ABSTRACT

MAY, ELIZABETH M. Using Unmanned Aircraft Systems in Municipal Power: A Cost Analysis. (Under the direction of Dr. Eric Klang.)

The work presented in this thesis examines the use of commercial-off-the-shelf (COTS) unmanned aircraft systems (UAS) as a tool in the municipal power industry. In particular, it explores the potential uses of UAS and determines which uses should be explored further. Those uses are then further investigated to create a cost model which compares the cost of current methods to the cost of utilizing UAS, thus determining when UAS should be used.

The potential uses of UAS were determined through brainstorming and a series of open-ended interviews with municipal utility companies. From these resources, a list of tasks was developed. This list is comprised of tasks which are regularly competed during the inspection of a power distribution system and could easily be completed with the use of UAS. Following the interviews and the creation of the task list, more information was collected on the current methods of power distribution system inspection through a survey. The results of this survey were collected and utilized in the creation of a model of the cost of current methods of power distribution system inspection.

Likewise, the cost of using UAS to complete the tasks was calculated. To do so, several potential UAS options were identified and investigated. These options, and the necessities of the tasks identified, were used in the creation of a model of the cost of using UAS in the inspection of power distribution systems.

These models, of the cost of current methods of inspection and of the cost of using UAS as an inspection tool, were combined to determine whether or not UAS would financially benefit a municipality. Through the models developed, it was determined that UAS are capable of contributing to the increased safety and effectiveness of municipal utility companies, while significantly decreasing the costs of a system-wide inspection.

Using Unmanned Aircraft Systems in Municipal Power: A Cost Analysis

by
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BIOGRAPHY

Elizabeth “Beth” May was born in New Jersey as the youngest daughter of John and Jeannie May. At the age of three, her family moved to Evans, Georgia, where they lived until Beth was thirteen. At that time, her family moved to Wilmington, North Carolina, where she completed high school. In 2014, she graduated from North Carolina State University with a B.S. in Mechanical Engineering, Magna Cum Laude. For the next two years, she continued her education at N.C. State in the same field, and expects to graduate in 2016 with her M.S., Mechanical Engineering.

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CHAPTER 1 – INTRODUCTION

In recent years, unmanned aircraft systems (UAS) have become a tool used by an ever-growing number of industries, and have generated a large amount of interest in civil industries. This growing interest in utilizing UAS in civil industries calls for a method of determining the value added by using this technology, novelty notwithstanding. One area of particular interest is the use of UAS in the inspection and maintenance of systems that are difficult or dangerous to access. This thesis focuses on one such type of system, a municipality-owned power distribution system.

Current methods of maintenance and inspection can put the inspectors of power distribution systems at risk, while also requiring a large investment of man-hours from the system owner. The use of UAS is, therefore, an attractive alternative, as it may improve not only the safety of the system inspectors, but it may also reduce the overall cost of the inspection process while improving the efficiency of maintenance. In this thesis, the potential uses of commercial-off-the-shelf (COTS) UAS in the municipal power industry are investigated, including inspection as well as a variety of other uses. The cost and effectiveness of utilizing UAS in the inspection and maintenance of power distribution systems is explored in further depth, including an investigation into current inspection methods, a proposal of the potential inspection process using UAS, and an analysis of the cost and effectiveness of each method.

This research was conducted with the assistance of ElectriCities of North Carolina, Inc., and with the input of several municipal utility companies in North Carolina, including Fayetteville, Washington, and Tarboro.

1.1. PROJECT SCOPE

The focus of this research is on the use of COTS UAS to support the operation and maintenance of municipal power distribution systems. This limitation of the scope, to focus on municipality-owned systems, is imposed due to the fact that such systems have different equipment than privately owned systems. Additionally, by focusing on municipality-owned power distribution systems, a variety of different system components can be considered, including high voltage transmission lines, low voltage distribution lines, and local substations. Furthermore, by working with systems that are owned and operated by local government, it is hoped that the requisite permits would be more easily obtained than those acquired for private businesses.

The limitation of the type of UAS considered to those available commercially was imposed due to the financial restraints of the municipal utility companies considered. While some privately owned companies may have the means to design and develop a custom UAS, a municipal utility company would certainly not have the budget to do so. Additionally, with changing Federal Aviation Administration guidelines regarding the use of UAS, it was decided that only UAS which have been thoroughly tested by third party companies and users should be considered.

The outcome of this research is an analysis of the cost and effectiveness of current inspection methods of power distribution lines compared to the cost and effectiveness of an inspection which utilizes UAS as a tool. This analysis is completed by first calculating the cost of completing the inspection of the power distribution system using current methods, then calculating the cost of the inspection using a variety of UAS. These costs are compared so that the lowest-cost UAS is suggested to the user as the optimal solution. For this comparison, a code was created which allows for the analysis of any power distribution system, allowing the user to input a variety of system parameters and preferences, further discussed in Section 6.1. Thus, each analysis completed with the code is customized to the user's needs and desires.

1.2. MOTIVATION

For power distribution systems, yearly inspections are highly recommended and maintenance is consistently needed [1]. However, a system-wide inspection requires a large investment of time and money from the company which owns and maintains the system. Most inspections require that the inspector use a bucket truck (or other lifting device) [1] to obtain access to the power lines in question. In some cases, when the power lines are not easily accessible, a helicopter or other mode of transportation is needed to complete the inspection [2]. An infrared (IR) camera is also desirable in system-wide inspections [1]. For many utility companies, particularly those that are owned by a municipality, the cost of a high-resolution infrared camera is more than the typical budget allows. If a helicopter is needed, the cost is far outside the budgetary constraints of the company. In this case, either the equipment is rented from an outside source or the inspection is simply not completed, leaving gaps in the inspection of the distribution system.

As the inspection process requires a large investment from the company, they are often left incomplete or only completed once in a number of years, despite the recommendations of experts [1]. This, combined with the gaps sometimes left in inspections due to a lack of proper equipment, means that faulty system components are often not discovered until they have failed, potentially damaging other components, and inconveniencing customers.

One potential solution is to simply lower the cost of power distribution system inspections, therefore increasing the likelihood of their completion. To do so, it has been proposed that UAS should be used as an inspection tool. UAS provide a relatively inexpensive alternative to helicopters, and may be able to decrease the cost of inspection by decreasing the amount of time needed for inspections.

A major impediment to the use of UAS in any civil industry is the regulation of UAS use by the Federal Aviation Administration (FAA). The rules proposed by the FAA which govern the use of UAS currently impose several restrictions which complicate the implementation of a UAS-based inspection scheme, but do not make such a plan impossible to execute. Several exemptions have already been granted to other companies which intend to use UAS in the inspection of power lines and other systems [3]. These are further discussed in later chapters.

1.3. RESEARCH GOALS

As previously mentioned, the focus of this work is on analyzing the potential benefits UAS could bring to the inspection and maintenance of municipality-owned power distribution systems. As such, two research questions are addressed in this thesis.

Research Question 1: How could UAS be used by the municipal power industry?

Research Question 1 explores the potential uses of UAS in the municipal power industry, not limited to the expected uses of inspection and maintenance. To fully explore this question, interviews were conducted with the employees of municipal power utility companies. These interviews are discussed further in Section 3.1.

Research Question 2: When should UAS be used by the municipal power industry?

Research Question 2 follows Research Question 1 by asking which of the possible uses of UAS should be pursued and explored. Some potential uses are eliminated due to the regulations imposed by the FAA, questions of practicality, concerns of safety, or lack of widespread interest. For the potential uses which are deemed worth further exploration, an analysis is performed to discover the financial cost of such a use. A cost-effectiveness analysis is performed to compare the costs associated with using current methods to the costs of using UAS.

CHAPTER 2 – BACKGROUND

Little can be found in existing literature on the method of evaluating the cost or value of utilizing COTS UAS in public industry. However, the use of UAS in industry is currently explosively popular; a wide range of industries are interested in the use of UAS, and many are investing without knowing the cost or value that using such a tool will bring about.

2.1. USE OF UAS

The potential use of UAS has been investigated and attempted in many diverse industries, ranging from vegetation management [4] to mineral exploration [5] to the power industry [6]. This research seeks to determine the value of UAS in the municipal power industry in particular. As such, prior research into the use of UAS, particularly where power distribution systems are concerned, is of particular interest.

2.1.1. USE OF UAS IN THE POWER INDUSTRY

While there have been several investigations into the potential use of UAS in the power industry, many of these investigations have focused on the use of UAS in the inspection of power transmission lines only [7–10]. While similar, there are several key differences between transmission lines and the power distribution systems which are more prevalent in municipalities. One such difference is in the type of power lines; the focus of these previous studies has been in high-voltage transmission lines only, while municipal power distribution systems often also include substations and lower-voltage power distribution lines. Another difference can be seen in the different types of regulatory restrictions which apply to long-distance transmission lines and local power distribution systems.

Furthermore, the scopes of these investigations have often been limited to the implementation of a particular UAS. The UAS in question is often a highly customized system created by the researchers solely for use in power transmission line inspections [7,8,11,12]. This development of a custom system is far beyond the abilities of a typical municipal utility company, and rests on the assumption that the time and money saved by using the UAS will be worth the amount of effort and capital invested.

Another important difference to note is that many previous researchers have attempted to create an automated system which can fly and, in some cases, identify problems without user input [12–14]. These systems are not available COTS and would require a much greater initial investment from the municipalities. Furthermore, these systems violate FAA regulations regarding the use of UAS by a company.

Finally, there are currently multiple investigations which take into consideration the use of UAS to inspect power distribution lines and systems on the same scale as this research [3,15]. However, some of the investigations in question only partially focus on power distribution systems, and do not attempt to ascertain the added value to the company which owns the inspecting UAS [15]; it simply assumes that the time and money saved by using the UAS will be worth the amount of effort and capital invested. The other investigations intend to explore the question of cost effectiveness in the future, but limit such questions to the specific UAS used [16]. Furthermore, there is no indication that they intend to develop a model which can be used to measure the cost effectiveness of any UAS for any power distribution system. Through this research, the financial impact of UAS on municipalities and local power distribution systems is evaluated. Using the tool created by this research, it is possible to evaluate the cost effectiveness of a range of UAS for any power distribution system.

2.2. VALUE ANALYSIS

An equally important aspect in the background of this research study is past research into value analysis. Simply put, the purpose of a value model is to successfully express the worth of a product as a function of the monetary value it can create [17]. There are several types of analyses which can be applied to systems to model their worth [18]. Cost-benefit analyses are typically used to evaluate systems such as the one explored in this research [19], but as there is no variation to the associated benefit, it is deemed an inappropriate method. Therefore, a cost effectiveness analysis is used instead.

A cost effectiveness analysis is typically used to assess the effectiveness of a new strategy or device compared to one previously used [20]. This approach is an appropriate choice for this analysis, as it investigates the cost and effectiveness of a new technology, UAS, relative to the current methods of power distribution line inspection. Cost-effectiveness analyses are often used in the medical field, but have been applied to many other types of systems as well [21,22]. Some examples include the selection of an energy system [23] and an analysis of the environmental protections implemented by power plants [24].

Rather than compare different benefits afforded by various solutions, a cost-effectiveness analysis asks whether the different approaches are equally effective. This model utilizes this approach to compare the costs associated with using a UAS to achieve the same outcome as current methods of power distribution line inspection, or to achieve an even more effective outcome than what is currently typical.

2.3. IDENTIFICATION OF COMMERCIAL-OFF-THE-SHELF UAS

One further exploration of the background of this research was the identification of potential commercial-off-the-shelf (COTS) UAS solutions. Several dozen UAS were identified; a list of the UAS vetted can be found in Appendix A. These UAS were investigated for their potential use by attempting to identify several key characteristics. These characteristics include the following: type of craft, manufacturer, cost, weight, fuel type, footprint/area, wing span, programmability, cruising speed, maximum speed, maximum altitude, maximum wind speed, range, rain operability, motor type, refueling/recharging speed, battery/fuel life, battery cost, camera specifications, payload specifications, and stability.

While some of these specifications are readily available (e.g. weight, fuel type, maximum speed), others are difficult or impossible to find (e.g. maximum wind speed, refueling/recharging speed, stability). Fortunately, it was determined that not all of these characteristics were needed to determine the effectiveness of the particular UAS in question. The necessary characteristics, and the selected UAS, are discussed further in Section 6.2.

2.4. CONCLUSIONS FROM BACKGROUND RESEARCH

From the background research discussed previously, it is clear that there is significant interest in utilizing UAS in civil industries, especially in the power industry. However, there has not yet been an investigation into all of the potential uses of the UAS, and a method of determining the cost or effectiveness of adding UAS as a tool to that industry has not yet been developed. This research attempts to address both of those shortcomings.

CHAPTER 3 – USER NEEDS

The end users of the UAS in this case would be the municipal power companies themselves. Therefore, in an effort to fully explore Research Question 1 and obtain a firm grasp of the user needs, several municipality-owned power companies were visited. Open-ended interviews were conducted at each municipality which explored options for UAS use and established the needs of the end users.

3.1. PARTICIPATING MUNICIPALITIES

Three municipalities of varying sizes were interviewed to ensure a certain level of geographic and population diversity. These municipalities were selected with the assistance of ElectriCities, Inc. of North Carolina. At each municipality, a variety of people were included in the discussion, ranging from linemen to managers.

The largest municipality was also the first interviewed. Fayetteville, North Carolina is a city with a population of just over 200,000 [25]. Its primary power provider is Fayetteville Public Works Commission (PWC), which provides power utility service to approximately 80,000 customers [26].

Following the interview at the Public Works Commission of Fayetteville, an interview was conducted at the Washington Electric Utilities office. Washington Electric Utilities, located in Washington, North Carolina serves 12,000 customers and contains 388 miles of power distribution lines [27].

The final municipality utility company interviewed was with Tarboro Electric Utility. This was also the smallest municipality contacted for an interview and is located in Tarboro, North Carolina. The power distribution system managed by the town of Tarboro has 5,828 measuring meters and is comprised of 120 miles of power distribution lines [28].

3.2. SUMMARY OF INFORMATION GATHERED

The interviews of each of the municipalities were conducted in an open-ended style, to allow for a deeper exploration of the potential uses of UAS. After all of the interviews were completed, it was determined that there were two general categories which covered the majority of the uses discussed. These two categories can be broadly termed “Emergency Response” and “Preventative Maintenance”.

3.2.1. FAYETTEVILLE

During the interview of employees of Fayetteville’s Public Works Commission, it was mentioned that an emergency response ability would be a significant advantage. The real-time information gained from a UAS flown following a hurricane or ice storm could be used in the prioritizing of responses, and would be particularly useful in instances when ground access would not be easily available. Utilizing a pre-programmed path with GPS checkpoints was suggested as another particularly useful aspect to using UAS as an emergency response tool.

It was also suggested that the UAS could be used as a “first responder” to check sites for damage following an unexpected loss of service. The example used in this instance was a car crashing into a distribution pole. A UAS could be sent out immediately to assess whether the pole itself will need to be replaced, or if the pole-top-assembly simply needs to be adjusted. With this, teams would not need to backtrack to a different location to pick up extra supplies; they would be aware of all necessary supplies before going to the incident location.

There were also several ideas discussed regarding the use of UAS in preventative maintenance. One of the heavily emphasized suggestions was the use of infrared cameras in the inspection of the whole distribution system. It was mentioned that all of the transmission lines within the PWC system were checked yearly with an infrared camera, but that it would be a valuable addition to be able to use such a tool on distribution lines and substations. While the use of infrared cameras was seen as a highly useful addition, access to color images of the distribution system was discussed as a necessity. With color images, it was said that nearly the entire distribution system could be checked, and potentially checked against the infrared images, as well. Color images could also be used to check right-of-ways for vegetation or building encroachment.

Several other suggestions were made regarding the use of UAS in preventative maintenance which were a bit more active solutions rather than simple inspections. For example, it was suggested that a UAS could be modified to carry a paintball-style gun that could shoot balls of lubricant at transformer switches, thus maintaining the switches. It was also suggested that UAS could be used to spray certain areas with herbicides, offering a solution to certain types of vegetation encroachment. Finally, it was suggested that some UAS could be used to accomplish a voltage check on active lines. While all of these suggestions were interesting, they would all require significant modifications to the UAS, and would therefore preclude the use of COTS UAS.

Overall, the employees of the Fayetteville Public Works Commission were extremely enthusiastic about the potential uses of UAS, regardless of the nature of those uses.

3.2.2. WASHINGTON

The interview with the employees of Washington Electric Utilities was similar in many ways to the one conducted with the employees of Fayetteville Public Works Commission. The fact that the City of Washington is located on the Pamlico River added some new dynamics into the potential uses of UAS, and complicated some of the previous suggestions.

The interviewees in Washington were also interested in the possibility of an emergency response and assessment option utilizing UAS, but were distinctly less enthusiastic about the idea than the interviewees from Fayetteville. From the Washington interview, it was clear that the ability to assess what resources are needed would increase the efficiency of the cleanup and repair that occurs following a major storm. As with the interviewees in Fayetteville, those in Washington said that a UAS with a programmable route would be very useful in the case of emergency assessment.

Much more emphasis was placed on the preventative maintenance option by the Washington interviewees. It was said that the first, and most important, piece of the system is the main transmission line. Inspecting the main transmission line is extremely important, as nearly all of the city’s power comes from the main transmission line. However, with current methods, the main transmission line can be difficult to access. This is due to the fact that transmission lines are generally taller than distribution lines, and therefore require a bucket truck with a longer reach. This means that the transmission line requires more time and effort to examine, and can even place employees at risk.

The inspection of substations was also heavily emphasized by the interviewees in Washington. According to the interviewees, there is a very limited area that is extremely difficult to see, but should be routinely inspected. This inspection would be easily accomplished with a UAS, where it currently requires significant effort.

The use of an infrared camera in the inspection of the distribution system was seen as a potentially valuable addition, particularly onboard a UAS. Washington Electric Utilities did not own an infrared camera, and therefore had to get a contractor to come photograph the key system pieces every year. Even this approach was limited in that there were only a limited number of angles available to the photographer.

One of the new ideas to come up at the Washington interview was that of system mapping, which involves collecting information on pole-top-assembly configurations and nameplate data from distribution poles. According to the interviewees, this is a fairly common procedure. However, this information is currently recorded only as the pole is ascended for inspection or repair. Another idea generated in this interview was to check the pole condition, particularly in swamp-like or continuously wet ground.

Overall, the interviewees in Washington seemed to be interested in the use of UAS as another tool to be used towards preventative maintenance. The idea of being able to more easily identify problems, and keep employees safe while doing so, was clearly very attractive to the employees of Washington Electric Utility.

3.2.3. TARBORO

There were some significant distinctions in the attitude toward using UAS in Tarboro compared to the other municipalities. The most obvious was the lack of interest in using UAS as an emergency response tool. The only reason this case was even considered was that, according to one of the interviewees, FEMA is beginning to require images of storm damage to give assistance funding. In general, the use of UAS in an emergency assessment situation seemed undesirable.

While there was decreased interest in the emergency response and assessment use case, there was consistently high interest in the use of UAS for preventative maintenance. In Tarboro in particular, there was a lack of equipment that was prevalent in other municipalities, to the extent that the Tarboro Electric Utility does not have the equipment needed to check transmission for either damage assessment or preventative maintenance. The entire distribution system in Tarboro was regularly checked, unlike some of the other municipalities. Checking the entire system required four to six crews, took longer than two weeks, and was done every year. Substations were also checked monthly; using current methods, it was a simple, visual check. However, it was said that a UAS could be used to get a more accurate view of the substation more easily.

The interviewees were also interested in some of the other potential applications of UAS, including their use in system mapping and their ability to carry infrared cameras. As in the City of Washington, the UAS could be used to keep an updated system catalog of where equipment is located.

Overall, the interviewees in Tarboro were not very interested in using UAS as a method of assessing damage. However, they were quite interested in the potential use of UAS as another tool of preventative maintenance. Most of the abilities beyond taking color photographs of the pole-top-assemblies were seen as nice additions, but certainly not necessities.

3.3. IMPORTANCE OF CAPABILITIES

In all three municipalities, two general use cases were discussed: the use of UAS for emergency response and assessment, and the use of UAS for preventative maintenance. The use of UAS for emergency response and assessment was not seen as equally desirable by all municipalities, but the interest in using UAS for preventative maintenance was strong and relatively equal in all three.

The use of UAS for emergency response and assessment would require that the drones be flown in higher wind speeds, in rain, and in poor visibility conditions. This would violate the FAA rules for the use of UAS by a business. Due to this unavoidable violation of the FAA rules, as well as the lack of interest in the use of UAS for emergency response and assessment in some of the municipalities consulted, it was determined that the use of UAS in this capacity would not be investigated further in this research. Instead, the use of UAS as a tool in the preventative maintenance and assessment of power distribution systems was chosen as the focus of this research.

3.4. TASKS LIST DERIVED

While the use of UAS in emergency conditions could prove useful, the use of UAS for preventative maintenance inspection was of much greater interest to the majority of the municipal utilities interviewed. In fact, all three municipalities interviewed were very interested in the use of UAS in preventative maintenance inspection. From these interviews, as well as source material on the inspection of power systems[1], several key tasks in the inspection of power distribution lines were identified. These tasks are listed below, in Table 1.

Table 1: Task List

Task 1	*Check Pole-Top Assemblies, Color Photography*	***Task 6***	*Check Right-of-Way Clearance*
Task 2	*Check Pole-Top Assemblies, IR Photography*	***Task 7***	*Check Substations, Color Photography*
Task 3	*Check Pole-Top Assemblies, Nameplate Data*	***Task 8***	*Check Substations, IR Photography*
Task 4	*Check Pole Condition*	***Task 9***	*Check Transmission Lines, Color Photography*
Task 5	*Pole and System Mapping*	***Task 10***	*Check Transmission Lines, IR Photography*

Each task listed in Table 1 was mentioned at least once during the interview process; most of them were mentioned by more than one of the municipalities interviewed. Nearly all of the tasks were discussed as part of a necessary yearly inspection. While several of the tasks can be easily grouped together, the interviewees could not verify that they were always completed at the same time. This question of frequency and grouping, as well as the uncertainties in regard to the cost of each of the tasks, were further explored through a survey of North Carolina municipal utilities, discussed further in Chapter 4.

CHAPTER 4 – SURVEY OF MUNICIPALITIES

4.1. GOALS OF THE SURVEY

In creating the municipality survey, the primary goal was to ascertain more information, and more accurate information, about the amount of time and money spent on the inspection of power distribution systems. This was necessary because of the lack of consistency of information gained from the interviews previously conducted. Each source of information seemed to have a different answer when it came to the amount of time dedicated to the system inspection, and each calculated the costs in a different manner.

The secondary goal of the survey was to determine which of the ten tasks discussed in Table 1 were grouped together. Tasks 1 and 3, for example, were often mentioned at the same time during the in-person interviews previously discussed in Chapter 3. By fielding the survey to a larger audience, it could be determined if this grouping was intentional or merely coincidental.

This survey was approved for the necessary exemptions by the North Carolina State University Institutional Review Board. It was submitted for approval on September 22, 2015, and was approved on October 15, 2015.

4.2. QUESTIONS ASKED

As with any research survey, the first question asked of the participant was for their consent to use their responses in research, providing that those responses lacked any personal information. Following that consent, basic demographic information was collected from the participant. The following questions were asked of the participant in the demographic information section:

1. What is the title of the company for which you work?
2. Where is that company located?
3. How much area (sq. miles) is managed by your company?
4. How many miles of distribution line does your company manage?
5. Approximately how many poles are there per mile of distribution line?
6. How many miles of transmission line does your company manage?
7. Approximately how many poles are there per mile of transmission line?
8. How many substations does your company manage?

The survey was structured in such a way that the same set of questions were asked regarding each task listed in Table 1. The questions asked follow, using the first task as a template:

1. What resources do you need to check pole-top assemblies (color photography)?
2. How much time does it take for you to check pole-top assemblies (color photography)? Please give a reasonable estimate for the time it takes to check a single pole, including setup. Please give your answer in minutes.
3. How much of that time is setup? Please give your answer in minutes.
4. How much does it cost to check pole-top assemblies (color photography)? This estimate may be most accurate as an hourly, daily, or per pole cost; please be sure to specify.

5. How many times a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.
6. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude and assessments which should be done more or less frequently.
    a. Check Pole-Top Assemblies, IR Photography
    b. Check Pole-Top Assemblies, Nameplate Data
    c. Check Pole Condition
    d. Pole and System Mapping
    e. Check Right-of-Way Clearance
    f. Check Substations, Color Photography
    g. Check Substations, IR Photography
    h. Check Transmission Lines, Color Photography
    i. Check Transmission Lines, IR Photography

These questions are presented for each task, with the appropriate changes to wording in questions 1, 2, 4, and 6. However, for tasks which are selected in question 6, the questions are not presented again. This question is used to indicate when the same resources are used in the completion of multiple tasks; therefore, each task selected in the question is exempt from further questions, as the answers have already been collected.

A sample of the survey questions, presented as they would appear to a survey participant, can be found in Appendix C.

4.3. SURVEY RESULTS

As can be seen from the questions asked in the survey, the information collected focused on the type of equipment needed to complete each task, the amount of time needed to complete each task, the frequency of each task, and the monetary cost of completing each task.

The information gathered yields the results shown in Table 2. This aggregate data confirms that several tasks are typically grouped together during an inspection. Color images, for example, are used to complete seven of the ten tasks outlined in the survey. Six of these seven are surrounding distribution and transmission lines, and are therefore extremely similar; these six tasks (1, 3-6, and 9) are grouped together in the following table. Similarly, Tasks 2 and 10 are grouped together, as they describe the inspection of transmission and distribution poles with infrared images. The remaining two tasks relate to the inspection of substations, which is quite different in terms of both the form of inspection and the amount of time needed. Therefore, Tasks 7 and 8 are set apart from the other tasks which require color and infrared images, respectively.

Table 2: Survey information

Task	***Related Tasks***	***Time (min)***	***Cost***	***Equipment***
Color Images	*1, 3-6, 9*	*32.5*	*$ 38.08 per pole*	*Camera, lineman, bucket truck*
IR Images	*2, 10*	*25*	*$ 29.43 per pole*	*Bucket truck, IR camera, lineman*
Substation Images	*7*		*$ 641 per day*	*Camera, lineman, bucket truck*
Substation IR Images	*8*		*$ 565 per day*	*Bucket truck, IR camera, lineman*

As mentioned previously, the grouping of Tasks 2 and 10 mirror the grouping of Tasks 1, 3-6, and 9. However, there are some significant differences between the two groups. For many municipalities, all infrared inspections are done simultaneously. This is to be expected, since many municipalities do not own infrared cameras, but instead hire a service to complete the infrared inspection. Naturally, this inspection is done as quickly as possible on as much of the system as possible. However, it is often impossible to complete an infrared inspection of the entire system within the time allotted. For this reason, the entire system is not always checked using an infrared camera, despite the benefits an infrared inspection can offer. Often, only the critical components of a power distribution system are checked using infrared technology. Transmission lines and substations are more important to the operation of a power distribution system, meaning that distribution poles and lines are often excluded from the infrared inspection.

CHAPTER 5 – DETERMINING THE COST OF NON-UAS BASED (CURRENT) INSPECTIONS

As the goal of this research is to judge the cost-effectiveness of a system which utilizes UAS compared to a system which does not use UAS, it is vital that an accurate model of both systems be developed. In this Chapter, such a model is explored for the cost-effectiveness of the current system, which does not utilize UAS in the inspection of power distribution systems. The following model is based on the task list detailed in Table 1 and the information collected from the survey discussed in Chapter 4.

5.1. USER INPUT

One of the important considerations in creating this model is that it should be capable of being used for a variety of different systems, and should therefore be used in conjunction with a certain amount of user input. In this model, the user will need to provide numbers for the following:

- Frequency of inspections (per year)
- Number of system distribution poles
- Number of system substations
- Number of system transmission poles

By providing this information, the current cost of inspecting the power distribution system can be calculated for a specific system.

5.2. CURRENT COST MODEL

The cost of current practices is evaluated through a combination of various equations, displayed below as Equations (1), (2), and (3). The variables used in these equations are defined in Table 3, found at the end of this Section.

Equation (1) calculates the amount of time, in minutes, spent on each pole or substation. It takes into account the number of people working at the site, S_t, as well as amount of time per site, t_p, number of different sites, N_p, and the frequency of the task, n.

$$Minutes = \left(t_p \cdot N_p \cdot n \cdot S_t\right) \tag{1}$$

Equation (2) calculates the risk, R, associated with completing the task. The probability of risk is directly related to the amount of time it takes to complete the task, as shown by inclusion of the final term, which divides the amount of time which is spent on a task with the number of minutes in a work year. The other terms, R_d and C_d, as well as R_D and C_D, refer to the risk and cost of damages and death, respectively.

$$R = (R_d \cdot C_d + R_D \cdot C_D) \cdot \frac{Minutes}{minutes_{wy}} \tag{2}$$

Equation (3) combines the cost of risk and the cost of personnel to calculate the total cost, C, of each task.

$$C = Minutes \cdot P_C + R \tag{3}$$

The variables used in these equations are defined in Table 3. Some of these variables are already known from research, while others were determined from the municipality survey discussed previously. The variables in Table 3 that were determined from the survey information are marked with a dagger (†).

Table 3: Definition of Variables

$\boldsymbol{C}$	*Total cost*	† $\boldsymbol{S_t}$	*Team size*
† $\boldsymbol{P_C}$	*Cost of personnel*	$\boldsymbol{R_d}$	*Risk of damages*
† $\boldsymbol{t_p}$	*Time per pole*	$\boldsymbol{C_d}$	*Cost of damages*
$\boldsymbol{N_p}$	*Number of poles*	$\boldsymbol{R_D}$	*Risk of death*
† $\boldsymbol{n}$	*Frequency of task*	$\boldsymbol{C_D}$	*Cost of death*

The last four variables defined contribute solely to the risk calculation, which takes into account the likelihood of damages or death of the inspector. For this investigation, these values were taken from a previous investigation into the risk of assessing and inspecting power distribution lines [29] and corroborated with statistics reported by an AFL-CIO profile of worker safety [30].

It should also be noted that the number of distribution poles was divided by three before being used in the above equations. This division was implemented because of the comments made during one of the interviews discussed in Chapter 3.

5.3. CONSIDERATION OF OTHER COSTS

As previously discussed, the purpose of creating this model is to be able to accurately predict the cost of completing an inspection of a power distribution system using current methods. That being said, there are some extraneous costs which are not included in this model. These costs include the insurance costs of the utility company as well as the cost of equipment purchase and upkeep.

The cost of insurance is not included in this model for the simple reason that the cost will likely not be decreased by using UAS, and can therefore be considered a constant cost. As it will not be affected by using UAS, it does not make sense to calculate this cost in this model.

Likewise, the cost of equipment purchase and upkeep is not considered because it will likely not be affected by utilizing UAS. While it is possible that using UAS could decrease the number of large bucket trucks needed, the calculation of decreased equipment purchases would vary depending on the age and condition of each utility company's current equipment.

One cost which could be significantly affected by using UAS instead of current methods is the cost of fueling the inspection vehicles. As a UAS could utilize a smaller vehicle than is typically used in inspections, the amount of gasoline being used could significantly decrease. However, this is by no means a certain cost savings, as the same vehicles could be used for either inspection. Furthermore, predicting future gasoline prices is beyond the scope of this project.

5.4. MODEL ACCURACY

The accuracy of this model was tested by generating the expected current costs using the method described above and comparing that cost to the expenditure estimates of municipal utility companies. The City of Washington Electric Utility estimated that the cost of a system-wide inspection would be roughly $80,000.00 [31]. The estimate generated by the model discussed in Section 5.2 was $80,864.90. This results in a difference of just over one percent.

5.5. SENSITIVITY ANALYSIS

In an effort to determine the robustness of the model created, a one-factor-at-a-time (OFAT) sensitivity analysis was applied [32]. It was determined that an OFAT analysis is an appropriate choice, as it allows for the exploration of the relationship between each factor and the overall cost to the system. These relationships can be shown graphically and compared.

Each factor analyzed is displayed below in a graph comparing the factor in question to the total cost of inspecting the system. A line of best fit is displayed for each relationship. A steep slope indicates a high level of sensitivity to the factor in question, while a gentler slope indicates a lower level of sensitivity. The graph for each analysis is accompanied by a discussion of the line of best fit and the significance of the slope of that line.

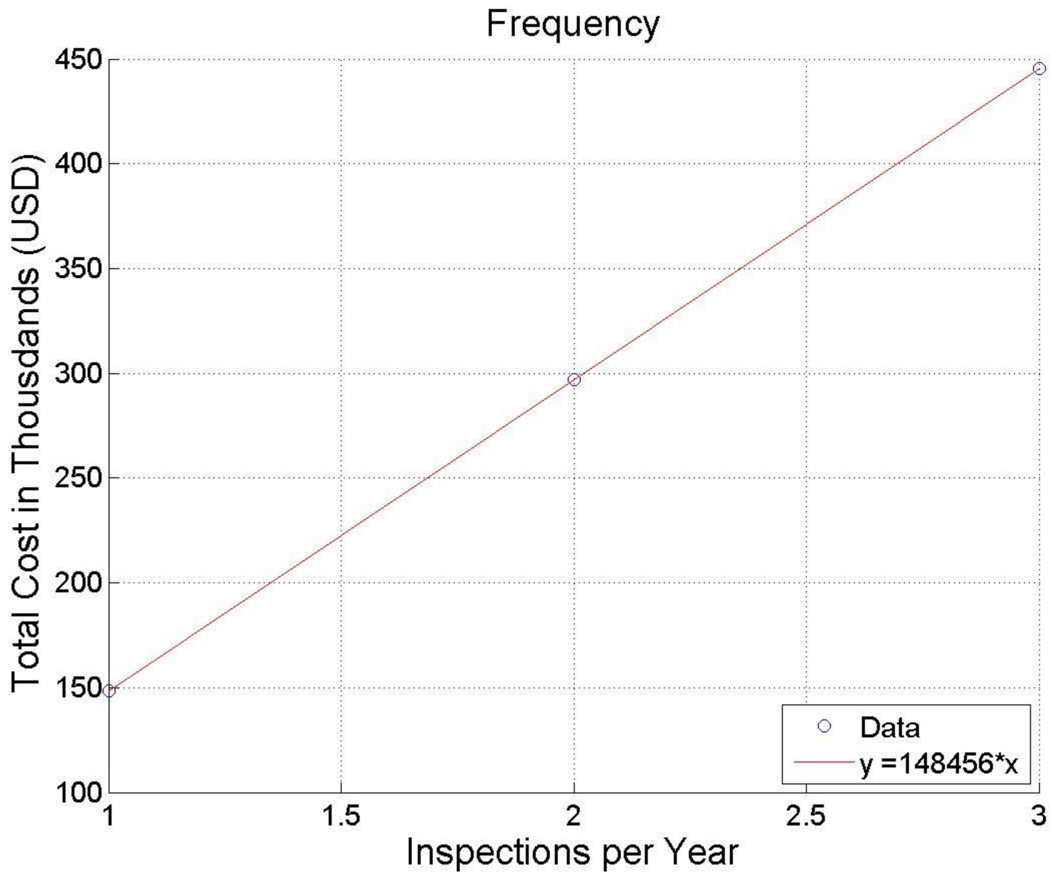

Figure 1: Effect of Frequency on Cost of Current Methods of Inspection

The first relationship studied was that between the frequency of inspection and the cost of completing those inspections using current methods. This relationship is shown above, in Figure 1. As expected, increasing the frequency of inspection drastically increases the cost of completing those inspections using current methods. The relationship is linear, as expected, and has an intercept at approximately zero. This line of fit has an R-squared value of 1.00, meaning that the line of fit exactly matches the data points.

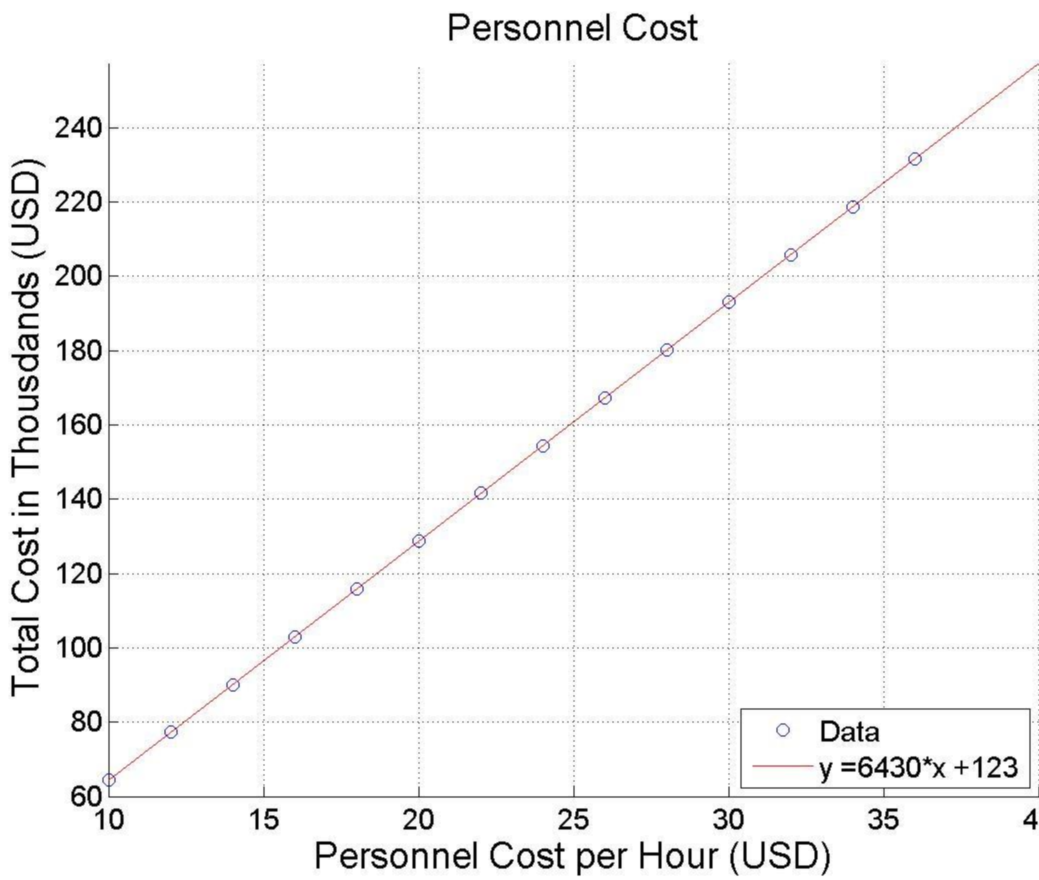

Figure 2: Effect of Personnel Cost on Cost of Current Methods of Inspection

The relationship between the cost of personnel and the cost of current methods of inspection was also considered. Unsurprisingly, the cost of inspection is extremely sensitive to any changes in personnel cost, as reflected by the equation displayed in Figure 2. The steep slope indicates a high sensitivity to this factor. The nonzero intercept of the equation displayed is a result of the calculation of risk embedded in the cost calculation for current methods; that is to say, the no matter what the personnel cost is, there will always be some cost associated with the inspection. This line of fit also has an R-squared value of 1.00.

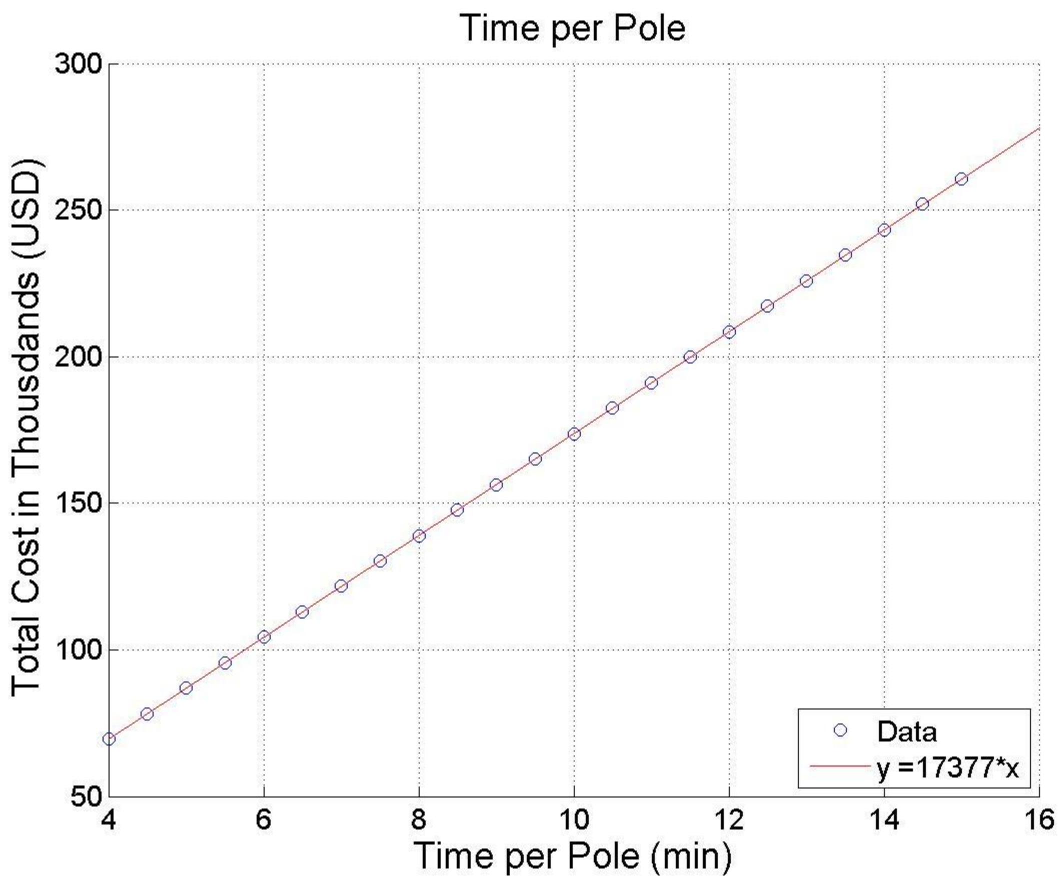

Figure 3: Effect of Time Spent per Pole on Cost of Current Methods

The effect of time spent on distribution pole tasks was identified early on as an important factor in the calculation of the cost of current methods of inspection. It was because of this realization that so much effort was put into the survey of municipalities discussed previously. The relationship displayed in Figure 3 above confirms that the cost of current methods of inspection is highly sensitive to the amount of time spent on each distribution pole. This extreme sensitivity occurs because the amount of time is multiplied by both the personnel cost and risk factors.

It should be noted that for this evaluation, only tasks which focused on the inspection of distribution poles using color photography were considered. As such, it was expected that the intercept of the line of best fit for this relationship would approach zero. If no time is spent on any tasks, then the inspection will not cost anything. This line of fit has an R-squared value of 1.00, meaning that there is no error between the line of fit and the data points.

Applying the OFAT process to further factors led to similar results. When the number of distribution poles was changed, and only those tasks which required distribution poles were considered, the slope of the line of best fit was determined to be 45 with an R-squared value of 1.00. This finding implies that for each added distribution pole, an additional cost of $45 is incurred in the inspection cost.

By applying the same analysis to the number of transmission poles, it was determined that the line of best fit had a slope of 42 with an R-squared value of 1.00. Again, it is clear that with each added transmission pole, the cost of inspection using current methods increases by $42. The same method of analysis was also applied to the number of substations being inspected. Unsurprisingly, the cost to the system was most sensitive to the number of substations being inspected, as the inspection of a substation requires more time than the inspection of either transmission or distribution poles. The slope of the line of best fit for this case was found to be 90, with an R-squared value of 1.00. Again, this implies that for each substation added to the system, an additional cost of $90 is added per inspection.

CHAPTER 6– DETERMINING THE COST OF UAS BASED INSPECTIONS

As the goal of this research is to judge the cost-effectiveness of a system which utilizes UAS compared to a system which does not use UAS, it is vital that an accurate model of both systems be developed. In this chapter, such a model is explored for the cost-effectiveness of a system which utilizes UAS in the inspection of power distribution systems. The following model is based on the task list detailed in Table 1 and information collected about the capabilities and use of UAS.

6.1. USER INPUT

As previously discussed, for a system representation to be accurate, user data will need to be collected. Therefore, the demographic information discussed in Section 5.1 will not be the only information collected from the user.

Task preferences will also be collected; if one (or several) of the tasks identified in Table 1 are not of interest to the user, then the cost of completing those tasks will not be taken into account in the calculation.

6.2. UAS INFORMATION

In the evaluation of UAS, some information is more important than others. The cost of the UAS is obviously a key characteristic, and one of the easiest pieces of information to find for most UAS. The battery cost, flight time, and charge time are also of key importance, as they allow the determination of some of the peripheral costs which need to be included in the initial investment in the UAS. Camera specifications, including camera type, resolution, and field of view, are also important in the determination of the amount of time needed to complete an inspection.

For at least one UAS, all of the previously discussed information is readily available. However, for many of the UAS investigated, some of this information is unavailable without purchasing the UAS and completing a testing procedure.

One proposed metric which is not represented by any of the UAS investigated is an ease-of-use metric. An ease-of-use metric would rate a UAS anywhere between 0.5 and a 2.0, depending on its ease of use and maneuverability. This proposed metric is inspired by the Cooper-Harper rating scale, which rates the handling and controllability of airplanes [33]. This metric is included below, in Table 4, as well as in Equation (4) in Section 6.3.

The final list of necessary information for the UAS options is shown below, in Table 4. An example UAS, a modified DJI Phantom 2 [34], is described by these metrics as a demonstration.

Table 4: UAS Options Metrics

Price (USD)	***Battery Cost (USD)***	***Flight Time (min)***	***Battery Charge Time (min)***	***Infrared Camera (N/Y)***	***Ease of Use***	***Vertical Field of View (°)***	***Infrared Vertical Field of View (°)***
7998	*150*	*25*	*45*	*1*	*1*	*55*	*23*

These metrics are used as the UAS metrics in the UAS cost model, discussed further in Section 6.3.

6.3. UAS COST MODEL

The cost of using UAS will be evaluated through a method similar to the previously discussed modeling method used to calculate the cost of the current method of system inspection. However, there are several key differences. The amount of time spent at each site, in particular, is a significantly different calculation; it is shown below, in Equation (4). The new variables included in the following calculations are called out in Table 5, at the end of this section, and are discussed with the equation in which they are presented.

$$Min_{UAS} = E_{ou} \cdot n_{passess} \cdot N_P \tag{4}$$

A new variable, n_{passes}, is introduced in Equation (4). This variable represents the number of passes the UAS will need to make around the pole-top assembly or over the substation to fully capture the site. It is calculated through Equation (5), below.

$$n_{passes} = \left\lceil \frac{2 \cdot \pi \cdot R_s}{2 \cdot s_i} \right\rceil + 1 \tag{5}$$

In this equation, the brackets used indicate that the number is rounded up to the nearest integer. The contents of the backets include s_i, which represents the vertical swath width of the camera on the UAS, and R_s, the radius of the sphere of interest surrounding the pole-top assembly. This sphere of interest is shown below, in Figure 4. This figure also shows the method of calculation of n_{passes}, which is based on the size of the sphere of interest, the vertical swath width of the UAS camera, and the distance of the UAS from the distribution pole.

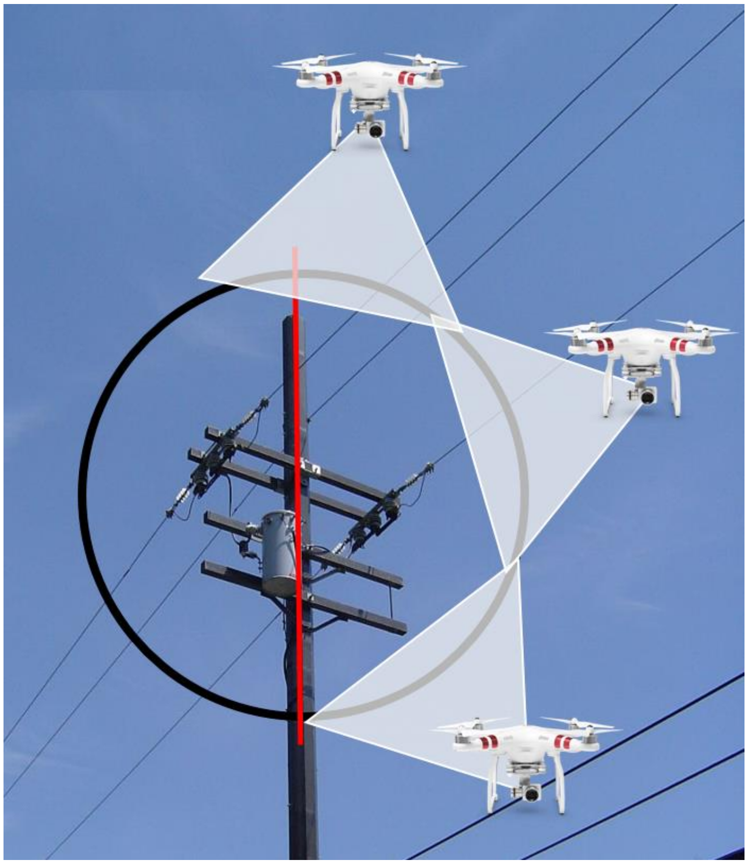

Figure 4: Sphere of Interest and n_{passes} Calculation

The vertical swath width of the UAS camera is calculated using the traditional orbital mechanics equation for swath width of an instrument [35]. This calculation uses Equation (6) through (10), below. The swath width of the instrument itself is calculated in Equation (6) using the central angle to the instrument's horizon, α_i, and R_s, the radius of the sphere of interest surrounding the pole-top assembly.

$$s_i = 2\alpha_i R_s \tag{6}$$

The central angle to the instrument's horizon, α_i, is calculated in Equation (7), using the nadir angle, β_i, and supplementary angles Γ and Γ'. These angles are visually defined in Figure 5.

$$\alpha_i = \pi - (\beta_i + \Gamma) = \Gamma' - \beta_i \tag{7}$$

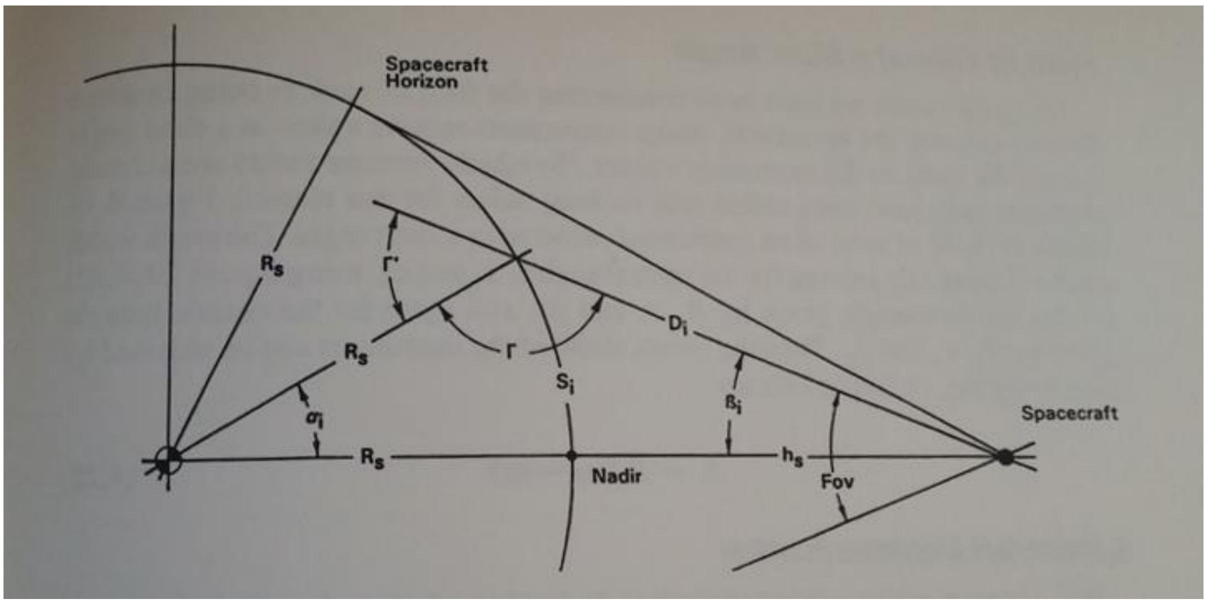

Figure 5: Definition of Angles α_i, β_i, Γ, and Γ' [35]

The nadir angle of the instrument is determined from the instrument's field of view, *Fov*. In this case, the field of view in question is the vertical field of view of the camera on the UAS.

$$\beta_i = \frac{Fov}{2} \tag{8}$$

The supplementary angles Γ and Γ' are determined using basic trigonometric and geometric identities, shown below in Equations (9) and (10). For these calculations, the distance of the UAS from the pole-top assembly, r, is needed.

$$\Gamma' = \left(\frac{r}{R_s}\right) \sin \beta_i \tag{9}$$

$$\Gamma = \pi - \Gamma' \tag{10}$$

The risk of using a UAS, as defined in Equation (11), can be calculated using nearly the exact same formula as the risk of inspecting a distribution line using a bucket truck. As with the risk calculated in Equation (2) and explained following Table 3, the values for the risk likelihood are taken from a previous study [29].

$$Risk_{UAS} = (R_d \cdot C_d + R_D \cdot C_D) \cdot S_t \cdot \frac{Min_{UAS}}{minutes_{wy}} \tag{11}$$

The cost of completing one of the ten tasks can be found through Equation (12), shown below. It should be noted that this cost cannot be considered the total cost, as it does not account for the cost of equipment. Equation (12) introduces several new variables, including two new personnel costs, P_{C1} and P_{C2}, which respectively account for the personnel cost of the pilot and the personnel cost of the other, non-licensed employees. Another variable introduced is the analysis time factor, A_n. The analysis time factor is used to represent the amount of extra time needed to inspect the images and videos captured by the UAS. For an analysis time factor of unity, no additional time is needed. For an analysis time factor of two, it would take as much time to inspect the images and video as it took to capture the images and video. It should be noted that in this calculation, it is assumed that only a single individual is analyzing the images and videos in question.

$$Cost_{UAS} = Risk_{UAS} + Min_{UAS} \cdot \left((S_t - 1) \cdot P_{C2} + P_{C1}\right) + Min_{UAS} \cdot P_{C2} \cdot (A_n - 1) \tag{12}$$

The number of UAS needed is calculated using Equation (13), which is a simple calculation relating the amount of time needed to complete the inspections and the minutes available in a work year.

$$num_{UAS} = \left\lceil \frac{Min_{UAS}}{minutes_{wy}} \right\rceil \tag{13}$$

The number of batteries per UAS is also needed to accurately determine the equipment costs incurred by this method of inspection. This is calculated through Equation (14), below.

$$num_{batt} = \left\lceil \frac{T_c}{T_f} \right\rceil \tag{14}$$

With the number of UAS and batteries needed, it is possible to determine the initial equipment costs incurred by using UAS. This is shown below, in Equation (15).

$$equip_{UAS} = C_{UAS} \cdot num_{UAS} + C_{batt} \cdot num_{batt} \cdot num_{UAS} \tag{15}$$

The total cost of each task now becomes a simple summation of all of the individual costs, as shown below in Equation (16).

$$TC_{UAS} = Cost_{UAS} + equip_{UAS} \tag{16}$$

All of the new variables introduced in Equation (4) through Equation (16) are defined below, in Table 5.

Table 5: Definition of Variables

$\boldsymbol{Min_{UAS}}$	*Time spent inspecting a pole using UAS*	$\boldsymbol{A_n}$	*Analysis time factor*
$\boldsymbol{E_{Ou}}$	*Ease of use of UAS*	$\boldsymbol{P_{C1}}$	*Cost of personnel, including pilot*
$\boldsymbol{n_{passes}}$	*Number of passes by the pole/site*	$\boldsymbol{P_{C2}}$	*Cost of personnel analyzing images*
$\boldsymbol{R_s}$	*Radius of sphere of interest*	$\boldsymbol{num_{UAS}}$	*Number of UAS needed for a system*
$\boldsymbol{s_i}$	*Swath width*	$\boldsymbol{num_{batt}}$	*Number of batteries needed for a UAS*
$\boldsymbol{\alpha_i}$	*Central angle to instrument's horizon*	$\boldsymbol{T_c}$	*Maximum battery charge time*
$\boldsymbol{\beta_i}$	*Nadir angle*	$\boldsymbol{T_f}$	*Time of flight*
$\boldsymbol{\Gamma, \Gamma'}$	*Supplementary angles*	$\boldsymbol{equip_{UAS}}$	*Total equipment cost of UAS*
Fov	*Field of view*	$\boldsymbol{C_{UAS}}$	*Cost of UAS*
$\boldsymbol{Risk_{UAS}}$	*Risk of UAS*	$\boldsymbol{C_{batt}}$	*Cost of UAS batteries*
$\boldsymbol{Cost_{UAS}}$	*Cost of using UAS, excluding equipment*	$\boldsymbol{TC_{UAS}}$	*Total cost of using UAS, with equipment*

As in the calculations previously discussed, the risk associated with using a UAS was taken from previous investigations [29,30].

One of the variables introduced in Equation (4) is defined in Table 5 as the "ease of use" of the UAS. This proposed metric was previously discussed in Section 6.2. As this metric has not been accepted by the UAS community, it does not need to be included in the calculation of the cost of using a UAS. The ease of use metric is simply a scalar which can be used to express the decreased or increased amount of time needed to complete a task based on the particular UAS in question.

It should also be noted that the number of distribution poles was divided by three before being used in the above equations. This division was implemented because of the comments made during one of the interviews discussed in Chapter 3.

6.4. CONSIDERATION OF OTHER COSTS

The cost of maintenance was not considered because many UAS, and in particular the UAS chosen, require little to no maintenance. The only suggested maintenance is a preventative maintenance check on all screws, bearings, motors, props, and batteries. It is also suggested that the body of the UAS should be visually inspected for cracks or other damage, particularly if the UAS has been dropped [36]. Of course, the UAS chosen as options were selected in part for their durability; if additional UAS were used, their maintenance costs may be higher and would therefore need to be calculated.

The lifetime of the UAS, in this program, is assumed to be one year. While it is widely supposed that the lifetime of the UAS in question will be closer to four years [37], the manufacturer warranty of the UAS only lasts for up to 12 months, and only for certain parts [38]. Thus, the lifetime of the UAS was assumed to be only one year.

In a similar vein, the insurance cost of UAS was not included in this model. In the United States, it is not required for a UAS to be covered by insurance, no matter how prudent it would be for the company flying the UAS [39]. However, insurance is required in some other countries, and it would be a prudent investment for any company wishing to use a UAS in its operations [39,40]. Obviously, the cost of insuring any equipment will vary depending on the training of the operators, the intended use of the equipment, and the maintenance plan of the equipment, but it has been suggested that a commercial insurance policy for one of the UAS options used in this model could cost as little as $1,350.00 per year [40].

Finally, the cost of training the UAS operator is not included in this model. It is currently required by the FAA that a licensed pilot be the operator of any commercially-UAS. This additional certification requirement is reflected in the higher personnel cost used in Equation (12). Should a municipal utility company decide to train one or more of their employees as a licensed pilot, this personnel cost may be expected to decrease. The cost of such training is expected to be $6,000.00 per person, not including the cost of wages for that person during their training [41].

6.5. SENSITIVITY ANALYSIS

In an effort to determine the robustness of the model created, a one-factor-at-a-time (OFAT) sensitivity analysis was applied in a manner similar to that described in Section 5.5. This type of analysis allows for the exploration of the effects of each factor on the overall cost of the inspection completed by UAS.

Each factor analyzed is displayed below in a graph comparing the factor to the total cost of inspecting the system. A line of best fit is displayed for each relationship. In this case, a steep slope indicates a high level of sensitivity to the factor in question, while a gentler slope indicates a lower level of sensitivity. The graph for each analysis is accompanied by a discussion of the line of best fit and the significance of the slope of that line.

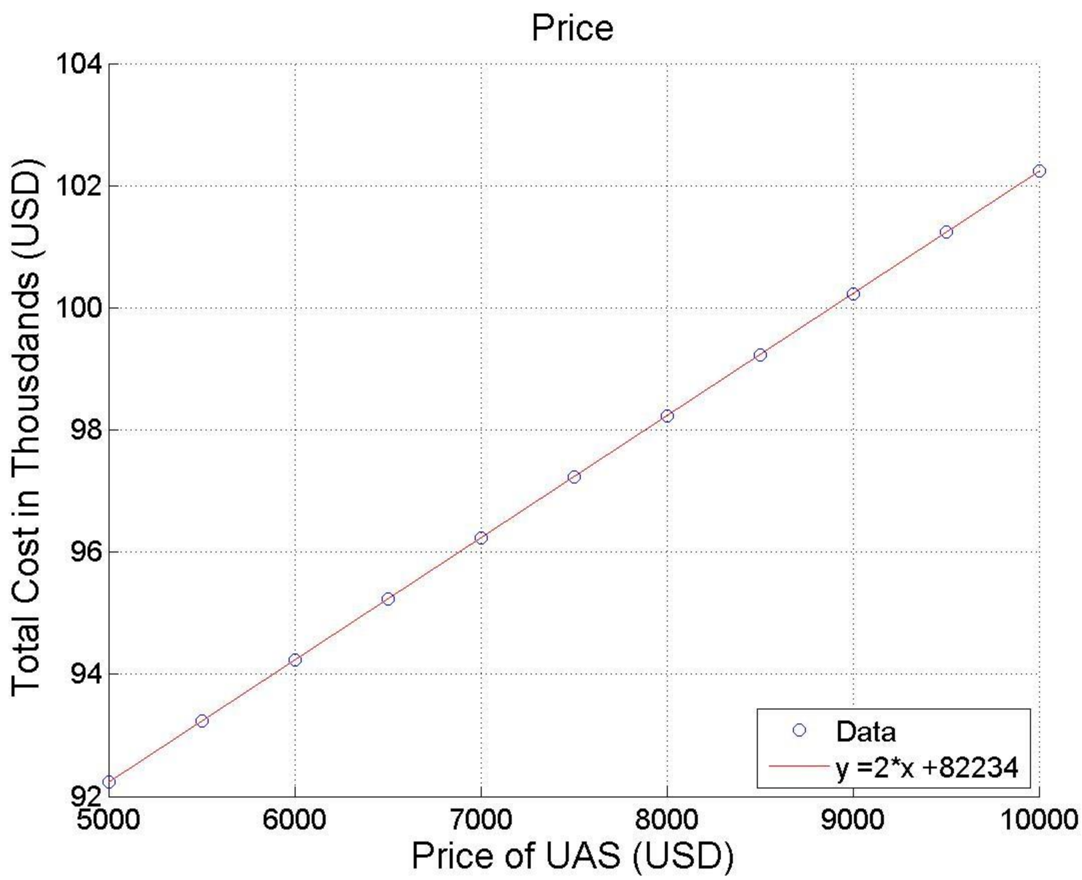

Figure 6: Effects of Changing UAS Price on Costs of UAS Inspection

For the evaluation shown in Figure 6 above, the sensitivity of the cost of completing an inspection using UAS to the cost of the UAS was investigated. From the slope of the line of best fit, it is clear that the overall cost is reasonably sensitive to the price of the UAS. The large intercept implies that much of the cost of the system comes not from the price of the UAS, but rather from other costs, such as the personnel cost. This line of fit has an R-squared value of 1.00, meaning that there is no error between the line of best fit and the data points.

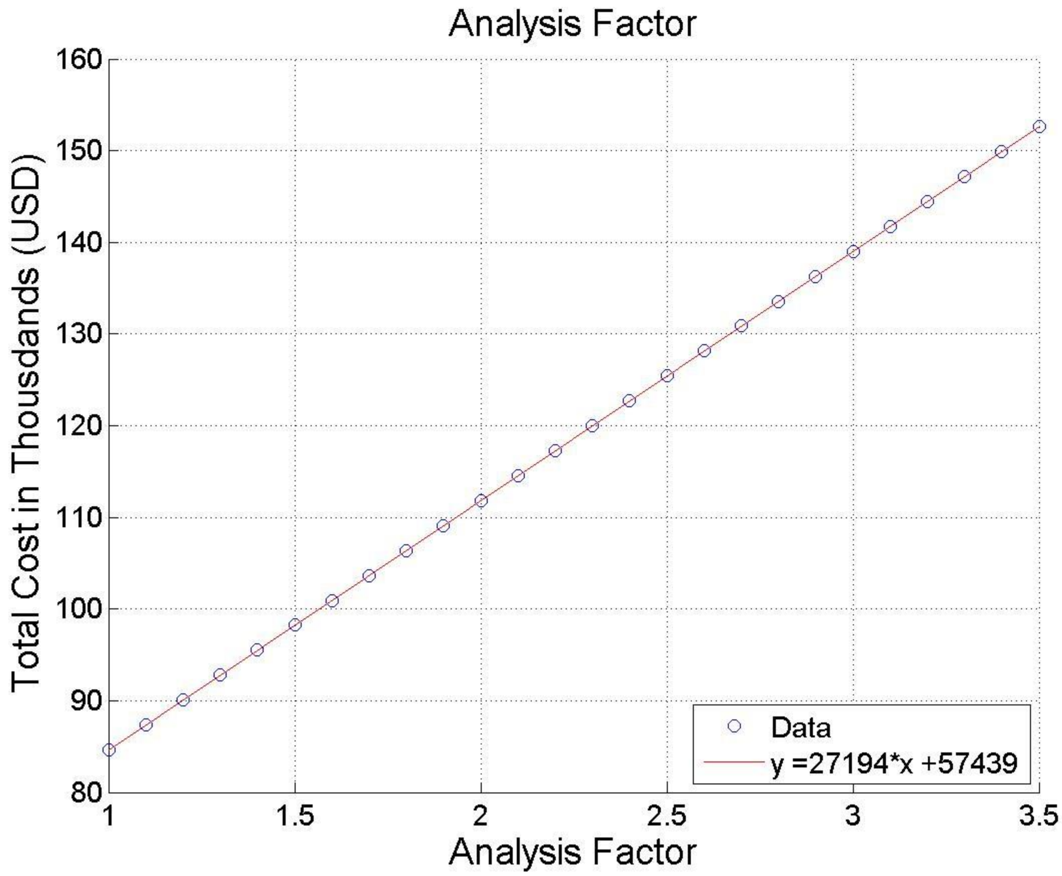

Figure 7: Effect of Changing Analysis Factor on Costs of UAS Inspection

The analysis factor, as expected, has a highly-sensitive linear relationship with the cost of UAS inspection. This relationship is shown above in Figure 7. As can be seen, changing the analysis factor drastically impacts the overall cost of inspecting the system using UAS. Any extra analysis time would increase the personnel cost of inspecting the system, and would therefore have a significant impact on the total cost. This line of fit has an R-squared value of 1.00, which means that there is perfect correlation between the line of best fit and the data points from which it was generated.

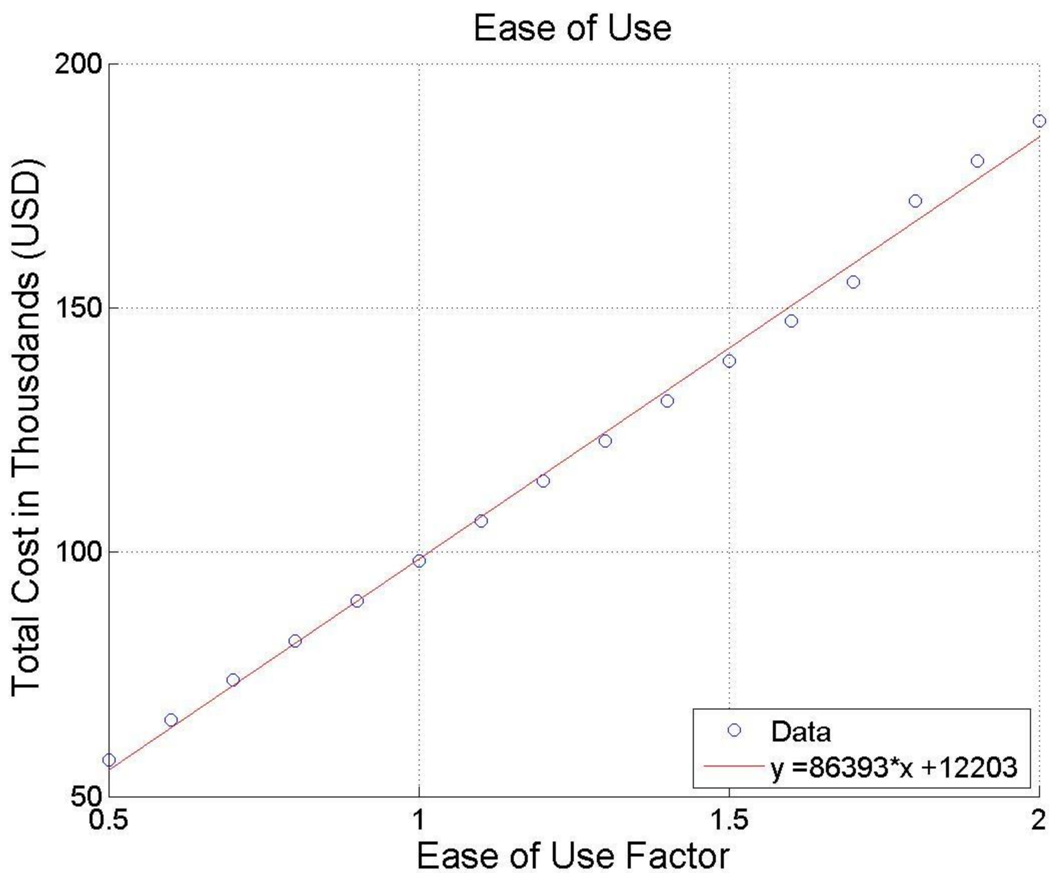

Figure 8: Effects of Varying Ease of Use Factors on Costs of UAS Inspection

Similarly, changing the ease of use factor dramatically impacts the total cost of inspecting the system using UAS, as shown above in Figure 8. The total cost of inspecting the system is even more sensitive to changing the ease of use factor than it is to changing the analysis factor, shown previously in Figure 7. This increased sensitivity is due to the simple fact that the analysis factor only impacts the amount of time spent analyzing the images and video taken, while the ease of use factor impacts the amount of time spent flying the UAS. This impacts the number of UAS needed, the amount of money spent towards the increased personnel costs necessitated by the employment of a licensed pilot, and the increase in risk. This line of fit has an R-squared value of 1.00.

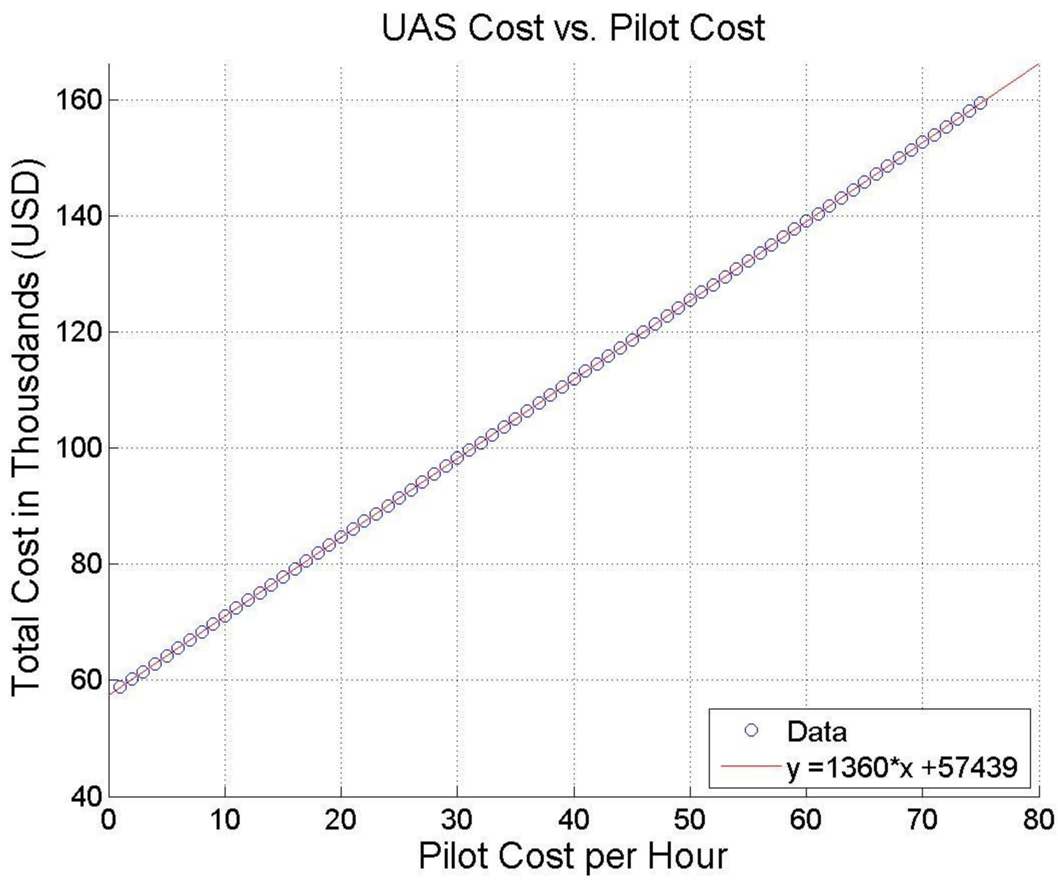

Figure 9: Effects of Changing Pilot Cost on Costs of UAS Inspection

The next relationship investigated was that which exists between the changing personnel cost incurred by employing a licensed pilot and the changing overall cost of inspections using UAS. The results of this investigation are shown in Figure 9, above. Clearly, the cost of inspections is highly sensitive to the hourly personnel cost of the licensed pilot employed.

It should be noted that this cost analysis does take into account the fact that the pilot and visual observer required by the FAA will not be paid at the same rate, as the visual observer is not required to have the same level of licensing as the pilot. The R-squared value for this line of best fit is 1.00.

Some of the remaining factors were not investigated using the OFAT method of sensitivity analysis, due to the nature of their responses. Such factors include the charge time of the UAS, the flight time of the UAS, and the distance of the UAS from the pole-top assembly. These factors were not assessed using OFAT analysis because the corresponding changes in the total cost would result in a stepped response rather than a linear one. The stepped response would exist due to the practice of rounding to the nearest integer which is shown in Equations (5) and (14).

CHAPTER 7 – MODEL RESULTS

The model results discussed in this Chapter were calculated using the methods discussed in Chapter 5 and Chapter 6. As previously discussed, these calculations utilize real data on the current practice of municipal power utilities as well as data collected from the user. This user-provided data is used in identifying the size of the system and the user's inspection preferences.

The specific model used to generate the numerical responses is based on the power distribution system in Washington, North Carolina. It is from this system that the size of the system discussed below was determined.

7.1. MODEL INPUT

Several datasets are required inputs for the model developed above. The first dataset deals primarily with the current practices of municipal utilities. The information contained in this dataset is shown below in Table 6. Each row of the table represents the information for a single task, while each column contains the information for one of the variables discussed in Section 5.2. For this simulation, the size data shown in Column 10 (N_p) was specifically chosen to represent the power distribution system in Washington, North Carolina.

Table 6: Numbers for the Current Methods in Use

Task	t_p	n	P_C	R_d	R_D	C_d	C_D	S_t	N_p	A_n
1	6.50	1	20	0.054	4.00E-05	26.04	920000	2	10400	1.5
2	28.00	1	25	0.054	4.00E-05	26.04	920000	2	10400	1.5
3	6.50	1	20	0.054	4.00E-05	26.04	920000	2	10400	1.5
4	6.50	1	20	0.054	4.00E-05	26.04	920000	2	10400	1.5
5	6.50	1	20	0.054	4.00E-05	26.04	920000	2	10400	1.5
6	6.50	1	20	0.054	4.00E-05	26.04	920000	2	10400	1.5
7	60.00	1	20	0.054	4.00E-05	26.04	920000	2	7	1.5
8	60.00	1	25	0.054	4.00E-05	26.04	920000	2	7	1.5
9	28.00	1	20	0.054	4.00E-05	26.04	920000	2	120	1.5
10	28.00	1	25	0.054	4.00E-05	26.04	920000	2	120	1.5

The second dataset considered contains the UAS option information. The UAS options used in this model are the Nighthawk Thermal P2, which is a modified version of the DJI Phantom 2 [34], and the DJI Phantom 3 [42]. The specifications of the UAS input into the system are shown below, in Table 7.

Table 7: UAS Options Metrics

Price (USD)	***Battery Cost (USD)***	***Flight Time (min)***	***Battery Charge Time (min)***	***Infrared Camera (N/Y)***	***Ease of Use***	***Vertical Field of View (°)***	***Infrared Vertical Field of View (°)***
7998	*150*	*25*	*45*	*1*	*1*	*55*	*23*
1259	*150*	*23*	*45*	*0*	*1*	*55*	*0*

These UAS options were chosen for multiple reasons. First, these UAS are made by the same manufacturer, DJI, and are both considered to be high-quality options which are extremely durable. Second, the two UAS considered are very similar systems; they are the same make, but different models. Finally, these UAS were considered because all of the necessary information was readily available.

The final dataset used in this model reflects the user preferences discussed in Section 5.1. For this simulation, it was assumed that the user would be interested in all tasks, resulting in the preference set shown in Table 8 below.

Table 8: Municipality Task Preferences

Task 1	***Task 2***	***Task 3***	***Task 4***	***Task 5***	***Task 6***	***Task 7***	***Task 8***	***Task 9***	***Task 10***
1	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*

7.2. ASSESSED COSTS

The resultant cost of current methods of inspection, using the numbers generated and displayed in Table 6, is shown below in Table 9. The cost is displayed as “cost per task”.

Table 9: Cost of Current Methods

Task	***Total Cost***	***Adjusted Cost***
1	*$ 15,038.02*	*$ 15,038.02*
2	*$ 80,958.49*	*$ 0.00*
3	*$ 15,038.02*	*$ 15,038.02*
4	*$ 15,038.02*	*$ 15,038.02*
5	*$ 15,038.02*	*$ 15,038.02*
6	*$ 15,038.02*	*$ 15,038.02*
7	*$ 280.27*	*$ 280.27*
8	*$ 350.27*	*$ 350.27*
9	*$ 2,242.14*	*$ 2,242.14*
10	*$ 2,802.14*	*$ 2,802.14*
Total	*$ 161,823.39*	*$ 80,864.90*

The total cost of completing these inspections, as highlighted in Table 9, is over one hundred thousand dollars. However, it is important to note that approximately half of this cost comes from Task 2, which is defined in Table 1 as checking the pole-top assemblies of distribution lines using infrared imaging. This task is typically not completed by municipal utilities. Excluding that cost, the total becomes a much smaller number, shown in the third column of Table 9. It should be noted here that, as discussed in Section 5.4, this value has been confirmed as correct by the Washington Electric Utility.

The cost of using the UAS for inspection, based on the UAS specifications shown in Table 7, is broken down into two different types of costs. The first type of cost, displayed in

Table 10 below, shows the cost of using each UAS for each particular task. This cost break-down does not include the equipment cost of purchasing the UAS or any peripheral equipment, and is separated into two different columns to demonstrate how the costs differ between the two UAS options.

Table 10: Cost of UAS Use

Task	***Cost of Using UAS Option 1***	***Cost of Using UAS Option 2***
1	*$ 8,326.10*	*$ 8,326.10*
2	*$ 6,938.42*	*$ 80,958.49*
3	*$ 8,326.10*	*$ 8,326.10*
4	*$ 8,326.10*	*$ 8,326.10*
5	*$ 8,326.10*	*$ 8,326.10*
6	*$ 8,326.10*	*$ 8,326.10*
7	*$ 140.09*	*$ 140.09*
8	*$ 140.09*	*$ 350.27*
9	*$ 720.46*	*$ 720.46*
10	*$ 480.31*	*$ 2,802.14*
Total	*$ 50,049.85*	*$ 126,601.14*

It should be noted that the cost of using UAS Option 2 for Tasks 2, 8, and 10 is the same as the cost of using current methods for those same tasks. These tasks, it should be noted, all require the use of an infrared camera. As the second UAS option does not have an infrared camera, this option would still rely on current methods for an infrared inspection of the power distribution system.

7.3. SOLUTION GENERATION

Once all of the costs per task have been identified for each UAS option, as shown in Table 10, the equipment needs for the system are calculated. First, the needs of the system are identified and, if necessary, broken into two distinct selections. If a user desires a solution with infrared imagining capabilities as well as one with the ability to capture color images, then the tasks list shown in Table 1 is split into two sections: tasks which require an infrared camera, and tasks which do not. For each task set, Equation (13) is used to determine the number of UAS needed for those tasks. Equation (14) is then used to determine the number of batteries needed for each UAS purchased, and Equation (15) is used to calculate the total equipment cost for each task set with either UAS option.

At this point, it is possible to calculate the total cost of both task sets, including the cost of equipment and the cost of completing the tasks in the set, for either UAS option. After this summation is completed, the lowest-cost alternative is selected for each task set. The resulting cost per task is shown below, in Table 11.

Table 11: Cost of UAS Solution per Task

Task	***Cost of Solution***
1	*$ 8,326.10*
2	*$ 6,938.42*
3	*$ 8,326.10*
4	*$ 8,326.10*
5	*$ 8,326.10*
6	*$ 8,326.10*
7	*$ 140.09*
8	*$ 140.09*
9	*$ 720.46*
10	*$ 480.31*
Total	*$ 50,049.85*

The solution proposed in this scenario is described by Table 12, below. This table shows the number of UAS and batteries which should be purchased from each of the two UAS options, as well as the cost of each piece of equipment.

Table 12: Proposed Solution and Equipment Cost

	Option 1	***Option 2***
Number of UAS	*1*	*1*
Cost of UAS	*$ 7,998.00*	*$ 1,259.00*
Number of Batteries	*2*	*2*
Cost of Batteries	*$ 150.00*	*$ 150.00*
Cost	*$ 8,298.00*	*$ 1,559.00*
Total Cost	*$ 9,857.00*	

These costs are used in the calculation of the difference in costs between the two methods, discussed further in the following section.

7.4. DIFFERENCE IN COSTS

Combining the UAS cost data from Table 11 and Table 12 with the adjusted current cost data from Table 9, we can see in Table 13 that the total cost of using UAS to inspect the power distribution system is less than the cost of completing the inspection using current methods. Furthermore, using UAS means that the inspection is more effective, as it includes the inspection of all pole-top assemblies with infrared imaging.

Table 13: Adjusted Cost Comparison

Method	***Cost of Inspection***
Current Method (Adjusted)	*$ 80,864.90*
UAS Inspection	*$ 59,906.85*
Difference in Cost	*$ 20,958.05*

This results in the municipality spending only 74.1% of the amount they would typically spend on a system inspection.

It should be noted that if the non-adjusted cost data from Table 9 is used, an even more impressive amount is saved by switching to a UAS-based inspection. However, as discussed previously, this amount is unrealistic and does not take into account the fact that many municipalities do not currently complete all of the desired tasks during a system inspection.

7.5. COMPARISON OF SYSTEMS

It is important to note that these results only reflect the impact of implementing UAS-based inspection in one example system. A comparison of a variety of systems was also completed, to demonstrate the ability of the code created over a range of systems. The analysis was completed on the systems shown in Table 14 below.

Table 14: Systems Investigated in Comparison of Savings

System	***Distribution Poles***	***Substations***	***Transmission Poles***
1	*3,510*	*0*	*0*
2	*10,400*	*7*	*120*
3	*47,337*	*31*	*33*
4	*24,174*	*19*	*0*
5	*15,624*	*12*	*819*
6	*31,000*	*14*	*504*
7	*1,200*	*3*	*0*
8	*2,100*	*1*	*0*
9	*44,000*	*15*	*4,000*

The size data displayed in Table 14 was collected through the interviews discussed in Chapter 3 and the survey discussed in Chapter 4. These municipality sizes were input into the model discussed previously with the same preferences as shown in Table 8 and with the same model, size excluded, as displayed in Table 6.

The results of this analysis are displayed below in Figure 10, which displays the cost of inspecting the system with current inspection methods as well as the cost of inspecting the system using UAS-based methods.

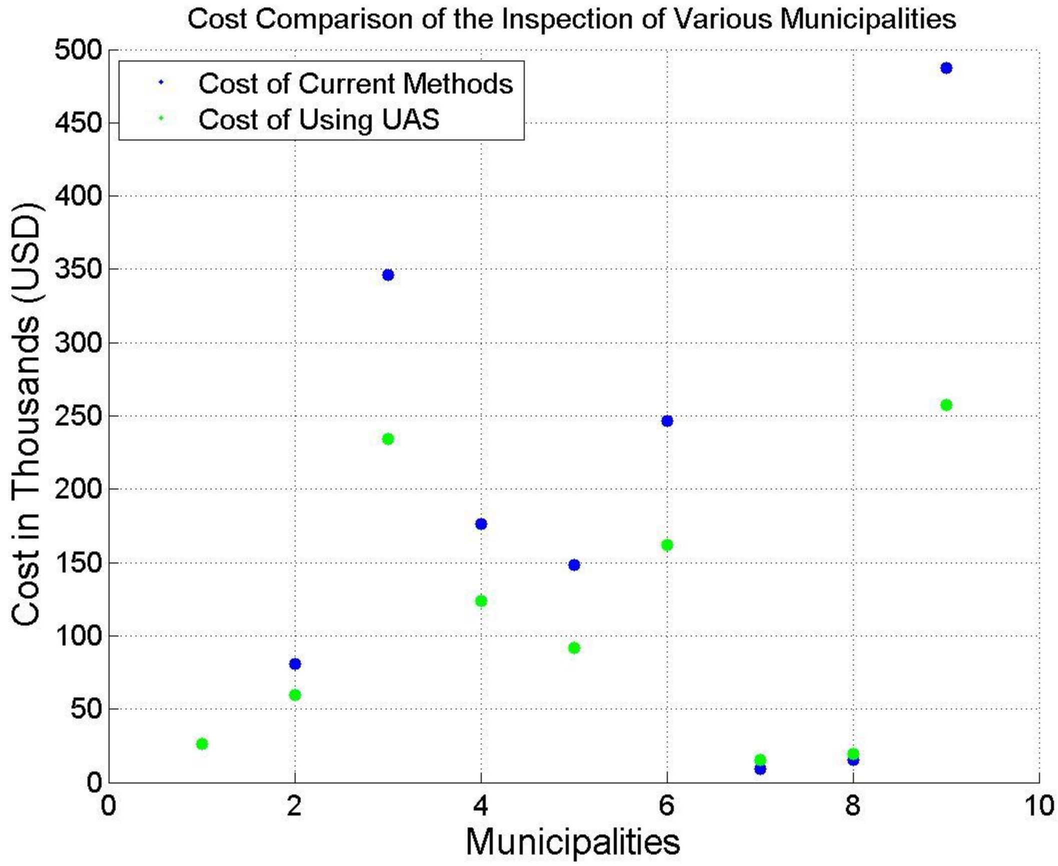

Figure 10: Cost Comparison of the Inspection of Different Municipalities

It can clearly be seen from Figure 10 that larger systems, such as Systems 3 and 9, can save large amounts of money by implementing a UAS-based inspection system. However, smaller systems, including Systems 1, 7, and 8, will most likely lose money by implementing such an inspection scheme. This conclusion is further supported by Figure 11, below.

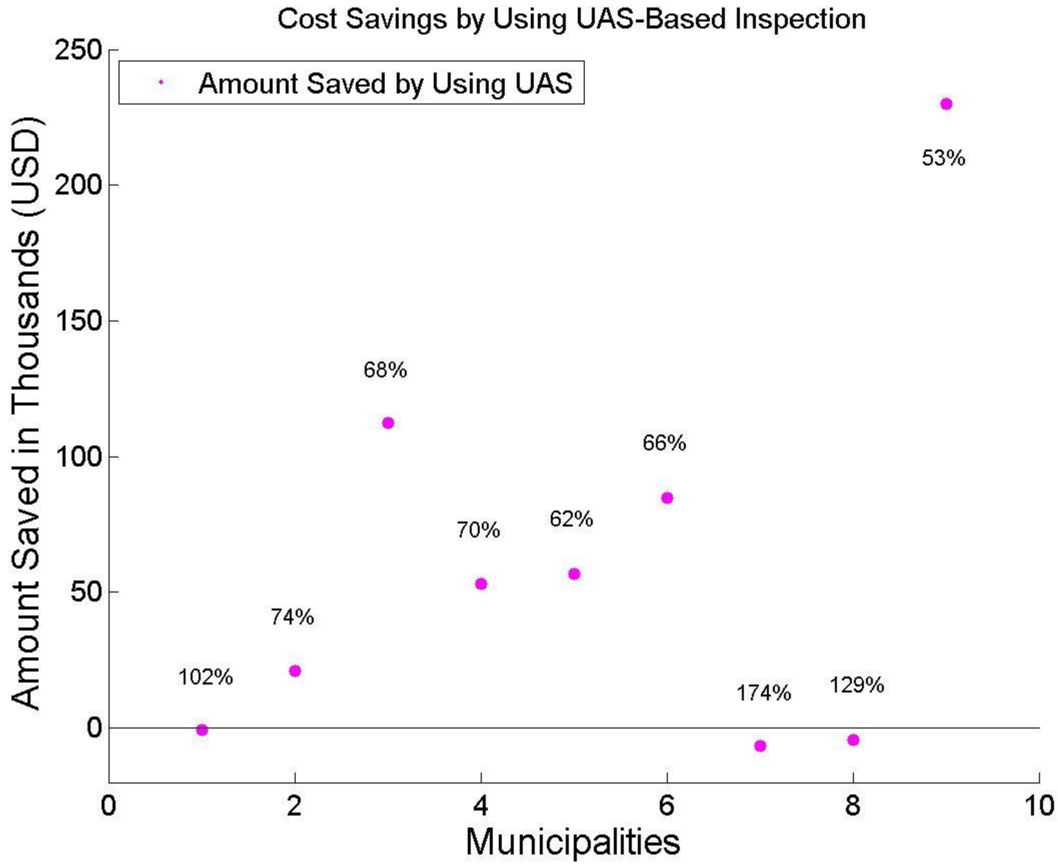

Figure 11: Cost Savings Generated by Implementing UAS-Based Inspections

This image displays not only the amount saved by each municipality by transitioning to UAS-based inspections, but also the percentage of the current inspection budget which would be spent on such an inspection. While there is not an inversely proportional relationship between percentage of budget spent and size of the municipality, it is clear that the more a municipality spends on its current inspections, the more likely it is to benefit from transitioning to UAS-based inspections.

CHAPTER 8 – CONCLUSION

As shown in Table 13 and Figure 11, a significant amount of money can be saved by a municipal utility company switching from current methods of inspection to UAS-based inspections. An exceptionally large cost savings is projected for municipalities which already complete a system-wide inspection with infrared imaging, while a more modest, but still significant amount saved is projected for municipal utilities which do not currently expend those resources.

More than simply saving money would be gained by implementing UAS-based power distribution system inspections. Through customer interviews and surveys, it was discovered that infrared inspections are often skipped for the majority of the power distribution system. With this UAS-based alternative, the effectiveness of the inspections increases, while still decreasing the overall cost.

8.1. RESEARCH QUESTION REVIEW

As discussed in Section 1.3, two questions were the focus of this research project. The first question is as follows:

Research Question 1: How could UAS be used by the municipal power industry?

This question was pursued through brainstorming, research, and interviews with customers. Through these methods, several potential uses were discovered and discussed. However, it was determined that UAS could best be used to assist the municipal power industry by being implemented as a tool used in power distribution system inspection.

Through further research and interviews, a specific task list was derived which related to the use of UAS as an inspection tool. This task list can be found in Table 1.

The second research question addressed the effectiveness of using UAS for the tasks identified. The question follows:

Research Question 2: When should UAS be used by the municipal power industry?

This research question was addressed by developing a method of calculating the cost and effectiveness of utilizing UAS to complete the tasks selected. The simple conclusion to this question is that UAS should be used when the municipal utility would financially benefit from using UAS. With the code created through this research, determining the financial benefit a UAS can bring to a utility company is a very simple and straightforward task.

8.2. RECOMMENDATIONS FOR FUTURE RESEARCH

This research explores the foundations of an interesting study, which could be continued through further investigation of the same goals, or could be expanded upon in a variety of ways.

8.2.1 EXTENSION OF PROJECT

There are two direct extensions of this research which should be carried out. The first is a series of tests to confirm the calculations and assumptions built into the code which was developed in this research. While the assumptions made herein are defensible and reasonable, a study could (and should) be done to verify and improve the numerical assumptions upon which the code is based.

The second extension of this research can be done by converting the code developed into a Microsoft Excel Add-In. By converting the code to an Excel Add-In, it could be distributed freely to municipalities and other utility companies, which would allow them to use the analysis tool for themselves.

8.2.2 RELATED PROJECTS

This research has unearthed several areas which merit future research. One of these areas which is desperately needed is a universally accepted method of defining the operating specifications of UAS. For many technologies, there is an expected list of specifications. One wouldn't purchase a phone without knowing the number of megapixels of the camera; nor would one purchase a computer without knowing the type of core or operating system. A similarly universal specifications list should exist for UAS. The challenge of determining this universal specifications list, of course, is creating a list that is universally accepted, and does not simply become another competing method of specification definition.

Finally, the potential use of UAS in emergency response situations merits investigation. In this research, this issue only came up as a matter of checking power distribution lines in the case of a natural disaster. However, it is the belief of the researcher that UAS could be used in a variety of emergency response situations, not just those associated with the power distribution industry.

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APPENDICES

APPENDIX A

List of UAS

1. Trigger Composites Pteryx UAV-Lite
2. Roboflight RF70
3. Sonic Modell Falcon
4. TBM UAV2
5. Aeromapper EV2
6. Inspire 1
7. QAV250 Mini FPV Quadcopter RTF – G10
8. Phantom 2 Vision+
9. Phantom 3 Professional
10. BLADE 350 QX3 AP Combo RTF: C-Go2
11. Typhoon Q500+
12. Bebop Drone
13. Alutra Zenith
14. Nighthawk Thermal P2 Aerial Kit
15. Aero-M
16. Flexrotor
17. Nova F6500
18. Nighthawk
19. Skate
20. Puma AE
21. Raven RQ-11B
22. ScanEagle
23. RQ-21 Blackjack
24. Swiper
25. Super Swiper
26. MQ-9 Reaper/Predator B
27. Guardian
28. Gray Eagle
29. Predator C Avenger
30. SkyStinger
31. APEX
32. Cutlass
33. Desert Hawk III
34. Vector P
35. Vector Wing 100
36. Bat 4
37. Super Bat DA-50

38. Maverick
39. Aerosonde Mark 4.7
40. Shadow 200 RQ-7B
41. RQ-4 Global Hawk
42. Spectra
43. Tempest
44. Recon
45. Qube
46. Shrike
47. Bravo 300
48. Alpha 100
49. Indago
50. Nova R8400
51. DP-6XT Whisper
52. K-Max Unmanned
53. SA-400 Jackal
54. MQ-8B Fire Scout
55. MQ-8C Fire Scout

APPENDIX B

City	***Emergency Response***	***Preventative Maintenance***
Fayetteville	*Assessment of damage after hurricanes* *-determine the extent of the damages* *-"would be huge"* *-would need streaming video/data, real time information* *-know the needed materials, would allow planning of material retrieval and general logistics* *-checks to see if poles are down, broken cross-arms, etc.*	
	Ground access is not always available	
	Would need to be able to operate in rain/inclement weather	
	Sending them out from a central location would be ideal *-GPS path planning would probably be better than having someone flying it; it would allow people to focus on other tasks*	
	"We need to have it"… not a contractor's drone, PWC's drone	
	"Quick down and dirty…trying to see what we've got."	*Go right up to the boundaries of Fort Bragg's airspace, in one place are in Fort Bragg's airspace*

	Aerial view: could allow logistics planning *-could also check access points?*	*IR scanning – checking for corona* *-would like a side-by-side image of color and IR* *-IR scanning should be done at least once a year* *-transmission is done once a year, distribution isn't done, substations should also be done*
		Paintball guns to shoot grease balls at a transformer switch? *-takes half a day to kill each switch and grease it* *-should be done once or twice a year*
		Pull fuses?
		Missing/broken ground wires – copper theft? (not very likely)
		For maintenance – a hover-capable drone would probably be best
		Gibb-Smith fiber-optic line; where something's been shot
		Check right-of-ways for encroachment *-check right-of-ways for vegetation* *-possibly use a drone to put down herbicide?* *-they currently use a manned skid to put down herbicide*
		Vegetation maintenance – fly over of underground systems? *-some areas do not have a clear-cut right of way, there could be visibility problems*
		LiDAR to check sag on lines and distance to ground and vegetation clearances, as well as any other type of clearances worth checking (clearances between distribution lines

		and cable overhead lines, etc.)
		Color image would be needed, or at least a great advantage
		Check the streetlights to see if they are on or off
		Check for coronas around damaged insulators, etc.
	Using a drone as a "first responder" to go check out an issue and send additional data back so people could know what's going on, what materials are needed, etc.	
	Would allow a much more effective and efficient response to an outage; wouldn't necessarily decrease the time, but would definitely increase efficiency	
		Voltage check on the lines? – secondary lines, going into homes, typically, but the meter system should be able to do this most of the time
		IR thermography over switches, especially – the problem is generally heat
		GIS system is supposed to give you the information of what the system looks like…
		Get rid of birds so they don't nest on poles, have it put out a frequency or something to discourage them
	Programmable GPS routes could be very helpful	*Programmable GPS routes could be very helpful*
	Multi-use for municipal utilities *--sewage leaks?* *Owning vs. leasing* *$350/hour for each crew (equipment and men)*	

	$100 to roll a two-man service crew

City	***Emergency Response***	***Preventative Maintenance***
Washington	*Close to the river, a lot of things are radial*	
	It's all about assessment – until you know the resources you need, the response is difficult	
	Some areas may be inaccessible due to flooding, whether it's an area we serve or not	
	Largest problem isn't usually flooding, but debris	*Main transmission line is radial, it's extremely important*
		You just have to get eyes on the transmission lines, but it can be very difficult to get to
		Inspection of switches with IR
		Anything that isn't working correctly is a danger to employees
		Substation – there's a limited area they can't see, can't see a routine need (maybe once or twice a year), maybe only 10% of the structure you can't get to fairly easily, would only be a short duration inspection
	Assessment from an aerial view allows a prioritization of work load as well as a true picture of what needs to be done; it allows hospitals and key circuits to be prioritized over other areas	*Save time and money with right-of-way inspections* *-follow up with herbicide spraying, tree crews, etc.*
	Helps in decision making of where your resources (people) need to go	
		Switches – thermal imagery done annually, costs about $3000/year, doesn't cover everything but does cover the main switches
		You really can't see everything from ground level, you either have to be far

		away or you have to only see the bottom
		Good usage: short range, still images mostly, video not a huge deal for the most part
		Check poles for woodpecker holes and rot
		Interchangeable components might be a good idea; it allows a lighter payload, but no combination
	Programmable GPS routes could be very helpful	*Programmable GPS routes could be very helpful*
		Mapping system to check transformer and nameplate data – collect coordinate location and asset management *-3000-4000 transformers, just need something to get the coordinate information and asset management information* *-nameplates are about the size of a playing card or post-it note*
		Ideally, a 30-45 minute flight time on a drone
		Checking for rot or hollowness about a foot above the ground, usually check by hitting it with a hammer
		Grease balls – not a very effective idea
	Would be okay with their people learning how to fly the drones. *A two-man bucket truck costs about $600/day, or about $1000/day for a taller truck.* *Service area of 280 sq. miles, ~400 miles of lines* *Something where you can protect people, potentially reduce the risk of people*	

City	Emergency Response	Preventative Maintenance
Tarboro	*Currently, the assessments are done by patrol, often during storms*	
	Not a priority because the town area is so small	
		Doesn't have the equipment to check transmission lines, for damage or preventative maintenance.
		Takes about 15 minutes to park the truck and put on gear and get up in the bucket.
		Check damages, crack in insulators *-you'll have to look under the insulators to be sure you can see it* *-sometimes have to touch the distribution line to be sure that it's attached properly*
		Lines are checked every year from the ground or from a bucket (only if there's a visual issue from the ground) *-poles and cross arms are checked for deterioration, cracks, etc.* *-check transformers, wires, make sure everything looks okay* *-usually takes 2+ weeks, with four to six crews*
		Substations are checked visually monthly, which would result in a much easier view
		The cost of IR imaging would probably outweigh the benefits, but it's worth looking into.
		Only has a half mile of transmission line, but not the equipment to check it; it's difficult to access because it's so high off the ground.

	Main problems are flooding and ice storms, but there have been tornadoes. All result in massive damage, but most of it is tree damage *-trees knock down lines or branches fall out of the trees*	
	Ride out to assess areas, then decide how to get the most people's power back on as quickly as possible *-there are main circuits which are a priority*	
	Buckets shouldn't be used in wind speeds above 35 mph; circuits aren't checked in severe thunderstorms.	
	There are a lot of "back alleys" which have pretty thick foliage; sometimes the trees are pretty close to the lines, probably between 5 feet and 10 feet clearance on either side.	
		Update GIS system; system maps and inventory/asset management.
	FEMA is beginning to require images of storm damage to give assistance funding.	*Drones would need to find serial numbers, as in Washington.*
		Line inspections would be the priority – it would be the most realistic use, as it would likely be a more frequently useable type of service.
	Believes there won't be a difference other than size; priorities should be the same across all regions. *If the eastern regions have problems, people from the western regions will come help and vice versa.* *It costs about $1800/year to get the critical components of the system checked with IR imaging.*	

APPENDIX C

C.1. SURVEY LOCATION

The survey used in this research can be found at the following URL:

https://ncsu.qualtrics.com//SE/?SID=SV_eM5tXNAFxW2B7Zb

C.2. SURVEY QUESTIONS

The following is an exact copy of the questions presented in the survey.

Q56. Consent Form

Q55.

What are some general things you should know about research studies?

You are being asked to take part in a research study. Your participation in this study is voluntary. You have the right to be a part of this study or to choose not to participate. The purpose of research studies is to gain a better understanding of a certain topic or issue. You are not guaranteed any personal benefits from being in a study. Research studies also may pose risks to those that participate. In this consent form you will find specific details about the research in which you are being asked to participate. If you do not understand something in this form it is your right to ask the researcher for clarification or more information.If at any time you have questions about your participation, do not hesitate to contact the researcher(s) named below.

What is the purpose of this study?

The purpose of this study is to collect information regarding the cost and frequency of various tasks which are completed during the inspection of power distribution lines.

What will happen if you take part in the study?

If you agree to participate in this study, you will be asked to answer a series of questions about several tasks. The tasks are as follows:

- Check Pole-Top Assemblies, Color Photography
- Check Pole-Top Assemblies, IR Photography
- Check Pole-Top Assemblies, Nameplate Data
- Check Pole Condition
- Pole and System Mapping
- Check Right-of-Way Clearance
- Check Substations, Color Photography
- Check Substations, IR Photography
- Check Transmission Lines, Color Photography
- Check Transmission Lines, IR Photography

There may be as many as five questions for each task or as few as one. In total, the survey should take less than an hour, and will be completed online through Qualtrics.

Risks
There are no risks associated with this survey.

Benefits
The information gathered by this survey will be used to create a value model comparing the cost and effort of completing these tasks using current methods to the cost and effort that would be required with different methods. This knowledge will certainly be used in this value study, and may be used in future studies as well.

Confidentiality
The information in the study records will be kept confidential to the full extent allowed by law. Data will be stored securely online through Qualtrics. No reference will be made in oral or written reports which could link you to the study. You will NOT be asked to write your name on any study materials so that no one can match your identity to the answers that you provide.

Compensation
You will not receive anything for participating. However, your participation is greatly appreciated.

What if you have questions about this study?
If you have questions at any time about the study or the procedures, you may contact the researcher, Elizabeth M. May, at emmay@ncsu.edu, or (910)-233-1927.

What if you have questions about your rights as a research participant?
If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Deb Paxton, Regulatory Compliance Administrator at dapaxton@ncsu.edu or by phone at 1-919-515-4514.

Consent To Participate
"I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may choose not to participate or to stop participating at any time without penalty or loss of benefits to which I am otherwise entitled."

I Agree to Participate	I Do Not Agree
◉	○

Q57. Demographic Information

Q1. Your participation is very important.

This questionnaire asks a series of simple questions regarding the resources used by municipalities in the assessment of power systems. Your time and input is greatly appreciated, and you should know that all of the information collected on further pages will be used to improve the efficiency of the assessments discussed.

Q2. What is the title of the company for which you work?

Q3. Where is that company located?

Q61. How much area (sq. miles) is managed by your company?

Q62. How many miles of distribution line does your company manage?

Q70. Approximately how many poles are there per mile of distribution line?

Q63. How many miles of transmission line does your company manage?

Q71. Approximately how many poles are there per mile of transmission line?

Q64. How many substations does your company manage?

Q58. Check Pole-Top Assemblies, Color Photography

Q4. What resources do you need to check pole-top assemblies (color photography)?

Q5. How much time does it take for you to check pole-top assemblies (color photography)? Please give a reasonable estimate for the time it takes to check a single pole, including setup. Please give your answer in minutes.

Q72. How much of that time is setup? Please give your answer in minutes.

Q6. How much does it cost to check pole-top assemblies (color photography)? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

Q7. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

Q8. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

- [ ] Check Pole-Top Assemblies, IR Photography
- [ ] Check Pole-Top Assemblies, Nameplate Data
- [ ] Check Pole Condition
- [ ] Pole and System Mapping
- [ ] Check Right-of-Way Clearance
- [ ] Check Substations, Color Photography
- [ ] Check Substations, IR Photography
- [ ] Check Transmission Lines, Color Photography
- [ ] Check Transmission Lines, IR Photography

Q59. Check Pole-Top Assemblies, IR Photography

Q9. What resources do you need to check pole-top assemblies (IR photography)?

Q10. How much time does it take for you to check pole-top assemblies (IR photography)? Please give a reasonable estimate for the time it takes to check a single pole, including setup. Please give your answer in minutes.

Q73. How much of that time is setup? Please give your answer in minutes.

Q11. How much does it cost to check pole-top assemblies (IR photography)? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

Q12. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

Q13. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

- ☐ Check Pole-Top Assemblies, Nameplate Data
- ☐ Check Pole Condition
- ☐ Pole and System Mapping
- ☐ Check Right-of-Way Clearance
- ☐ Check Substations, Color Photography
- ☐ Check Substations, IR Photography
- ☐ Check Transmission Lines, Color Photography
- ☐ Check Transmission Lines, IR Photography

Q60. Check Pole-Top Assemblies, Nameplate Data

Q14. What resources do you need to check pole-top assemblies (nameplate data)?

Q74. How much of that time is setup? Please give your answer in minutes.

Q15. How much time does it take for you to check pole-top assemblies (nameplate data)? Please give a reasonable estimate for the time it takes to check a single pole, including setup. Please give your answer in minutes.

Q16. How much does it cost to check pole-top assemblies (nameplate data)? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

Q17. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

Q18. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

- ☐ Check Pole Condition
- ☐ Pole and System Mapping
- ☐ Check Right-of-Way Clearance
- ☐ Check Substations, Color Photography
- ☐ Check Substations, IR Photography
- ☐ Check Transmission Lines, Color Photography
- ☐ Check Transmission Lines, IR Photography

Q65. Check Pole Condition

Q19. What resources do you need to check pole condition?

Q20. How much time does it take for you to check pole condition? Please give a reasonable estimate for the time it takes to check a single pole, including setup. Please give your answer in minutes.

Q75. How much of that time is setup? Please give your answer in minutes.

Q21. How much does it cost to check pole condition? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

Q22. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

Q23. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

- [ ] Pole and System Mapping
- [ ] Check Right-of-Way Clearance
- [ ] Check Substations, Color Photography
- [ ] Check Substations, IR Photography
- [ ] Check Transmission Lines, Color Photography
- [ ] Check Transmission Lines, IR Photography

Q66. Pole and System Mapping

Q24. What resources do you need for pole and system mapping?

Q25. How much time does it take for you to record pole and system mapping information? Please give a reasonable estimate for the time it takes to check a single pole, including setup. Please give your answer in minutes.

Q76. How much of that time is setup? Please give your answer in minutes.

Q26. How much does it cost to record pole and system mapping information? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

Q27. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

Q28. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

- ☐ Check Right-of-Way Clearance
- ☐ Check Substations, Color Photography
- ☐ Check Substations, IR Photography
- ☐ Check Transmission Lines, Color Photography
- ☐ Check Transmission Lines, IR Photography

Q67. Check Right-of-Way Clearance

Q29. What resources do you need to check right-of-way clearance?

Q30. How much time does it take for you to check right-of-way clearance? Please give a reasonable estimate for the time it takes to check your system, including setup. Please give your answer in minutes, or indicate if another time frame is more reasonable.

Q77. How much of that time is setup? Please give your answer in minutes, or indicate if another time frame is more reasonable.

Q31. How much does it cost to check right-of-way clearance? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

Q32. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

Q33. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

- ☐ Check Substations, Color Photography
- ☐ Check Substations, IR Photography
- ☐ Check Transmission Lines, Color Photography
- ☐ Check Transmission Lines, IR Photography

Q68. Check Substations, Color Photography

This question was not displayed to the respondent.

Q34. What resources do you need to check substations (color photography)?

This question was not displayed to the respondent.

Q35. How much time does it take for you to check substations (color photography)? Please give a reasonable estimate for the time it takes to check a single substation, including setup. Please give your answer in minutes, or indicate if another time frame is more reasonable.

This question was not displayed to the respondent.

Q78. How much of that time is setup? Please give your answer in minutes, or indicate if another time frame is more reasonable.

This question was not displayed to the respondent.

Q36. How much does it cost to check substations (color photography)? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

This question was not displayed to the respondent.

Q37. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

This question was not displayed to the respondent.

Q38. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

This question was not displayed to the respondent.

Q69. Check Substations, IR Photography

This question was not displayed to the respondent.

Q39. What resources do you need to check substations (IR photography)?

This question was not displayed to the respondent.

Q40. How much time does it take for you to check substations (IR photography)? Please give a reasonable estimate for the time it takes to check a single substation, including setup. Please give your answer in minutes, or indicate if another time frame is more reasonable.

This question was not displayed to the respondent.

Q79. How much of that time is setup? Please give your answer in minutes, or indicate if another time frame is more reasonable.

This question was not displayed to the respondent.

Q41. How much does it cost to check substations (IR photography)? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

This question was not displayed to the respondent.

Q42. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

This question was not displayed to the respondent.

Q43. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

This question was not displayed to the respondent.

Q70. Check Transmission Lines, Color Photography

This question was not displayed to the respondent.

Q44. What resources do you need to check transmission lines (color photography)?

This question was not displayed to the respondent.

Q45. How much time does it take for you to check transmission lines (color photography)? Please give a reasonable estimate for the time it takes to check your system, including setup. Please give your answer in minutes, or indicate if another time frame is more reasonable.

This question was not displayed to the respondent.

Q81. How much of that time is setup? Please give your answer in minutes, or indicate if another time frame is more reasonable.

This question was not displayed to the respondent.

Q46. How much does it cost to check transmission lines (color photography)? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

This question was not displayed to the respondent.

Q47. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

This question was not displayed to the respondent.

Q48. Does, should, or could this assessment already include any of the following? Please select all which apply and add any amendments to resources, time, or cost. Please exclude any assessments which should be done more or less frequently.

This question was not displayed to the respondent.

Q71. Check Transmission Lines, IR Photography

This question was not displayed to the respondent.

Q49. What resources do you need to check transmission lines (IR photography)?

This question was not displayed to the respondent.

Q50. How much time does it take for you to check transmission lines (IR photography)? Please give a reasonable estimate for the time it takes to check your system, including setup. Please give your answer in minutes, or indicate if another time frame is more reasonable.

This question was not displayed to the respondent.

Q82. How much of that time is setup? Please give your answer in minutes, or indicate if another time frame is more reasonable.

This question was not displayed to the respondent.

Q51. How much does it cost to check transmission lines (IR photography)? This estimate may be most accurate as an hourly, daily, or per pole cost, but please be sure to specify.

This question was not displayed to the respondent.

Q52. How many times in a year is this assessment done? If this is different than the number of times a year it should be done (or would be preferred), please specify that as well.

This question was not displayed to the respondent.

C.3. SUVEY RESPONSES

The responses of the survey are recorded below, in Table 15. These responses are broken down by question number. Each answer corresponds to one of the questions listed above, in Section C.2.

Table 15: Survey Responses

Question	*Resp. 1*	*Resp. 2*	*Resp. 3*	*Resp. 4*	*Resp. 5*	*Resp. 6*
2	*Power Systems Engineer*	*City of High Point*	*ElectriCities of NC Inc.*	*Laurinburg*	*Rocky Mount Energy Resources*	*Wilson Energy*
3	*Gastonia NC*	*High Point, NC*	*Huntersville, NC*	*Laurinburg, NC*	*Rocky Mount NC*	*Wilson NC*
61	*49*	*50*	*25-50*	*78*	*144*	*374*
62	*474*	*410-dist, 332-ung*	*10*	*100*	*744*	*1200*
70	*51*	*31000*	*1200*	*21*	*21*	*44000*
63	*0*	*28*	*0*	*NA*	*39*	*200*
71	*0*	*18*	*0*	*NA*	*21*	*20*
64	*19*	*14*	*3*	*1*	*12*	*15*
4	*Bucket truck and digital camera*	*We are currently using a camera (ikeGPS)/GPS unit to inventory assemblies and then record them on the GIS (ESRI ArcGIS) system.*	*High resolution photography. Infrared. Visual Inspections.*	*Binoculars, camera, bucket trucks*	*Color photography, aerial lift*	*Bucket truck and lineman*
5	*30*	*10*	*50*	*20*	*25*	*60*
72	*15*	*5*	*35*	*10*	*15*	*10*
6	*67.25 per hour*	*5*	*80*	*32 per pole*	*16.75 per pole labor only*	*100*
7	*as needed*	*once every 7 years*	*1*	*Once every 2 years*	*none, yes*	*1*

8	*3, 4*	*3-9*	*2-8*	*2, 4-8*	*2-10*	*2-10*
9	*NA*	*We currently have a IR camera, the ikeGPS handheld pole data collection camera/software, SpidaCalc, and GIS system.*				
10	*NA*	*10*				
73	*NA*	*5*				
11	*NA*	*565/day*				
12	*NA*	*once every 7 years*				
13		*8, 10*				
14						
15						
74						
16						
17						
18						
19						
20						
75						
21						
22						
23						
24	*Portable GPS device*					

25	*30*					
76	*10*					
26	*25 per hour*					
27	*as needed*					
28						
29	*Scheduled and contracted based on bi-annual schedule*					
30	*NA*					
77						
31						
32						
33						
34	*SCADA system - motion cameras in each substation*					
35						
78						
36						
37						
38						
39	*NA*					
40	*NA*					
79	*NA*					

41	*NA*					
42	*NA*					
43						
44	*NA*		*NA*			
45	*NA*		*NA*			
81	*NA*		*NA*			
46	*NA*		*NA*			
47	*NA*		*NA*			
48						
49	*NA*		*NA*			
50	*NA*		*NA*			
82	*NA*		*NA*			
51	*NA*		*NA*			
52	*NA*		*NA*			