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Benefits and challenges of using unmanned aerial systems in the monitoring of electrical distribution systems

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ABSTRACT

This paper presents a study coming from an academic and industry partnership with the goals of exploring potential uses for UAS in distribution system operation and maintenance, establishing baseline costs and capabilities via equipment field tests, and simulating the cost benefits of increased maintenance. Existing UAS technology is shown to be capable of providing situational awareness for disaster response as well as increasing the number of maintenance inspections and speeding them up.

1. Introduction

The 2017 hurricane season was the 9th most energetic on record and included three major landfalls on the US mainland (Erdman, 2017). The ability of low-cost UAS to traverse areas that sustained severe infrastructure damage, or that had been flooded, aided time sensitive recovery efforts. These efforts included search and rescue following Harvey in Houston (Murphy, 2017), damage assessment to prioritize the distribution of recovery assets (Ziskin, 2017), and helping utilities navigate uncertain terrain to accelerate the repair process (Sydell, 2017). Jacksonville Electric was able to complete inspections of their system within 24 h of Hurricane Irma, and Florida Power and Light (FPL) used UAS to inspect areas unreachable by vehicle to accelerate recovery efforts and facilitate repair crews safety (FAA, 2017). In Puerto Rico, AT&T deployed drones as proxy cellular towers to restore internet service far in advance of traditional recovery methods (Reuters, 2017). The growing technical capabilities of UAS, together with the willingness of the FAA to quickly provide regulatory exemptions for emergency work, suggests that they will become more integral to disaster response and recovery in future events.

This paper assesses the monetary benefits and institutional challenges of introducing UAS for disaster response and scheduled electric infrastructure inspections. There are several existing examples of UAS use in normal utility operations by several companies in Europe (Aeryon Labs Incorporated, 2011; Aibotix International, 2014; Alpiq, 2014; CyberHawk, 2017) and one FAA-authorized pilot project by San Diego Gas & Electric (McNeal, 2014). While UAS adoption has begun, the value proposition for incorporation is less clear. Many of the UAS integration efforts focus on the over 200,000 miles of high-voltage transmission lines in the United States. Yet, distribution lines cover over 6,000,000 miles, and similar benefits of improved system reliability and worker safety would also be expected. This study sought to understand what specific activities would benefit from UAS and the value associated with those capabilities.

The project consisted of three phases. The first phase used employee interviews at three municipal utilities in North Carolina to identify possible UAS roles and desired UAS capabilities/performance. Interview subjects included a variety of stakeholder roles including linemen, engineers, and managers. The second phase involved purchase and flight tests of two UAS systems – a DJI Phantom 3 and a DJI Inspire. These flights explored the learning curve for flying commercial-off-the-shelf products around utility poles to support maintenance-related activities, take color and thermal pictures and video, and identify what could be learned from the pictures and video. Flights were conducted around electrical equipment on NC State's campus and at a Huntersville/Cornelius facility. The final phase used simulations to quantify the value proposition of using UAS to conduct grid inspections.

2. Interviews conducted to identify possible use cases

The first portion of the study consisted of interviews with municipal utilities in North Carolina to understand how UAS might be used in distribution system maintenance. These interviews were arranged with the assistance of partners at ElectriCities, Inc. of North Carolina. Four municipalities were interviewed as part of this research: Fayetteville Public Works Commission (PWC) servicing approximately 80,000 customers (Fayetteville's Hometown Utility, 2018), Washington Electric Utilities serving 12,000 customers and servicing 388 miles of power

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distribution lines (Washington, 2010), Tarboro Electric Utility servicing 5828 measuring meters and 120 miles of power distribution lines (Town of Tarboro, 2016), and finally the Huntersville/Cornelius branch of Electricities Inc. servicing 4000 customers.

Interviews involved at least 6 members from the participating municipality, ranging from lineman to managers. The most excitement about UAS possibilities and questions about capabilities came from the interview with Fayetteville PWC. Two general categories of use were identified: emergency management and preventative maintenance. Descriptions of use for each category, along with quotes from interviews, are discussed in the following sections.

2.1. Emergency management

Enhanced emergency response was described as very desirable. Use of UAS in recovery efforts following Irma, Harvey, and Maria support the interviewee responses. North Carolina is subject to hurricanes, ice storms, and severe thunderstorms that can cause distribution system damage. Additionally, there are non-storm related outages caused by wildlife or accidental damage that are less severe but occur more frequently.

One of the most valuable capabilities provided by UAS after a storm is enhanced situational awareness. This was demonstrated by utility use in Florida (FAA, 2017) and also identified during the interviews. Downed trees, flooded roads, and icy conditions can make it difficult for utility personnel to assess the location and severity of damage. Fayetteville PWC interviewees described the added capability as “huge”. Aerial inspection can be accomplished more quickly and safely to inform the recovery process, which is especially important when damage impacts critical infrastructure like hospitals or shelters. Only one utility (Fayetteville PWC) explicitly expressed the desire for real-time imaging. The other subjects viewed photo and video processing after the drone landed as acceptable, and there was limited interest in having the system deployed in poor weather conditions.

UAS were also seen as possible “first responders” to localized outages. UAS could be used to check sites for damage once an outage is reported. There were two advantages identified with using a UAS as a first responder. First, the presence of the UAS overhead would alert those on the ground that the outage had been detected by the distributor and that a repair team could be expected. Second, photos and videos from the UAS could be used to identify the supplies/equipment needed for the repair thereby increasing efficiency and reducing outage time. This is what was done by Jacksonville Electric and FPL in Florida to speed restoration of service after Hurricane Irma (Florida Power and Light, 2017). Video from FPL operators show that UAS can be used in dense foliage to provide situational awareness about damaged equipment.

2.2. Preventative maintenance

Several opportunities were identified for using UAS in preventative maintenance. Utilities vary in the type and timing of inspections performed on their systems. The interviewees identified the ability for a UAS to help perform more/better inspections, and considered multiple sensor packages as advantageous. At a minimum, access to color images was considered a necessity.

A primary type of surveillance is the inspection of overhead components including transformers, switches, poles, and insulators. The interviewed utilities had various inspection strategies from annual inspections to ad-hoc inspections wherever linemen happen to travel. Estimates for the time to set up a truck with linemen to perform and inspect overhead components ranged from 10 to 45 min per pole. Utility personnel were also excited about the possibility to inspect equipment that is difficult to reach like secondary lines that cross backyards or substations with limited visibility.

Right-of-way management was also identified. Right-of-way inspections typically have a formal timeline and ensure that lines, poles, and equipment are located sufficiently far from vegetation or other encroachments. A 2012 Congressional Research report on Weather-Related Power Outages highlights the importance of tree-trimming schedules and associated inspections as important for the prevention of storm related outages (Campbell, 2012).

Interviewees were most interested in combining UAS mobility with thermal imaging because distribution components often overheat before failing. Replacing components before failure prevents outages and can prevent the need to remediate further damage caused by catastrophic component failure. Most interviewed utilities paid for ground-based annual thermal inspections of major components. Current practice involved inspecting the system at least once a year, and reported costs were between $1800 and $3000, depending on the size of the system. One interviewee stated “you really can’t see everything from the ground level; you either have to be far away or you have to only see the bottom.” Thermal imaging can also be used to identify dead or dying trees bordering the right-of-way (FLIR, n.d.).

A currently unavailable but desired capability is for the UAS to perform autonomous inspections. This is not currently possible due to FAA regulations and UAS duration limits, but remains an attractive future possibility.

3. Flight testing of purchased equipment

The second phase of the project involved purchasing equipment and conducting three different test flights to assess current costs and capabilities. Two different craft were purchased, a DJI Phantom 3 (DJI, n.d.) and a DJI Inspire (DJI, n.d.) with thermal camera attachment. A key selling point of the Inspire 1

The thermal camera purchased was the DJI Zenmuse XT thermal camera (DJI, 2017). Four different lenses can be chosen as the point of purchase (7.5 mm, 9 mm, 13 mm, and 19 mm), and control of the camera allows for temperature spot metering. Photos can also be taken while recording video. Specifications for the two purchased UAS can be found in Table 1.

3.1. Costs

Given the growth of UAS as an industry, the pace of technological advancement for these systems are expected to continue or accelerate. As price and detailed specification information will become quickly dated, this section discusses the types of costs that are likely to be incurred when establishing and maintaining a UAS program.

Current commercial UAS provide most features a utility might desire. Custom software for additional automation or physical modifications involves additional cost, but the price of the example UAS is equivalent to, or less than, the cost of the thermal imaging sensor. As seen in Table 2, the all-in equipment price was on the order of $10,000 including a thermal imaging sensor.

There are several other potential costs that should be considered. There is liability insurance that may have to be purchased to cover the

Table 1
UAS specifications of the systems used in this study.

Specification	DJI Inspire 1	DJI Phantom 3 Pro
Weight with Camera (kg)	3.06	1.28
Max Horizontal Speed (kph)	79	57
GPS Hover Accuracy (m)	Vertical: ± 0.5 Horizontal: ± 2.5	Vertical: ± 0.1 (Vision Positioning) ± 0.5 (GPS Positioning) Horizontal: ± 0.3 (Vision Positioning) ± 1.5 (GPS Positioning)
Max Flight Time (min)	18	23

Table 2
Supplies purchased for the test flights.

Item	Unit price	Quantity purchased
DJI Inspire 1 with Zenmuse XT thermal camera	$8197.00	1
DJI Phantom 3 pro bundle	$999.00	1
iPad mini 4	$629.00	2
iPad mini cases	$21.90	2
iPad mini 4 screen protector	$9.99	2
64GB SanDisk MicroSD card	$18.99	2

risk of equipment damage due to a UAS. Municipalities should also consider the cost associated with educating the public about their UAS use.

Pilot training is likely to be the most time intensive effort required. Control technology in higher end commercial-off-the-shelf systems are advanced enough that a relatively small amount of practice is sufficient for basic videography and crash prevention. However, navigating dense foliage, negotiating optimal imagery range, and remaining outside a live line clearance is more challenging and will require time and training. Larger municipalities may be able to designate an individual or small group to perform all needed inspections, but smaller municipalities may have to add flight training as a collateral lineman duty. Currently a small UAS certification license from the FAA costs $150 and commercial training programs cost from $100 for test preparation to $1500 for flight training with specific UAS (Dart Drones, 2018; Drone Pilot Ground School, 2018).

3.2. *Flight testing*

The first and second flights focused on equipment familiarization and taking images of pole-mounted equipment. Two undergraduate research assistants with minimal flight experience flew the aircraft. There was a 5–10 MPH breeze, but UAS internal stabilization routines compensated effectively. Video display to the iPad Mini made it easy to navigate, and images were not distorted. A suite of test maneuvers was executed and images of nearby pole equipment were taken.

Fig. 1 shows sample pictures from the test flight. The team assessed the ease of capturing images from different angles. This included overhead shots and connection points between electrical equipment. The images selected here are only a few of the many images taken.

Thermal images were also taken, and a subset are shown in Fig. 2. Side shots were judged to be particularly effective. However, when there is no significant temperature differential, it may become difficult to distinguish the equipment, and image post-processing can provide greater clarity. The third test flight was of a distribution subsystem. Multiple videos were taken, capturing gigabytes of data. Fig. 3 shows a transmission corridor right of way and Fig. 4 shows a substation. The substation thermal imagery shows clear temperature differences with energized equipment.

4. Cost and reliability – metrics and simulation

Quantifying the value of a system can be difficult due to the variety of system stakeholders. Yet, when faced with a design problem that has multiple and competing objectives, a decision maker must be able to measure value in a way such that a rational choice can be made between competing alternatives. A fundamental assumption of this investigation is that cost and reliability are the two primary metrics of interest. This study focuses on what residents value, to what degree it is valued, and how those values can be used to quantify what benefit might come from incorporating a UAS program.

4.1. *Grid reliability*

Grid reliability is a topic of national importance. A study commissioned by the White House in 2013 concluded that the average annual cost of power outages caused by severe weather is between $18 billion and $33 billion per year. Years with large storms like 2008 have even higher economic costs with outages estimated to be between $40 billion and $75 billion (Executive Office of the President, 2013). Estimates of this magnitude reveal a significant economic opportunity if grid reliability can be improved.

A 2010 study by the Department of Energy (DOE) focused on preparation for hurricane season suggested that utilities operate a distribution system inspection program, perform aerial patrols of transmission lines, have a program to manage encroachment by vegetation, and deploy additional sensors to increase situational awareness (Hoffman et al., 2010). Biennial reports by the American Public Power Association present survey results where vegetation management/tree trimming was the most popular program in 2015. At number three was routine distribution inspection and maintenance, and number four was to perform thermographic circuit inspections (Islam et al., 2016, 2014).

Quantifying and standardizing measures of reliability and their value is difficult because the U.S. electric grid is a large and operating under a variety of ownerships and regulations. There are three measures of reliability generally reported to state Public Utility Commissions (PUCs): System Average Interruption Duration Index (SAIFI), System Average Interruption Duration Index (SAIDI), and the Momentary Average Interruption Frequency Index (MAIFI) (Eto and Lacommare, 2008). According to the IEEE 1366-2003 (IEEE Power and Engineering Society, 2012) these are defined as:

$$SAIFI = \frac{\sum Total\ Customers\ Interrupted}{Total\ Customers\ Served} \tag{1}$$

Fig. 1. Overhead shot of a utility pole (left) and side shot of a utility pole from 5 ft (right) (images have been cropped to show detail).

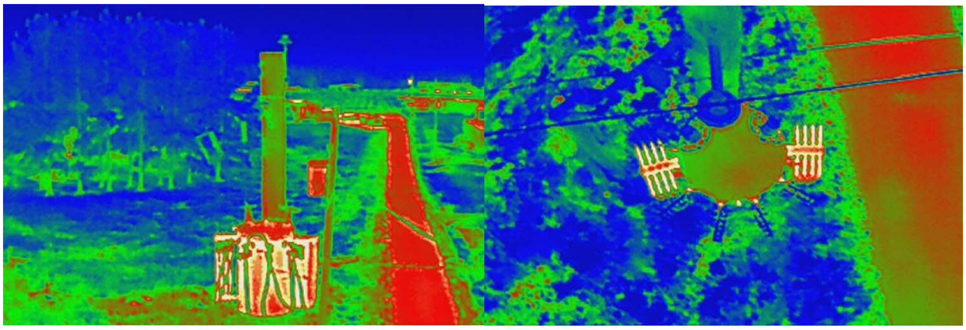

Fig. 2. Thermal image taken from the side (left) and top (right) of the equipment.

$$SAIDI = \frac{\sum Customer\ Minutes\ of\ Interruption}{Total\ Customers\ Served} \tag{2}$$

$$MAIFI = \frac{\sum Total\ Customer\ Momentary\ Interruptions}{Total\ Customers\ Served} \tag{3}$$

The MAIFI is important because momentary outages are the most frequent kind of outage, but reporting data is sparse and varies wildly. A 2015 APPA study found approximately half the respondents defined momentary as less that one minute, with most of the remaining respondents defining momentary at under five minutes.

The statistical influence of larger outages could hide smaller daily trends, so larger outages are reported as Major Event Days (MED). Once an outage reaches a certain threshold it is removed from the statistics defined above and is reported as an MED event. The next task is to establish the value of reliability. This necessitates a conversion between the above reliability measures to a specific dollar value. A 2009 report from LNLL provides a framework from which to attempt exactly this sort of analysis (Sullivan et al., 2009).

In brief, the study assembled information from different classes of electricity users (Medium and Large Commercial and Industrial, Small Commercial and Industrial, and Residential) to determine the economic damage done by outages of various durations. These damage estimates are based on reported economic loss or a willingness-to-pay to avoid the outage. For the following analysis only the most general information was used and is presented in Table 3.

The number of customers and their type are provided by the utility under analysis and corresponding interruption costs are found from the 2009 LLNL report. Outage information is then provided for two categories: outages that would be reported as major events and those that would not. For MED events the inputs include: frequency of occurrence, average and standard deviation fraction of customers to lose service, and average and standard deviation for return to service. The return to service distribution is modeled as a log-normal distribution given the data found in (Executive Office of the President, 2013).

4.2. Simulation methodology

A Monte Carlo simulation was created to statistically project the economic benefit for a range of improvements to that utility's reliability indices. Fig. 5 provides an overview of the process used to calculate the projected value. The simulation has a module for MED events and conventional events. For outages that do not reach a sufficient threshold to qualify as MED event (labeled as conventional outages), the nominal SAIDI, SAIFI, and MAIFI (along with a standard deviation to account for index variability) are provided for each customer category. The number of MED events that occur in each trial is determined by having a user input the number of storms likely to occur that year. This is used to determine the probability of a MED event on a given day.

For each MED event the simulation uses the input distribution to generate the fraction of customers affected by the outage. For each customer experiencing an outage, a return to service time is generated. A similar procedure is used for conventional events. The number of outages affecting each customer is generated from the SAIFI and MAIFI. For momentary outages, a triangular distribution between 0 and 5 min is used. For sustained outages the SAIDI and SAIFI are combined to form an outage duration distribution. Generated durations are likewise binned in the appropriate customer category.

Finally, an anticipated fractional improvement to MED event outage duration, MED event customer outage fraction, and conventional customer outage fraction attributable to the implementation of a UAS program is input. This final input is based on expert opinion, so the program can be run with a set of improvement fractions to determine a range for potential values.

Fig. 3. Image of transmission right of way.

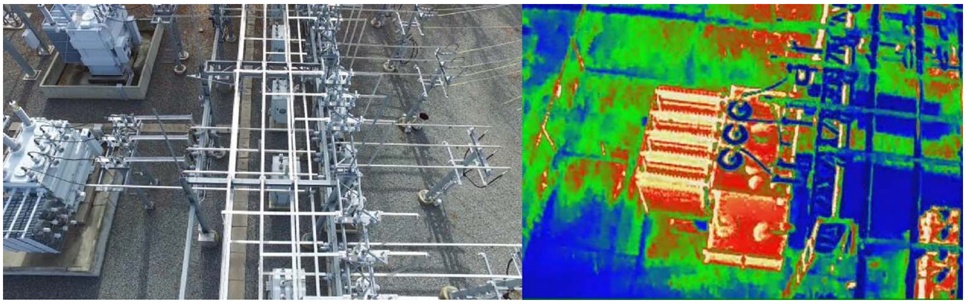

Fig. 4. Visual and thermal images from substation.

Economic impact is calculated using an interpolation of cost data from Table 3. The economic impact for the modified and unmodified results are calculated and compared to calculate the economic loss offset by the UAS program.

4.3. Case study for the city of Fayetteville, NC

A case study was performed with data for the municipal electric utility for Fayetteville, NC. As one of the larger municipalities in the state, it provides an example of the magnitude of value expected to arise from UAS program implementation. A sensitivity analysis is included to highlight which parameter most impacts the projected economic benefit.

Customer distribution information was taken from the City of Fayetteville's Public Works Commission's website (Utility, n.d.). To match the reported energy sales for the city it was necessary to increase the number of "Medium and Large Commercial and Industrial" customers and remove them from the non-residential category. The final numbers used were: 150 Medium and Large Commercial and industrial, 8702 Small Commercial and Industrial, and 70900 Residential customers.

The SAIDI (146 min) and SAIFI (1.31) used are the reported national averages found in an analysis of US outage information (Eto and Lacommare, 2008). MED events were not included in these indices since disasters would be handled separately. A MAIFI value of two was used to include the effects of more frequent momentary outages.

Several parameters of importance have no reported estimates. For the disaster model these parameters and their values include:

- Average number of MED events per year (1,3, and 5)
- Fraction of residents experiencing a MED event outage (0.2, 0.5, and 0.8)
- Average time to restore power to customers (12, 24, and 36 h)
- UAS reduction in fraction of initial outages and the fractional reduction in return to service time (0.001, 0.005, and 0.1 for both).
- For conventional outages, the fractional reduction in SAIFI and MAIFI due to UAS was 0.001, 0.01, and 0.05.

Results for selected variables from the sensitivity analysis for conventional outages are shown in Figs. 6 and 7. An increase in SAIDI correlates with increased UAS value at a non-linear rate. The fraction of outages prevented by the UAS has an expectedly strong effect on system value. The lowest value for any case was $51,043 and was found with for a SAIFI of 1, a SAIDI of 100 min, and an outage reduction fraction of 0.001.

Results for MED event outages are shown in Figs. 8 and 9. The MED event sensitivity analysis had 81 combinations for each point of interest. Reducing the number of outages appears to be significantly more impactful on UAS value than reducing the duration of outages. It is likely that this effect is due to cost of an outage when measure per unserved kWh. Since a great deal of lost productivity is reported at the beginning of an outage, the cost of the first minutes and hours is higher than subsequent periods of time. Reducing the duration of an outage reduces the minutes after the cost per un-served kWh has fallen to its lowest point and therefore does not have as much value. This indicates that effort spent on practices like vegetation management and preventative maintenance – which reduce the number of MED event outages – may provide more value than effort spent accelerating recovery from those events.

The most pessimistic results avoided $144,228 in economic damage from conventional and MED outages. An additional test was run which used the best guess estimates of 1 MED event per year, 0.4 of the customer base affected by the event, an average return to service time of 12 h, a 0.001 fractional improvement to MED outage duration, and a 0.001 fractional improvement to number of customers affected by a conventional or MED event. This best guess projected annual avoided economic loss of $282,813.

Table 3
Estimated average electric customer interruption costs US 2013$ anytime by duration and customer type (Sullivan et al., 2015).

Interruption cost	Interruption duration					
	Momentary	30 min	1 h	4 h	8 h	16 h
Medium and Large C&I (Over 50,000 annual kWh)						
Cost per event	$12,952	$15,241	$17,804	$39.458	$84,083	$165,482
Cost per average kW	$15.9	$18.7	$21.8	$48.4	$103.2	$203.0
Cost per unserved kWh	$190.7	$37.4	$21.8	$12.1	$12.9	$12.7
Small C&I (Under 50,000 annual kWh)						
Cost per event	$412	$520	$647	$1880	$4690	$9055
Cost per average kW	$187.9	$237.0	$295.0	$857.1	$2,138.1	$4,128.3
Cost per unserved kWh	$2,254.6	$474.1	$295.0	$214.3	$267.3	$258.0
Residential						
Cost per event	$3.9	$4.5	$5.1	$9.5	$17.2	$32.4
Cost per average kW	$2.6	$2.9	$3.3	$6.2	$11.3	$21.2
Cost per unserved kWh	$30.9	$5.9	$3.3	$1.6	$1.4	$1.3

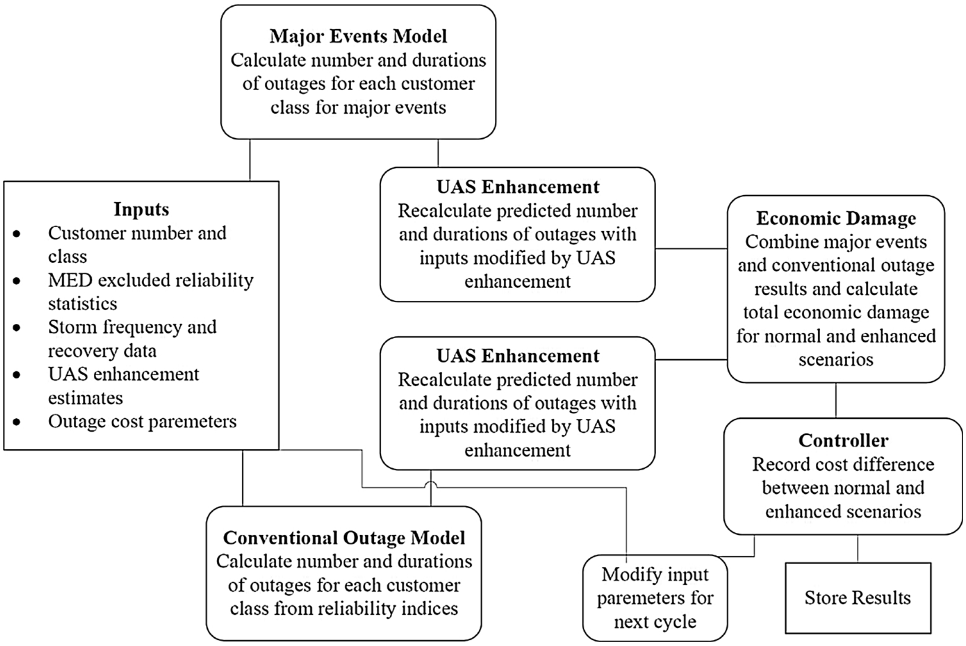

Fig. 5. Reliability model framework used in Monte Carlo simulations.

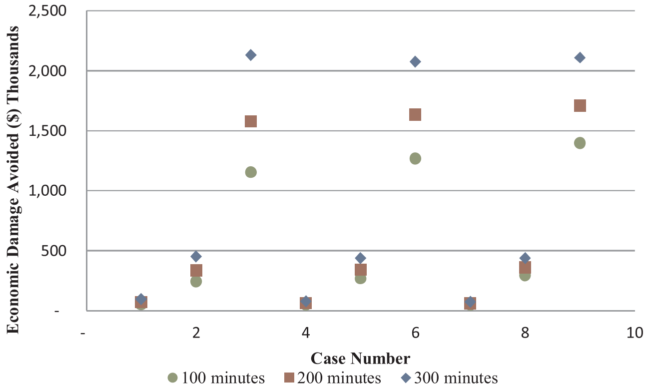

Fig. 6. Conventional outage sensitivity study: SAIDI.

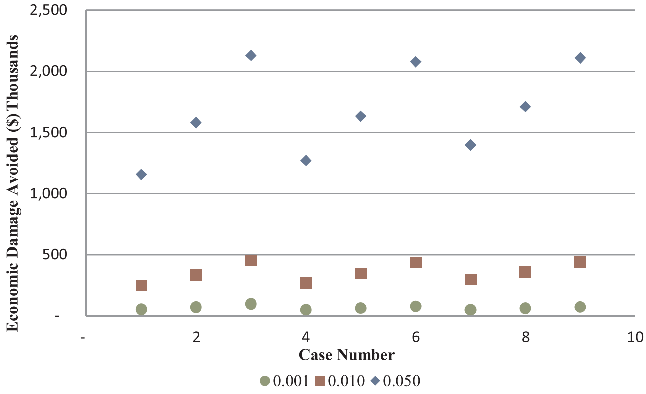

Fig. 7. Conventional outage sensitivity study: UAS improvement fraction.

5. Overall conclusions

Based on the data presented in the previous sections, multi-rotor UAS solutions are a viable technology option that should be incorporated for both preventative maintenance and damage assessment. Changes to flight rules made by the FAA in the summer of 2016 have significantly reduced the barriers to entry, as pilots can be easily trained

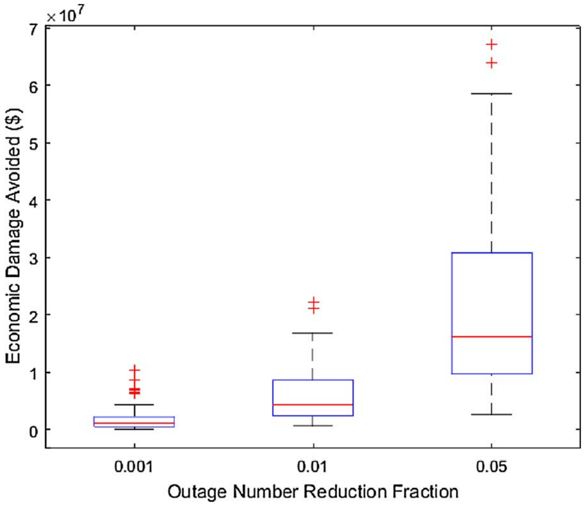

Fig. 8. Major outage sensitivity study: Reducing outages with UAS.

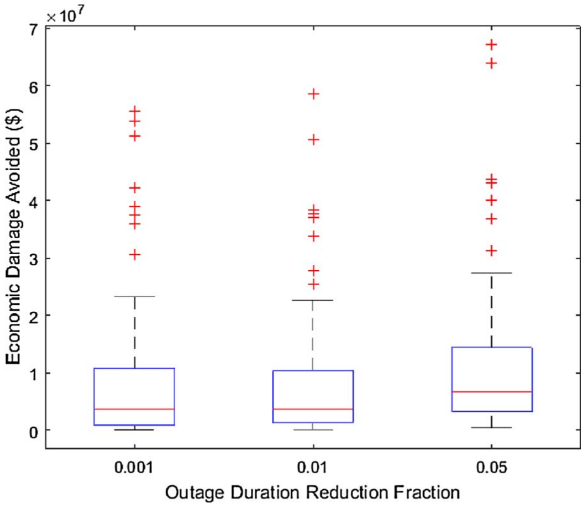

Fig. 9. Major outage sensitivity study: Reducing outage duration with UAS.

and certified and the FAA has demonstrated a willingness to expedite regulatory wavers following disasters.

Initial flight tests of a commercial-off-the-shelf UAS showed that high quality images can be captured. High resolution color pictures can be taken that allow for component identification – helping with system mapping – and the pictures themselves have GPS location embedded into their data file. Color images can also allow for immediate right-of-way assessment. Thermal imagery allows for the identification of component failures before they become a larger problem. However, future research is needed into image post-processing, especially for thermal images. This is often done for pictures coming from handheld thermal cameras.

UAS also enhance response capability when conducting damage assessment, though the full benefit of such systems may not be realizable today. While the technology exists to fly an entire distribution system autonomously (most likely using a fixed wing aircraft), current regulations prevent this solution from being realized as it would violate line-of-sight guidance.

The commercial-off-the-shelf options at the time of writing this report are quite effective for preventive maintenance missions. These systems are easy to fly – basic flight control can be quickly mastered by a beginning pilot. Overall, the flight tests and simulations run as part of this study demonstrate that UAS provide significant value and will continue to do so as technology improves and costs fall.

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