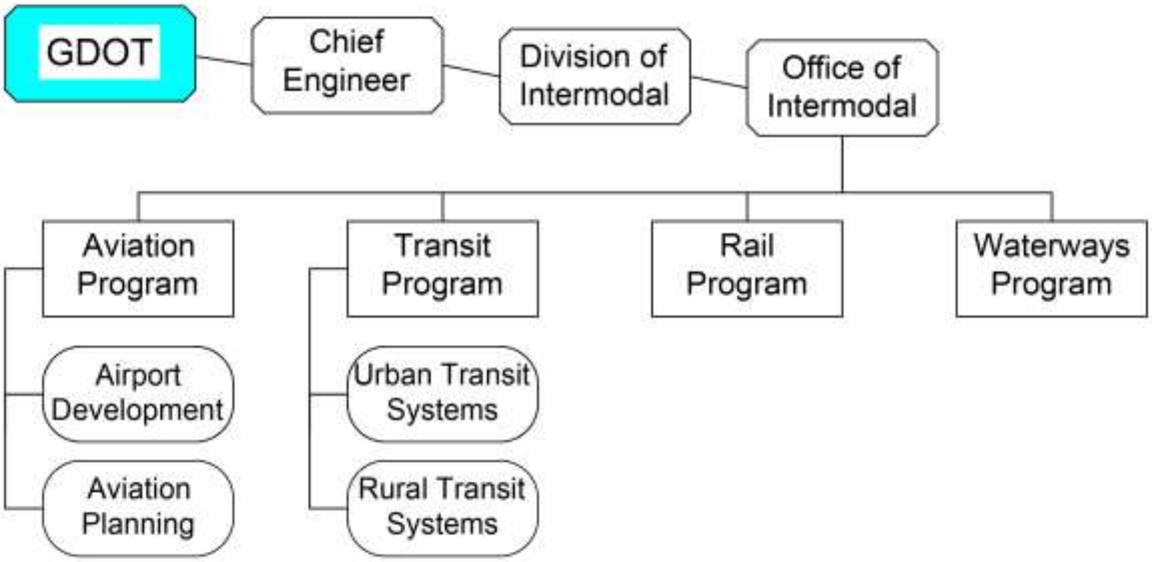


Figure 3-5: Organizational chart of GDOT intermodal division (adopted from GDOT website, access date: March 2013)

3.4. Permits and Operations Division

The Permits and Operations Division ensures a safe and efficient transportation system by collecting traffic data, addressing maintenance needs (e.g. related to traffic lights) and regulating the proper use of the state highway system. In order to improve traffic flow and coordinate traffic engineering, traffic safety, and incident management statewide, the division collects traffic data (e.g. flow, speed, counts) using a wide range of devices (e.g. video cameras, microwave sensors, and computer applications pertaining to traffic services). This division consists of four offices: Transportation Data, Utilities, Traffic Operations, and Maintenance.

The office of traffic operations is collecting traffic data (e.g. flow, speed, counts) using surveillance video cameras (i.e. permanent traffic data collection devices), traffic counting device (i.e. microwave sensors), and INRIX traffic app. Road closure, traffic detours and special events are supervised through daily coordination with the traffic operation office. The task includes having real-time traffic data in the case of special events (e.g. hurricane and evacuation) to choose the best way to detour or evacuate the traffic, or during an incident (for people at the scene). Most accidents require one or more individuals to investigate its circumstances to see how it happened, who caused it, and how it could have been avoided. Many times the facts discovered in the investigation will be pertinent to a claim by the injured party for damages and relevant to future settlement negotiations or a civil trial to assess fault and damages. Thus, this office is responsible for the investigation of accident scenes and mapping the area (e.g. location of signs) and topography.

In order to assess intersections, GDOT traffic operations personnel at district level use turning movement counters to quantify the movement of vehicles through the area. Turning movement counts represents the various approach movements (left and right thru) that pass through an intersection over a given period of time. They are collected for a variety of purposes at signalized and un-signalized intersections. Furthermore, traffic signal maintenance and repair issues are the common concerns experienced by the office of maintenance. The ownership and maintenance responsibilities for all traffic signal devices erected on the State Route System are described by GDOT prior to their installation. A typical traffic signal installation costs around $150,000, and has an annual maintenance and power costs of about $5,000. Interviews were conducted with seven engineers at management, district and area office levels. Figure 3-6 shows the organizational chart for permits and operations division and shows how interviews fit into the organizational chart.

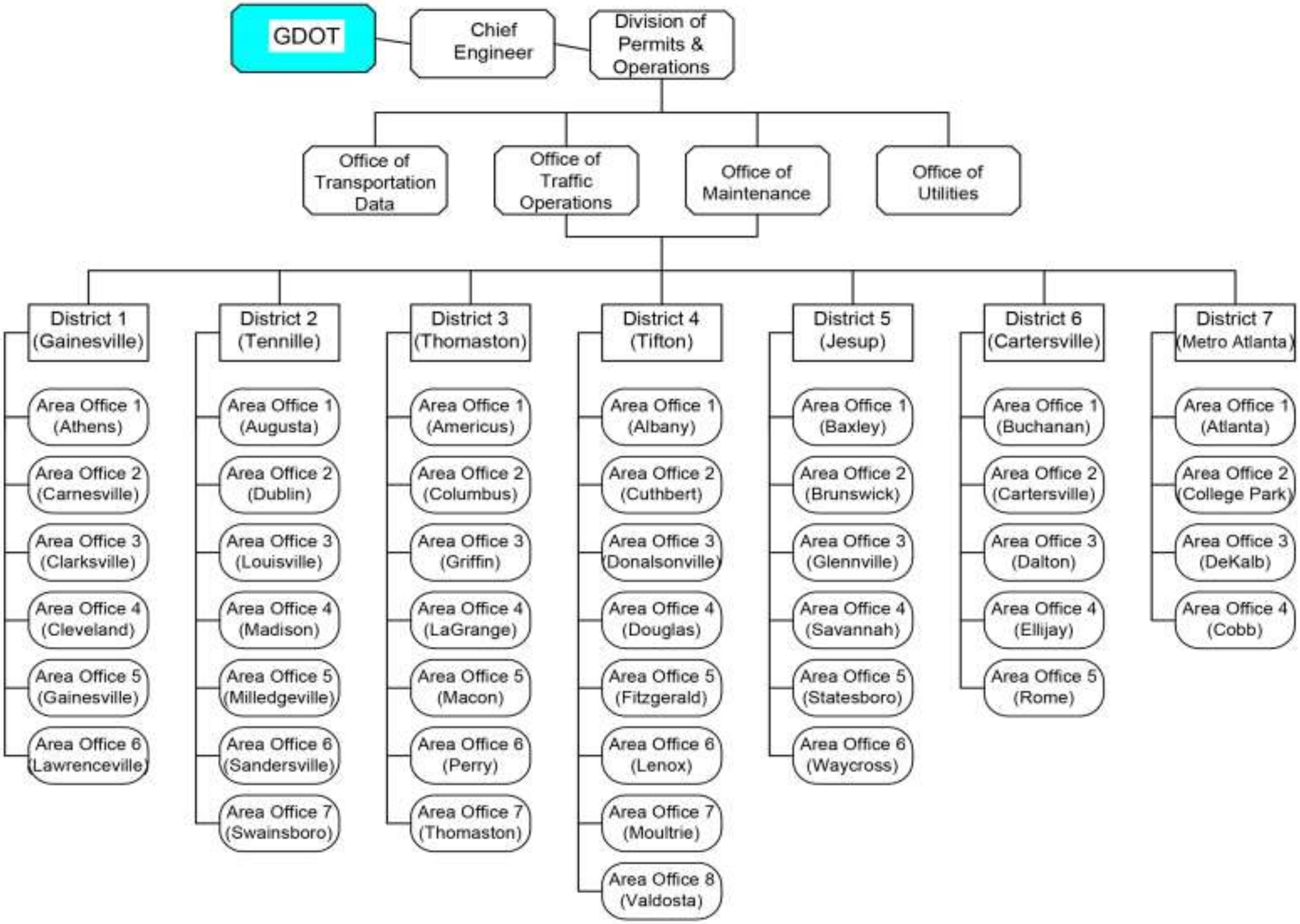


Figure 3-6: Organizational chart of GDOT permits and operations division (adopted from GDOT website, access date: March 2013)

4. CHAPTER IV

4. Identification of Operational Requirements

The operational requirements incorporated into the study were taken from a series of interviews with employees at the division and office level from four divisions (construction, engineering, intermodal, and permits and operations). Of the twenty four experts that were interviewed, eight were construction employees, four were in charge of activities conducted by the engineering division, five were intermodal employees, and seven were permits and operations employees. These experts were chosen because of their knowledge of and their experiences with activities and operations related to each identified GDOT division and/or offices. In order to determine the operational requirements for UAS usage for a specific division that could benefit from such technology, a user-centered top-down approach was chosen. In this user focused approach, the overall tasks and user requirements are categorized into various functions and components, enabling a comprehensive understanding of users' goals, their working environment, and decision-making processes.

The data sample comprised of 24 GDOT employees in the major fields of construction, engineering, intermodal and traffic operations who volunteered to participate in the study. Prior to the interview, all participants were required to give informed consent which explains to an individual who volunteers to participate in the study, the goals, processes, and risks involved. Therefore, each participant was presented with an Informed Consent Form for him or her to read in agreement to participate in the study. The university's Institutional Review Board (IRB) evaluated and approved the study protocol. The approved consent form is presented in Appendix B. The demographic characteristics include gender, age, years of experience, education level, and whether the participant used UAS for any application etc. Table 4-1 presents a summary of the major demographic characteristics of the participants in the study.

Table 4-1: Demographic and work-related statistics of participants

Variable	Percentage	Variable	Percentage
Gender (N=24)		Age (N=22)	
Male	79	20-29	15
Female	21	30-39	35
		40-49	40
		50 <	10
Size of department (N=22)			
1-3 people	14	Highest degree attained (N=24)	
3-10 people	32	High school diploma	18
10-50 people	46	Associate's degree	9
50-100 people	4	Bachelor	64
More than100 people	4	Master	9
Work experience (total) (N=24)		Work experience (GDOT) (N=24)	
0-5 years	14	0-5 years	23
5-10 years	23	5-10 years	17
10-20 years	36	10-20 years	46
20-30 years	23	20-30 years	14
30 < years	4	30 < years	0

Based upon the investigations conducted at the various divisions and offices within GDOT (Chapter III), the user requirements for specific divisions that have the potential to implement UAS technology are identified in this chapter. Therefore, a set of UAS design characteristics that fulfill user requirements of each previously identified division is determined.

The selected approach consists of four different considerations, as shown in Figure 4-1: (1) defining the operational tasks in the division, (2) studying the environmental conditions of operational workplace, (3) analyzing the user characteristics, and (4) investigating the current technologies and tools used in the division’s operations. Interview guides containing five sets of questions were prepared beforehand for collecting data for each consideration and for an evaluation of potential applications of UAS technology in the interviewee’s area of expertise.

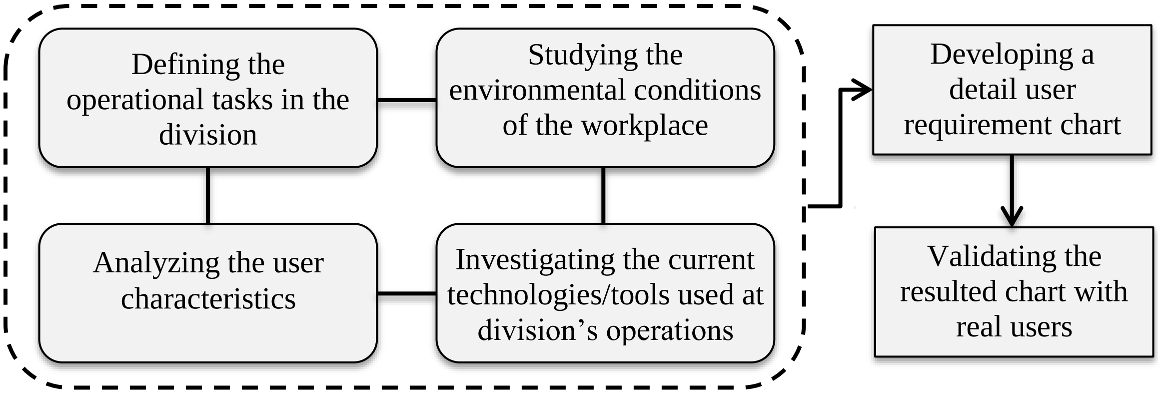


Figure 4-1: User requirements identification workflow

4.1. Defining the Operational Tasks in the Division

The first consideration is to define the tasks and operations performed in the identified division. A semi-structured interview format was chosen to develop exact definitions of those tasks and to expand their scope. The questions of this step are related to the basic goals of the operators, their major decisions for accomplishing those goals, and the information requirements for each decision. This step has resulted in identifying more than 40 tasks that could benefit from the implementation of UAS technology. The majority of the tasks are centered around collecting data, providing information, and decision making based on the data. Examples of the tasks for each division are given in Table 4.2. Currently most of the related data are collected through field personnel.

Table 4-2: Examples of the tasks performed by each GDOT division

Division	Task Description	Duration	Frequency
Construction	GDOT construction engineers take field measurements of contractual items. The task includes performing several linear, areas, and counting measurements in the construction site.	2-3 Hrs.	several times per week
	For overseeing the work at the construction site, the task includes having near real-time (aerial) photography to see the project overview and also enhancing the project personnel's perception of the environment.	N/A	several times per week

Division	Task Description	Duration	Frequency
Construction	GDOT construction engineers take field measurements of underground piping and utilities. The task includes performing measurements and documenting the items underground (e.g. pipes).	N/A	several times per month
	It is GDOT construction engineers' responsibility to make sure projects are completed on schedule, within budget, and in a way that is safe and follows the GDOT codes and laws. The task includes having an overview of the project.	N/A	several times per month
	All data, queries, commands, or responses must be entered into the GDOT server through some sort of interface (e.g. SiteManager software). The task includes entering the field data into GDOT computer systems.	N/A	several times per week
	The task includes measuring spread rate of concrete and asphalt while inspecting a construction job site. This is necessary for invoicing and quality control.	2-3 Hrs.	several times per week
	GDOT construction engineers must communicate with many individuals, including contractors, and GDOT people in the office. The task includes communicating to the GDOT people involved in a project from the construction jobsite.	N/A	several times per week
	GDOT construction engineers use soil compaction measuring devices (e.g. nuclear gauge testing) to check and measure soil compaction.	15-30 minutes	several times per year
	GDOT construction engineers take field measurements of concrete and earthmoving activities. The task includes measuring the concrete poured (or earthwork) for construction cubic yards (or cubic feet).	30-60 minutes	several times per week
	GDOT construction engineers are responsible to ensure proper execution of erosion control. The task includes documenting erosion control measures in an accurate and timely fashion.	N/A	several times per year

Division	Task Description	Duration	Frequency
Engineering	The GDOT Design Policy and Support Division has recent and historical aerial imagery of the entire state of Georgia to assist in the design of highways and other transportation improvements. There is a need for aerial photography at conceptual and engineering level (i.e. elevation dependent). Also, in order to avoid tampering and for litigation prevention the GDOT needs to collect existing condition of catastrophic crashes and destruction data quickly. The task includes managing archive of aerial photography procured by GDOT and other cooperating agencies.	N/A	several times per year
	In general, Archeological and Environmental Site Assessments are conducted in response to the federal laws. In this process, there are some supportive information such as historical aerial photographs, and photographic logs. The task includes taking aerial photography for environmental or archeological assessments.	N/A	annually
	The GDOT Bridge Inspection Engineers are responsible for the inspection of all bridges and bridge culverts within a two year cycle. In addition, GDOT construction engineers are responsible to inspect the bridge (e.g. bridge foundation, beams) during construction.	N/A	several times per week
	Routine Simple Bridge Inspection: A Routine Inspection is a regularly scheduled inspection to determine the physical and functional condition of a bridge and to identify any changes since previous inspections. Furthermore, Routine Inspections serve to ensure a bridge continues to satisfy all applicable serviceability requirements. These inspections are generally conducted from deck level, ground or water levels, or from permanent-access structures.	30-60 minutes	several times per week

Division	Task Description	Duration	Frequency
Engineering	In-Depth Bridge Inspection: This is a close-up, hands-on inspection of one or more members to identify deficiencies not normally detected during Routine Inspections. They are generally completed at longer intervals than Routine Inspections and may include the use of more advanced Non-destructive testing techniques.	1-2 Hrs.	several times per month
	Specialized Bridge Inspection: A Specialized Inspection is completed to assess structural damage resulting from environmental or human actions. The scope of each Damage Inspection is unique, with the general goal of assessing the need for further action. Special inspections could also be warranted for complex bridge structures (major river bridges, movable, suspension, cable stayed, and other bridges with unusual characteristics) or inspections of underwater parts of a bridge.	2-3 Hrs.	several times per year
Intermodal	The conditions of airports are assessed by the Aviation Program through field investigation. Airport investigations for compliance with relevant GA codes as well as the collection of data for federal agencies, including assessing the location of trees, airport and runway geometry, lighting and wildlife and bird control/monitoring. The tasks includes inspecting airports and their surrounding areas, identifying obstructions and determining the geometry of the runway	3-4 Hrs.	several times per month
	The Port of Savannah handles 80% of the ship-borne cargo entering Georgia. The Waterways Program is the local sponsor for the Savannah Harbor and is responsible for: (1) Providing easements and rights-of-way for upland disposal areas, and (2) Providing 35% of the cost required raising the dikes at the upland disposal areas in the Savannah Harbor. The task includes conducting field surveys to determine the existing height and capacity of disposal areas.	2-3 Hrs.	several times per year

Division	Task Description	Duration	Frequency
Intermodal	The Waterways Program is the local sponsor for the Savannah Harbor and is responsible to help wildlife along the intercostal waterways. The task includes monitoring birds' nesting, keep and put some bird's islands in the areas of flooded and then count the number of birds	N/A	several times per month
	The Railroad Program includes railroad track inspections and safety investigations in cooperation with the Federal Railroad Administration and preservation of railroad corridors for current and future use. The task includes having near real-time (aerial) photography to see the railroads overview and also check the environment.	N/A	several times per month
	Rail Program Engineers must communicate with many individuals, including contractors, and GDOT personnel in the office. The task includes communicating with GDOT personnel involved in a project from the construction jobsite.	15-30 minutes	several times per month
Permits and Operations	In order to coordinate traffic engineering, traffic safety, traffic management and incident management statewide, the task includes collecting traffic data (e.g. flow, speed, counts) using surveillance video cameras (i.e. permanent traffic data collection devices), traffic counting device (i.e. microwave sensors), and INRIX traffic app.	1-2 Hrs.	several times per week
	The main roads in the State affected by special events and/or accidents. Road closure, traffic detours and special events are supervised through daily coordination with the traffic operation division. The task includes having real-time traffic data in the case of special events (e.g. hurricane and evacuation) to choose the best way to detour or evacuate the traffic, or during an incident (for people in the scene).	1-2 Hrs.	several times per month

Division	Task Description	Duration	Frequency
Permits and Operations	Most accidents require one or more individuals to investigate its circumstances to see how it happened, who caused it, and how it could have been avoided. Many times the facts discovered in the investigation will be pertinent to a claim by the injured party for damages and relevant to future settlement negotiations or a civil trial to assess fault and damages. The task includes the investigation of accident scenes and mapping the area (e.g. location of signs) and topography.	15-30 minutes	several times per month
	Traffic signal maintenance and repair issues are the common concerns experienced by GDOT. The ownership and maintenance responsibilities for all traffic signal devices erected on the State Route System are described by GDOT prior to their installation. A typical traffic signal installation costs around $150,000, and has an annual maintenance and power costs of about $5,000. The task includes providing traffic signal maintenance or checks the traffic signals.	15-30 minutes	several times per week
	The HERO unit's primary purpose is to minimize traffic congestion by clearing wrecked or disabled vehicles from the roadway lanes and providing traffic control at incident scenes. In the case of accident, the task includes clearing the accident scene and re-opens the lane.	30-60 minutes	several times per week
	The traffic operations uses traffic counts to identify which routes are used most, and to either improve that road or provide an alternative if there is an excessive amount of traffic. A traffic count is a count of traffic along a particular road, either done electronically or by people counting by the side of the road. The task includes measuring traffic counts (as well as speed sample).	2-3 Hrs.	several times per month

Division	Task Description	Duration	Frequency
Permits and Operations	The task includes monitoring the traffic and counting the number of cars, as well as speed control. By conducting site visits, GDOT traffic operations staffs at district level monitor traffic conditions, and may use real-time (i.e. live) view of situations from varying directions.	2-3 Hrs.	several times per month
	In order to assess intersections, GDOT traffic operations personnel at district level use turning movement counters to quantify the movement of vehicles through the area. Turning movement counts, which represent the various approach movements (left, thru, right) that pass through an intersection over a given period of time, are collected for a variety of purposes at signalized and un-signalized intersections. The task includes the assessment of intersections using turning movement counters.	1-2 Hrs.	several times per month
	The traffic operations office reviews driveway permits and road changes. Purpose of driveway, entrance and property characteristics, exact location of present and proposed driveway are common information for the review process. Therefore, the task includes field assessment in order to review driveway permits or road changes (e.g. adding an access).	1-2 Hrs.	several times per month

4.2. Studying the Environmental Conditions of the Workplace

Another important consideration that should be taken into account is the environmental conditions, in which the tasks are performed. These environmental conditions affect the design requirements for a UAS. Ambient noise levels, lighting levels, susceptibility to weather and temperature variations, vibration, privacy, expected pace of operations, position of use (e.g. sitting, standing, while mobile), and frequency of use (e.g. occasional, intermittent, frequent, continuous) are some issues that should be considered (Endsley 2003). Each task is also characterized by some attributes that yield a better understanding of the environmental conditions including locations where the tasks are performed. A *local* task occurs at one location or a job site that can be best described as a patch of land where the primary descriptor would be the length and width of the area. A *distributed* task occurs on a strip of land (i.e. along a road, a river, or a railway), or any other place where the primary descriptor would be a length or distance. The size of the task area (or task area dimension) is defined as the range of physical features or facilities in the workplace, which provides a means to directly compare the dimension and physical characteristics of different task. The span of task area dimension ranges from 100 yards in the small workplaces to over 10 miles in some large size workspaces. The time required to complete a given task is determined by the duration of the task and the frequency of the task occurrence (see Table 4-2).

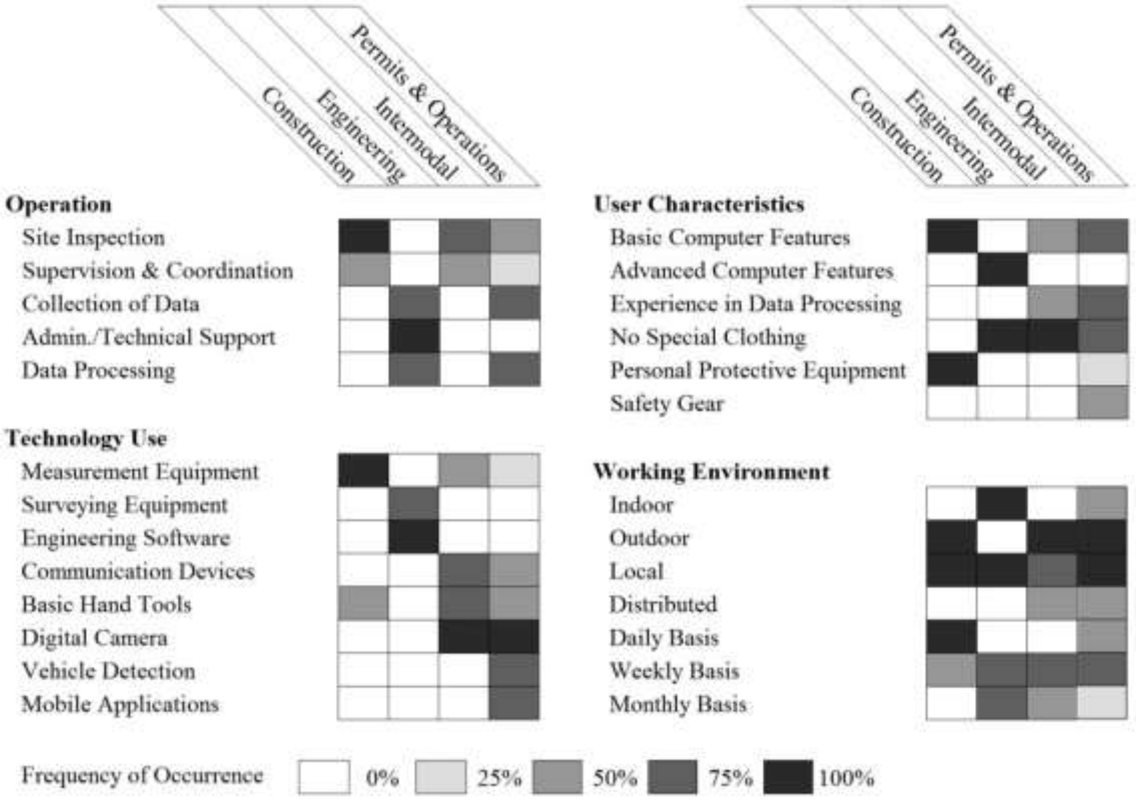
4.3. Analyzing the User Characteristics

The third consideration is to identify user characteristics such as gender, skill level (e.g. familiarity with basic computer features), training, background knowledge (including technical capability), age ranges (with special note of young or aging populations), and languages to be accommodated. Other user characteristics related to special clothing also appear to have a significant effect on performance. Thus, it is also desirable to take the type of special clothing of the user into consideration. Gloves, masks, backpacks, and any personal protective equipment are examples of clothing items that can be used while working. Upon completion of an interview, the team convened to review the interview notes. During the team debriefing, key quotes and trends were extracted alongside summary of the interview. The summaries were in turn used to derive user characteristics across user demographics and interviews.

4.4. Investigating the Current Tools/Technologies Used in Division's Operations

Then, as the last consideration, all different technologies or tools being used by the identified division's personnel should be evaluated for possible integration with the UAV platform. There might be a need for integrating hardware (e.g. sensors, radars, or different type of cameras) with the UAV hardware or software. Additionally, the user interface might be required to incorporate or be compatible with other technologies that are currently used by GDOT in the identified division (e.g. asset management or traffic software). Based on the records and interviews, the study team created a list of tools used while performing the identified tasks. The tools (and technology) used by the GDOT personnel can be classified under eight categories: Measuring equipment are used in various linear, areas, and counting measurements. Examples include measuring wheel and tape, distance meter, air meters, scoops, and thermometer. Surveying equipment (e.g. theodolite, total station, GPS devices, etc.) are used to produce accurate maps and dimensions of the site. Engineering software tools are used to collect and process observation data from the workplace. The most important example is “Site Manager” software that is used by construction office. Computer hardware, specialized software, and communication devices are used together to collect, analyze, and transmit data collection and communication processes. Basic hand tools and digital cameras are frequently used by GDOT employees traveling out-of-office. Finally, many of the tasks performed by the division of permits and traffic operations require vehicle detection and mobile application tools. Examples include traffic counter, radar gun, range finder, and turning movement counter.

Figure 4-2 shows the result operational requirement matrix that includes each division’s operation, user characteristics, working environment, and technology use. The frequency of occurrence is calculated based upon the number of tasks performed in each division. To identify missing information and errors in the matrix and validate its outcomes, this matrix was then taken back to the subject matter experts who were interviewed. All of the information was validated through feedback of the interviewees (see Appendix C). The feedback was collected and further analyzed to minimize apparent similarities between the identified tasks. As a result, 19 main tasks were selected as the tasks with the greatest potential use of UAV in the near term. For convenience, the list of all the validated tasks in this stage is reported in Appendix D. The foundation for identifying the technical requirements towards a UAV to be used within GDOT stems from the collected response data.



Operation	Construction	Engineering	Intermodal	Permits & Operations
Site Inspection	100%	0%	75%	50%
Supervision & Coordination	50%	0%	50%	25%
Collection of Data	0%	75%	0%	75%
Admin./Technical Support	0%	100%	0%	0%
Data Processing	0%	75%	0%	75%

Technology Use	Construction	Engineering	Intermodal	Permits & Operations
Measurement Equipment	100%	0%	50%	25%
Surveying Equipment	0%	75%	0%	0%
Engineering Software	0%	100%	0%	0%
Communication Devices	0%	0%	75%	50%
Basic Hand Tools	50%	0%	75%	50%
Digital Camera	0%	0%	100%	100%
Vehicle Detection	0%	0%	0%	75%
Mobile Applications	0%	0%	0%	75%

User Characteristics	Construction	Engineering	Intermodal	Permits & Operations
Basic Computer Features	100%	0%	50%	75%
Advanced Computer Features	0%	100%	0%	0%
Experience in Data Processing	0%	0%	50%	75%
No Special Clothing	0%	100%	100%	75%
Personal Protective Equipment	100%	0%	0%	25%
Safety Gear	0%	0%	0%	50%

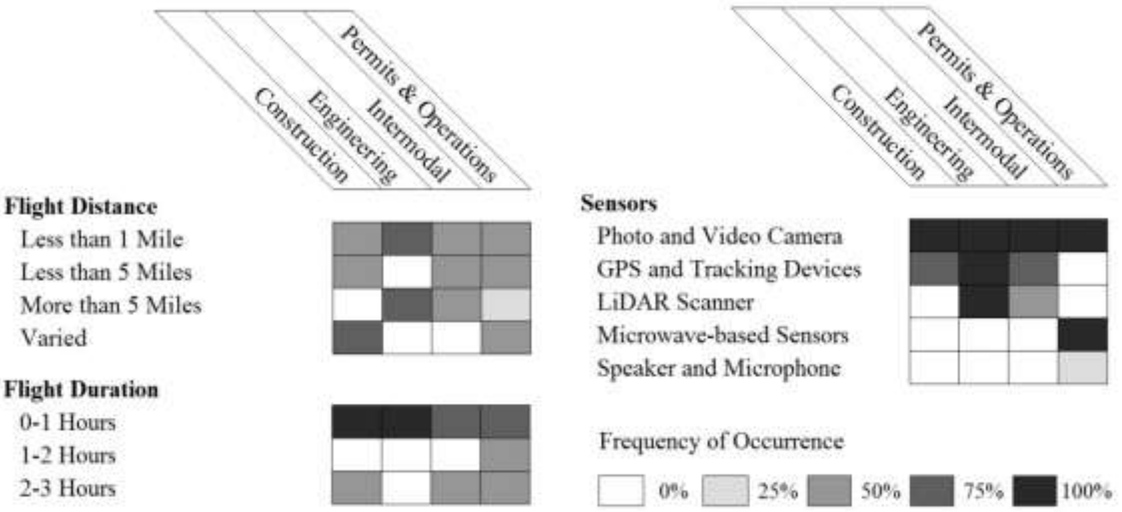
Working Environment	Construction	Engineering	Intermodal	Permits & Operations
Indoor	0%	100%	0%	50%
Outdoor	100%	0%	100%	100%
Local	100%	100%	75%	100%
Distributed	0%	0%	50%	50%
Daily Basis	100%	0%	0%	50%
Weekly Basis	50%	75%	75%	75%
Monthly Basis	0%	75%	50%	25%

Frequency of Occurrence ☐ 0% ▨ 25% ▨ 50% ▨ 75% ■ 100%

Figure 4-2: Operational requirements matrix

4.5. Identification of Technical Requirements

The details of the technical requirements for performing the identified tasks are discussed in the next chapter. How certain aspects of the identified tasks contribute to the UAV technical requirement is discussed here. Figure 4-3 shows the created UAV requirement matrix for the identified divisions within GDOT; the left part is pertaining to the notion of UAV classes, while the right part shows the sensor suites. Based upon the task classification of being either local or distributed, the related primary descriptor (a length or an area, respectively), and the task attributes duration and frequency, the identified tasks can be binned. Skipping questions related to the control station(s) and the necessary human machine interface for the moment, several classes of potentially utilizable UAVs can be created and associated with these task bins. Once these classes have been established, combining them with a sensor and/or actuator suite provides a particular UAS capable of aiding a particular set of tasks. The combination of the class and sensor suite descriptors then provide the technical requirements for a system used in



Flight Distance	Construction	Engineering	Intermodal	Permits & Operations
Less than 1 Mile	▒	▓	▒	▒
Less than 5 Miles	▒	□	▒	▒
More than 5 Miles	□	▓	▒	░
Varied	▓	□	□	▒

Flight Duration	Construction	Engineering	Intermodal	Permits & Operations
0-1 Hours	■	■	▓	▓
1-2 Hours	□	□	□	▒
2-3 Hours	▒	□	▒	▒

Sensors	Construction	Engineering	Intermodal	Permits & Operations
Photo and Video Camera	■	■	■	■
GPS and Tracking Devices	▓	■	▓	□
LiDAR Scanner	□	■	▒	□
Microwave-based Sensors	□	□	□	■
Speaker and Microphone	□	□	□	░

Frequency of Occurrence
□ 0% ░ 25% ▒ 50% ▓ 75% ■ 100%

Figure 4-3: Technical requirements matrix

all the tasks that fall into the class related bin and have data collection needs fulfillable by the particular sensor suite.

A major discriminator in classifying UAVs is whether the vehicle is a fixed wing system (e.g. an airplane), or a rotary wing system (e.g. a helicopter). The sizing of the vehicle is then driven by the required payload capacity in the context of the airframe choice. For the most part, it can be assumed that payload can be divided among carried fuel and sensors (and/or other devices) required for the task. The fuel requirement of a specific task can be related to the primary descriptor, used as a notion for the required operational range, and to a certain degree, the task duration, as a notion for the required operational endurance. Using the airframe choice, the range requirement can then be transformed into an additional endurance requirement based upon different nominal cruise speeds of fixed wing and rotary wing systems. Based on the chosen binning, the UAV classes can then be picked in the continuous endurance/payload/size design space. At this point, it could also be decided whether a particular class should have the potential to trade fuel for sensors, for example through a modular sensor rack.

Sensor and other device requirements, the other main component making up the required payload, can also be extracted from the created operational requirements list. Unfortunately, there is no direct one-to-one correspondence between the list of tools utilized (by a human) and the required set of sensors for the UAV. However, having an understanding of the underlying data collection requirements of the tasks on the one hand and selecting from variable options to collect that data with a UAV on the other, opens up the potential for multi-use of installed sensors. Multi-use can lead to a reduced number of installed sensors and an overall expansion of the data collection capabilities of a particular UAV sensor suite. Of special interest in this context are sensors that could be considered “free” as they are already required for the operation of the UAS. Examples are global navigation satellite system sensors (e.g. GPS), inertial measurement units, or cameras, which, when combined with sufficient computational power and a suitable navigation solution, could harness the potential of geo-referenced pictures. A collection of several different sensors, multi-use and specialized, into sensor suites provides another set of discriminators for building the technology requirements matrix.

Depending on the characteristics of the chosen classes and the sensors, not all possible combinations of UAV classes with sensor suites are possible. One limiting factor is mass (installed sensors vs. carried fuel), and another one is power consumption (sensor runtime vs. vehicle endurance). A possible combination of a class with a sensor suite provides the largest part of the technical requirements for a UAV that should be suitable to aid all tasks that are in the corresponding class and sensor suite bins.

To complete the set of technical requirements, several other aspects have to be taken into account. Depending on the UAV class, there might be the option for either an electric or gasoline powered system. The collected task frequency data could provide some guidance for specifying power system, for example through limitations on recharge time or the number of spare battery packs that can be utilized. Additionally, the frequency could give a hint whether a system could be shared among users or whether several systems are required to fulfill the needs of all users. Several other technical requirements can be associated with the control station. The major group of requirements in this section can be related to the operation of the system. The level of autonomy can vary from just slightly augmented tele-operation within the line of sight of the operator to point-and-click interfaces through which centralized UAS users could interact remotely with the system.

Another group of requirements associated to the control station is a set of basic questions about the human machine interface; for smaller ad-hoc deployable systems, issues are related to things such as operability with gloves, outdoor readability, ingress protection ratings, or actual usability of the underlying software. For larger systems requirements also focus on requirements related to the utilized data links, for example availability, bandwidth, lag, and security. An additional aspect for all systems is the amount of required training a current performer of the task would need to utilize the UAS aid. Furthermore, requirements also arise from needed backend interfaces of the UAS to other potential software systems which the operator has to feed the collected data.

5. CHAPTER V

5.1. Analysis of UAS Requirements

This section details the transition process from the validated data collected in the interviews to a set of five reference UAS systems which could be used to support GDOT operations.

5.1.1. Introduction

In line with the goal of this study to create a higher level understanding of the potential use of UAS by GDOT, the research team has focused the UAS specific analysis on the operational aspects of UAS use across GDOT divisions and the requirements resulting from that. In an effort to capture system specific interconnections, an adoption of the viewgraph type "House of Quality" (HoQ) has been chosen to capture the relations between GDOT tasks and potential UAS aiding those. The process leading to the creating of the HoQ is depicted in Figure 5-1.

Based upon the validated data resulting from the interview process (see Chapter IV), the researchers used their expertise to group tasks based upon a "best fit" to potential UAS. The process entailed an assignment of GDOT tasks to UAV airframe categories through an iterative process: initially the categories where based on commercial-of-the-shelf (COTS) airframe options, but throughout the iterations of modifying the airframe and reassigning the tasks, some changes included non-COTS components to better match apparent GDOT needs.

The resulting reference systems – five systems have been identified – are represented in the HoQ in the Technical Requirements section, above which the Correlations section captures some of the design correlations among the technical requirements. The validated data is represented in the HoQ in the Operator Requirements section and tries to capture the most pertinent requirements of GDOT with respect to the use of UAS.

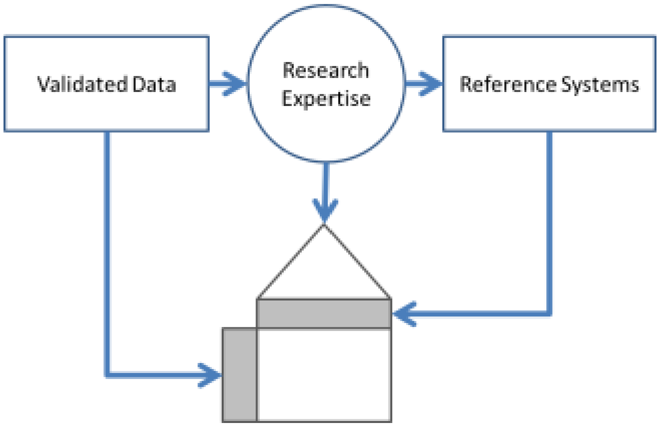


Figure 5-1: House of Quality creation process

5.1.2. UAS Technical Requirements

Part of the iterative process leading to the reference systems is the identification of technical requirements for the UAS. These requirements, which are correlated with each other (see Chapter IV), try to capture design requirements for certain aspects of the identified tasks.

For the analysis, a UAS is broken into three components: Vehicle, Control Station, and System. The Vehicle section groups requirements for the UAV, which are mainly airframe hardware related requirements. The section Control Station groups requirements for hard- and software for the control station utilized by the UAS operator, however, the software considered is related to the graphical user interface (GUI) of the interface and does not include specific guidance, navigation, and control (GNC) aspects. Those requirements are grouped into the System section, which mainly contains capability features of the reference systems. To further simplify, the three categories could be seen as primarily representing the hardware aspects of the UAV (Vehicle), the control station and human machine interface used by the operator (Control Station), and the algorithmic features the GNC and other specialized software provides (System).

Vehicle Requirements

Airframe Ruggedness: Airframe ruggedness tries to capture the overall “sturdiness” of the UAV. A rugged airframe can on one side better deal with in-flight collisions (at slow speeds), for example, an inadvertent bump into a wall, and on the other side withstand a rougher handling, for example, when placed in a trunk or a truck bed. Ruggedness also can include protection from the elements, for example, rain or dust.

Airframe Availability: Airframe availability is one major factor in the overall availability of the UAV, which in essence consists of the airframe, the avionics (the "autopilot"), and the payload[1] (i.e. sensors). If the avionics are modular enough, it could be sufficient to instrument a readily available COTS R/C airframe. This could allow for cheaper maintenance as spare parts should be readily available and, depending on the configuration, alternates from other manufacturers might be substituted. However, the drawback of COTS airframes could be an extended integration time, as the airframes might not easily accommodate the avionics or the payload. Custom build airframes could provide a better performance, but the lead time and per unit cost could be higher than for adapted COTS airframes.

Endurance: Endurance is an abstract high level requirement that tries to capture the technical aspects of available operational time. Endurance for airframes is mainly driven by the chosen aircraft category (for example, a rotary or fixed wing vehicle) and the size. In general, airplanes have a longer endurance than rotary wing aircraft and larger aircraft have a longer endurance than smaller ones; however, the overall UAV endurance is dependent on a lot more factors than the aircraft category and the size.

Actuated Video Camera: The requirement for an actuated video camera is a fairly specific need, which requires a video sensor of the airframe to be moveable. The actuation could be in any or all of the three axis of motion, roll, pitch, and yaw, and could either be automated or externally driven. A use of an automated video camera could be in first-person video (FPV) flight, where automation would use the actuation to compensate for the attitude changes of the airframe, comparable to how an onboard pilot would move her head while piloting a full size aircraft. Alternatively, the actuation could be used to steer the video sensor towards a point of interest while the airframe remains stationary (for vehicle capable of hovering flight) or loitering (for all others), comparable to the

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[1] Payload – UAV onboard equipment, most often sensors, that are necessary to complete a task but which are not strictly necessary for autonomous UAV flight. Note, however, that data gathered through payload sensors can benefit the overall GNC performance.

controls to conventional pan/tilt camera turrets, for example, the cameras used for GDOT’s Navigator program.

Actuated Non-Video Sensor Package: The requirement for an actuated non-sensor package captures the need to steer other payload sensors, potentially independent of the video source. This could be used, for example, to scan the airframe surroundings for potential collision hazards or to expand a sensing frustum.

Telepresence: Certain identified tasks require establishing communication with people in the vicinity of the aircraft. Telepresence should at least encompass a voice communication feature, which is in the presence of a speaker and a microphone of sorts. Depending on the situation, the addition of a visual presence can be beneficial, effectively establishing a rudimentary video conferencing capability.

Manipulator and/or Effector: The telepresence can be taken to the next step through the addition of manipulator arms or other effectors. Their presence in an airframe could allow an operator to conduct tasks that normally would have to be done by a human (e.g. pressing buttons or moving objects). Effectors could range from simple grappling hooks to fully articulate and very dexterous robotic arms.

Control Station Requirements

Interactive Object Selection and Identification: This requirement relates to the GUI of the control station and requests a simple interface to directly interact with video coming from the UAV. The operator should be able to simply interact with the system through clicking, dragging, or drawing onto the video, enabling the operator to, for example, determine the next waypoint, move the vehicle, or determine a segment of a road for further inspection.

Ruggedness: Just like the airframe, the control station hardware will be used outdoors, potentially in harsh conditions such as the construction site. Ruggedness for a control station also includes the “sturdiness” of the hardware, for example, protection against damage from drops, water spills, or dust. Ruggedness also includes the ability to operate the control station while wearing personal protective gear appropriate for the location, such as gloves, hearing protection, or glasses. Ruggedness also includes the use of appropriate connectors where necessary, for example, for charging, interfacing with other computers, or necessary local infrastructure, for example external antennas.

Portability: Portability covers the requirement to easily transport the control station. Depending on the task or system at hand, this not only includes the portability of the operator interface, but the entire infrastructure comprising the control station, potentially including a (tablet) computer, external data link or GPS antennas, and potentially power sources.

System Requirements

Sense and Avoid: Sense and avoid is the UAS realization of the “See and Avoid” principle for flight under Visual Flight Rules (VFR). Sense and avoid allows a UAS to detect cooperative as well as non-cooperative traffic in the vicinity of the aircraft and conduct evasive maneuvers if a collision might be imminent. Sense and avoid can be extended to include stationary obstacles as well, essentially allowing a UAS to navigate an area with potentially unknown obstacles.

Waypoint Navigation: Waypoint navigation allows a UAS to follow a flight plan through the means to waypoints. Waypoints, most likely given through GPS coordinates, are ordered in a certain sequence which the UAS will follow. They could also capture certain maneuvers such as “landing” or “hovering”.

Kinematically Constrained Operations: Conventionally UAVs are assumed to move freely through space, constrained solemnly through their dynamic limitations (aircraft, unlike helicopters, for example, normally can’t move “backwards”). Kinematically constrained operations further restrict the possible motion through physical means. Examples include flying while tethered to a power source through a flexible cable, flying while connected to a rigid structure, or flying while docking (i.e. physically attaching to a connector).

Unattended Deployment and Return: The requirement for unattended deployment and return imposes the requirement for automatic take-off and landing without the presence of an external pilot within the line of sight of the landing or take-off site.

High-precision Navigation: Autonomous flight most of the time relies on the presence and availability of a GNSS (e.g. GPS). The accuracy of a navigation solution (i.e. the system internal estimation of the current location of the aircraft) is to a large degree governed by the accuracy achievable with the utilized GNSS; for GPS this could be as good as several meters for non-aided systems and potentially down into the centimeter range when differential GPS systems are used. High precision navigation poses the requirement to achieve a navigation solution that is comparable to the accuracy achievable through the use of ground surveying methods (e.g. total station equipment).

Simultaneous Location and Mapping: Simultaneous location and mapping (SLAM) describes the capability of a system to navigate through a priori unknown environment while building a map of that environment – which is simultaneously used to navigate in the (known portions) of the environment. SLAM generally requires the presence of sensors which can accurately capture the environment (a prominent choice being a Light Detection and Ranging system (LiDAR)), as well as a considerable amount of computational power to process the sensor data. It can also be used to navigate with respect to a priori available data, for example, the plans of a building under construction, which then is matched to the current sensing of the environment.

Advanced Data-link and Networking: The requirement for advanced data-link and networking features captures the need for Radio Frequency (R/F) communication capabilities beyond a simple point-to-point link between the UAV and its control station. Examples for advanced networking could include the use of external networks in which both, the UAV and the control station, are clients (for example, using a corporate large scale Wi-Fi network), or the creating of other mobile ad-hoc networks (MANETs). MANETs could be either relying on external infrastructure or they could be completely independent, meaning that all involved networking nodes (i.e. UAVs and control stations) would span the network. Advanced data-link requirements could be certain security measures, validation of received data, or special requirements towards the involved R/F hardware, for example, special bands, modulations, antennas, etc.

Sensor Data Abstraction and Reduction: With an increase in payload sensors comes an inevitable increase in available raw sensor data. In an effort to offload UAS operators from data interpretation tasks, this requirement captures the need for the system to automatically process raw sensor data and only provide the (abstract) result to the operator. An example for this could be an iconographic representation of an item that the system is tasked to identify. Instead of overloading the operator with the raw sensor data (e.g. the raw 3D point cloud of a LiDAR), the system only provides its findings, potentially with a confidence margin (e.g. a simple line drawing representing a wall).

Vision Based Data Extraction: Vision based data extraction captures the request for any kind of computer vision based algorithm like pattern recognition, optical flow, or feature point based processes. These could allow, in combination with the navigation solution from the UAV and camera calibration data, to generate 3D coordinates of (feature) points, based upon the stereo-from-motion principles. Vision based augmentation systems can also be used to augment the navigation solution in areas with limited GNSS availability.

5.1.3. Intra-system Correlations

The correlations part of the House of Quality viewgraph presents a rough and simplified overview of the interplay between and among the selected technical requirements for the reference systems' Vehicle, Control Station, and System sections (see Figure 5-2). The figure indicates the high independence of the Control Station section from the Vehicle section as nearly no correlations are identified. This stipulates that future research could treat these two units independently and that both parts could be specifically tailored to the actual need at hand while allowing reusing of previous technology. The correlation between the Control Station and the System sections is a little stronger, indicating that the UAS operator primarily interacts with the UAS on a system level as opposed to a pilot level; the later would be comparable, for example, to radio controlled flight of a model airplane. A strong correlation between the System and Vehicle sections is expected, as System essentially represents (GNC software) capabilities which require the presence of certain features in Vehicle. Additional information for the individual correlations can be found in Appendix G, which lists a brief rationale for each correlation.

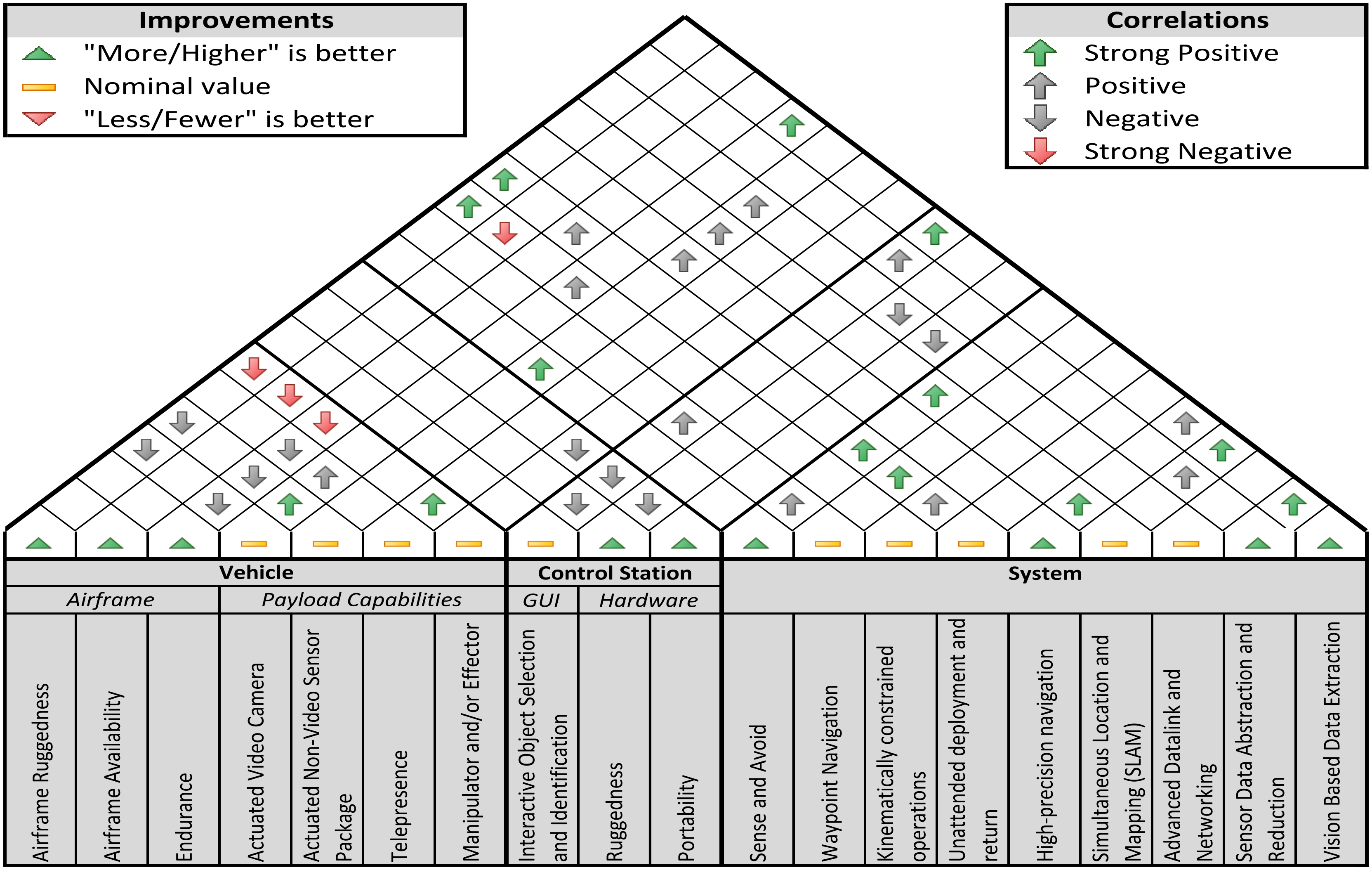

Figure 5-2: The correlations part of the House of Quality showing the interplay between the technical requirements

5.1.4. Operator Requirements

First-Person Video (FPV) Operation

First-Person Video operation describes a mode of piloting an aircraft in which an external pilot controls an aircraft while using a live video feed from a perspective that mimics a pilot's position. FPV operations, particularly in combination with stability augmentation systems[2] (SAS), can simplify the piloting of an aircraft as the overall setup is comparable to many computer or console games. However, depending on the FPV setup, the overall situational awareness (SA) of the pilot can be reduced due to the limits of the visible environment. This is especially notable during take-off and landing when the aircraft is within the line of sight of the operator and the operator could control the aircraft from a third-person perspective which allows capturing the overall representation of the aircraft within its environment. Overly simplifying, FPV operations are comparable to first-person video games and have the benefit of a relatively low requirement for autonomous operations as a pilot, the operator, is always in the control loop of the vehicle.

Non-FPV Operation

Non-FPV operations describe control schemes in which the operator never directly assumes the role of an external pilot, but controls the UAV on a very high system level, most likely through the use of waypoints. For example, a non-FPV operation could be the creating of a flight plan on a map, uploading that flight plan to the system and executing it. The operator interacts with the system comparable to the way how air traffic control (ATC) can interact with a general aviation airplane: issuing holding patterns, rerouting it, requesting climbs and descends, etc.

Pilot-independent sensor package control

Pilot independent sensor package control replicates a work load sharing comparable to a two pilot cockpit: a pilot-flying (PF; be it a human operator or automation) and a pilot-non-flying (PNF), who is responsible for the systems. This arrangement allows the PF to

---

[2] Stability Augmentation Systems; a piloting aid which considerably lessens the workload of a pilot through augmenting the pilot's control inputs.

focus on piloting, e.g. complying with ATC directions or avoiding other aircraft and obstacles, while the PNF can focus on utilizing the payload sensors to collect the data required.

Use at construction site

This requirement captures UAS operations under the environmental conditions present at a construction site: outdoors, in the presence of semi-structured dirty environments and heavy machinery, and generally rather “rough.” It also encompasses the operation over and among workers present on the site and as such poses the requirement to be safely operable among cooperative[3] people.

Use at traffic signal site

The use at traffic signal site is comparable to the use at a construction site, however several significant differences exist. Traffic signal sites pose a special collision hazard through the presence of comparatively small obstacles (e.g. wires, small trusses, sign or light posts). Furthermore, the presence of non-cooperative[4] traffic and people as well as the extended accident possibility as a result of system failures pose special safety requirements.

Metro-area range/coverage

The UAS should be able to operate throughout the Atlanta metro area, which is an area of roughly 400 square miles. This poses a requirement to the airframe for endurance and, to a certain extent, speed, as well as on the R/F system utilized to communicate with the UAV. The utilized data-link could, for example, either be a long range point-to-point data-link, a setup incorporating several interconnected smaller ground based broadcast stations, or a swarm based MANET.

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[3] The term cooperative in this context is meant to describe that people in the vicinity of the UAV are cooperating with the UAS in the sense of being made aware of its operations (and correspondingly looking out for it), as well as being asked to engage in certain safety measures, for example, wearing a hard hat and safety glasses. Cooperating people are also assumed to know who controls the UAV and hence are able to voice warnings or concerns to the operator.

[4] Non-cooperative are all people in the vicinity of the UAV that are not among the cooperative people (as stated above), like pedestrians or motorists. These people might not be aware of the UAV operations, its intentions, and whom to address with safety concerns.

Get point coordinates

The operator should be able to get geo-referenced 3D coordinates of a point or feature shown on the video feed from the UAV. (See the related task description in Appendix E.)

Measure site dimensions

The operator should be able to measure linear distances between points identified on the video feed of the UAV, get elevations of them, and obtain a reasonable estimate for any polygonal area determined by a sequence of identified points. (See the related task description in Appendix E.)

Estimate volumes

The operator should be able to utilize the system to get estimates for volumes, for example of earth work on a construction site. (See the related task description in Appendix E.)

Create digital elevation model

Using the UAS, the operator should be able to create a digital elevation model of the terrain with an accuracy sufficient for the task context, i.e. lower for earth volume estimates, higher for survey situation, and comparable to the accuracy currently achieved without UAS aid.

Count/track/detect items

The operator should be able to mark items on a map and later get their location and count. (See the related task description in Appendix E.)

Precise navigation

The position accuracy of the UAS navigation solution should be good enough to operate the UAV in close presence to obstacles without a dedicated need of sensing them. For example, the operator should be able to maneuver the UAV close to such an obstacle, let go of any controls, and the vehicle should be able to maintain its position within some epsilon ball small enough to not collide with the obstacle (if the vehicle is capable of hovering).

Provides survey-quality data

The navigation solution of the UAS should be good enough so that provided coordinates for features sensed by the system have a quality comparable to a conventional survey performed, for example, with a total station.

Correlate sensor data to plans/drawings

The operator should be able to overlay digital plans or drawings with the video feed coming from the UAV to correlate both data sets. Also, if SLAM is available, the system should be able to include digital plans and drawings into the SLAM map to provide measurements relative to those plans and drawings.

"Line-of-sight" clearance measurements

The UAS should be able to determine its attitude well enough to create a line of site measurement and identify either a clear line of sight or the presence of obstacles.

Collect floating traffic samples

The system should be able to track a vehicle identified by the operator through normal traffic and extract data pertinent to that vehicle from the systems navigation solution and the video data. Data of interest would be, for example, speed, acceleration, or distance traveled.

Allows triggering a "reset"

The UAV is equipped with a mechanism to trigger a (electro-) mechanical reset function on a cooperative device.

Interact with inspected element

The UAV is capable to manipulate an element in its close vicinity, either through an manipulator or effector or through “bumping” into the element. Interaction also includes the use of certain measurement or probing devices with the element under inspection.

Establish contact to people

The UAS can be utilized to establish a two-way conversation between people present at the location of the UAV and the operator or any other third party connected to the UAS' communication link.

Eliminate need for human task execution

The UAS is capable of performing all tasks a human would do during a certain task. These requirements established the need to be able to complete or perform a task previously executed by a human remotely, preferably by that same human as an expert operator.

Conduct traffic counts

The UAS can conduct a set of traffic counts for a given location. This includes simple counts, turning movement counts, speed samples, and throughput measurements. (See the related task description in Appendix E.)

Data on demand

The UAS can be utilized in a manner in which the operator is agnostic of the underlying system or the actual physical operations necessary to obtain the requested data. An example of such an operation could be a first response coordinators request for live video of a certain location within the coverage area of the UAS.

5.2. Reference Systems

Based upon the reviewed data, five reference systems are proposed. These systems capture the majority of the tasks identified through the interview process and cover a wide spectrum of capabilities, expandability, but also availability. This chapter describes the proposed systems. Although the presented systems are described in certain detail, none of them are fully evaluated for feasibility, performance, or optimality of any kind. As such, the described systems are meant to simply describe a potentially possible setup that could be used for certain identified tasks and provide a basis for further in depth studies.

5.2.1. Commonalities

The presented system descriptions put an emphasis on the air vehicles and the associated (hardware) infrastructure, focusing on sensing and data acquisition. The system-level capabilities that provide use to GDOT most likely stem from processing this acquired data. Active research is currently conducted in many of the related fields and thus the reference system descriptions do not provide detail on those algorithms but simply assume their availability.

In accordance to the correlations between the UAV, the control station and the operator, all reference systems are assumed to provide a level of autonomy comparable to that reached by GUST (Georgia Tech UAV Simulation Tool). GUST provides a level of autonomy that allows operators with minimal or no radio controlled (R/C) experience to fly a UAV as the operator interacts with the UAV on a system level and not on a pilot level. For example, this allows for a “computer game”-like joystick interface which decouples the actual flight dynamics from the joystick input: stick forward is simply “forward flight” and not as in R/C flight, for example for airplanes, elevator deflection down.

5.2.2. System A – Flying Camera

The air unit of System A, the Flying Camera, provides the most basic functionality of placing a (video) camera anywhere in the accessible space and streaming live video to the operator (see Figure 5-3)..

Usage Scenario:

The Flying Camera could be used in any situation where a video or picture is all that is needed as a data input. The operator would simply start the system, use FPV to frame the picture or video needed, record the images and finish the task at hand. The data post processing could be as simple as storing the resulting still photo or video sequence or interacting with the live video feed from the UAV.

Airframe:

The airframe for System A would need to be VTOL capable, fairly robust, and safe to be used around people, for example a small scale quad rotor with shrouded propellers. The benefit of a quad rotor over a conventional helicopter would be the reduced mechanical complexity and hopefully a resulting increase in robustness.

Payload:

System A would most likely not carry any special payload beside a video camera. Actuating the camera could improve the performance, so, in order to maintain a high level of robustness, a virtual camera tilting could be implemented through several small scale cameras. The setup could provide a low resolution feed and, upon operator request, high(er) definition onboard video recording or still photography.

Control Station:

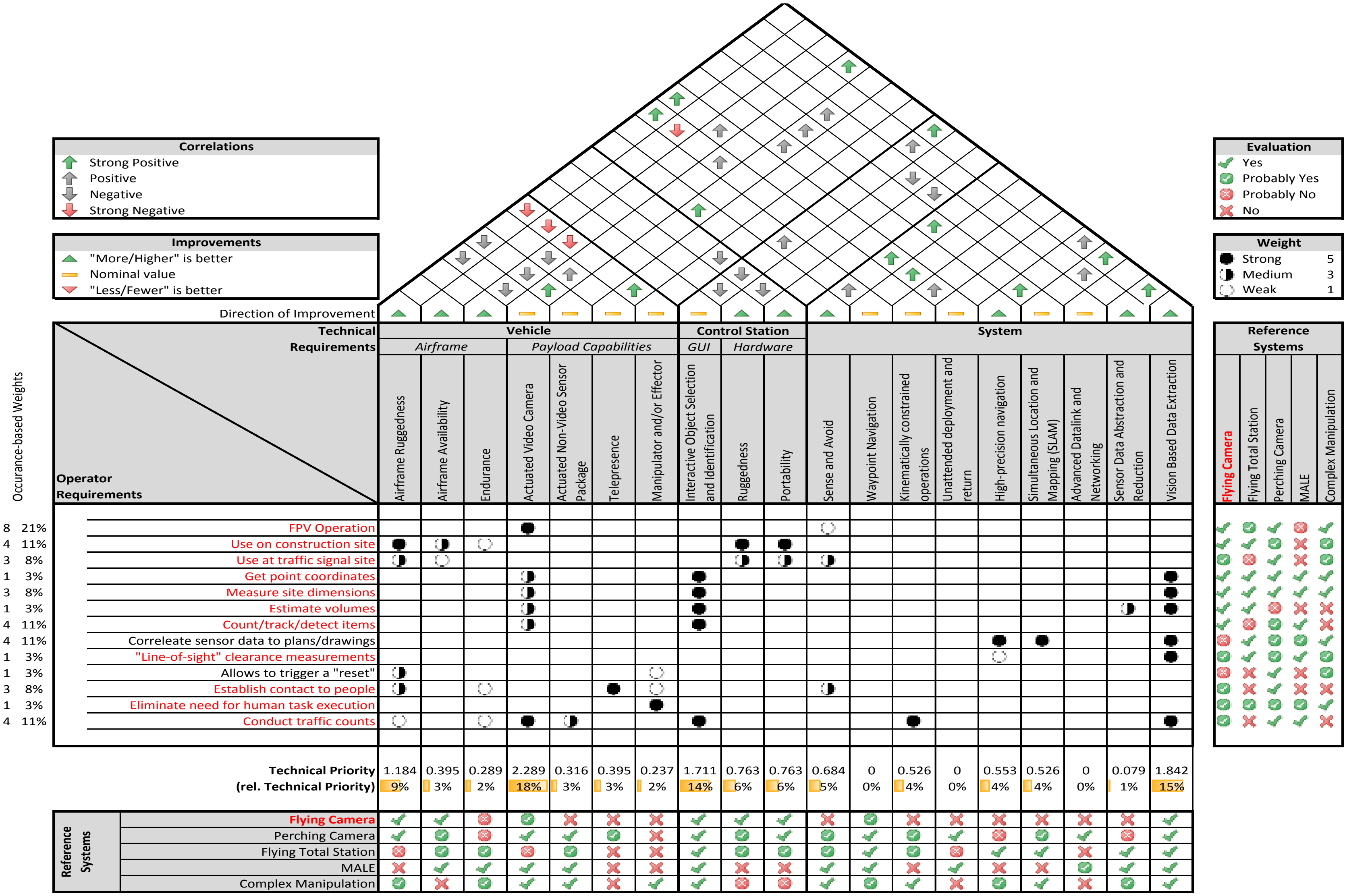
The control station would be primarily focused on ruggedness and portability. A first implementation could be a based on a tablet computer, utilizing on-screen virtual controls, with the potential to expand the setup with a dedicated game pad style controller or a pair of video goggles for improved FPV operation. If goggles are used, the GUI interface of the tablet based control station software would need to be adapted to be compatible to the utilized controller.

Required Infrastructure:

No special infrastructure is necessary to operate System A. However, there is the need for training, maintenance, and recharging, which needs to be organized. As the system presumably would be small enough to be transported in a protective case in a car’s trunk or pickup bed, no special transport equipment should be needed.

Capabilities:

The systems capabilities would mainly rely on computer vision based algorithms performed off board (i.e. with a transmission time delay) and only with the limited computational power available in a tablet.



Correlations
- ⇧ Strong Positive
- ⇧ Positive
- ⇩ Negative
- ⇩ Strong Negative

Improvements
- ▲ "More/Higher" is better
- ▬ Nominal value
- ▼ "Less/Fewer" is better

Evaluation
- ✓ Yes
- ☑ Probably Yes
- ☒ Probably No
- ✗ No

Weight		
●	Strong	5
◐	Medium	3
○	Weak	1

		Technical Requirements	**Vehicle**							**Control Station**			**System**									**Reference Systems**				
			Airframe			*Payload Capabilities*				*GUI*	*Hardware*															
Occurance-based Weights		**Operator Requirements**	Airframe Ruggedness	Airframe Availability	Endurance	Actuated Video Camera	Actuated Non-Video Sensor Package	Telepresence	Manipulator and/or Effector	Interactive Object Selection and Identification	Ruggedness	Portability	Sense and Avoid	Waypoint Navigation	Kinematically constrained operations	Unattended deployment and return	High-precision navigation	Simultaneous Location and Mapping (SLAM)	Advanced Datalink and Networking	Sensor Data Abstraction and Reduction	Vision Based Data Extraction	**Flying Camera**	Flying Total Station	Perching Camera	MALE	Complex Manipulation
		Direction of Improvement	▲	▲	▲	▬	▬	▬	▬	▬	▲	▲	▲	▬	▬	▬	▲	▬	▬	▲	▲					
8	21%	FPV Operation				●							○									✓	☑	✓	☒	✓
4	11%	Use on construction site	●	◐	○						●	●										✓	✓	☑	✗	☑
3	8%	Use at traffic signal site	◐	○							◐	◐	◐									☑	☒	✓	✗	☑
1	3%	Get point coordinates				◐				●											●	✓	✓	✓	✓	✓
3	8%	Measure site dimensions				◐				●											●	✓	✓	✓	✓	✓
1	3%	Estimate volumes				◐				●										◐	●	✓	✓	☒	✗	✗
4	11%	Count/track/detect items				◐				●												✓	☒	☑	✓	✗
4	11%	Correleate sensor data to plans/drawings															●	●			●	☒	✓	☑	☑	✓
1	3%	"Line-of-sight" clearance measurements															○				●	☑	✓	☑	✓	☑
1	3%	Allows to trigger a "reset"	◐						○													☒	✗	✓	✗	☑
3	8%	Establish contact to people	◐		○			●	○				◐									☑	✗	✓	✗	✗
1	3%	Eliminate need for human task execution							●													☑	☑	☑	☑	✓
4	11%	Conduct traffic counts	○		○	●	◐			●					●						●	☑	✗	✓	✓	✗
		Technical Priority	1.184	0.395	0.289	2.289	0.316	0.395	0.237	1.711	0.763	0.763	0.684	0	0.526	0	0.553	0.526	0	0.079	1.842					
		(rel. Technical Priority)	9%	3%	2%	18%	3%	3%	2%	14%	6%	6%	5%	0%	4%	0%	4%	4%	0%	1%	15%					

Reference Systems	Airframe Ruggedness	Airframe Availability	Endurance	Actuated Video Camera	Actuated Non-Video Sensor Package	Telepresence	Manipulator and/or Effector	Interactive Object Selection and Identification	Ruggedness	Portability	Sense and Avoid	Waypoint Navigation	Kinematically constrained operations	Unattended deployment and return	High-precision navigation	Simultaneous Location and Mapping (SLAM)	Advanced Datalink and Networking	Sensor Data Abstraction and Reduction	Vision Based Data Extraction
Flying Camera	✓	✓	☒	☑	✗	✗	✗	✓	✓	✓	✗	☑	✗	✗	✗	✗	✗	✗	✓
Perching Camera	✓	☑	☒	✓	✓	☑	✗	✓	☑	✓	☑	✓	☑	✓	☒	☑	✓	☒	✓
Flying Total Station	☒	☑	☑	☒	☑	✗	✗	✓	☑	☑	☑	✓	☑	☒	✓	✓	✗	✓	✓
MALE	✗	✓	✓	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗	☑	✓	✓
Complex Manipulation	☑	✗	☑	✓	✓	✗	✓	✓	☒	☒	✓	☑	✓	✗	☑	✓	✗	☑	✓

Figure 5-3: House of Quality for System A (Flying Camera)

5.2.3. System B – Flying Total Station

System B expands upon System A by providing higher quality measurements of the environment. The main focus of the system is to act as a flying total station, i.e. perform tasks similar to the ones done by a survey crew, but faster, especially in otherwise unprepared environments. As the systems' expected operational radius is limited, the UAV could be tethered to a power outlet at the control station site (see Figure 5-4).

Usage Scenario:

The flying total station could be used anytime survey data or location data of survey quality is needed. The system could be brought on scene, maneuvered to the area to be surveyed (either through FPV video or conventional third person flying), and the survey could be started. Post processing would presumably be similar to post-processing regular total station data.

Airframe:

System B would need an airframe that is capable of prolonged hover operations, precise positioning, and a certain level of failure tolerance to protect against the loss of potentially expensive sensors. These requirements would point towards a multi copter which is designed for redundancy. This could be a hexa- or octocopter which is sized so that not all rotors are needed to stay airborne. As people, both cooperative as well as non-cooperative, would presumably negatively impact the survey process by blocking line of sight, it can be assumed that the system would be operated in the presence of relatively few cooperative people, as such reducing the requirements for safety through shrouds, etc.

Payload:

The system would presumably carry LiDAR equipment to replicate a total station. Additionally, altimeter, for example sonar or laser based, could be used to establish a correct above ground altitude and in reverse determine the elevation of the terrain. Additional onboard computational power might be required to process the LiDAR data.

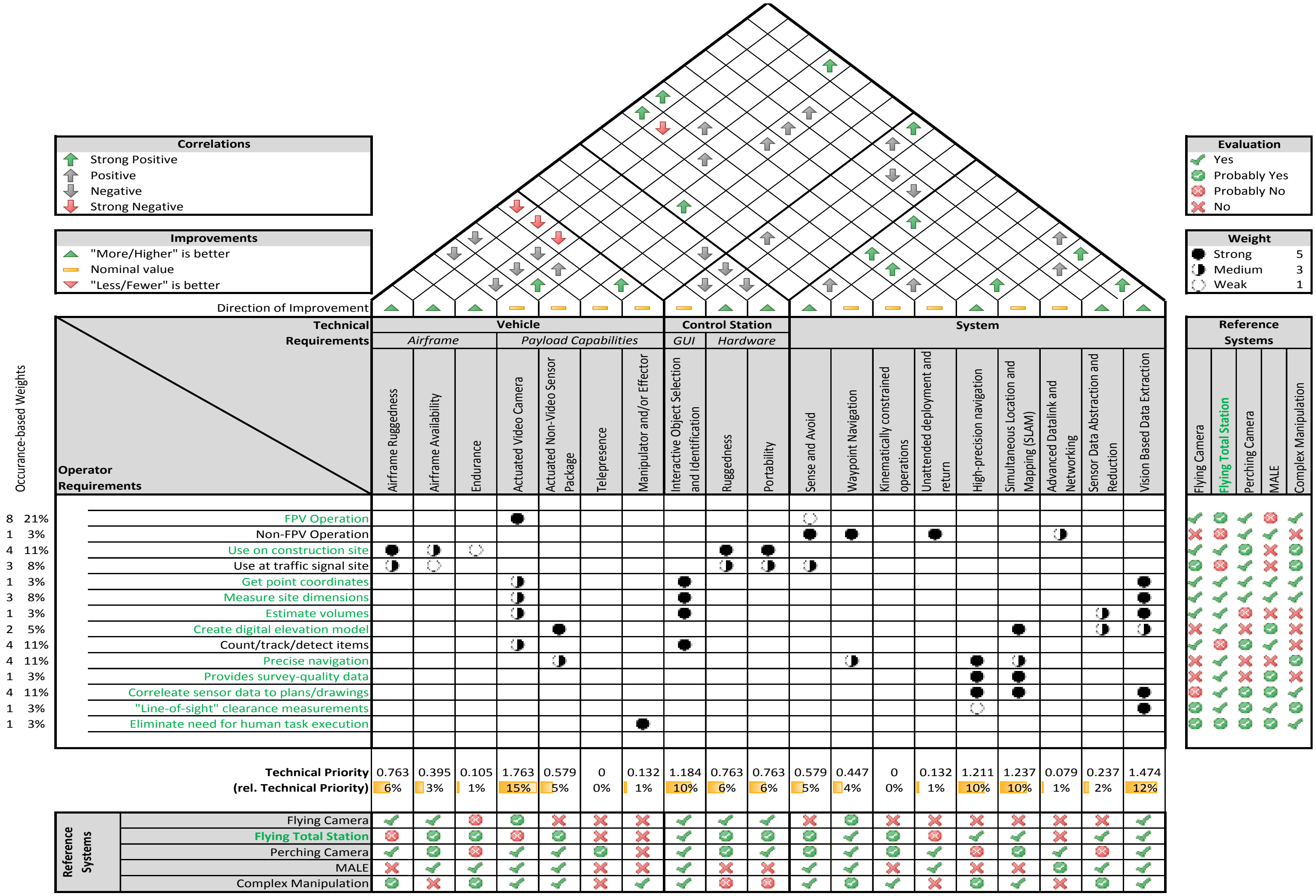


Figure 5-4: House of Quality for System B (Flying Total Station)

Control Station:

The control station for System B would most likely be comprised of a powerful ruggedized laptop as well as a GNSS reference station to establish a differential correction for the navigation solution.

Required Infrastructure:

System B would not need any special communications landing site infrastructure to be operated. However, due to the size of the UAV as well as the additional antennas for the control station, the system most likely would be comprised of some larger crates (to be transportable by pickup or SUV). An alternative would be a dedicated trailer or van. (For more details on dedicated vehicles, see Section 5.2.6, the infrastructure requirements for System E.)

Capabilities:

The increased computation power both on- as well as offboard would allow the system to not only utilize vision to detect and identify objects, but also to process video data in combination with the LiDAR data to perform SLAM-based high precision navigation. Furthermore, the system should be able to allow working with digital plans and drawings, for example to check the correct location of construction features, roadway markings, or property boundaries.

5.2.4. System C – Perching Camera

System C is also expands upon System A, but mainly focusing on a prolonged capturing of the environment. Based upon that, operational endurance is a main application goal of System B. This could either be achieved through highly efficient flight, which might be hard to achieve given that a considerable amount of that flight time could be hover or hover-like operations, or it could be achieved through perching (see Figure 5-5).

Usage Scenario:

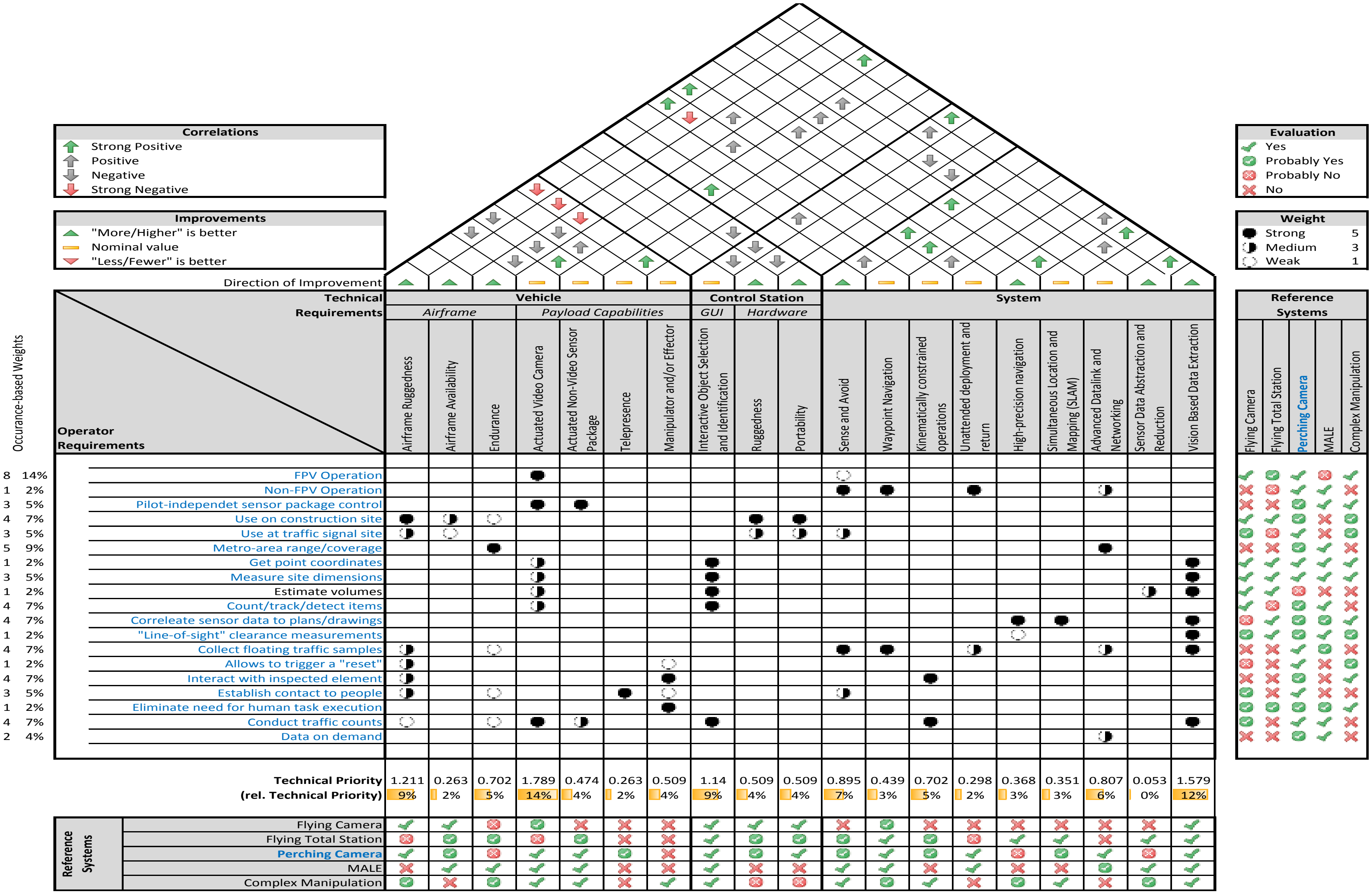
Due to the pertinent standby capability perching provides, System C could mainly be used in two modes: as an ad-hoc deployed UAS for local, on-site inspection or measurement tasks, or as a deployed-on-demand system. The former usage is comparable to that of System A. The later usage would imply that System C UAVs have strategically located fixed “base stations,” which would serve as recharging stations and potentially as communication towers. A user requiring services provided by System C would use a control station, request a UAV, and be given control over the closes available air unit. Once the operator doesn’t need the services any longer, the UAV would be released and return to a base station.

Airframe:

As a result from the perching requirement, the airframe is required to be relatively small to be able to get to potential perching locations as well as being robust to inadvertent collisions close to the selected perching location. Furthermore, the airframe needs to be equipped with a landing gear of sorts to facilitate perching on poles, or traffic signal installations. These requirements could be realized with a smaller scale hexa-copter or potentially a small electric conventional helicopter.

Required Infrastructure:

The perching capability recommends System C for an extended dual use: one the one hand as a mobile UAS with the described capabilities, on the other hand as a static continuously operating camera. A potential scenario could be the deployment of several dedicated perching locations which could double as a charging or refueling station. If the System C units then provide a MANET capability, System C units could, for example, replace the conventional Navigator cameras installed throughout the Atlanta metro area. Resulting from that, a set of permanent perching locations are needed. These base stations would provide recharging capabilities, allow easy access for maintenance, and could also double as R/F communication outlets spanning the MANET utilized by System C.



Correlations
- ⬆ Strong Positive
- ↑ Positive
- ↓ Negative
- ⬇ Strong Negative

Improvements
- ▲ "More/Higher" is better
- — Nominal value
- ▼ "Less/Fewer" is better

Evaluation
- ✓ Yes
- ☑ Probably Yes
- ☒ Probably No
- ✗ No

Weight
- ● Strong 5
- ◐ Medium 3
- ○ Weak 1

Occurance-based Weights		Technical Requirements	Vehicle							Control Station			System									Reference Systems				
			Airframe			Payload Capabilities				GUI	Hardware															
		Operator Requirements	Airframe Ruggedness	Airframe Availability	Endurance	Actuated Video Camera	Actuated Non-Video Sensor Package	Telepresence	Manipulator and/or Effector	Interactive Object Selection and Identification	Ruggedness	Portability	Sense and Avoid	Waypoint Navigation	Kinematically constrained operations	Unattended deployment and return	High-precision navigation	Simultaneous Location and Mapping (SLAM)	Advanced Datalink and Networking	Sensor Data Abstraction and Reduction	Vision Based Data Extraction	Flying Camera	Flying Total Station	Perching Camera	MALE	Complex Manipulation
		Direction of Improvement	▲	▲	▲	—	—	—	—	—	▲	▲	▲	—	—	—	▲	—	—	▲	▲					
8	14%	FPV Operation				●							○									✓	☑	✓	☒	✓
1	2%	Non-FPV Operation											●	●		●			◐			✗	☒	✓	✓	✗
3	5%	Pilot-independet sensor package control				●	●															✗	✗	☑	✓	✓
4	7%	Use on construction site	●	◐	○						●	●										✓	✓	☑	✗	☑
3	5%	Use at traffic signal site	◐	○							◐	◐	◐									☑	☒	✓	✗	☑
5	9%	Metro-area range/coverage			●														●			✗	✗	☑	✓	✗
1	2%	Get point coordinates				◐				●											●	✓	✓	✓	✓	✓
3	5%	Measure site dimensions				◐				●											●	✓	✓	✓	✓	✓
1	2%	Estimate volumes				◐				●										◐	●	✓	✓	☒	✗	✗
4	7%	Count/track/detect items				◐				●												✓	☒	☑	✓	✗
4	7%	Correleate sensor data to plans/drawings															●	●			●	☒	✓	☑	☑	✓
1	2%	"Line-of-sight" clearance measurements															○				●	☑	✓	☑	✓	☑
4	7%	Collect floating traffic samples	◐		○								●	●		◐			◐		●	✗	✗	✓	☑	✗
1	2%	Allows to trigger a "reset"	◐						○													☒	✗	✓	✗	☑
4	7%	Interact with inspected element	◐						●						●							✗	✗	☑	✗	✓
3	5%	Establish contact to people	◐		○			●	○				◐									☑	✗	✓	✗	✗
1	2%	Eliminate need for human task execution							●													☑	☑	☑	☑	✓
4	7%	Conduct traffic counts	○		○	●	◐			●					●						●	☑	✗	✓	✓	✗
2	4%	Data on demand																	◐			✗	✗	☑	✓	✗
		Technical Priority	1.211	0.263	0.702	1.789	0.474	0.263	0.509	1.14	0.509	0.509	0.895	0.439	0.702	0.298	0.368	0.351	0.807	0.053	1.579					
		(rel. Technical Priority)	9%	2%	5%	14%	4%	2%	4%	9%	4%	4%	7%	3%	5%	2%	3%	3%	6%	0%	12%					

Reference Systems	Airframe Ruggedness	Airframe Availability	Endurance	Actuated Video Camera	Actuated Non-Video Sensor Package	Telepresence	Manipulator and/or Effector	Interactive Object Selection and Identification	Ruggedness	Portability	Sense and Avoid	Waypoint Navigation	Kinematically constrained operations	Unattended deployment and return	High-precision navigation	Simultaneous Location and Mapping (SLAM)	Advanced Datalink and Networking	Sensor Data Abstraction and Reduction	Vision Based Data Extraction
Flying Camera	✓	✓	☒	☑	✗	✗	✗	✓	✓	✓	✗	☑	✗	✗	✗	✗	✗	✗	✓
Flying Total Station	☒	☑	☑	☒	☑	✗	✗	✓	☑	☑	☑	✓	☑	☒	✓	✓	✗	✓	✓
Perching Camera	✓	☑	☒	✓	✓	☑	✗	✓	☑	✓	☑	✓	☑	✓	☒	☑	✓	☒	✓
MALE	✗	✓	✓	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗	☑	✓	✓
Complex Manipulation	☑	✗	☑	✓	✓	✗	✓	✓	☒	☒	✓	☑	✓	✗	☑	✓	✗	☑	✓

Figure 5-5: House of Quality for System C (Perching Camera)

Payload:

Given that perching could limit the achievable attitudes while landed, actuated video and non-video sensor packages are presumably necessary to compensate for that. Given the use cases for System C, it seems likely that the system would also provide telepresence equipment as well as advanced networking capabilities.

Control Station:

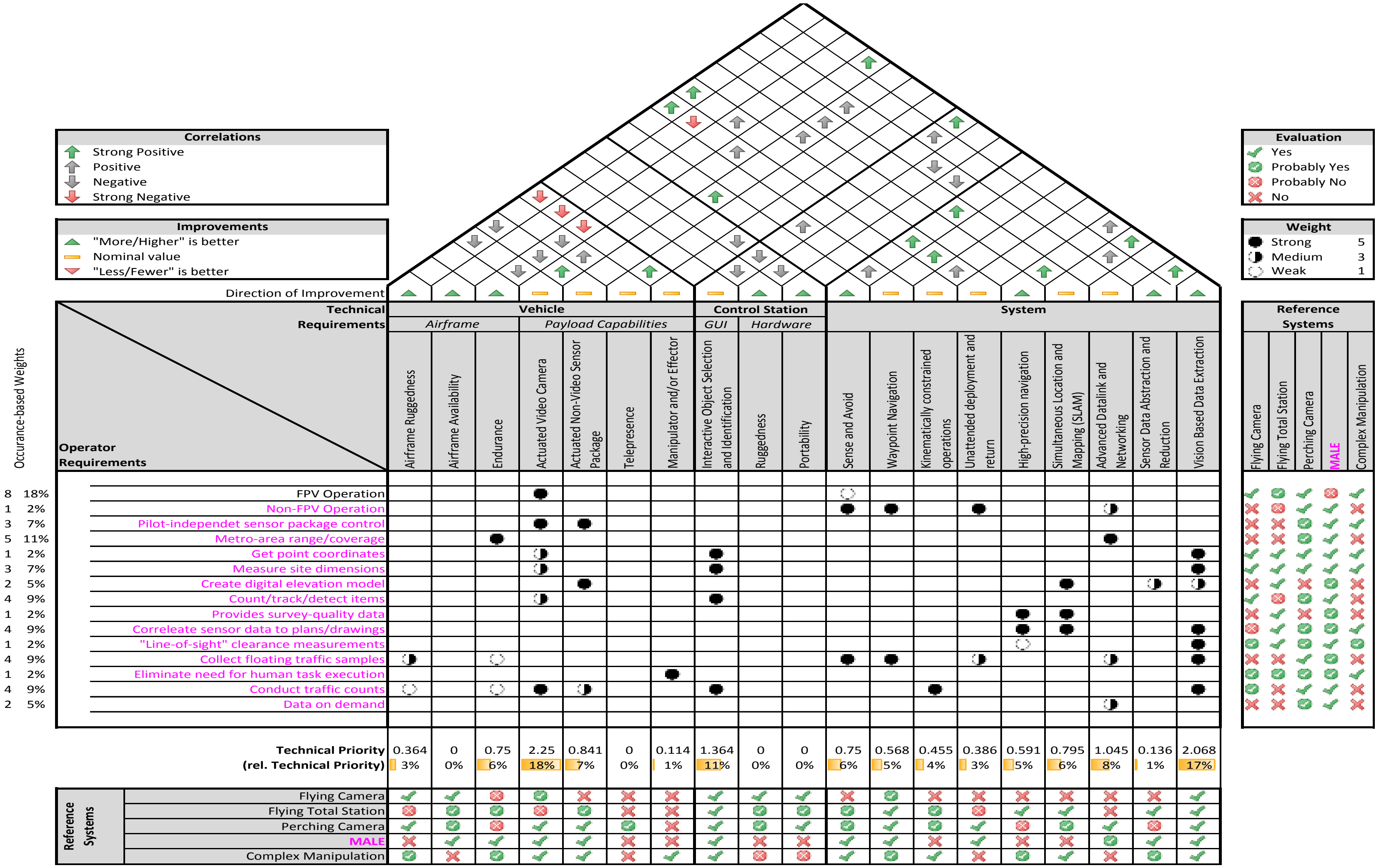
The control stations for System C could be of several types. Given the potential use cases, operators should be able to use control stations tailored to them and their particular needs: HERO personnel, for example, could utilize a rugged tablet computer based system comparable to a unit used to control System A; GDOT employees working in the Traffic Control Center could use a software that operates on their desktop computers; traffic engineering and traffic management personnel could use a laptop. The control station would provide a FPV interface and a graphical tool for waypoint navigation as well as indicating measurement areas or regions of interest.

Capabilities:

System C would mainly provide vision based capabilities, potentially making use of dedicated external computation centers to support limited computation power available in tablet based control stations. The system would expand upon the capabilities of System A, especially toward traffic related tasks.

5.2.5. System D – Medium Altitude, Long Endurance (MALE)

Whereas the proposed Systems A through C could be classified as having a local operational area, System D is designed to expand this to a regional scale. The UAV would allow long operational usage throughout a county-sized area. The system separates the piloting tasks from the payload operation and data acquisition tasks, allowing for a very high level of operator interaction (see Figure 5-6).



Correlations
- ⇧ Strong Positive
- ⇧ Positive
- ⇩ Negative
- ⇩ Strong Negative

Improvements
- ▲ "More/Higher" is better
- ▬ Nominal value
- ▼ "Less/Fewer" is better

Evaluation
- ✓ Yes
- ☑ Probably Yes
- ☒ Probably No
- ✗ No

Weight
- ● Strong 5
- ◐ Medium 3
- ○ Weak 1

Occurance-based Weights		Operator Requirements	Airframe Ruggedness	Airframe Availability	Endurance	Actuated Video Camera	Actuated Non-Video Sensor Package	Telepresence	Manipulator and/or Effector	Interactive Object Selection and Identification	Ruggedness	Portability	Sense and Avoid	Waypoint Navigation	Kinematically constrained operations	Unattended deployment and return	High-precision navigation	Simultaneous Location and Mapping (SLAM)	Advanced Datalink and Networking	Sensor Data Abstraction and Reduction	Vision Based Data Extraction	Flying Camera	Flying Total Station	Perching Camera	MALE	Complex Manipulation
		Technical Requirements	Vehicle							Control Station			System									Reference Systems				
			Airframe			Payload Capabilities				GUI	Hardware															
		Direction of Improvement	▲	▲	▲	▬	▬	▬	▬	▬	▲	▲	▲	▬	▬	▬	▲	▬	▬	▲	▲					
8	18%	FPV Operation				●							○									✓	☑	✓	☒	✓
1	2%	Non-FPV Operation											●	●		●			◐			✗	☒	✓	✓	✗
3	7%	Pilot-independet sensor package control				●	●															✗	✗	☑	✓	✓
5	11%	Metro-area range/coverage			●														●			✗	✗	☑	✓	✗
1	2%	Get point coordinates				◐				●											●	✓	✓	✓	✓	✓
3	7%	Measure site dimensions				◐				●											●	✓	✓	✓	✓	✓
2	5%	Create digital elevation model					●											●		◐	◐	✗	✓	✗	☑	✗
4	9%	Count/track/detect items				◐				●												✓	☒	☑	✓	✗
1	2%	Provides survey-quality data															●	●				✗	✓	✗	☑	✗
4	9%	Correleate sensor data to plans/drawings															●	●			●	☒	✓	☑	☑	✓
1	2%	"Line-of-sight" clearance measurements															○				●	☑	✓	☑	✓	☑
4	9%	Collect floating traffic samples	◐		○								●	●		◐			◐		●	✗	✗	✓	☑	✗
1	2%	Eliminate need for human task execution							●													☑	☑	☑	☑	✓
4	9%	Conduct traffic counts	○		○	●	◐			●					●						●	☑	✗	✓	✓	✗
2	5%	Data on demand																	◐			✗	✗	☑	✓	✗
		Technical Priority	0.364	0	0.75	2.25	0.841	0	0.114	1.364	0	0	0.75	0.568	0.455	0.386	0.591	0.795	1.045	0.136	2.068					
		(rel. Technical Priority)	3%	0%	6%	18%	7%	0%	1%	11%	0%	0%	6%	5%	4%	3%	5%	6%	8%	1%	17%					
Reference Systems		Flying Camera	✓	✓	☒	☑	✗	✗	✗	✓	✓	✓	✗	☑	✗	✗	✗	✗	✗	✗	✓					
		Flying Total Station	☒	☑	☑	☒	☑	✗	✗	✓	☑	☑	☑	✓	☑	☒	✓	✓	✗	✓	✓					
		Perching Camera	✓	☑	☒	✓	✓	☑	✗	✓	☑	✓	☑	✓	☑	✓	☒	☑	✓	☒	✓					
		MALE	✗	✓	✓	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗	☑	✓	✓					
		Complex Manipulation	☑	✗	☑	✓	✓	✗	✓	✓	☒	☒	✓	☑	✓	✗	☑	✓	✗	☑	✓					

Figure 5-6: House of Quality for System D (MALE)

Usage Scenario:

System D could operate in two ways, comparable to System C. In the ad-hoc mode, the UAV would be stationed at an airfield and would get airborne as soon as an operator requests control over a system. In the data-on-demand scenario, the air unit(s) of System C would loiter over a dedicated operational area in a low energy standby mode. Once an operator requests data, the system would relocate to the specific area requested and start to operate its payload sensors.

Airframe:

The airframe of choice for System D would most likely be a fixed wing aircraft design, sized somewhere in the 2 m to 6 m wingspan regimen. The airframe would provide all mandated general aviation equipment, for example, aviation band radios, a transponder, and most likely an Automatic dependent surveillance-broadcast (ADS-B) transceiver, as the system would have to operate within the (controlled) national airspace, among other general aviation traffic.

Payload:

The system would primarily provide a calibrated pan/tilt/zoom video sensor to provide high quality aerial photography. The system could augment this with ground scanning LiDAR systems and directional antennas for advanced networking features. Further sensor equipment could include microwave based systems to detect traffic movements or near and far infrared systems to aid in the localization of stranded motorists at night or the detection of wild fires. Further optional payload capabilities could include R/F relay stations for first responder disaster response communication systems.

Control Station:

The control station for System D would most likely be consisting of several independent units. One of them would be the payload focused unit available to the payload focused operators. Related to that would be a highly portable data display unit, available to first responders on site, which could be used to access the data provided from the system. Separate from that would be a control station for an external pilot which would aid the system during taxi, take-off, and landing operations as well as serve as a voice relay when conversing with ATC.

Required Infrastructure:

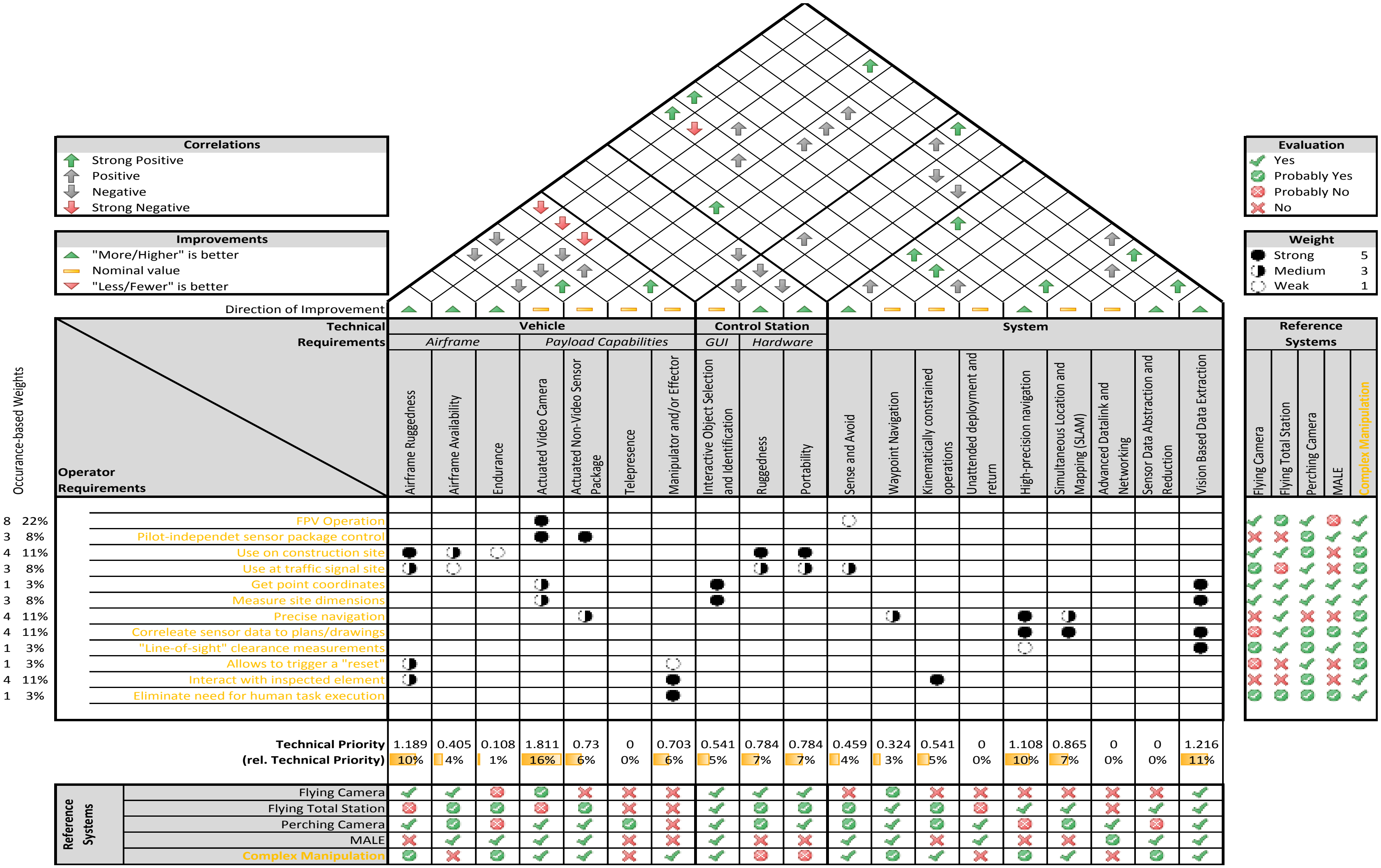
System D would require an airstrip for take-off and landing. Given that the system should need much smaller take-off and landing distanced, operation out of a general aviation (GA) airport is not necessary and a dedicated airstrip might mitigate a lot of integration into GA ground operations. If a dedicated airstrip is chosen, external pilots for take-off and landing aiding could also have better access to the runway strip. As the system should provide longer range operations, ground communication stations with dedicated directional antennas might be necessary and could also be located at the utilized airstrip. Furthermore, maintenance and refueling opportunities need to be provided.

Capabilities:

System D would primarily provide aerial photographic and video data, which would satisfy the quality requirements of photogrammetric applications. The payload operator could also make live feeds of the video data available to first responders or HERO units. System D could also be used as a disaster response communication relay station in case conventional ground based infrastructure would not be available. System D could also provide Navigator like traffic sensing capabilities, which could allow temporary traffic data capturing during larger events outside the conventionally covered areas.

5.2.6. System E – Complex Manipulation

An example for this category: This most likely would be a custom made multi-rotor with 8 or more rotors or an even more special “inverted” helicopter, where the main rotor sits below most of the airframe. The multi-rotor configuration or the low main rotor configuration would most likely be necessary to allow an tele-robotics style manipulator to act above the rotor disc(s), as this most likely would be safest for working under bridges. The system would be transported in a dedicated van/truck and could potentially be tethered to allow for prolonged operations in hover and/or while powering the manipulator. The system would most likely have an external (safety) pilot as we well as a remote operator (in the van/truck) (see Figure 5-7).



Correlations
- ⇧ Strong Positive
- ⇧ Positive
- ⇩ Negative
- ⇩ Strong Negative

Improvements
- ▲ "More/Higher" is better
- ▬ Nominal value
- ▼ "Less/Fewer" is better

Evaluation
- ✓ Yes
- ☑ Probably Yes
- ☒ Probably No
- ✗ No

Weight

●	Strong	5
◐	Medium	3
○	Weak	1

Occurance-based Weights		Operator Requirements \ Technical Requirements	Vehicle							Control Station			System									Reference Systems				
			Airframe			Payload Capabilities				GUI	Hardware															
			Airframe Ruggedness	Airframe Availability	Endurance	Actuated Video Camera	Actuated Non-Video Sensor Package	Telepresence	Manipulator and/or Effector	Interactive Object Selection and Identification	Ruggedness	Portability	Sense and Avoid	Waypoint Navigation	Kinematically constrained operations	Unattended deployment and return	High-precision navigation	Simultaneous Location and Mapping (SLAM)	Advanced Datalink and Networking	Sensor Data Abstraction and Reduction	Vision Based Data Extraction	Flying Camera	Flying Total Station	Perching Camera	MALE	Complex Manipulation
		Direction of Improvement	▲	▲	▲	▬	▬	▬	▬	▬	▲	▲	▲	▬	▬	▬	▲	▬	▬	▲	▲					
8	22%	FPV Operation				●							○									✓	☑	✓	☒	✓
3	8%	Pilot-independet sensor package control				●	●															✗	✗	☑	✓	✓
4	11%	Use on construction site	●	◐	○						●	●										✓	✓	☑	✗	☑
3	8%	Use at traffic signal site	◐	○							◐	◐	◐									☑	☒	✓	✗	☑
1	3%	Get point coordinates				◐				●											●	✓	✓	✓	✓	✓
3	8%	Measure site dimensions				◐				●											●	✓	✓	✓	✓	✓
4	11%	Precise navigation					◐							◐			●	◐				✗	✓	✗	✗	☑
4	11%	Correleate sensor data to plans/drawings															●	●			●	☒	✓	☑	☑	✓
1	3%	"Line-of-sight" clearance measurements															○				●	☑	✓	☑	✓	☑
1	3%	Allows to trigger a "reset"	◐						○													☒	✗	✓	✗	☑
4	11%	Interact with inspected element	◐						●						●							✗	✗	☑	✗	✓
1	3%	Eliminate need for human task execution							●													☑	☑	☑	☑	✓
		Technical Priority	1.189	0.405	0.108	1.811	0.73	0	0.703	0.541	0.784	0.784	0.459	0.324	0.541	0	1.108	0.865	0	0	1.216					
		(rel. Technical Priority)	10%	4%	1%	16%	6%	0%	6%	5%	7%	7%	4%	3%	5%	0%	10%	7%	0%	0%	11%					
Reference Systems		Flying Camera	✓	✓	☒	☑	✗	✗	✗	✓	✓	✓	✗	☑	✗	✗	✗	✗	✗	✗	✓					
		Flying Total Station	☒	☑	☑	☒	☑	✗	✗	✓	☑	☑	☑	✓	☑	☒	✓	✓	✗	✓	✓					
		Perching Camera	✓	☑	☒	✓	✓	☑	✗	✓	☑	✓	☑	✓	☑	✓	☒	☑	✓	☒	✓					
		MALE	✗	✓	✓	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗	☑	✓	✓					
		Complex Manipulation	☑	✗	☑	✓	✓	✗	✓	✓	☒	☒	✓	☑	✓	✗	☑	✓	✗	☑	✓					

Figure 5-7: House of Quality for System E (Complex Manipulation)

System E allows its operators to completely perform a task through telepresence and tele-robotics in areas that are either complicated or dangerous to access for humans. As such the focus of the system shifts from a primarily sensing oriented operation to tasks which include also portions in which previously inspected elements need to be manipulated.

Usage Scenario:

System E is specifically slanted to be used for bridge or other structural inspection activities. As such the system would be relocated to the current site under inspection and the operated on site for the duration of the inspection. The main motivation behind System E is to replace special access equipment needed during complex inspection tasks in order to get the human inspector(s) to the inspection site.
The system would presumable be used by at least two operators: a dedicated external pilot, primarily responsible for piloting the UAV and maneuvering the unit to the inspection site and a dedicated payload operator who would focus on using the manipulator and effectors to conduct the actual inspection task. As the later presumably would need a feedback device to control the manipulator, the payload operator is assumed to work out of a dedicated control station vehicle, while the pilot operator is located at a vantage point that provides good situational awareness of the situation the UAV operates in. Both operators would have voice communication equipment to coordinate their efforts.

Airframe:

The airframe of System E most likely would have to be a custom designed system. As the system’s tasks include object manipulation, the airframe has to support a manipulator or effector of sorts which raises the question of the general geometry of the system. The airframe would have to be able to hover and provide VTOL capabilities, which would mean rotors, but also provide a large operational range for the manipulator. A possible solution could be a large scale multi-rotor where the manipulator is mounted above the main rotor disk, which allows using the system to be used, for example, under bridges. Multirotor configurations are preferable for such arrangements as it is easier ti build airframe structure through the non-rotor occupied center. However, fixing this arrangement would limit the system to tasks in which the manipulator wouldn't have to be used below the main rotor discs of the multirotor setup. Switching this to a conventional helicopter setup with a rotor head configuration that allows for highly negative pitch angles could, in combination with advanced GNC algorithms, be used to allow such a system to continuously operate in both orientations: manipulator above the main rotor as well as below. The airframe furthermore would have to be strong enough to support not only the manipulator, but also all the forces applied through it. Additionally several thrusters could be needed to provide pushing or pulling forces without major changes in the vehicle attitude.

Payload:

The primary payload of System E would be the manipulator or effector and the supporting telepresence and situational awareness sensors. These could include a stereo vision rig, a time-of-flight camera or some similar close range 3D sensor, and LiDAR systems. Additionally the system potentially would have to carry a selection of grappling interfaces and probing tools.

Control Station:

The control station most likely would also be split into two parts, one more tailored towards the needs of an external safety pilot, and more tailored towards the needs of the main payload operator. The former would need to focus on providing the external pilot with a good situational awareness of the surroundings of the vehicle, later would need to include a device to control the installed manipulator and request necessary manipulating forces in addition to the forces needed to maintain flight.

Required Infrastructure:

System E would need a dedicated vehicle. This vehicle would on the one side serve as the transport vehicle to get the system to the different inspection sites and on the other side double as the control station once the system is unloaded. The vehicle would provide a source of power, an indoor workstation for the payload operator, and the required computer systems. Additionally it would also carry all the other required elements for the inspection tasks, i.e. any potentially necessary specialized sensors, etc. The vehicle furthermore would carry traffic control devices to setup and secure the operations.

Capabilities:

The system would mainly provide capabilities comparable to a trained human worker operating out of a bucket truck or a similar reach extending device. To maintain prolonged operations, the system could be tethered to an external power source and would need to provide the ability to operate under kinematic constraints, not only from the tether, but also and especially when latchet onto other objects.

6. CHAPTER VI

6. Cost Analysis

The following section contains Rough Order of Magnitude (ROM) cost estimates for the development, acquisition, and operation of the reference systems described in Chapter V. These are based on knowledge the authors have about the development of such systems, information about related existing systems, and by aggregation of lower level estimates of contributing elements. It is important to point out that this is a rapidly evolving area, and so estimates made this year could be very different next year or the year after. There is tremendous uncertainty here, but estimating cost is an exercise worth doing to support decision-making.

6.1. System A – Flying Camera

There are off-the-shelf systems here that enable perhaps the most accurate cost estimate for all of the reference systems. Companies with systems for sale today that could potentially perform this mission are numerous. In fact, hobbyists today are able to construct similar systems using easily obtainable components. In addition, complete off-the-shelf systems are available at less than $10,000. It is important to realize that the lower cost systems are typically not going to be suitable for effective work – given their limitations in terms of reliability, availability (for example, the weather conditions they can tolerate) and image quality. A number more like $25,000 is appropriate for a robust complete turn-key system with ground control equipment, redundant airframes, and multiple battery packs.

The next important implication of the wide array of existing system is that development costs here would be minimal. It is probable that an existing system could be utilized outright. Work within GDOT would largely be around the management, development on detailed procedures, and training. However, these systems are often quite simple – and involve training regiments for new users on the order of one day. Future requirements on UAS operators in general may end up being the primary training driver. Taken together, an estimate today would be a week for initial training of a new operator and one day every six months recurring training.

6.2. System B – Flying Total Station

Although there are an extremely small number of systems put forth that perform aerial survey from a UAS, it appears this reference system would require substantial development to bring to fruition – although with relatively low technical risk. Because of applications outside of GDOT, it is likely that these development costs could be shared or included within the platform costs of a product sold more widely. Today, it would take approximately $1-2M and one year for one of several agile small UAS companies to transition some of their current work to evolve such a system.

The sensor costs (laser and differential GPS), the necessary system redundancy to go along with carrying said sensor, and the importance of precision in all aspects of this reference system result in a substantially more expensive aircraft. Including a likely dedicated ground vehicle or trailer, a complete system would likely be on the order of $250,000.

Training for operating the aircraft would be perhaps somewhat more than System A, but similar. There would likely be entail domain-specific training associated with the surveying itself and the use of the data. However, at this point it is hard to see how this aspect would be substantially easier or harder than with existing tools. It would also be important to provide some minimal training/awareness to those people near the aircraft when it operates.

6.3. System C – Perching Camera

As an extension of System A, a certain amount of development is necessary to achieve to perching function and to make the maximum use of it through communication systems. Although these types of behaviors have been demonstrated in limited flight testing, a certain amount of technical risk should be associated with an ability to perch a camera in more than a minority of situations. For example, weather and the conditions of the immediate surroundings can create real limitations on what can be done at a particular time in a particular place. Development efforts would seek to minimize these limitations.

This reference system also includes the potential notion of multiple base stations with multiple aircraft that would need to be maintained as part of a larger network. This is an area with application beyond GDOT, where it is likely considerable effort will be put forth in the coming years to explore these ideas (recent press stories have included pizza delivery and package delivery for example). This is such a forward looking idea that it would be wild speculation to make a cost estimate on today. However, one can think about a single aircraft operation today and still consider this reference system.

The system itself would be more than System A, perhaps doubling due to the additional capabilities and specialization to on the order of $50,000 for a complete system. Training for operating the aircraft would be perhaps somewhat more than System A, but similar. There is an assumption here that useful perching can be achieved without the need for a highly skilled human operator.

6.4. System D – Medium Altitude, Long Endurance

This is another reference system that could perhaps be largely off-the-shelf. The authors would point to the AAI RQ-7 Shadow and Insitu RQ-21A Blackjack as examples. These are both military systems, where a civil version would have some differences. These differences though are not enough to turn them away as a basis for a cost estimate, however, they include launch and recovery equipment. Development costs should be relatively small here (at least compared to the per system cost) given the maturity of the existing systems.

That AAI Shadow costs approximately $15M per system (four aircraft, launch recovery equipment, two control stations in High Mobility Multi-Purpose Wheeled Vehicles (HMMWVs), a dedicated ground support vehicle, and maintenance equipment). A single aircraft is approximately $750,000. A complete Insitu SeaScan (precursor to the Blackjack) was approximately $3M several years ago and an early version of the Blackjack system was $8M. The former includes four aircraft, control station, and launch/recovery equipment.

It takes a large number of people to operate these current systems – on the order of ten once you include maintenance and specialized takeoff/landing tasks. It is also important to realize that several of the ten people involved need specialized training.

6.5. System E – Complex Manipulation

This reference system involves the highest level of technical uncertainty, and so perhaps the greatest development costs. The closest precedent is perhaps the use of Unmanned Underwater Vehicles (UUVs) to perform these types of manipulation tasks. A serious dedicated development effort of more than $5M is likely necessary over several years to achieve a few of the proposed operational capabilities. However, this is another domain with applications beyond GDOT, so it is unlikely that GDOT would need to take on the entire burden of bringing such a capability to fruition.

Once developed, an individual system would likely have cost at least as high as the most capable bomb disposal robots or similar unmanned underwater vehicles. This would be on the order of $500,000. It is interesting to speculate that such a system may have such a wide application beyond GDOT (construction, building maintenance, painting, disaster response, etc.) that economies of scale could lower this figure substantially.

Operators of such a system would likely be highly skilled and specialized, and include perhaps three to five dedicated people to support such a system.

6.6. Cost-Benefit Analysis

Part of the research was to attempt a cost-benefit analysis of UAS-aided operations in selected GDOT divisions, however this turned out as being infeasible within the context of this research effort as no actual comparison of unaided vs. aided task execution could be performed.

The semi-structured interviews tried to extract information about a “per task” cost of the individual task, based upon approximate task durations, publicly accessible salary information, and estimates about required equipment, etc. The resulting computed number was returned to the interviewees for validation (compare the “Cost Estimation” section of the validation form example in Appendix C), but the returned validated data showed a large spread (the per-task data shown in Appendix D provides an approximation of the average of all returned data for a particular task), indicating a fair amount of uncertainty in it.

Technical Requirements	Vehicle							Control Station			System									Cost
	Airframe			*Payload Capabilities*				*GUI*	*Hardware*											
Reference Systems	Airframe Ruggedness	Airframe Availability	Endurance	Actuated Video Camera	Actuated Non-Video Sensor Package	Telepresence	Manipulator and/or Effector	Interactive Object Selection and Identification	Ruggedness	Portability	Sense and Avoid	Waypoint Navigation	Kinematically constrained operations	Unattended deployment and return	High-precision navigation	Simultaneous Location and Mapping (SLAM)	Advanced Datalink and Networking	Sensor Data Abstraction and Reduction	Vision Based Data Extraction	Rough Order of Magnitude Per-System Cost (which could be several air units)
Flying Camera	✓	✓	🔴	🟢	✗	✗	✗	✓	✓	✓	✗	🟢	✗	✗	✗	✗	✗	✗	✓	$ 25 k
Flying Total Station	🔴	🟢	🟢	🔴	🟢	✗	✗	✓	🟢	🟢	🟢	✓	🟢	🔴	✓	✓	✗	✓	✓	$ 1-2 M
Perching Camera	✓	🟢	🔴	✓	✓	🟢	✗	✓	🟢	✓	🟢	✓	🟢	✓	🔴	🟢	✓	🔴	✓	$ 50 k
MALE	✗	✓	✓	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗	🟢	✓	✓	$ 750 k - 15 M
Complex Manipulation	🟢	✗	🟢	✓	✓	✗	✓	✓	🔴	🔴	✓	🟢	✓	✗	🟢	✓	✗	🟢	✓	$ 500 k - 5 M

Evaluation	
✓	Yes
🟢	Probably Yes
🔴	Probably No
✗	No

Figure 6-1: Extremely reduced House of Quality for all Systems, also showing estimated rough order of magnitude cost.

In addition to the unattainable data showing the cost of the current task execution, the cost associated with the procurement and operation of the proposed UAS also doesn’t allow a task or divisions based analysis of a tangible cost benefits for each of the identified tasks. To elaborate on this, Figure 6-1 shows an extremely reduced version of the House of Quality viewgraph (Appendix F for the complete viewgraph) combined with the cost estimates given in Sections 6.1 through 6.5 above. Depending on the System, the estimated Rough Order of Magnitude (ROM) costs not only capture differences in hardware costs, for example, a different number of aerial units per system (the Flying Camera is most likely one UAV per GCS unit, whereas the MALE system has most likely several UAVs per GCS), but also a wide amount of associated costs resulting from the use or personnel (the Flying Camera would most likely only involve one person per executed task – which already omits any personnel required for maintenance and repairs – whereas the MALE system most likely would require a larger crew to operate a single aerial unit, at least during certain phases of a task execution). Without more specific information about those secondary effects, comparable, for example, to the inclusion of maintaining the vehicle fleet in the cost of the current task execution, it doesn’t seem to be feasible to come up with any sort of reasonable overhead estimations for the individual units, yet alone for the individual tasks identified to possibly benefit from UAS utilization.

Without at least some elementary field testing it also seems unlikely to quantify the intangible benefits of UAS utilization with respect to the cost of the associated systems. Among the intangible benefits are most certainly an increase in operator safety in all occasion where a UAS operator can remain on safe ground instead of putting her- or himself in potentially dangerous locations, for example, during a complex bridge inspection, an inspection of a traffic signal installation over flowing traffic, or the measuring and counting of items on a busy construction site or in otherwise undeveloped pre-construction sites.

This, in combination with the uncertainties in the acquisition and maintenance cost of the proposed systems as well as no validated operational description of UAS-aided task executions, led the researchers to stop the attempt to create a cost benefit analysis.

7. CHAPTER VII

7. Recommendations for Future Work

After conducting interviews with 24 individual in the four selected GDOT divisions, the research team identified tasks that could benefit from the use of UAS technology. The majority of the tasks in GDOT divisions with the highest potential for benefitting from UAS technology are centered around collecting data, providing information, and decision making based on the data. Each task is also characterized by particular attributes (e.g. location where the tasks are performed and the time required to complete a given task) that yield a better understanding of the environmental conditions. Thus, UAS technical requirements that embed the operational and technical requirements for development of a potential UAS have been investigated. The result of this investigation was the identification of five potential systems

Given the issues with cost related data collection in this study, it is recognized that additional research is needed to obtain a clearer idea of the economic and intangible benefits of the use UASs for GDOT operations. A possible departure point would be the selection of construction related tasks. It would be possible to perform a detailed tasks analysis for a construction jobsite inspection task to set the base for UAS operator system interface needs. The analysis would include a detailed assessment of the current practice and shadowing of personnel performing the task. In that way an estimate of the time and cost of performance could be developed. Based on this analysis, a potential UAS flight path through a jobsite could be established. Using a staff mounted sensor suite as a UAS mock-up or an off-the –shelf UAS, sensor data including video would be collected along the established flight paths. Then, a software replica of the site would be developed, using the collected data. The system developed would be used in a staged field test in an access-controlled construction site to validate the simulation results. This activity (and preparations for it) would include direct coordination with the FAA. The technical requirements determined would also aid in more rapid development of test UASs for GDOT use as well as advance GDOT's implementation of UAS(s) to help accomplish the Department's goals.

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Appendix

Appendix A: Interview Sheet

1- Demographic Questions / User

☐ 1.1 Why are you here?

☐ 1.2 Gender:

☐ 1.3 Age: ________________ yrs.

☐ 1.4 Which department/office are you working at?

☐ 1.5 What is the job title of your current position?

☐ 1.6 Please briefly explain your role and responsibility at this job:

☐ 1.7 Years of experience in current job:

☐ 1.8 Total years of experience in total:

☐ 1.9 How big is the size of the department/office you are working at?
Number of employees:

☐ 1.10 Educational/training background (e.g. Civil Engineering, Finance, Architecture, …)

☐ 1.11 Education/training attainment:

☐ 1.12 High school diploma, ☐ Bachelor, ☐ Masters, ☐ PhD

☐ 1.13 Other (please specify): ____

2- Operational Requirements

2.1 Division Statistics

☐**2.1.1 Workforce breakdown**: total number, white-vs.-blue collar, indoor-vs-outdoor, data gatherer vs. data processors

☐**2.1.2 Project load breakdown:** total number of projects per year, average number of parallel projects

☐**2.1.3 Project type breakdown:** in-house data usage vs. external/shared data usage

☐**2.1.4 IT:** data storage, data sharing, agreements, data classification and access (public vs. non-public)

2.2 Specific Division Tasks

☐**2.2.1** What are the different tasks/operations performed in your department?

☐**2.2.2** Who are the key decision-makers/performers of those tasks?

☐**2.2.3** What are the goals and sub goals when performing each task?

☐**2.2.4** What are the decisions should be made for achieving each decision?

☐**2.2.5** What are the information requirement for making those decisions and performing each sub-goal?

3- Technology Analysis

3.1 Data Collection

☐**3.1.1** Tools used on the job site and in the office

☐**3.1.2** Training and or qualifications necessary to use those tools with a focus on using the tools to collect usable data.

☐**3.1.3** Generic vs. specialized tools

☐**3.1.4** Tools used as a means to an end, i.e. tool necessary to enable work on site but not involved in the direct data collection process, i.e. tools used as an enabler and not as a sensor

3.2 Data Access

☐**3.2.1** Interaction type
☐**3.2.2** Paper vs. electronic format
☐**3.2.3** Mobile/handheld
☐**3.2.4** 2D/3D CAD/visualization tools/software
☐**3.2.5** Internet Access
☐**3.2.6** Software
☐**3.2.7** Common Sensors (Video/picture (Real-time), GPS, Surveying Tools) Other?:

3.3 Collected data

☐**3.3.1** What is the raw collected data and how does that relate to the actually needed data.

- ☐Directly collectable data vs. inferred data
- ☐Data requirements: accuracy, timeliness, repeatability
- ☐Importance: necessary primary data vs. easily collectable data providing context
- ☐Cost vs. value of data collection

3.4 Data post-processing

☐ **3.3.2** Is the data collected indeed the data needed?

- ☐ Immediate post-processing actions necessary to extract the required data (in cases where a direct collection isn't possible)
- ☐ Cost vs. value: post-processing, data storage
- ☐ Classification: useful vs. useless, public vs. non-public
- ☐ Training requirements to do the post-processing.

4- Working Environment

☐**4.1** Location of site: near, far, indoors, outdoors

☐**4.2** Time of year: all seasons vs. a prevailing season

☐**4.3** Site safety: hard hat area, ongoing construction, site specific hazards

☐**4.4** Site specific training requirement

____

☐**4.5** Equipment necessary to access the site (enabling tools)

____

☐**4.6** Sitting vs. Standing vs. While mobile

____

☐**4.7** Indoors vs. Outdoors

____

☐**4.8** Issues affecting your tasks in either indoor or outdoor environments?

☐Heat ☐Cold ☐Wind ☐Rain ☐Snow ☐Humidity ☐Perspiration

____

☐**4.9** Preferred/fluent/first language (Choose one):

☐ English, ☐ Spanish, ☐ French, ☐
Other:_________________________________

☐**4.10** Which type of special clothing might you wear while working?

☐ Hardhat, ☐ Earplugs/hearing protection, ☐ Gloves, ☐ Goggles, ☐ Mask,
☐ Backpack☐ Other (please specify): ___________________________________

5- UAVs in Your Department /Office

5.1 Questions about each identified tasks

☐**5.1.1** “Revisiting X, do you think this is the best way doing it? What would you change of you hadn't budget or time constraints?”

☐**5.1.2** “If you had a magic lamp with a genie at your disposal, what specific wishes would you have on the job site?”

5.2 Sensor tool questions

☐**5.2.1** Aerial photography

____

☐**5.2.2** Limited in framing your photo

____

☐**5.2.3** Change your perspective

____

☐**5.2.4** A third person spectator

____

☐**5.2.5** Geo-referenced pictures

____

☐**5.2.6** A real time or time-lapse video

____

☐**5.2.7** Image in a different spectrum (e.g. Near or far infrared)

____

☐**5.2.8** Positioning of your scanner

____

☐**5.2.9** Overlying photographic pictures over your collected 3D data

____

☐**5.2.10** A point in the sky that you could reference stuff to

☐**5.2.11** A GPS with latitude, longitude, and altitude readout instead of you geodetic equipment ____

☐**5.2.12** Visualize locations in 3D-space, i.e. the elevation of the third floor or the

clearance of a planned bridge
____

☐**5.2.13** Wind speeds and directions on you site
____

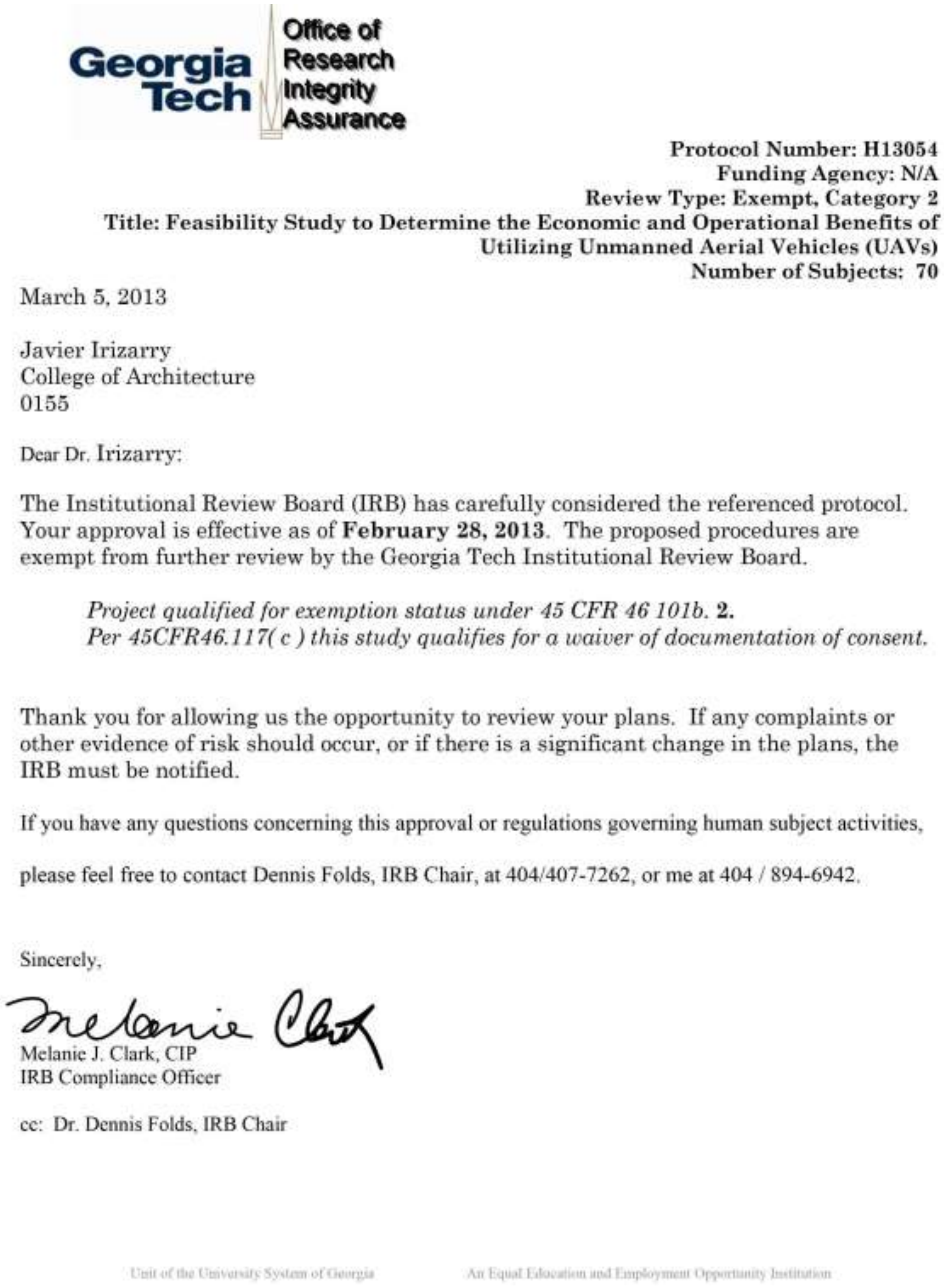
☐**5.2.14** Somebody on lookout and count X for you over the course of a day or two

____

☐**5.2.14** A motion track of equipment X over the course of a day
____

☐**5.2.15** A 3D overlay of X right now on your iPad
____

Appendix B: IRB and Consent Forms



Georgia Tech
Office of Research Integrity Assurance

Protocol Number: H13054
Funding Agency: N/A
Review Type: Exempt, Category 2
Title: Feasibility Study to Determine the Economic and Operational Benefits of Utilizing Unmanned Aerial Vehicles (UAVs)
Number of Subjects: 70

March 5, 2013

Javier Irizarry
College of Architecture
0155

Dear Dr. Irizarry:

The Institutional Review Board (IRB) has carefully considered the referenced protocol. Your approval is effective as of **February 28, 2013**. The proposed procedures are exempt from further review by the Georgia Tech Institutional Review Board.

> *Project qualified for exemption status under 45 CFR 46 101b.* **2.**
> *Per 45CFR46.117(c) this study qualifies for a waiver of documentation of consent.*

Thank you for allowing us the opportunity to review your plans. If any complaints or other evidence of risk should occur, or if there is a significant change in the plans, the IRB must be notified.

If you have any questions concerning this approval or regulations governing human subject activities,

please feel free to contact Dennis Folds, IRB Chair, at 404/407-7262, or me at 404 / 894-6942.

Sincerely,

Melanie Clark
Melanie J. Clark, CIP
IRB Compliance Officer

cc: Dr. Dennis Folds, IRB Chair

Unit of the University System of Georgia   An Equal Education and Employment Opportunity Institution

Consent to be a Research Participant

GA Tech Schools of Building Construction and Aerospace Engineering

Project: Feasibility Study to Determine the Economic and Operational Benefits of Utilizing Unmanned Aerial Vehicles (UAVs)

Principal Investigator: Dr. Javier Irizarry (678-480-6035)

Co-Principal Investigators: Dr. Eric N. Johnson (404-385-2519)

Students: Masoud Gheisari (404-385-6779), Claus Christmann (404-894-0657), and Ebrahim P. Karan (404-385-6779)

Duration of Study: One hour

Total Compensation: None

Number of Participants: 70 volunteers (Directors and administrators at GDOT divisions/offices)

Participation limitations: Normal or corrected to normal vision.

General: You are being asked to be a volunteer interviewee in a research study. To participate, you must read and agree to the following before you may proceed with the survey.

Study Description: All divisions and offices of the Georgia Department of Transportation (GDOT) would be studied to identify the ones that have the potential for using UAVs. This analysis is performed by investigating the operations, mission and sets of responsibilities that each division and their internal offices might have. Interviewing directors or administrators of each division or office would help to build a clearer picture of what would be general goals and tasks of different divisions and offices.

Procedures: A semi-structured interview will take place in which you will be asked about (1) your goals and sub-goals, (2) decisions you make for achieving those goals, and (3) information you might need for achieving each of those goals. You, as a professional GDOT employee, are being asked to take part in the interview and answer the questions you are asked by the interviewer.

Benefits: There is no direct benefit to you, however; your participation will help advance scientific knowledge in the GDOT practices.

Compensation and cost: You will not be compensated for participating in this study and there are no costs to you by participating in this study.

Foreseeable Risks or Discomforts: There are no foreseeable risks to you by participating.

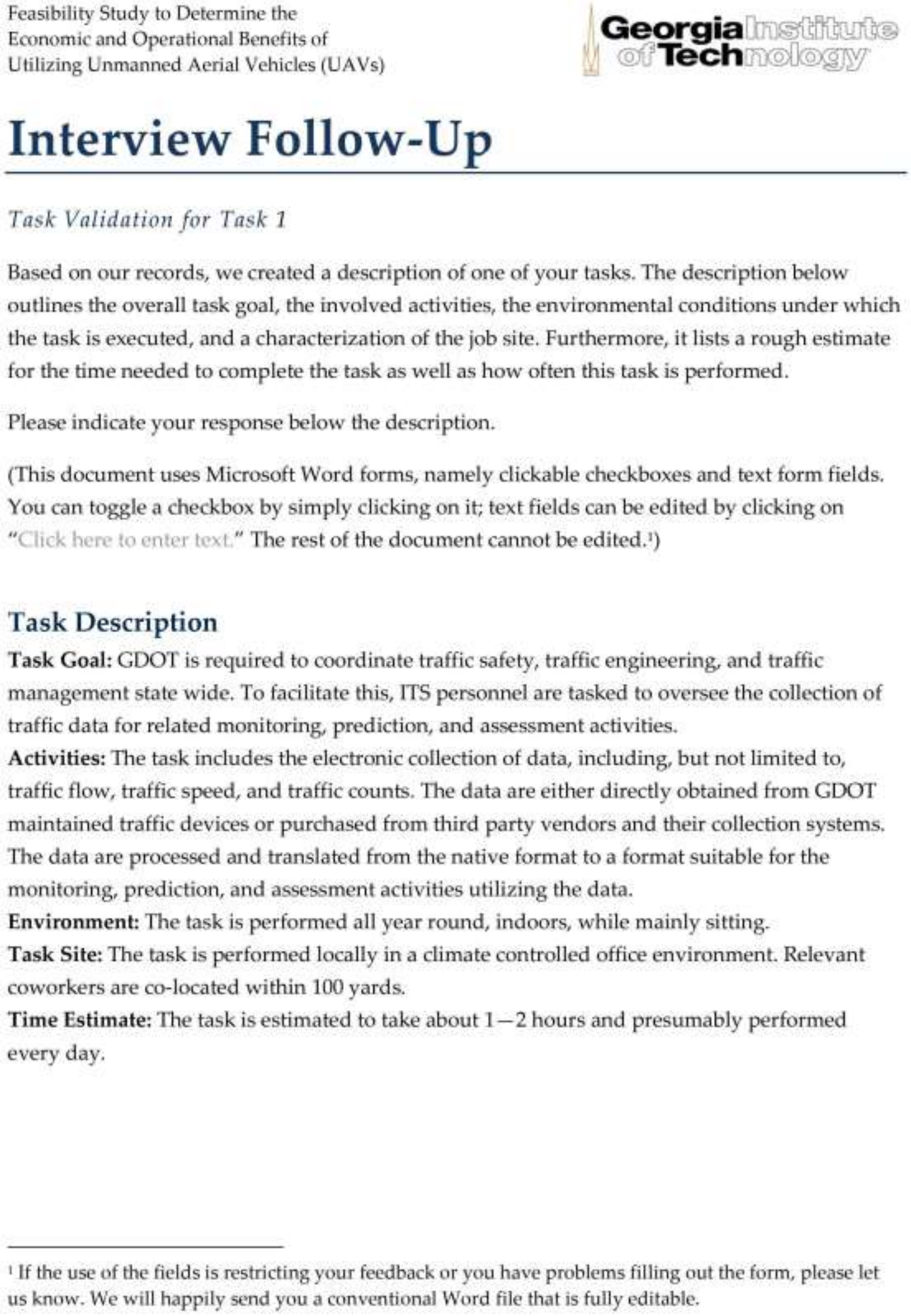
Confidentiality: The following procedures will be followed to keep your personal information confidential in this study: Data that is collected from you will be kept private to the extent allowed by law. Neither your name nor any other fact that might point to you will not be collected for this research. To further protect your privacy, your records will be kept under a coded number unrelated to you. Your records will be kept in locked files and only the project investigators and the student researcher you worked with will be allowed to look at them. Since your name or other identifiers will not be collected, there is no possibility that your name will appear when results of this study are presented or published. To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology Institutional Review Board will review the study records. Furthermore, the Office of Human Research Protections may also look over study records during required reviews.

Contact: If you have any questions about this study or its procedures, please contact Dr. Javier Irizarry at telephone # (678) 480-6035.

Statement of Rights: Your participation in this study is voluntary. You do not have to be in this study if you don't want to be. You have the right to change your mind and leave the study at any time without giving any reason, and without penalty. If you have any questions about your rights as a research volunteer, call or write to: The Institutional Review Board, Office of Research Compliance, 505 Tenth Street, Atlanta, GA 30318. Phone: 404-385-2175; Fax: 404-385-2081.

Consent: If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

Appendix C: Interview Validation Form (Example)



Feasibility Study to Determine the
Economic and Operational Benefits of
Utilizing Unmanned Aerial Vehicles (UAVs)

Georgia Institute of Technology

Interview Follow-Up

Task Validation for Task 1

Based on our records, we created a description of one of your tasks. The description below outlines the overall task goal, the involved activities, the environmental conditions under which the task is executed, and a characterization of the job site. Furthermore, it lists a rough estimate for the time needed to complete the task as well as how often this task is performed.

Please indicate your response below the description.

(This document uses Microsoft Word forms, namely clickable checkboxes and text form fields. You can toggle a checkbox by simply clicking on it; text fields can be edited by clicking on "Click here to enter text." The rest of the document cannot be edited.[1])

Task Description

Task Goal: GDOT is required to coordinate traffic safety, traffic engineering, and traffic management state wide. To facilitate this, ITS personnel are tasked to oversee the collection of traffic data for related monitoring, prediction, and assessment activities.
Activities: The task includes the electronic collection of data, including, but not limited to, traffic flow, traffic speed, and traffic counts. The data are either directly obtained from GDOT maintained traffic devices or purchased from third party vendors and their collection systems. The data are processed and translated from the native format to a format suitable for the monitoring, prediction, and assessment activities utilizing the data.
Environment: The task is performed all year round, indoors, while mainly sitting.
Task Site: The task is performed locally in a climate controlled office environment. Relevant coworkers are co-located within 100 yards.
Time Estimate: The task is estimated to take about 1—2 hours and presumably performed every day.

---

[1] If the use of the fields is restricting your feedback or you have problems filling out the form, please let us know. We will happily send you a conventional Word file that is fully editable.

Your Response

☐ This task description is correct.

☐ The description of the **Task Goal** should be altered: Click here to enter text.

☐ The description of the **Activities** should be altered: Click here to enter text.

☐ The description of the **Environment** should be altered: Click here to enter text.

The characterization of the **Site** should be altered to (check one): ☐ local, ☐ distributed
(A *local* task happens at one place or a job site that that can be best described as an patch of land where the primary descriptor would be the length and width of the area. A *distributed* task happens on a strip of land, i.e. along a road, a river, a railway, or any other place where the primary descriptor would be a length or distance.)

The estimate of the primary site **Dimension** should be altered to (check one):
☐ < 10 yards, ☐ 10–100 yards,☐ 100– 880 yards, ☐ 0.5–1 mile, ☐ 1–3 miles, ☐ 3–5 miles,
☐ 5–10 miles, ☐ > 10 miles

The estimate of the **Duration** of the task should be altered (check one):
☐ 5–15 min, ☐ 15–30 min, ☐ 30–60 min, ☐ 1–2 h, ☐ 2–3 h, ☐ 3–4 h, ☐ 4–5 h, ☐ > 5 h

The estimate of the **Frequency** of the task occurrence should be altered (check one):
☐ several times per day, ☐ several times per week ☐ several times per month,
☐ several times per year

☐ Please also incorporate the following general additions and corrections to the task description:
Click here to enter text.

Utilized Tools

Based on our records, we created a list of tools used while performing this task.
Please check all the tools that you are indeed using while performing the task described above and leave tools unchecked if you are not using them.
Please add tools that we have missed in the text field below the table.

☐ Ramp Meters
☐ Live Video Feeds
☐ Fire and Police Depts.
☐ Microwave Detection
☐ INREX Data
☐ Towing Service Providers
☐ Optical Flow Devices
☐ "511" calls
☐ GDOT Databases

Your Response

Additionally the following tools are used (please list all the tools that we have missed):
Click here to enter text.

Cost Estimation

Based upon our time estimates and some average cost and salary levels, we estimated the cost for a single execution of the above described task as follows:

Line Item		Amount	Rate	Sum
	Labor			
1	Engineer (42 h per week, 52 weeks per year, $ 74,000 per year)	1.5 h	$33.88 per hour	$ 50.82
	Equipment			
2	n/a		$ -	$ -
	Material			
3	n/a		$ -	$ -
	Other			
4	n/a		$ -	$ -
			Total	**$ 50.82**

Your Response

We realize that this per-task-per-incident cost is most likely not how you think about the value of the task you are performing as part of your work; however, this allows for a more detailed analysis of the collected data.

If you feel that this estimate is wrong, please correct it to the best of your knowledge by putting corrections in the text field below (if possible, please use the line item numbers as references):
Click here to enter text.

Appendix D: Validated Tasks

Task ID#: 1	**Division:** Traffic Operations	**Subjects Responded:** 1, 9, 10, and 16
Task Goal: GDOT is required to coordinate traffic safety, traffic engineering, and traffic management state wide. To facilitate this, ITS personnel are tasked to oversee the collection of traffic data for related monitoring, prediction, and assessment activities.		
Task Activities: The task includes the electronic collection of data, including, but not limited to, traffic flow, traffic speed, and traffic counts. The data are either directly obtained from GDOT maintained traffic devices or purchased from third party vendors and their collection systems. The data are processed and translated from the native format to a format suitable for the monitoring, prediction, and assessment activities utilizing the data.		
Environment Summary:	All year around, Indoor, Sitting, and Local	
Task Dimension (average):	80 yds.	
Task Distance (average):	- hrs.	
Task Duration (average):	3.3 hrs.	
Task Frequency (most):	daily	
Tools:	"511 Calls", Fire and Police Depts., GDOT Databases, Ramp Meters, Ball Bank Indicator, DMI, Radar Detection, Tube Counters, Microwave Detection, Optical Flow Devices, Live Video Feeds, INRIX Data, And Towing Service Providers.	
Average Cost:	$113	

<table>
<tr><td>Task ID#: 2</td><td>Division: Traffic Operations</td><td>Subjects Responded: 1, 9, 10, and 16</td></tr>
<tr><td colspan="3">Task Goal: Throughout the state various special events affect arterial roadways and other main roads. GDOT personnel is tasked to supervise special event traffic detours and road closures and to coordinate the work of the traffic operation division with other involved agencies.</td></tr>
<tr><td colspan="3">Task Activities: The task includes the processing of real-time traffic data in the context of special events (e.g. sport events, festivals, demonstrations) or weather effects (e.g. flooding, fallen trees) that adversely affect traffic in order to optimize traffic throughput. This involves, but is not limited to, optimizing detour routes, managing non-event traffic in the affected area, and coordinating with other agencies at the scene (e.g. fire and police departments, event management companies).</td></tr>
<tr><td>Environment Summary:</td><td colspan="2">All year around, Indoor, Sitting, and Local</td></tr>
<tr><td>Task Dimension (average):</td><td colspan="2">0.8 mile</td></tr>
<tr><td>Task Distance (average):</td><td colspan="2">- hrs.</td></tr>
<tr><td>Task Duration (average):</td><td colspan="2">2 hrs.</td></tr>
<tr><td>Task Frequency (most):</td><td colspan="2">Daily &
Weekly</td></tr>
<tr><td>Tools:</td><td colspan="2">Real-Time Traffic Data, Event Schedules, Historic Traffic Data, Communication equipment to on-site agencies</td></tr>
<tr><td>Average Cost:</td><td colspan="2">$288</td></tr>
</table>

Task ID#:	3	**Division:**	Traffic Operations	**Subjects Responded:**	1, 9, 10, and 16

Task Goal: GDOT personnel perform post-incident site inspections to investigate the incident circumstances and how the incident could have been affected through traffic management devices present at the scene. The discovered facts could be pertinent to claims filed by the involved parties, potentially including the assessment of fault and damages. If the installed devices are deemed insufficient to prevent a similar incident in the future, a follow up improvement investigation might be triggered.

Task Activities: The task includes a site inspection that involves a rough mapping of the site's layout and topography and an overview of the installed traffic management devices and their location(s) on site. Potentially damaged GDOT equipment is catalogued.

Environment Summary:	All year around, Outdoor, both Mobile and Sitting, and Local
Task Dimension (average):	0.28 mile (or 490 yds.)
Task Distance (average):	2 hrs.
Task Duration (average):	1 hr.
Task Frequency (most):	Weekly
Tools:	Incident Reports, Maps and Plans, Historic Traffic Data, Communications equipment to on-site agencies, "GEARS" (Traffic Data Software), GPS, Camera, Measuring Wheels, DMI, Ball Bank Indicator, Level
Average Cost:	$47

Task ID#: 6	**Division:** Traffic Operations	**Subjects Responded:** 1, 9, 10, and 16

Task Goal: GDOT District Personnel is tasked to oversee the installation and maintenance of traffic signal devices on State Routes in order to keep the system(s) functioning correctly. In this context, GDOT employees oversee and/or perform proactive maintenance and repair activities on traffic signal systems in their district.

Task Activities: The task involves the inspection of a traffic signal installation either as a response to a failure or malfunction report or in the context of a routine maintenance schedule. At the site of the traffic signal installation, the task requires confirming either the correct operation or the presence of a malfunction or physical damage. In the case of incorrect operation of the device, the appropriate response is triggered. Potential (interim) remedies could involve a system reset or shut down.

Environment Summary:	All year around, Outdoor, Mobile, and Local
Task Dimension (average):	100 yds.
Task Distance (average):	1 hr.
Task Duration (average):	1.3 hrs.
Task Frequency (most):	Hourly & Daily
Tools:	Personal high-visibility safety gear, Device Manual/Handbook, Malfunction Report, Pen and Paper, Basic Hand Tools, GDOT Vehicle, Computer
Average Cost:	$50

Task ID#:	43	**Division:**	Traffic Operations	**Subjects Responded:**	1, 9, 10, and 16

Task Goal: GDOT District Personnel is required to maintain an understanding of the overall traffic situation in their area in order to properly develop and update traffic plans. In this regard, GDOT personnel collect representative speed samples.
Task Activities: The task includes the identification of appropriate site locations for conducting speed sample measurements. Depending on the selected site, the sample is taken either with a RADAR gun, from a floating sample, or deduced from INRIX data. The collected data are processed and translated into the proper format for further traffic evaluation and modeling tasks.

Environment Summary:	All year around, Outdoor, Sitting, and Distributed
Task Dimension (average):	2.9 mile
Task Distance (average):	2 hrs.
Task Duration (average):	2 hrs.
Task Frequency (most):	Weekly & Monthly
Tools:	Radar Gun, Speedometer, GDOT Vehicle, Pen and Paper, Plans and Maps, Radar Gun, Speedometer, INRIX Data
Average Cost:	$80

Task ID#:	44	**Division:**	Traffic Operations	**Subjects Responded:**	1, 9, 10, and 16

Task Goal: GDOT District Personnel is required to maintain an understanding of the overall traffic situation in their area in order to properly develop and update traffic plans, in addition to evaluate the need for signalization and geometric modifications. In this regard, GDOT personnel conduct traffic counts.
Task Activities: The task includes the identification of appropriate site locations for conducting traffic counts. Depending on the selected site, the count is taken with either an automated or manual counting device or inferred from INRIX data. The collected data are processed and translated into the proper format for further traffic evaluation and modeling tasks.

Environment Summary:	All year around, Outdoor, both Mobile and Sitting, and Local
Task Dimension (average):	100 yds.
Task Distance (average):	2 hrs.
Task Duration (average):	2.5 hrs.
Task Frequency (most):	Weekly
Tools:	Plans and Maps, Tube Counter, Manual Counter, Video Based Counter, INRIX Data, Pen and Paper, GDOT Vehicle
Average Cost:	$94

<table>
<tr><td>Task ID#:</td><td>45</td><td>Division:</td><td>Traffic Operations</td><td>Subjects Responded:</td><td>1, 9, 10, and 16</td></tr>
<tr><td colspan="6">Task Goal: GDOT District Personnel is required to maintain an understanding of the overall traffic situation in their area in order to properly develop and update traffic plans. In this regard, GDOT personnel conduct turning movement counts.</td></tr>
<tr><td colspan="6">Task Activities: The task includes the identification of appropriate intersections for conducting turning movement counts. Depending on the selected site, the count is taken with either an automated or manual counting device or inferred from INRIX data. The collected data are processed and translated into the proper format for further traffic evaluation and modeling tasks.</td></tr>
<tr><td colspan="2">Environment Summary:</td><td colspan="4">All year around, Outdoor, both Mobile and Sitting, and Local</td></tr>
<tr><td colspan="2">Task Dimension (average):</td><td colspan="4">100 yds.</td></tr>
<tr><td colspan="2">Task Distance (average):</td><td colspan="4">2 hrs.</td></tr>
<tr><td colspan="2">Task Duration (average):</td><td colspan="4">3 hrs.</td></tr>
<tr><td colspan="2">Task Frequency (most):</td><td colspan="4">Weekly</td></tr>
<tr><td>Tools:</td><td colspan="5">Plans and Maps, Tube Counter, Video Based Counter, GDOT Vehicle, Turning Movement Counter</td></tr>
<tr><td colspan="2">Average Cost:</td><td colspan="4">$96</td></tr>
</table>

Task ID#:	46	**Division:**	Traffic Operations	**Subjects Responded:**	1, 9, 10, and 16

Task Goal: GDOT District Personnel is tasked to continuously improve the flow of traffic and respond to activities potentially impacting it. In this regard, GDOT personnel conduct on-site inspections to improve already installed systems or to study and assess the impact of proposed alterations of, for example, traffic devices or the right-of-way.

Task Activities: The task includes the initial familiarization with the inspection site as well as the collection of several traffic data types. Amongst the measurements taken could be traffic counts, speed samples, traffic flow, and sight distances. Furthermore, GDOT personnel could review safe speeds (depending on road conditions and ball bank measurements), the installation of signage, and existing of planned striping. The collected data are processed and translated to support a following evaluation and subsequent assessment of either the current situation or the proposed alteration.

Environment Summary:	All year around, Outdoor, both Mobile and Sitting, and Distributed
Task Dimension (average):	1.4 mile
Task Distance (average):	2 hrs.
Task Duration (average):	1.8 hrs.
Task Frequency (most):	Weekly
Tools:	Plans and Maps, Manual Traffic Counter, Radar Gun, Distance Meter, Measuring Wheel, Range Finder, Pen and Paper, GDOT Vehicle
Average Cost:	$60

Task ID#:	4	**Division:**	Construction	**Subjects Responded:**	2, 6, 8, 11, 12, 13 and 14

Task Goal: GDOT construction engineers are responsible to oversee, inspect, and monitor contractual field work. In this regard, they enforce standard specifications, coordinate testing of installed materials and take field measurements of pay items. Also, they deal with land owners, local and state stakeholders, both public and private.

Task Activities: The task includes performing several linear measurements, computing areas and volumes from linear measurements, and taking counts of items billed as "each". The data are collected on site and respective notes are taken, primarily on paper. After the collection of the raw measurements and counts, some post-processing is done to compute areas or volumes. After that, the data are transferred into the software "Site Manager" for further processing.

Environment Summary:	All year around, Outdoor, Mobile, and mostly Local
Task Dimension (average):	2.9 mile
Task Distance (average):	1.8 hrs.
Task Duration (average):	2.6 hrs.
Task Frequency (most):	Hourly
Tools:	Measuring Wheel, Tape Measure, Pen and Paper, "Site Manager", Plans and Drawings, Computer, "Word", "Excel", "Outlook", Calculator, Distance Meter, Mobile Internet in Vehicle, Traffic Marking Paint, Level and Grade Rod
Average Cost:	$66

Task ID#:	22	**Division:**	Construction	**Subjects Responded:**	2, 6, 8, 11, 12, 13 and 14
Task Goal: GDOT construction engineers are responsible to oversee, inspect, and monitor contractual field work. In this regard they take field measurements of pay items to ensure accountability for invoicing and quality control.					
Task Activities: The task includes measuring spread rates and Air/Slump/Depth of concrete and asphalt while inspecting a construction job site. Furthermore, “tickets” are collected to document the utilized amount of concrete and/or asphalt. After the data are collected in the field, they are transferred into the software “Site Manager” for further processing.					
Environment Summary:	Spring to Fall, Outdoor, Mobile, and mostly Local				
Task Dimension (average):	1.9 mile				
Task Distance (average):	1.8 hrs.				
Task Duration (average):	3.5 hrs.				
Task Frequency (most):	Daily				
Tools:	Measuring Tape, Pen and Paper, Slump Cone, "Site Manager", Measuring Wheel, Air Meter, Calculator, Scoops, Wheel Barrow, Shovels, Cylinders, Thermometer, Air Bucket, Traffic Marking Paint, Air Entrained Measuring Device for Concrete				
Average Cost:	$85				

Task ID#:	24	**Division:**	Construction	**Subjects Responded:**	2, 6, 8, 11, 12, 13 and 14

Task Goal: GDOT construction engineers record data collected by Lab Technicians using soil compaction measuring devices or use soil compaction measuring devices to check and measure soil compaction to ensure appropriate conditions according to the requirement of the ongoing construction.

Task Activities: The task includes performing a soil compaction measurement at a location outlined in correspondence with the governing plans and drawings, recording of the measured data, as well as the related post-processing steps necessary to document the measurement, e.g. via the software "Site Manager".

Environment Summary:	Spring to Fall, Outdoor, Mobile, and mostly Local
Task Dimension (average):	0.5 mile (or 900 yds.)
Task Distance (average):	1.8 hrs.
Task Duration (average):	1 hr.
Task Frequency (most):	Daily
Tools:	Pen and Paper, Nuclear Density Gauge, Plans and Drawings, Sampling Tools (shovel, etc.), "Site Manager" (Software), Plans and Drawings, Weight Scales, Torches, Calculators, Hammers
Average Cost:	$26

Task ID#:	25	**Division:**	Construction	**Subjects Responded:**	2, 6, 8, 11, 12, 13 and 14
Task Goal: GDOT construction engineers are responsible to oversee, inspect, and monitor contractual field work. In this regard, they take field measurements of pay items such as concrete to ensure correct invoicing.					
Task Activities: The task includes measuring the material poured for construction in cubic yards (or cubic feet) to document the utilized amount of concrete and/or asphalt as well as checking the amount of the related earthwork. This is done either directly via the collection of "tickets" from the dispensing device or indirectly via the computation of volumes, based on manual linear measurements. After the data are collected in the field, they are transferred into the software "Site Manager" for further processing.					
Environment Summary:	Spring to Fall, Outdoor, Mobile, and mostly Local				
Task Dimension (average):	1.9 mile				
Task Distance (average):	1.8 hrs.				
Task Duration (average):	1.5 hrs.				
Task Frequency (most):	Hourly				
Tools:	Measurement Tape, Pen and Paper, "Tickets" (Concrete or Asphalt), "Site Manager" (Software), Calculator, Plans and Drawings, Thermometer, Measurement Wheel, Slum Cones, Air Meters, Scoops, Traffic Marking Paint, Distance Meter. Air Entrained Device for Concrete				
Average Cost:	$46				

<table>
<tr><td>Task ID#:</td><td>9</td><td>Division:</td><td>Intermodal</td><td>Subjects Responded:</td><td>9</td></tr>
<tr><td colspan="6">Task Goal: GDOT’s Intermodal Division is tasked to inspect general aviation airports in GA biennially for compliance with state and federal law as well as to record relevant data for dissemination amongst the general aviation community. If a noncompliance is detected, appropriate remedy measures are to be triggered.</td></tr>
<tr><td colspan="6">Task Activities: The task mainly involves the collection of obstacle related data. The approach and departure corridors are checked to be clear of obstacles; if obstacles are detected, their location is recorded and, if possible, their removal triggered. Furthermore, data is collected with respect to the overall geometry of the runway(s), the state of the runway(s), potential obstacles on or in the direct vicinity of the airport, and wildlife activity which could interfere with general aviation procedures.</td></tr>
<tr><td colspan="2">Environment Summary:</td><td colspan="4">Spring to Fall, Outdoor, Mobile, and Local</td></tr>
<tr><td colspan="2">Task Dimension (average):</td><td colspan="4">3 mile</td></tr>
<tr><td colspan="2">Task Distance (average):</td><td colspan="4">4 hrs.</td></tr>
<tr><td colspan="2">Task Duration (average):</td><td colspan="4">3.5 hrs.</td></tr>
<tr><td colspan="2">Task Frequency (most):</td><td colspan="4">Weekly</td></tr>
<tr><td colspan="2">Tools:</td><td colspan="4">Measuring Wheel, Range Finder, Pen and Paper, Clinometer, Compass, Camera</td></tr>
<tr><td colspan="2">Average Cost:</td><td colspan="4">$227</td></tr>
</table>

Task ID#:	47	**Division:**	Intermodal	**Subjects Responded:**	21

Task Goal:	GDOT intermodal engineers are responsible to oversee, inspect, and monitor contractual field work in the context or rail operations. In this regard, they take field measurements of pay items.
Task Activities:	The task mainly involves the collection of obstacle related data. The approach and departure corridors are checked to be clear of obstacles; if obstacles are detected, their location is recorded and, if possible, their removal triggered. Furthermore, data is collected with respect to the overall geometry of the runway(s), the state of the runway(s), potential obstacles on or in the direct vicinity of the airport, and wildlife activity which could interfere with general aviation procedures.
Environment Summary:	All year around, Outdoor, Mobile, and Distributed
Task Dimension (average):	5 mile
Task Distance (average):	2 hrs.
Task Duration (average):	2.5 hrs.
Task Frequency (most):	Weekly
Tools:	Form 5010, Paper and Pencil, Range Finder, Compass, Measuring Wheel, Camera, Aviation Radio, Yellow Signal Lights, Placement Flags, Airport/Facility Directory, Inspection questionnaire and checklist, Inclinometer
Average Cost:	$165

Task ID#:	48	**Division:**	Bridge Inspection	**Subjects Responded:**	23a

Task Goal: GDOT employees are tasked to conduct regularly scheduled routine inspections of conventional bridges in Georgia. The goal of this task is to determine the physical and functional condition of a bridge and to identify changes compared to previous inspections. Furthermore, these routine inspections are to ensure that a bridge continues to satisfy all applicable serviceability requirements.	
Task Activities: These inspections associated are mainly visual inspections. The task is performed either from the deck or ground level or from permanent-access structures, potentially in the presence of regular traffic over and under the structure. Personal safety gear is worn.	
Environment Summary:	All year around, Outdoor, Mobile, and Distributed
Task Dimension (average):	1 mile
Task Distance (average):	2 hrs.
Task Duration (average):	45 min.
Task Frequency (most):	Daily
Tools:	Maps and Plans, Flashlight, Sounding Hammer, Measurement Tape, Plumb Bob, Ladder, Safety Harness, Knife, chest waders, hip waders, Laser distance meter, range rod, 25’ telescoping survey rod, 100’ fiberglass tape weighted, wire brush, calipers, digital level, angle finder, binoculars, digital camera, GPS, cordless drill, timber probe, machete, thermometer, pole camera, bush axe, bore scope, and thermal imagining camera.
Average Cost:	$50

Task ID#:	49	**Division:**	Bridge Inspection	**Subjects Responded:**	23a

Task Goal: GDOT employees are tasked to conduct in-depth inspections of bridges in Georgia. The goal of this task is to identify deficiencies not normally detectable during regular routine inspections.	
Task Activities: The inspections associated with an in-depth inspection normally involve the use of non-destructive examination techniques beyond a visual inspection. The task is performed either from the deck or ground level or from permanent-access structures, potentially in the presence of regular traffic over and under the structure. Personal safety gear is worn.	
Environment Summary:	All year around, Outdoor, Mobile, and Distributed
Task Dimension (average):	1 mile
Task Distance (average):	2 hrs.
Task Duration (average):	2.5 hrs.
Task Frequency (most):	Weekly
Tools:	Maps and Plans, Flashlight, Sounding Hammer, Measurement Tape, Plumb Bob, Ladder, Safety Harness, Dye Penetrant Testing Device, Knife, chest waders, hip waders, safety glasses, gloves, Laser distance meter, range rod, 25’ telescoping survey rod, 100’ fiberglass tape weighted, wire brush, calipers, digital level, angle finder, binoculars, digital camera, GPS, cordless drill, timber probe, machete, thermometer, boat (paddles and PFD’s), pole camera, bush axe, bore scope, and thermal imagining camera.
Average Cost:	$103

Task ID#:	50	**Division:**	Bridge Inspection	**Subjects Responded:**	23a

Task Goal: GDOT employees are tasked to conduct special or damage inspections of conventional bridges in Georgia. The goal of this task is to identify the physical and functional condition of a structure, including deficiencies not normally detectable during regular routine inspections, especially after potentially negative environmental of man-made events in order to assess structural damage and the need for further follow-up actions. (1: As opposed to complex bridges, e.g. major river bridges, movable, suspension, cable stayed, or other bridges with unusual characteristics.)

Task Activities: The scope of each special inspection is unique and depends on the structure and the event triggering the special inspection, but could involve the use of special access equipment.

Environment Summary:	All year around, Outdoor, Mobile, and Distributed
Task Dimension (average):	1 mile
Task Distance (average):	2 hrs.
Task Duration (average):	2.5 hrs.
Task Frequency (most):	Weekly
Tools:	Maps and Plans, Flashlight, Sounding Hammer, Measurement Wheel, Plumb Bob, Ladder, Safety Harness, Rebar Locator, Dye Penetrant Testing Device, Access Enabling Equipment (Under Bridge Inspection Snoopers, Sectional Barge, Man Lifts, Bridge Rigging), Knife, chest waders, hip waders, Laser distance meter, range rod, 25’ telescoping survey rod, 100’ fiberglass tape weighted, wire brush, calipers, digital level, angle finder, binoculars, digital camera, GPS, cordless drill, timber probe, machete, thermometer, boat (paddles and PFD’s), pole camera, bush axe, bore scope, and thermal imagining camera.
Average Cost:	$1140

Task ID#:	51	**Division:**	Bridge Inspection	**Subjects Responded:**	23a

Task Goal: GDOT employees are tasked to conduct special or damage inspections of complex bridges in Georgia. The goal of this task is to identify the physical and functional condition of a structure, including deficiencies not normally detectable during regular routine inspections, especially after potentially negative environmental of man-made events in order to assess structural damage and the need for further follow-up actions (e.g. major river bridges, movable, suspension, cable stayed, or other bridges with unusual characteristics.)
Task Activities: The scope of each special inspection is unique and depends on the structure and the event triggering the special inspection, but could involve the use of special access equipment.

Environment Summary:	All year around, Outdoor, Mobile, and Distributed
Task Dimension (average):	1 mile
Task Distance (average):	2 hrs.
Task Duration (average):	3.5 hrs.
Task Frequency (most):	Weekly
Tools:	Maps and Plans, Flashlight, Sounding Hammer, Measurement Tape, Measurement Wheel, Plumb Bob, Ladder, Safety Harness, GDOT Vehicle, Rebar Locator, Access Enabling Equipment (Under Bridge Inspection Snoopers, Sectional Barge, Man Lifts, Bridge Rigging), Knife, chest waders, hip waders, safety glasses, gloves, Laser distance meter, range rod, 25’ telescoping survey rod, 100’ fiberglass tape weighted, wire brush, calipers, digital level, angle finder, binoculars, digital camera, GPS, cordless drill, timber probe, machete, thermometer, boat (paddles and PFD’s), pole camera, bush axe, bore scope, and thermal imagining camera.
Average Cost:	$1164

Task ID#:	52	**Division:**	Bridge Inspection	**Subjects Responded:**	23a

Task Goal: GDOT employees are tasked to conduct inspections of underwater elements and structures of bridges in Georgia. The goal of this task is to routinely identify the physical and functional condition of the elements, identify changes compared to previous inspections, and to detect deficiencies not normally detectable during routine or in-depth above water inspections.

Task Activities: The task includes getting divers to the underwater elements, potentially briefing the divers with special requests, conducting the inspection, and evaluating the data returned from by the divers. The task is performed mainly being swimming/diving; with non-related water traffic is presumably being suspended. Personal safety gear is worn.

Environment Summary:	All year around, Outdoor, Mobile, and Local
Task Dimension (average):	100 yds.
Task Distance (average):	2 hrs.
Task Duration (average):	4.5 hrs.
Task Frequency (most):	Monthly
Tools:	Maps and Plans, Flashlight, Camera, Measurement Tape, Diving Equipment, Life Jackets, Safety Harness, GDOT Vehicle, Barge or Boat, Pen and Paper, While not used on every inspection, in addition to the items checked above, we also use: Imaging Sonar, Underwater video camera, knife, machete, range rod, bush axe, 25’ telescoping survey rod, calipers, thermometer, sounding hammer, oyster scrapers, depth finder, and 100’ weighted tape.
Average Cost:	$405

Appendix E: Exemplary Process Descriptions for UAS-aided Tasks

The iterative process used to categorize the identified GDOT tasks (see Chapter IV) included creating process descriptions of the identified tasks which would utilize one of the proposed reference systems. As these assumed process descriptions provide theoreticized examples of using one of the proposed UAS, they are reproduced here to describe possible GDOT usage scenarios.

Three identified tasks are unlikely to be aided through UAS and hence have no related process description: asphalt and concrete inspections, soil compaction measurements, and underwater bridge inspections. The first two tasks involve equipment that is likely to be unmovable by UAV sized for the task environment and the third application would require an unmanned underwater vehicle (UUV).

Construction Site Measurements

GDOT Division: Construction Proposed UAS: Flying Camera (A)

- physically relocate to centroid of current activity area
- deploy system
- for small linear measurement: position system so that extends are in view, select linear measurement mode, click start and end in Utility Cam screen, read length estimate
- for large linear measurement: position system at start of stretch to be measured, engage measurement mode, fly to next corner, click on Utility Cam screen, read length estimate
- for small area measurement: position system so that extends are in view, select area measurement mode, click corners in Utility Cam screen, read area estimate
- for large area measurement: position system so that the first corner is in view, select on Utility Cam, fly to next corner(s), select, read area estimate
- for volume measurement: position system so that extends are in view, select volume measurement mode, click corners of boundary in Utility Cam screen, start automatic measurement flight, read volume estimate
- for counting operations: fly system to items to be counted, aim FPV or Utility Cam screen at item, click to count and mark, read running total
- upload to Site Manager

Traffic Signal Installation Inspection

GDOT Division: Traffic Operations Proposed UAS: Perching Camera (C)

- determine closest UAV to traffic signal site and deploy it
- fly to traffic signal site (FPV or waypoints)
- use Utility Cam to determine if signal is functional correctly/incorrectly
- if signal is malfunctioning and rigged accordingly, trigger traffic signal reset

Note: System C is not equipped for "manipulating" elements other than through "bumping into" them.

Traffic Signal Installation Inspection

GDOT Division: Traffic Operations Proposed UAS: MALE (D)

- determine closest airborne UAV to traffic signal site and activate it
- fly to traffic signal site (waypoints)
- orient sensor package to lock on to the signal installation and loiter
- use E/O video sensor to determine if signal is functional correctly/incorrectly
- use "click to locate" to get georeferenced coordinates to identify locations for potentially necessary follow ups.

Note: System D would be flying high above the installation. See Post-Incident Inspection for a related application.

On-Site Traffic Inspection

GDOT Division: Traffic Operations Proposed UAS: Flying Camera (A)

- physically relocate to the traffic inspection site
- deploy system
- use FPV to do an initial "visual inspection": explore the site and detect and localize traffic related items such as signs, signals, and striping through interaction with the relayed video feed.
- use the system to measure site dimensions (see Construction Site Measurements for details.)

Note: System A would most likely not have the capability to perform vision based traffic data collection.

On-Site Traffic Inspection

GDOT Division: Traffic Operations Proposed UAS: Perching Camera (C)

- determine closest UAV to traffic signal site and deploy it
- fly to traffic inspection site (FPV or waypoints)
- use FPV to do an initial "visual inspection": explore the site and detect and localize traffic related items such as signs, signals, and striping through interaction with the relayed video feed.
- use the system to measure site dimensions (see Construction Site Measurements for details.)
- determine a suitable perching position, land the system and conduct vision based traffic data collection (see Traffic Data Collection, Traffic Count Measurement, Traffic Movement Measurement for details.)
- engage Return-to-Base after data were collected

Airport Inspection

GDOT Division: Intermodal Proposed UAS: Flying Total Station (B)

- preload airport plans and map into the system
- physically relocate to the airport
- deploy the system
- use high precision navigation to fly to the runway ends
- use calibrated video to determine approach/departure corridor clearance
- use "click to localize" feature to mark intruding obstructions

Note: The physical extends of an airport most likely render tethered operations infeasible (also, cut tethers could lead to FOD). In the future, LiDAR based SLAM could be used the check taxi- and runway clearances to buildings (see Rail Site Inspection)

Bulk Material Measurement

GDOT Division: Construction Proposed UAS: Flying Camera (A)

- physically relocate to centroid of current activity area
- deploy system
- use area measuring techniques (see Construction Site Measurement) to compute the area material is poured over
- manually measure (average) thickness of layer
- compute volume from thickness and area
- report to Site Manager

Bulk Material Measurement

GDOT Division: Construction Proposed UAS: Perching Camera (C)

- physically relocate to site
- deploy system at the pouring machine
- track volume by "scanning" tickets with the Utility Cam
- report to Site Manager

Bulk Material Measurement

GDOT Division: Construction Proposed UAS: Flying Total Station (B)

- physically relocate to site
- deploy system
- generate a precise terrain map before the bulk material activity
- (idle/wait till the activity is finished)
- generate a precise terrain map after the bulk material activity
- compute volume as the delta between the two

Note: this application could potentially be conducted while tethered.

Rail Site Inspection

GDOT Division: Intermodal Proposed UAS: Flying Total Station (B)

- preload rail section plans and map into the system
- physically relocate to the rail section
- deploy the system
- use high precision navigation to fly over the rail track
- use calibrated video and/or (downward looking) 2D LiDAR to measure rail track alignment
- use calibrated video and/or (forward looking) 3D LiDAR to measure clearance above and around the track
- auto-detect misalignments and obstructions, georefenrence the locations
- use "click to localize" feature to manually mark points of interest

Note: The physical extends of a rail track render tethered operations most likely infeasible. However, potentially the system could be used in combination with a road-rail vehicle trailing behind.

Traffic Data Collection

GDOT Division: Traffic Operations Proposed UAS: Perching Camera (C)

Note: This is a combination of Speed Sample Measurement, Traffic Count Measurement, and Turning Movement Measurement.

Speed Sample Measurement

GDOT Division: Traffic Operations Proposed UAS: Perching Camera (C)

Optical Flow Process:

- relocate to the measurement site
- deploy system
- determine a suitable location for perching
- aim Utility Cam to sampling sector
- identify lanes and direction of travel via the GUI
- specify sampling time and start autonomous (vision based) speed measurements

Floating Sample Process:

- relocate to the measurement site
- deploy system
- determine suitable perching location
- determine the road to sample, direction of travel, and start and end points of the measurements
- aim Utility Cam at starting zone

- upon detection of a (single) vehicle entering the starting zone, the system autonomously follows the vehicle at a safe altitude until the end point and averages the measured speed
- the system returns to its perching location and waits for the next vehicle

Extended (Relay) Tracking Process:

- determine the tracking corridor (route, start and end points)
- determine participating (already perching) systems
- upon entry of a (easily distinguishable) vehicle into the corridor, the first participating system starts to track the vehicle and "hands it off" to the next system at the next perching location
- recorded data is joined and evaluated

Speed Sample Measurement

GDOT Division: Traffic Operations Proposed UAS: MALE (D)

Extended Tracking Process:

- determine operational boundary, loiter area, stay-out zones, un-/safe altitudes, emergency procedures (lost link, collision avoidance, etc.)
- determine the tracking corridor (route, start and end points)
- deploy a system
- upon entry of a (easily distinguishable) vehicle/blob into the corridor the blob is visually tracked

Traffic Count Measurement

GDOT Division: Traffic Operations Proposed UAS: Perching Camera (C)

- determine closest system to measurement site and deploy it
- fly to traffic inspection site (FPV or waypoints)
- determine suitable perching location
- point Utility Cam at measuring site
- determine and identify measurement zones
- conduct count
- autonomous Return-to-Base

Turning Movement Measurement

GDOT Division: Traffic Operations Proposed UAS: Perching Camera

- determine closest system to intersection and deploy it
- fly to traffic inspection site (FPV or waypoints)

- determine suitable perching location
- point Utility Cam at measuring site
- determine and identify lines and measurement zones (entry zone and potential exit zones)
- conduct count
- autonomous Return-to-Base

Special Event Supervision

GDOT Division: Traffic Operations Proposed UAS: MALE (D)

- determine operational boundary, loiter area, stay-out zones, un-/safe altitudes, emergency procedures (lost link, collision avoidance, etc.)
- determine the area of interest (boundaries, start and end points of entry/exit routes to supervise)
- deploy a system
- upon reaching the area of interest the system starts to compute flow data for the determined routes
- operators can utilize the sensor suite for real time observation

Post-Incident Inspection

GDOT Division: Traffic Operations Proposed UAS: MALE (D)

- determine closest airborne UAV to incident site and activate it
- fly to incident site (waypoints)
- orient sensor package to lock on the incident location and loiter
- use E/O video sensor to determine site status
- use "click to locate" to get georeferenced coordinates to identify locations for potentially necessary follow ups.

Note: System D would be flying high above the installation. See Traffic Signal Installation Inspection for a related application.

Conventional Bridge Inspection

GDOT Division: Bridge Inspection Proposed UAS: Complex Manipulation (E)

- physically relocate to the bridge
- deploy system
- use FPV to maneuver system to inspection points

Detailed Bridge Inspection

GDOT Division: Bridge Inspection Proposed UAS: Complex Manipulation (E)

- physically relocate to the bridge
- deploy system

- use FPV to maneuver system to inspection points
- scan structure for latching hard-points
- use Manipulator to latch and prepare inspection point
- use Sensor Suite to inspect and record findings

Special Bridge Inspection

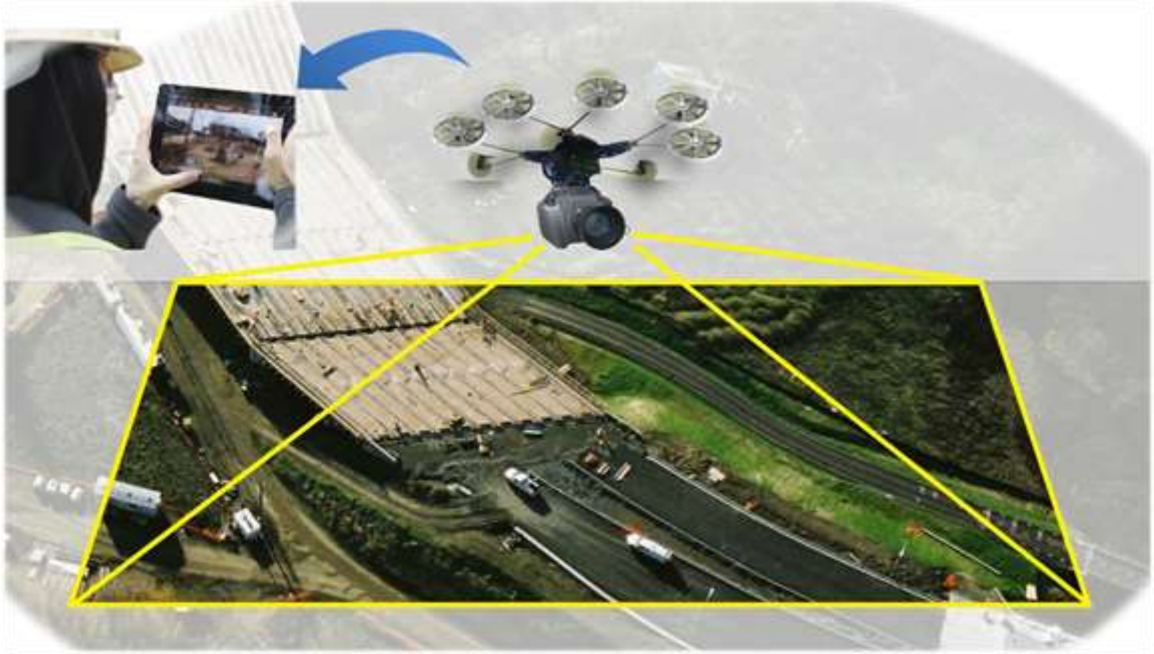
GDOT Division: Bridge Inspection Proposed UAS: Complex Manipulation (E)

- physically relocate to the bridge
- deploy system
- use FPV to maneuver system to inspection points
- scan structure for latching hard-points
- use Manipulator to latch and prepare inspection point
- use Sensor Suite to inspect and record findings

Special Bridge Inspection (Complex)

GDOT Division: Bridge Inspection Proposed UAS: Complex Manipulation (E)

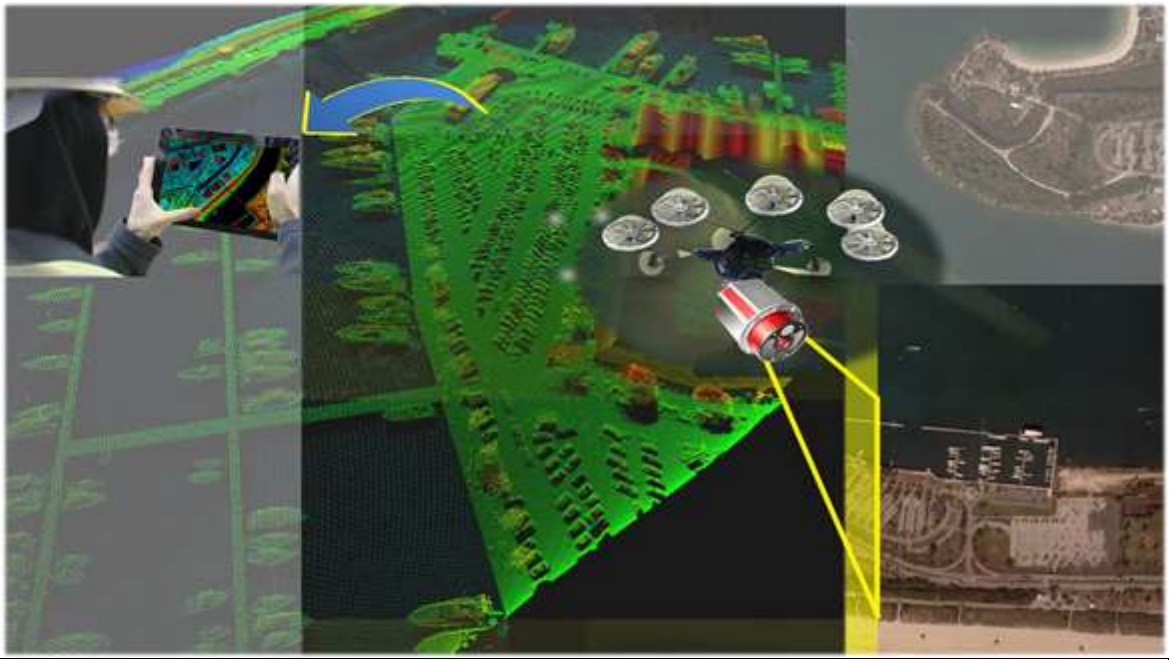
- physically relocate to the bridge
- deploy system
- use FPV to maneuver system to inspection points
- scan structure for latching hard-points
- use Manipulator to latch and prepare inspection point
- use Sensor Suite to inspect and record findings



UAS Specifications			
Airframe	Payload	Control Station	System Capabilities
Rugged, Available	Actuated Video Camera	Portable, Interactive, Rugged	Waypoint Navigation, Vision Based Data Extraction

Usage Scenarios
Construction Division (construction site measurement): The operator would simply start the system, hover the UAV over the construction site while capturing video. The captured video is transmitted back to the control station. Finally, the captured video and/or image is utilized and processed to extract the quantities (e.g. linear, volume) of construction items.
Engineering Division (conventional bridge inspection): The operator would simply start the system, hover the UAV over/under the selected scene while capturing video. The real time video is transmitted back to the control station. Finally, the captured video and/or image is utilized to provide visual overview of the bridge.
Intermodal Division (airport inspection): The operator would simply start the system, hover the UAV over the airport while capturing video. The captured video is transmitted back to the control station. Finally, the captured video and/or image is utilized to extract the geometry of the airport.
Permits and Operations Division (supervise special events): The operator would simply start the system, hover the UAV over the special event's traffic while capturing video. The real time video is transmitted back to the control station. Finally, the captured video and/or image is utilized and processed to extract traffic data (e.g. flow, speed, counts) of roads or junctions.

UAV System B **Flying Total Station**



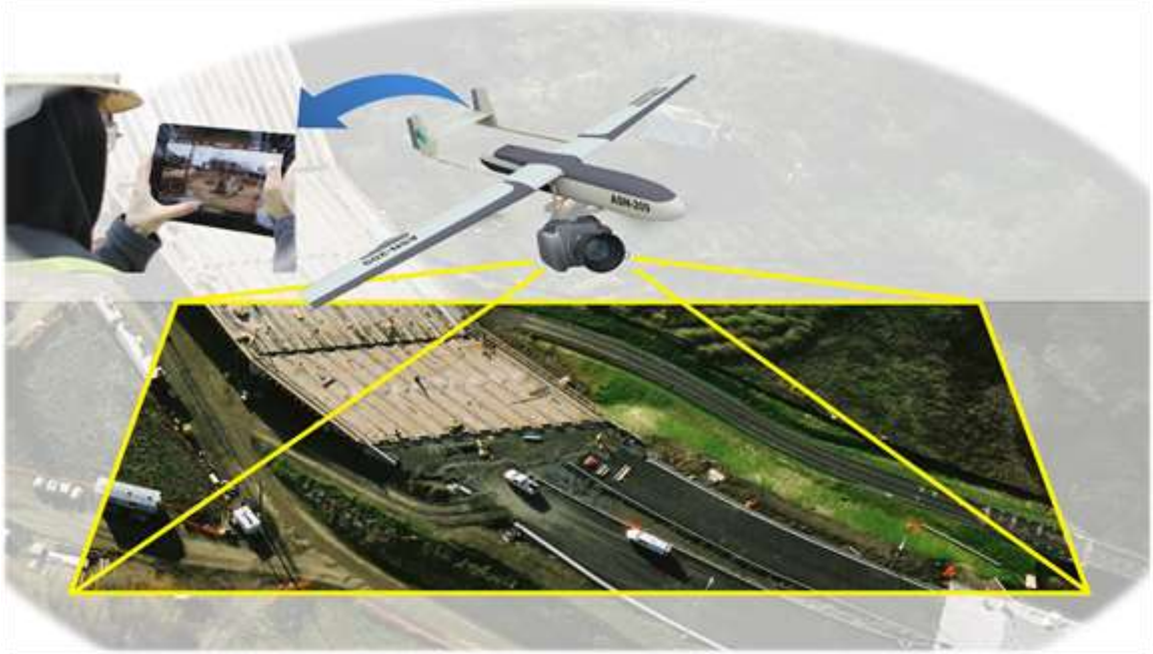
UAS Specifications			
Airframe	Payload	Control Station	System Capabilities
Probably available	Actuated Sensor Suite	Portable, Interactive	Sense and Avoid, Waypoint Navigation, Tethering, High-precision Navigation, SLAM, Data Abstraction, Vision Based Data Extraction

Usage Scenarios
Construction Division (bulk material measurement): The operator would simply start the system, hover the UAV over the construction site while sending laser beams. The returned laser pulse is transmitted back to the control station. Finally, the digital terrain map is utilized and processed to extract the quantities (e.g. linear, volume) of bulk construction items.
Engineering Division (aerial surveying): The operator would simply start the system, hover the UAV over the selected scene while sending laser beams. The returned laser pulse is transmitted back to the control station. Finally, the digital terrain map is utilized for surveying, highway design, corridor development, critical infrastructure protection, and highway safety.
Intermodal Division (airport inspection): The operator would simply start the system, hover the UAV over the airport while sending laser beams. The returned laser pulse is transmitted back to the control station. Finally, the digital surface map is utilized to extract the geometry of the airport and location of obstructions.
Permits and Operations Division (post-incident site inspections): The operator would simply start the system, hover the UAV over the incident site while sending laser beams. The returned laser pulse is transmitted back to the control station. Finally, the digital surface map is utilized and processed to mapping of the site's layout and topography and the location of the installed traffic management devices.

UAS Specifications			
Airframe	Payload	Control Station	System Capabilities
Rugged, probably available	Actuated Video and Sensor Suite, Telepresence System	Interactive, Rugged, Portable	Sense and Avoid, Kinematic Constraint, Unattended deployment and return, SLAM, Advanced Networking, Vision Based Data Extraction

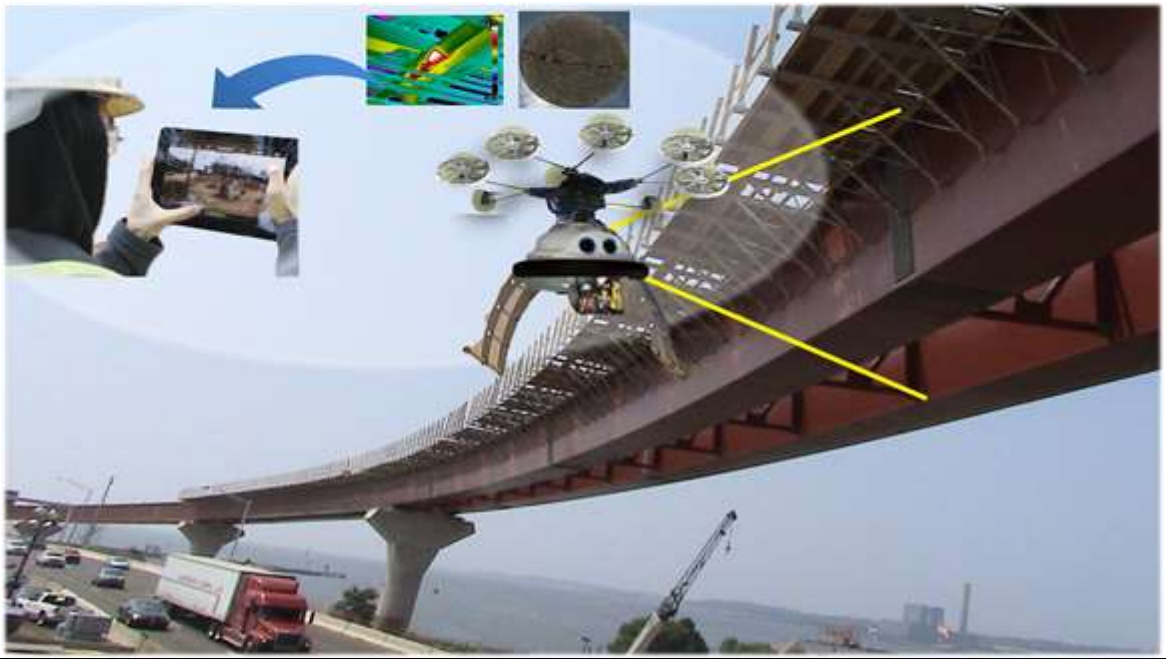
Usage Scenarios
Construction Division (bulk material measurement): The operator determines the closest UAV to the site, deploys and hovers the UAV over the construction site capturing video. The UAV tracks the volume by scanning the material tickets with the Utility Cam. Finally, the captured video and data is utilized and processed to extract the quantities (e.g. linear, volume) of bulk construction items.
Engineering Division (conventional bridge inspection): The operator determines the closest UAV to the site. Then he/she simply start the system, hover the UAV over/under the selected scene while capturing video. The real time video is transmitted back to the control station. Finally, the captured video and/or image is utilized to provide visual overview of the bridge.
Intermodal Division (airport inspection): The operator determines the closest UAV to the site. Then he/she would start the system, hover the UAV over the airport while capturing video. The captured video is transmitted back to the control station. Finally, the captured video and/or image is utilized to extract the geometry of the airport.
Permits and Operations Division (traffic signal installation inspection): The operator determines the closest UAV to the site and deploys it. UAV uses the Utility Cam to determine if signal is functional correctly or not. If signal is malfunctioning and rigged accordingly, trigger traffic signal reset.

UAV System D **MALE**



UAS Specifications			
Airframe	Payload	Control Station	System Capabilities
Available, Endurance	Actuated Video and Sensor Suite	Interactive	Sense and Avoid, Waypoint Navigation, Unattended deployment and return, Advanced Networking, Data Abstraction, Vision Based Data Extraction

Usage Scenarios
Permits and Operations Division (speed sample measurement): The operator would determine operational boundary, loiter area, stay-out zones, un-/safe altitudes, and the tracking corridor (route, start and end points). Then starts the system, hover the UAV over the location. Upon entry of a (easily distinguishable) vehicle into the corridor, the vehicle is visually tracked. The real time video is transmitted back to the control station. Finally, the captured video and/or image is utilized and processed to extract traffic data (e.g. flow, speed, counts) of roads or junctions.



UAS Specifications			
Airframe	Payload	Control Station	System Capabilities
Rugged	Actuated Video and Sensor Suite, Manipulator	Interactive, Mobile	Sense and Avoid, Waypoint Navigation, Kinematic Constraints, High-precision Navigation, SLAM, Data Abstraction, Vision Based Data Extraction

Usage Scenarios
Engineering Division (bridge inspection): The operator would physically relocate the UAV to the bridge and deploy the system. Then, he/she uses FPV to maneuver system to inspection points and uses Sensor Suite to inspect and record findings. For special bridge inspection, the process continues with scanning the structure for latching hard-points. The operator would use Manipulator to latch and prepare inspection point and use Sensor Suite to inspect and record findings.

Appendix F: Complete House of Quality Viewgraph

Operator Requirements	Occurance-based Weights		Vehicle: Airframe: Airframe Ruggedness	Vehicle: Airframe: Airframe Availability	Vehicle: Airframe: Endurance	Vehicle: Payload Capabilities: Actuated Video Camera	Vehicle: Payload Capabilities: Actuated Non-Video Sensor Package	Vehicle: Payload Capabilities: Telepresence	Vehicle: Payload Capabilities: Manipulator and/or Effector	Control Station: GUI: Interactive Object Selection and Identification	Control Station: Hardware: Ruggedness	Control Station: Hardware: Portability	System: Sense and Avoid	System: Waypoint Navigation	System: Kinematically constrained operations	System: Unattended deployment and return	System: High-precision navigation	System: Simultaneous Location and Mapping (SLAM)	System: Advanced Datalink and Networking	System: Sensor Data Abstraction and Reduction	System: Vision Based Data Extraction	Reference Systems: Flying Camera	Reference Systems: Flying Total Station	Reference Systems: Perching Camera	Reference Systems: MALE	Reference Systems: Complex Manipulation
FPV Operation	8	13%				●							○									✓	🟢	✓	⊗	✓
Non-FPV Operation	1	2%											●	●		●			◐			✗	⊗	✓	✓	✗
Pilot-independet sensor package control	3	5%				●	●															✗	✗	🟢	✓	✓
Use on construction site	4	6%	●	◐	○						●	●										✓	✓	🟢	✗	🟢
Use at traffic signal site	3	5%	◐	○							◐	◐	◐									🟢	⊗	✓	✗	🟢
Metro-area range/coverage	5	8%			●														●			✗	✗	🟢	✓	✗
Get point coordinates	1	2%				◐				●											●	✓	✓	✓	✓	✓
Measure site dimensions	3	5%				◐				●											●	✓	✓	✓	✓	✓
Estimate volumes	1	2%				◐				●										◐	●	✓	✓	⊗	✗	✗
Create digital elevation model	2	3%					●											●		◐	◐	✗	✓	✗	🟢	✗
Count/track/detect items	4	6%				◐				●												✓	⊗	🟢	✓	✗
Precise navigation	4	6%					◐							◐			●	◐				✗	✓	✗	✗	🟢
Provides survey-quality data	1	2%															●	●				✗	✓	✗	🟢	✗
Correleate sensor data to plans/drawings	4	6%															●	●			●	⊗	✓	🟢	🟢	✓
"Line-of-sight" clearance measurements	1	2%															○				●	🟢	✓	🟢	✓	🟢
Collect floating traffic samples	4	6%	◐		○								●	●		◐			◐		●	✗	✗	✓	🟢	✗
Allows to trigger a "reset"	1	2%	◐						○													⊗	✗	✓	✗	🟢
Interact with inspected element	4	6%	◐						●						●							✗	✗	🟢	✗	✓
Establish contact to people	3	5%	◐		○			●	○				◐									🟢	✗	✓	✗	✗
Eliminate need for human task execution	1	2%							●													🟢	🟢	🟢	🟢	✓
Conduct traffic counts	4	6%	○		○	●	◐			●					●						●	🟢	✗	✓	✓	✗
Data on demand	2	3%																	◐			✗	✗	🟢	✓	✗
Technical Priority			1.078	0.234	0.625	1.594	0.766	0.234	0.453	1.016	0.453	0.453	0.797	0.578	0.625	0.266	0.719	0.734	0.719	0.141	1.5					
(rel. Technical Priority)			8%	2%	5%	12%	6%	2%	3%	8%	3%	3%	6%	4%	5%	2%	6%	6%	6%	1%	12%					
Reference Systems: Flying Camera			✓	✓	⊗	🟢	✗	✗	✗	✓	✓	✓	✗	🟢	✗	✗	✗	✗	✗	✗	✓					
Reference Systems: Flying Total Station			⊗	🟢	🟢	⊗	🟢	✗	✗	✓	🟢	🟢	🟢	✓	🟢	⊗	✓	✓	✗	✓	✓					
Reference Systems: Perching Camera			✓	🟢	⊗	✓	✓	🟢	✗	✓	🟢	✓	🟢	✓	🟢	✓	⊗	🟢	✓	⊗	✓					
Reference Systems: MALE			✗	✓	✓	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗	🟢	✓	✓					
Reference Systems: Complex Manipulation			🟢	✗	🟢	✓	✓	✗	✓	✓	⊗	⊗	✓	🟢	✓	✗	🟢	✓	✗	🟢	✓					

Appendix G: Reference System Technical Requirement Correlations

Vehicle Intra-relations

Airframe Ruggedness | Actuated Video Camera: negative
Actuated parts imply more moving parts which implies more potential for failure.

Airframe Ruggedness | Actuated Non-Video Sensor Package: negative
Actuated parts imply more moving parts which implies more potential for failure.

Airframe Ruggedness | Manipulator and/or Effector: strong negative
Manipulators and effectors most likely are mechanically dexterous, which implies joints and motors or servos which could break.

Airframe Availability | Manipulator and/or Effector: strong negative
Manipulators and effectors could come from telerobotics or telemedicine applications. Such devices would most likely have to be redesigned for reduced weight and as such are not commercially available off-the-shelf products.

Endurance | Actuated Video Camera: negative
Everything that consumes power has a negative effect on endurance.

Endurance | Actuated Non-Video Sensor Package: negative
Everything that consumes power has a negative effect on endurance.

Endurance | Telepresence: negative
Everything that consumes power has a negative effect on endurance.

Endurance | Manipulator and/or Effector: strong negative
Manipulators and effectors most likely are mechanically dexterous, which implies joints and motors, which in turn would require to be powered.

Actuated Video Camera | Actuated Non-Video Sensor Package: strong positive
If both systems can be collocated on a single pan-tilt turret, the overhead for adding the second system should be rather small.

Actuated Video Camera | Telepresence: positive
While landed or perching, an actuated video camera could improve the situational awareness for telepresence applications.

Telepresence | Manipulator and/or Effector: strong positive
The presence of an effector expands the telepresence beyond pure audio-visual applications.

Control Station Intra-relations

Interactive Object Selection and Identification | Ruggedness: negative
Ruggedized outdoor readable screens could be darker and lower in resolution, which could diminish operator interaction through a touch based interface. Furthermore, rugged interface could have to be operable with gloved hands, further decreasing precision of tactile operations.

Interactive Object Selection and Identification | Portability: negative
Larger improve identification and interaction, but smaller screens are preferable for portable devices.

Ruggedness | Portability: negative
Rugged systems tend to be larger and bulkier than non-protected systems.

System Intra-relations

Sense and Avoid | Waypoint Navigation: positive
Sense and avoid allows to drop the free space assumption[5] while navigating waypoints.

Sense and Avoid | Unattended Deployment and Return: strong positive
Sense and avoid allows for a command and forget[6] strategy while deploying and/or returning from or to the base.

Sense and Avoid | Simultaneous Location and Mapping (SLAM): strong positive
These two systems could use the same sensors, e.g. a LiDAR.

Waypoint Navigation | Unattended Deployment and Return: strong positive
These two components enable completely unpiloted (via FPV) operations.

Kinematically constrained operations | Unattended Deployment and Return: positive
Depending on the chosen landing pad or perching location, the initial and last phases of take-off and landing, respectively, could pose kinematic constraints, for example while

High-precision Navigation | Simultaneous Location and Mapping (SLAM): strong positive
If the system has access to a priori map information, SLAM can be used to very precisely position the vehicle relative to the environment.

High-precision Navigation | Vision Based Data Extraction: positive
Vision based systems provide a very good augmentation to GPS, potentially increasing the navigation accuracy.

Simultaneous Location and Mapping (SLAM) | Sensor Data Abstraction and Reduction: positive
SLAM senses and maps the environment. Recognizing features of the environment and reducing the raw sensor data related to that can improve the SLAM navigation solution.

Sensor Data Abstraction and Reduction | Vision Based Data Extraction: strong positive
If vision based features can be associated with a certain element of the environment, the detection and recognition of that element could be simplified.

Vehicle Control Station Inter-relations

Manipulator and/or Effector | Portability: negative
Effective use of a manipulator most likely will require a haptic feedback device to control it. Such devices are normally larger than conventional joysticks or gamepads, reducing the overall portability.

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[5] Free Space Assumption: the maneuvered space is free of (unknown) obstacles.

[6] Simply issue a “Go home” command and drop human oversight.

Vehicle System Inter-relations

Airframe Ruggedness | Kinematically Constrained Operations: strong positive
While operating under kinematic constraints, collisions with the element(s) providing these constraints most likely will occur. A rugged airframe could prevent any resulting damage.

Airframe Ruggedness | Unattended Deployment and Return: strong positive
Autonomous take-off and landing maneuvers can result in potentially damaging impacts with objects or debris, especially during operations around improvised landing sites. A rugged airframe could prevent any resulting damage.

Airframe Availability | Kinematically constrained operations: strong negative
The number of Commercial of the shelf (COTS) components for tethered or otherwise constrained operations are limited.

Endurance | Unattended Deployment and Return: positive
Unattended deployment and return could be used for operator-transparent hot-swapping of the air vehicle, which could “extend” the mission duration without interrupting the operator.

Actuated Video Camera | Kinematically constrained operations: positive
If the vehicle is kinematically constrained to reach certain attitudes, e.g. during perching, an actuated camera could compensate for such limitations.

Actuated Video Camera | Vision Based Data Extraction: strong positive
Camera actuation could keep the vision sensor pointed at features beneficial to vision algorithms while the airframe could move unconstrained.

Actuated Non-Video Sensor Package | Sense and Avoid: strong positive
A pan-tilt turret allows for vehicle body independent sensor sweeps, expanding the sensor coverage frustum.

Actuated Non-Video Sensor Package | High-precision Navigation: positive
Actuated sensors pointed at features beneficial to navigation algorithms could improve performance, for example for long range altimeters.

Actuated Non-Video Sensor Package | Simultaneous Location and Mapping (SLAM): positive
A pan-tilt turret in combination with a single point laser range finder could provide low frequency scans for SLAM or increase the coverage of other lidar systems.

Actuated Non-Video Sensor Package | Advanced Datalink and Networking: positive
A pan-tilt system could be used to point a directional antenna, increasing R/F range and robustness.

Control Station System Inter-relations

Interactive Object Selection and Identification | Waypoint Navigation: positive
A GUI based interface simplifies flight plan and waypoint navigation.

Interactive Object Selection and Identification | Sensor Data Abstraction and Reduction: positive
If raw sensor data can be abstracted, representing this abstract data to the operator for interactions can be simplified.

Interactive Object Selection and Identification | Vision Based Data Extraction: strong positive
A GUI could allow an operator to draw polygonal detection zones, for example for traffic counting operations (lanes, turning areas, etc.)

Ruggedness | Advanced Datalink and Networking: negative
Rugged system might require smaller, less sophisticated antennas.

Portability | Advanced Datalink and Networking: negative
Directional or other higher gain antennas might be larger or require external tripods, thus reducing portability.