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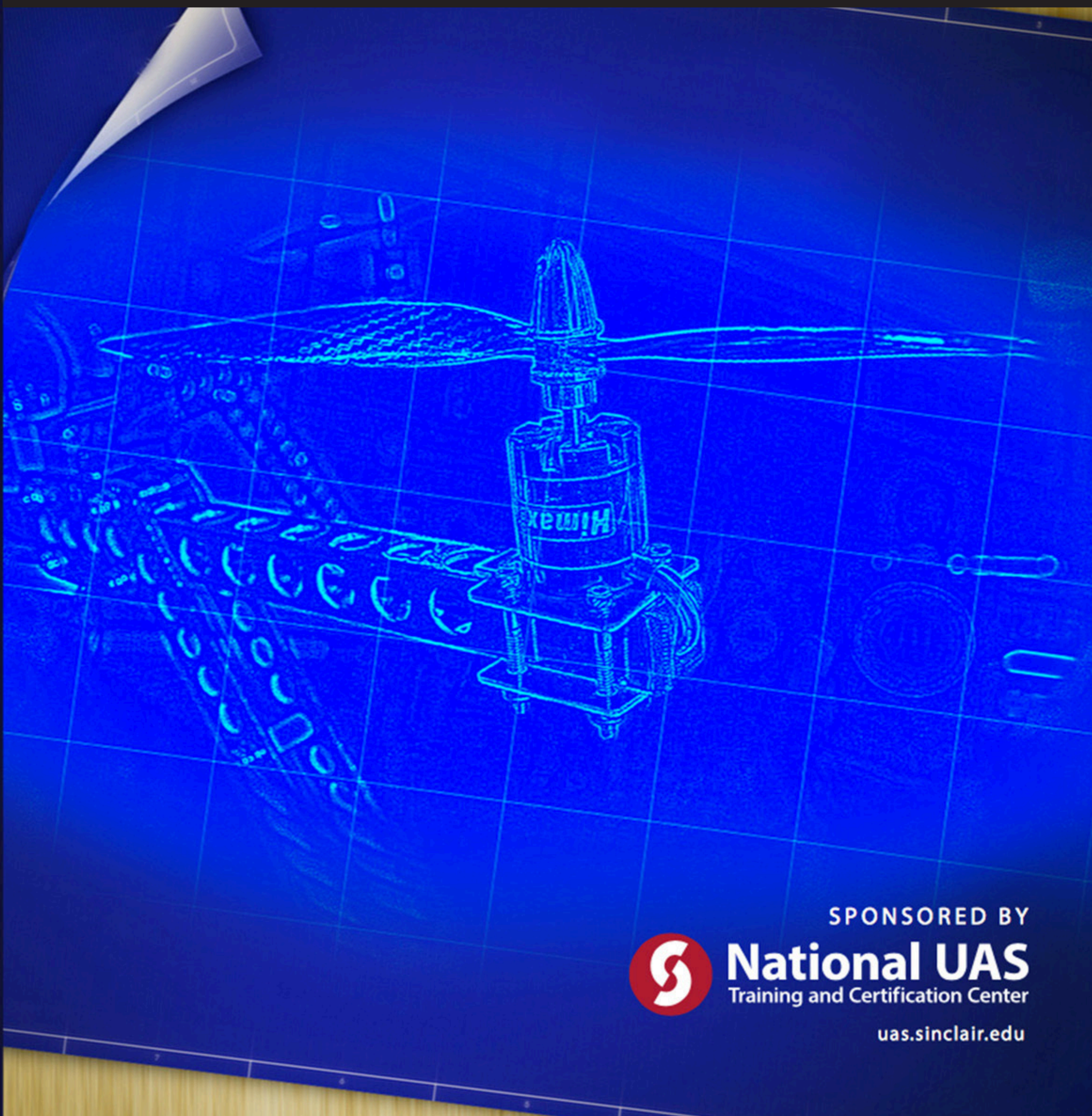

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ABOUT OUR SPONSOR

Sinclair Community College: National UAS Training & Certification Center

Sinclair College's National UAS Training and Certification Center, located in Dayton, Ohio, represents the culmination of a focused vision dedicated to creating one of the most comprehensive and pioneering facilities for the advancement of UAS training and applied research support. Since 2008, Sinclair College has been at the forefront of UAS innovation, creating partnerships, developing leading curriculum, and investing significantly to establish a nationally prominent program dedicated to meeting the workforce needs of the growing UAS industry.

Created through cumulative investments of more than $10 million, Sinclair's UAS Center provides students and researchers with the ability to work with new UAS technologies in an immersive and hands-on environment. The facility supports research, development, and training on vehicles and components through advanced unmanned and manned simulation, sensors, avionics, maintenance, advanced manufacturing and rapid prototyping, data analytics, and wind tunnel labs. Additionally, indoor flight training and testing is made possible in both the UAS Indoor Flight Range and the custom built UAS Indoor Flying Pavilion. Sinclair actively operates UAS in the National Airspace System, with the most flights of any entity in Ohio since 2014, through 13 Certificates of Authorization and a Section 333 Exemption.

Sinclair strives to remain at the cutting-edge of UAS training and applied research support through collaborations with leading UAS organizations in academia, government, and industry. The college is honored to be included as an partner in both the Federal Aviation Administration ASSURE UAS Center of Excellence and National Science Foundation Center for Unmanned Aircraft Systems, maintains active Educational Partnership Agreements focused on UAS with the Air Force Research Laboratory and the Air Force Institute of Technology, and is engaged in applied UAS research with NASA enabled through a Space Act Agreement. Sinclair also founded and continues to sponsor the Journal of Unmanned Aerial Systems, a peer-reviewed publication that serves the public as an open-access online resource enabling the development and distribution of knowledge for the UAS industry.

EDITORIAL

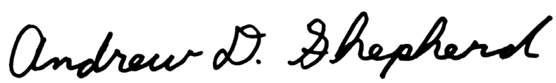
From the Managing Editor: Dr. Andrew Shepherd

Welcome to the second edition of the *Journal of Unmanned Aerial Systems*. We are excited to build on the success of our first publication in 2015 as we continue to provide an outlet for the free exchange of ideas related to UAS. Staying true to our founding principles, the *Journal* remains an online and open-source resource to encourage broad distribution, use, and benefit to our readers.

This second volume, and indeed the *Journal* itself, would not be possible without the dedicated volunteers serving as Reviewers, Editorial Board, and Publishing Board members. I would like to personally and publically acknowledge their contributions and thank them for their efforts. As the *Journal* continues to grow, we welcome inquiries from those that may be interested in volunteering to support this important work.

I would also like to thank the authors selected for publication for their attention to detail and trust placed in the *Journal* as the means to share their work. I am confident that their research will be both informative and significant in the advancement of the UAS industry. The *Journal* has already begun receiving submission that are in review for our next publication and we encourage all with current research to consider our publication as the means to distribute their work.

The publication of Volume 2, Issue 1 supports our goal of the *Journal of Unmanned Aerial Systems* becoming a standard reference and the premier academic UAS publication. We look toward the future with optimism and hope that you will support us by informing others about the *Journal*, submitting your own work, and considering joining us as a volunteer.



Andrew D. Shepherd, PhD – Managing Editor
Director, Unmanned Aerial Systems, Sinclair Community College

JOURNAL OF UNMANNED AERIAL SYSTEMS

PEER-REVIEWED ARTICLE

MEDIUM ALTITUDE LONG ENDURANCE REMOTELY PILOTED AIRCRAFT TRAINING: A PILOT STUDY IN BLENDED LEARNING

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ABSTRACT

Since April of 2011, research and development efforts between the Air Force Research Laboratory (AFRL) and the University of North Dakota (UND) have progressed through the "Science and Technology for Warfighter Training and Aiding." Cooperative Agreement. One product of these cooperative efforts has been a Heads Down Display (HDD) Menu Trainer. Designed to familiarize students with the layout and manipulation of the HDD menus for either the MQ-1 or MQ-9, a parallel pretest/posttest design was designed to examine the efficacy of this HDD menu trainer as training aid in traditional, blended, and distance pedagogies.

Results of a mixed ANOVA indicated the trainer significantly improved performance from pretest to posttest scores across all groups ($p<0.001$), however comparing these scores according to instructional intervention (i.e. Traditional, Blended, and Distance) found no significant effect. No significant differences were observed between pretest, posttest, or percent change scores according to instructional intervention. Analysis of the same variables with respect to pilot certification revealed that learners holding a Commercial pilot certificate scored significantly higher on the pretest than those with no FAA (Federal Aviation Administration) pilot certification ($p<0.05$), and learners with no FAA pilot certificate demonstrated significantly higher percent changes from pretest to posttest than learners with Commercial pilot certificates ($p<0.05$). While, it is clear that the HDD menu trainer has demonstrated effectiveness in improving a student's ability to navigate and manipulate the MQ-9 menu structure, the subtle differences between instructional methods will require further investigation. Future studies are encouraged to investigate the benefits and effectiveness of each instructional method while controlling for pilot certification.

In the past two decades, the availability and capability of computer technologies have greatly expanded the educational options available to learners and instructors alike (Osguthorpe & Graham, 2003). Integrating these advances into pedagogy, which recognizes and capitalizes on the inherent strengths of both traditional (i.e. face-to-face) and distance systems of delivery, is the challenge that blended learning offers. Computer Based Training (CBT) modules offer a specific and contemporary example of these expanded educational options, and have been defined as "… self-contained, interactive, often asynchronous, computer-based program[s] designed for self-paced instruction that uses features of learner control coupled with predesigned material, required responses and feedback" (Bedwell & Salas, 2010, p. 240).

Statement of the Problem

Since April of 2011, research and development efforts between the Air Force Research Laboratory (AFRL) and the University of North Dakota (UND) have progressed through the "Science and Technology for Warfighter Training and Aiding." Cooperative Agreement. This CA (FA8650-11-2-6212), is producing a state-of-the-art curriculum for Medium Altitude, Long Endurance Remotely Piloted Aircraft (MALE RPA) pilots and sensor operators, as well as establishing infrastructure for future research efforts. One product of these cooperative efforts has been a Heads Down Display (HDD) Menu Trainer. This CBT module, developed by UND's Aerospace Network, was designed to familiarize students with the layout and manipulation of the HDD menus for either the MQ-1 or MQ-9.

The efficacy of the HDD menu trainer to improve a student's ability in navigating and manipulating the MQ-9 menu structure, as well as its application as training aid in blended pedagogy, or standalone teaching tool in distance pedagogy have not yet been examined. This need for evaluative validation fits well into gaps in extant literature regarding Computer Aided Instruction (CAI) (Adler & Johnson, 2000). In characterizing literature related to CAI, Adler and Johnson (2000) concluded that evaluation articles on the topic remain uncommon in comparison to demonstrations and media-comparative studies, and call for future research to be more aware of these gaps if CAI literature is to mature.

Purpose of the Study

The purpose of this pilot study was to examine the expertise of students in navigating and manipulating the Heads-Down Display (HDD) menus of MALE RPA when provided either traditional, blended, or distance instruction. Learner knowledge gains between groups were measured by both pretest and posttest assessments to assess the effectiveness (1) of the HDD menu trainer, and (2) its potential for use in a variety of instructional methods.

Literature Review

Blended learning

While used frequently throughout academic journals and conferences (Osguthorpe & Graham, 2003), a strict definition of blended learning appears elusive in the extant literature. In his work describing the definitions and directions of blended learning environments, Osguthorpe (2003) offered that,

> "Blended learning combines face-to-face with distance delivery systems… the internet is involved, but it's more than showing a page from a website on the classroom screen. And it all comes back to teaching methodologies – pedagogies that change according to the unique needs of learners. Those who use blended learning environments are trying to maximize the benefits of both face-to-face and online methods – using the web for what it does best, and using class time for what it does best." (Osguthorpe & Graham, 2003, p. 227)

Osguthorpe and Graham (2003) stress that blended approaches are based upon the assumption that inherent benefits, and weaknesses, exist for both face-to-face interaction and distance delivery. Educators employing blended approaches to instruction must discern the best balance between online access to knowledge and face-to-face human interaction as they develop each course (Osguthorpe & Graham, 2003). Evaluative works on curricula which fall under Osguthorpe and Graham's (2003) working definition of blended learning strategies, or are specific to Bedwell & Salas (2010) definition of CBT, are reviewed in the sections that follow. These efforts have been organized according to domains regarding (1) knowledge gains, (2) learner attitudes, and (3) learning efficiency, as offered by Chumley-Jones, Dobbie, and Alford (2002).

Learner knowledge gains

Efforts addressing learner knowledge gains have assessed change in participant performance as a result of intervention with some manner of computer assisted, or computer based instruction. The majority of studies in this domain measured change using multiple choice test-scores. Pretest/posttest self-controlled studies were the most common design, however others such as self-selected controlled studies, assigned crossover trials, and randomized controlled trials methodologies were also noted (Chumley-Jones et al. 2002). Several within-group methodologies were able to successfully document significant increases in performance as a result of distance instruction (Boyle, Bradley, Chalk, Jones, & Pickard, 2003; Curran, Hoekman, Gulliver, Landells, & Hatcher, 2000; Engel, Crandall, Basch, Zybert, & Wylie-Rosett, 1997; Francis, Mauriello, Phillips, Englebardt, & Grayden, 2000; Harris, Salasche, & Harris, 2001; Kronz, Silberman, Allsbrook Jr., & Epstein, 2000; Perryer, Walmsley, Barclay, Shaw, & Smith, 2002).

Although within-group assessments of distance instruction were common, between group methodologies allow comparisons to be made across or against alternative pedagogical strategies (i.e. traditional face-to-face, blended, and standalone distance). In these designs, literature which indicated a lack of significant difference in terms of knowledge gains appear to be the majority when distance and traditional pedagogies are compared (Baumlin, Bessette, Lewis, & Richardson, 2000; Bell, Fonarow, Hays, & Mangione, 2000; Block, Felix, Udermann, Reineke, & Murray, 2008; Rivera & Rice, 2002; Rose, Frisby, Hamlin, & Jones, 2000; Sakowski, Rich, & Turner, 2001; Woo & Kimmick, 2000). Allen, Mabry, Mattrey, Bourhis, Titsworth, & Burrell (2004) also found little distinction between traditional and distance learning classrooms on the basis of performance, but offer that no clear decline in educational effectiveness is noted when utilizing distance education technology.

Other between-groups designs did identify significant differences in favor of distance and blended pedagogies. For example, in their examination of potential pedagogic advantages of distance methods of instruction, Lipman, Sade, Glotzbach, Lancaster, and Marshall (2001) compared a traditional classroom course with the same course supplemented by internet-based discussion. Results indicated that performance was higher ($p < 0.005$) in the blended course than the traditional course (Lipman et al. 2001). Melton, Graf, and Chopak-Foss (2009) compared student achievement in blended and traditional pedagogies with mixed results. However, the grades of students in the blended course were found to be significantly higher ($p<0.05$) than those in the traditional course (Melton et al. 2009).

In 2007, Pereira, Pleguezuelos, Meri, Molina-Ros, Molina-Tomas, and Masdeu, examined the efficiency of blended pedagogy, and found that students receiving blended learning received significantly higher grades ($p < 0.0001$) than those in the traditional group (Pereira, et al., 2007). Student feedback also indicated that students felt the course design was an effective (88%) and efficient (92%) method of learning, and helped to familiarize them with resources on the internet (96%) (Pereira, et al., 2007). Further, students' confidence, measured before and after the intervention, showed significant improvement ($p < 0.001$).

Learner attitudes

Since, the late 1990's students have valued the "…flexibility, timeliness, efficiency and breadth of access to relevant information offered by the [internet]" (Agius & Bagnall, 1998, p. 337). Another facet commonly used to evaluate pedagogy, and the second category offered by Chumley-Jones et al. (2002), learner attitudes have been measured and examined regularly in the extant literature.

In their study, Baumlin, et al. (2000) examined course satisfaction with a participant survey. Results indicated that 65% of participants said they wanted computer-assisted instruction as an adjunct to their course curricula, but only 28% of the students with access actually utilized the module. Participants who did use it rated it useful (4.2/5), easy to use (4.4/5), and easy to access (4.1/5). Of the students with access to the online module who chose not to use it, 77.8% reported a lack of time as the reason for not using the module (Baumlin, et al. 2000). In Bell et al. (2000), ratings on a learner satisfaction scale indicated that students using the online tutorial displayed higher satisfaction with the curriculum (Bell et al. 2000).

The 2000 work of Curran et al. also made a general measure of learner attitude. Participants indicated high satisfaction with the self-paced instruction and use of the asynchronous computer conferencing for collaboration among colleagues (Curran et al. 2000). A voluntary satisfaction survey by Harris et al. (2001), indicated extremely high user satisfaction with a distance curriculum. A learner satisfaction survey by Melton et al. (2009), indicated higher satisfaction from students receiving blended learning course delivery ($p < 0.01$). Authors concluded that the blended course delivery was preferred over the traditional lecture format, challenging teachers' traditional approach to delivering general health courses at the university level (Melton et al. 2009). Horsch, Balback, Melnitzki, and Knauth (2000) conducted a simple survey design to measure learner attitudes regarding a distance course. On a scale of 1 to 5, (1=*very good;* 5=*very bad*) students (n = 32) rated the online module at 1.93. In a self-assessment of knowledge gained, 18 of 32 students indicated they had acquired new knowledge, and 10 indicated that learning with the online text was more efficient than learning with a conventional textbook (Horsch et al. 2000).

Hsu and Hsieh (2011) utilized four scales (i.e. the Case Analysis Attitude Scale, Case Analysis Self-Evaluation Scale, Blended Learning Satisfaction Scale, and Metacognition Scale) for students to rate their own performance in blended and traditional delivery courses. Results indicated no difference between groups on any of the self-reported performance scales measured at pretest and posttest. Authors offer that these results demonstrate that both blended learning and traditional classroom lectures are both effective avenues for presenting materials and exchanging ideas to understand course content, and recommend that newly developed course modules and innovative course components should be tested repeatedly for effectiveness (Hsu & Hsieh, 2011). Smyth, Houghton, Cooney, and Casey (2012) interviewed focus groups of students regarding their blended learning experience, and found that students received the blended learning method positively, but offered that the online component meant little time away from study, suggesting that it was more invasive on their everyday life (Smyth et al. 2012).

In their examination of the effectiveness of traditionally and distance courses, Rose et al. (2005) also made a point to measure student satisfaction. No significant differences were reported for (1) communication with classmates, (2) instructor, (3) assignments, (4) review sessions, (5) relevance of course, or (6) the overall course (Rose et al. 2000). Pereira et al. (2007) also observed no statistical difference in overall satisfaction between their blended and traditional courses. Rivera and Rice (2002), who conducted a pilot study evaluating three class formats (i.e. traditional, distance, and blended) found that measures of student satisfaction seemed to indicate that relative to the traditional and blended courses, students in the distance course were less satisfied. Woo and Kimmick (2000) also compared student satisfaction, but found that participants in the distance course reported significantly higher ($p < 0.05$) stimulation of learning compared to those in the traditional lecture course.

As with the efforts addressing learner knowledge gains, measurements of learner attitudes have returned mixed responses. Aside from noting a positive disposition toward pedagogies utilizing some manner of computer assisted, or computer based instruction from the majority of the works, these results are difficult to generalize. While measuring learner attitudes toward experimental curriculums appears commonplace, there seems to be little standardization or congruence in method of measurement.

Learning efficiency

The final and briefest of the three categories examined is learning efficiency. Requiring at minimum a between groups comparison for quantitative results, measures of learning efficiency for interventions with some manner of computer assisted, or computer based instruction compared to traditional delivery methods are rare. Only two studies were identified as addressing this topic. The first was also reviewed in the learner attitude section. In their examination of knowledge gains, learning efficiency and learner satisfaction between an online tutorial program and printed materials, Bell et al. (2000) assessed students ($n = 162$) enrolled in family medicine and internal medicine residency programs at four universities. Results indicated no significant difference in posttest scores between those students using the online tutorial and the printed text materials. However, those utilizing the online tutorial spent less time studying ($p < 0.001$), demonstrating greater learning efficiency. The second study, also reviewed in the learner attitudes section was a simple survey study design to collect student attitudes regarding a distance medical course. In a self-assessment of knowledge gained, 18 of 32 students indicated they had acquired new knowledge, and 10 indicated that learning with the online text was more efficient than learning with a conventional textbook (Horsch et al. 2000). As with program cost, a fourth category offered by Chumley-Jones et al. (2002), this category of evaluative research regarding computer assisted, or computer based instruction requires further exploration.

METHODOLOGY

The present study examined the effectiveness of the HDD menu trainer in improving a student's ability to navigate and manipulate the MQ-9 menu structure, as well as potential impacts of either traditional, blended, or distance instruction on this process. Using the HDD menu trainer developed under the "Science and Technology for Warfighter Training and Aiding." Cooperative Agreement between AFRL and UND, pretests and posttests were used to measure learner knowledge gain. Learner attitude was assessed using a satisfaction survey.

Sample

The sample for this study consisted of individuals both with and without FAA pilot certification at the University of North Dakota John D. Odegard School of Aerospace Sciences (n = 15). Of this sample, 3 participants held no FAA pilot certificate, 5 participants held a Private Pilot Certificate, and 7 participants carried Commercial Pilot certification. The average subject age was 27.73. Subject responses were not separated by race or gender, and no subject's results were excluded from analysis. Participants were randomly assigned to one of three groups (i.e. Traditional, Distance, and Blended) receiving various instructional interventions with respect to MQ-9 HDD menus.

Instrument

The HDD menu trainer, developed by UND's Aerospace Network was designed to familiarize students with the layout and manipulation of the HDD menus for either the MQ-1 or MQ-9. The trainer contains (1) a tutorial describing menu layout, menu navigation, button types, and button arrangement, (2) a walk-through function, which guides students through each root menu and its submenus, (3) an exercise function, which tests the student's ability to navigate and execute specific commands within a set time limit, and finally (4) a freeplay function, which allows the students to navigate and explore the HDD menus without specific focus or limits on time.

The menu trainer was delivered to the distance and blended groups via an open source, online Learning Management System (LMS) administered by the researcher. All subjects had access to the LMS for completion of the pretest and posttest measures. Subjects were briefed on use of the LMS at the start of the intervention.

The pretest and posttest measures utilized a modified version of the HDD menu trainer's exercise function. These assessments, designed by an Original Equipment Manufacturer (OEM) certified MQ-9 IP, reflect those menu functions most commonly used or most critical for gauging a student's expertise with navigating and manipulating the HDD menus. Roughly 25 pilot orientated menu functions were selected from the pool of 260 which constitute the menu trainer's exercise function, and were adapted for delivery as the pretest and posttest measures. These measures, like the menu trainer's exercise function, measure the student's ability to navigate and execute specific commands within a set time limit. Performance was assessed according both the speed and accuracy of the student's response.

Data Collection and Analysis

This study was reviewed and approved by the University of North Dakota's Institutional Review Board. Subjects were informed of the study with advertisements posted throughout the campus aerospace facilities as well as the aviation student email listserve. Subjects were briefed on the purpose and nature of the study prior to participation. Due to the sensitive nature of the MQ-9 HDD menus, participants were also required to present proof of U.S. citizenship by means of a passport, and/or birth certificate and driver's license and sign an International Traffic in Arms Regulations (ITAR) Statement of Understanding.

Subjects were randomly assigned to one of three study groups to receive instruction on navigating and manipulating the HDD menus of the MQ-9. As illustrated in Table 1, students assigned to the distance group were granted access to the HDD menu trainer. Subjects assigned to the blended group were granted access to the HDD menu trainer, but also attended a classroom discussion guided by an Original Equipment Manufacturer (OEM) certified MQ-9 Instructor Pilot (IP). Subjects assigned to the traditional group were not granted access to the HDD menu trainer, but received a lecture and lesson on the HDD Menus from an OEM certified MQ-9 IP. The lesson completed by the traditional group was conducted using an MQ-9 part-task trainer which simulated the same HDD menus but provided no innate instructional aspects (i.e. no tutorial, walk-through, or exercise functions). The layout and functionality of the menus simulated in this part-task trainer were identical to those used in the pretest and posttest measures, as well as those used by the distance and blended groups.

	Traditional Group	Blended Group	Distance Group
HDD Menu Trainer	No	Yes	Yes
MQ-9 Instructor Pilot	Yes	Yes	No

Table 1, Research Design

Descriptive and inferential statistics were collected from the data. The means, standard deviations, minimum, maximum, range, and measures of skewness and kurtosis indices were calculated using raw scores from each group. A one way ANOVA was used to assess differences between the groups on pretest, posttest, and percent change scores. In cases where parametric assumptions were violated, Kruskal-Wallis non-parametric procedures were used to assess potential relationships. Significance in all statistical tests were set at a minimum of $p<0.05$.

RESULTS

Learner Knowledge Gains

Illustrated in Table 2 are descriptive statistics for each of the three groups in their pretest, posttest, and percent change measures. Each task in the parallel pretest and posttest measures was assigned 15 possible points. Points were deducted for incorrect keystrokes as well as when a task could not be completed inside 30 seconds. If a task was skipped, a score of 0 was assigned. Percent change was calculated as the difference between the pretest and posttest score divided by the pretest Score. Also included in Table 2 are z-scores for the skewness and kurtosis of each factor's score distribution. For these measures, absolute values greater than 1.96 indicate significantly non-normal distributions at $p<0.05$ (Field, 2009). Except for skewness in the percent change measure of the distance group, all measure distributions failed to differ significantly from a normal distribution in either skewness or kurtosis.

	N	Mean	SD	Minimum	Maximum	Z skewness	Z kurtosis
PRE-TEST							
Traditional	5	244.00	68.58	157.00	324.00	0.00	-0.86
Blended	5	264.60	49.26	191.00	309.00	-0.87	-0.23
Distance	5	270.40	56.79	175.00	326.00	-1.70	1.57
POST-TEST							
Traditional	5	331.40	26.95	308.00	365.00	0.67	-1.45
Blended	5	334.00	27.59	299.00	371.00	0.21	-0.26
Distance	5	332.00	25.95	308.00	366.00	0.48	-0.58
PERCENT CHANGE							
Traditional	5	42.91	33.28	12.65	96.18	1.34	0.73
Blended	5	28.85	18.41	6.47	56.54	0.72	0.58
Distance	5	27.26	28.14	5.12	76.00	2.07*	1.92

* Indicates significance at the 0.05 level

Table 2, Descriptive Results According to Instructional Method

Results of the one way ANOVA (Table 3) comparing pretest, posttest, and percent change scores between groups found no significant differences between the three groups on any of the measures. Although non-normality was noted in the skewness of the distance group in percent change, the same patterns of significance were noted using non-parametric Kruskal-Wallis procedures comparing the mean ranks of percent change, as well as pretest and posttest scores, with respect to instructional method.

	Traditional Group		Blended Group		Distance Group		
	Mean	SD	Mean	SD	Mean	SD	P
PRE-TEST	244.00	68.58	264.60	49.26	270.40	56.79	0.761
POST-TEST	331.40	26.95	334.00	27.59	332.00	25.95	0.987
PERCENT CHANGE	42.91	33.28	28.85	18.41	27.26	28.14	0.620

* Indicates significance at the 0.05 level

Table 3, One Way ANOVA Results According to Instructional Method

A mixed ANOVA indicated the trainer significantly improved performance from pretest to posttest scores across all groups $F(1,12) = 49.01$ ($p<0.001$), however comparing these scores by instructional intervention (i.e. Traditional, Blended, and Distance) found no significant effect. To summarize, an overall effect of instruction was observed, but did not vary across the three types of instructional intervention.

Regarding pilot certification

Analysis of pretest and posttest scores, as well as percent change in scores with respect to pilot certification revealed several relationships meriting consideration for future studies in this area. In Table 4, results of a one way ANOVA and Tukey *post hoc* analysis indicated that participants holding a commercial pilot certificate scored significantly higher on the pretest than those with no FAA pilot certification ($p<0.05$). No significant effect of pilot certification was found in an analysis of the post test scores. Furthermore, significantly higher percent changes from pretest to posttest were observed in participants with no FAA pilot certificate than those with commercial certificates ($p<0.05$). Again, a similar pattern of results were found when analysis was repeated using the Kruskal-Wallis procedure.

	None (n = 3)		Private (n = 5)		Commercial (n = 7)		
	Mean	SD	Mean	SD	Mean	SD	P
PRE-TEST	191.67	17.00	258.80	67.11	289.43	27.92	0.024*
POST-TEST	306.00	6.25	339.20	25.15	339.00	23.90	0.114
PERCENT CHANGE	60.45	14.01	37.88	34.05	17.77	10.47	0.041*

* Indicates significance at the 0.05 level

Table 4, One Way ANOVA results According to Pilot Certification

Learner Attitudes

A learner satisfaction survey was used to gauge participant satisfaction with the instruction they received. Participants were asked to respond to 8 statements regarding course satisfaction on a five point Likert scale (1=*Strongly Disagree*; 5=*Strongly Agree*). Sum totals and descriptive statistics for these responses are found in Table 5 below. While results of a one way ANOVA did not indicate a significant difference between course satisfaction and instructional method, patterns in the open ended responses offer some differentiation.

	N	Mean	SD	Minimum	Maximum	Z skewness	Z kurtosis
ATTITUDE							
Traditional	5	29.20	5.45	22	35	-0.59	-0.99
Blended	5	32.60	6.23	23	39	-1.02	-0.38
Distance	5	29.00	1.00	28	30	0.00	-1.50

* Indicates significance at the 0.05 level

Table 5, Descriptive Results of Learner Attitude

Open-ended responses to the prompts "Please describe improvements, if any, which would better assist your learning of the course material." and "Please describe specific aspects of the course or instruction which promoted your learning." provide qualitative context. Members of the traditional group commonly felt that additional time and access to the HDD trainer would have better assisted their learning "… As someone who prefers to study alone, access to the trainer", "More time to teach the material", "More time with software" and "I would have benefitted from some practice exams at home." While the ability to govern instructional pace was a common theme in aspects of the course which promoted learning for members of the distance group, preference for an introductory lecture preceding self-study was noted as a way to better assist their learning. In the blended group, the combination of self-paced practice and the availability of instructor expertise in classroom discussions surfaced as positive aspects of the course.

Learning Efficiency

The traditional group was presented a 15 minute lecture followed by a simulated lesson in a part-task trainer Ground Control Station (GCS) for 45 minutes. As a single crew includes 1 pilot position and 1 sensor operator, this instruction only permitted 2 individuals to work directly with the IP at a time, while the remainder of the class observed. Following this lesson, participants were not allowed access to the menus excluding a 1 hour practice period in the simulated GCS. Self-reported study times for the distance group indicated an average of 1.3 hours of effort (0.84 *SD*) with the HDD menu trainer. Finally the self-reported study times for the blended group showed an average of 3.5 hours of effort (2.58 *SD*) preceding a 1 hour classroom discussion and review prior to the posttest.

DISCUSSION

The results above demonstrate that the HDD menu trainer is effective in improving a student's ability to navigate and manipulate the MQ-9 menu structure. Results for learner knowledge gains, learner attitudes, and learning efficiency offer preliminary indications of the trainer's potential as training aid in blended pedagogy, as well as standalone teaching tool in distance pedagogy. Similar to many previous efforts reviewed, the HDD menu trainer was at least as effective as the traditional method of instruction currently used in terms of learner knowledge gains. Although inferential results of the learner satisfaction survey did not reflect differing levels of satisfaction, written responses to the open ended portions of the instrument indicated that learners clearly identified with classic strengths and weaknesses of both traditional and distance pedagogies. The group receiving traditional instruction benefitted from the interaction and expertise of the live instructor, but requested additional time with the material or ways to study according to their individual needs. Members of the distance group, meanwhile, appreciated the ability to self-govern the pace of their learning but noted instructor availability as a way to improve their learning.

While it may have been anticipated that the blended group would outperform the other groups, benefitting from the advantages of instructor availability as well as the ability to govern their own preferences for pace and duration of instruction, the relatively small sample sizes likely affected this in two ways. First, if instructional method commands only a small effect size on learner knowledge gains, much larger sample sizes will be required to reliably detect a genuine effect when one exists. Second, as overall class size approaches the size of a single RPA crew, the unique differences between the instructor delivered portions of the blended and traditional approaches lessen. As class size approaches the size of a single crew, the lecture received by the traditional group increasingly resembles the individual attention normally reserved for individual lessons. Likewise, with fewer members of the blended group, individual members may benefit less from the questions and discussion generated between their peers and the instructor. As such, it may be that the blended pedagogy has a greater effect on learning knowledge gain and learning efficiency (in terms of instructor time) as class size increases.

Conclusion and Future Studies

As the availability and capability of instructional technologies continues to expand, opportunities to adapt, validate, and improve pedagogy accordingly are many. Extant literature reflecting evaluative efforts on distance and blended instruction generally report that these instructional methodologies are able to perform at least as well as traditional methods and in some circumstances, better. Blending the advantages of traditional face-to-face instruction with the benefits of computer aided delivery systems for learners is the focus of blended learning. The purpose of this pilot study has been to examine the expertise of students in navigating and manipulating the HDD menus of MALE RPA to assess (1) the effectiveness of the HDD menu trainer, and (2) its potential for use in traditional, blended, or distance instructional methods.

Results of a mixed ANOVA indicated the trainer significantly improved performance from pretest to posttest scores across all groups ($p<0.001$), but comparisons by instructional intervention (i.e. Traditional, Blended, and Distance) found no significant effect. A lack of significant differences between pretest, posttest, and percent change scores between groups indicates that the HDD menu trainer may be assumed as equally effective in terms of learner knowledge gains across the instructional designs examined.

Exploration of the relationship between pilot certification and performance revealed an additional aspect influencing MALE RPA training, which must be controlled in future studies seeking variation uniquely attributable to instructional method. This pilot study found that learners holding a commercial pilot certificate scored significantly higher on the pretest than those with no FAA pilot certification ($p<0.05$). Such tendencies beg further investigations into the relationship of FAA pilot certification and MALE RPA training. What skills, knowledge, or experience, captured by these aviation benchmarks, accounts for the increased initial performance? Is the lack of significant difference between posttest scores with respect to certification the result of an artificial ceiling effect with the instrument? Does the ability to navigate and manipulate these menus represent understanding of their function? Perhaps considerations such as these can be used to adapt initial operations training in these platforms to the qualifications of those best qualified or most likely to be entering this new and rapidly evolving discipline.

As demand for MALE RPA pilots and sensor operators grows, adapting pedagogy and technologies to provide the highest standard of instruction at the greatest efficiency will remain an enormous challenge for all. Future studies involving the HDD menu trainer are underway utilizing the results of this pilot effort to isolate the unique variance in performance explained by instructional method and possible interactions between instruction and pilot certification. Informed by the results of this study, these efforts will utilize larger samples to map this relationship. Other studies are encouraged to document and reflect on learning efficiency, investigating whether use of such training aids can reduce instructor and/or simulator training time while engendering equivalent knowledge, skills, and abilities. Examining the pedagogy of MALE RPA training with consideration to learner knowledge gains, learner attitude, and learning efficiency will support the comprehensive understanding necessary to advance and mature this training domain.

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JOURNAL OF UNMANNED AERIAL SYSTEMS

PEER-REVIEWED PAPER

PERCEPTIONS OF PROGRAM LEADERS ON THE USE OF UNMANNED AIRCRAFT SYSTEMS FOR FOREST HEALTH MANAGEMENT

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Abstract

Forests are a significant resource to the national economy in terms of forest-related products, environmental impact, and recreation. The US Forest Service manages federally owned national forests and collaborates to provide assistance to states and private individuals in management of state and private forests. Wildland fires and insect and disease outbreaks threaten the health of the forests in the US. The Forest Service is tasked with monitoring forest health and aerial surveys contribute extensively to the achievement of this goal. However, these surveys are time-consuming and expensive. Given the current need to decrease government budgets, the organization is challenged to provide adequate forest surveillance, while at the same time lowering cost. The addition of unmanned aircraft system (UAS) technology could be part of the solution to this problem. Recent studies suggest UAS technology can be used to provide quality data collection regarding forest health at a lower cost than traditional methods. In order to introduce this new technology within such a large organization, management support would be needed. This descriptive qualitative case study explored the attitudes of key forest health personnel on the concept of UAS technology through informal conversational interviews. Diffusion of innovations theory was used to guide the research process. The participants included forest health program managers and data collectors from all nine geographic regions of the United States that are managed by the Forest Service. The researcher explored their knowledge of UAS technology and its potential use in improving forest health surveillance within their programs, as well as their attitude regarding this innovation. Seventeen themes were identified including overall acceptance of the technology, reasons for favorability and concerns about the technology, overall knowledge level as well as educational needs, uncertainty of cost effect, and overall belief that this technology will improve data quality. The results added to the current limited literature regarding implementation of new technology in a government organization. Implications of using UAS technology in forest health management are presented regarding privacy, educational needs, budgets, and effects on cost and quality. Recommendations are presented for future research.

Background

The Forest Service, an agency that falls under the direction of the US Department of Agriculture (USDA), is an organization comprised of personnel who manage large areas of forested public lands ("About us," 2011) and interface with states and private landowners to provide support in the management of forests ("State and Private Forestry," 2010). The Forest Service manages 193 million acres of national forests and grasslands in the United States, including 155 national forests and 20 grasslands ("About us," 2011). The mission of the organization is to sustain the health, diversity, and productivity of the forests and grasslands in order for these resources to be able to meet the needs of the present and future generations ("Mission," 2008).

The value of the public forest resources to the US national economy is significant with respect to forest-related products, environmental impact, and recreation ("USDA Forest Service Strategic Plan FY 2007-2012," 2007). National forests, especially in the west, are a significant source of the nation's water supply with the estimated annual value of water flowing from national forests of $3.7 billion (Kimbell, 2010). Recreation on the national forests and grasslands contributes an estimated $14 billion per year to the nation's economy ("National visitor use monitoring results," 2010). A key challenge to the organization is to protect the resources contained in national forests ("Forest Health," 2011). Since 1990, concerns have increased due to weather extremes, severity of wildland fires, and insect and disease outbreaks that threaten the health of the forests and disrupt ecosystems ("National roadmap," 2010). Between 65 and 82 million acres of national forests and grasslands need some type of restoration (USDA-Forest Service, 2012). This fact emphasizes the need to increase the pace and scale of restoration (USDA-Forest Service, 2012). These facts only strengthen the idea that there is not only a need to restore, but to protect the undamaged areas and monitor the progress of the ongoing restoration. This task will be accomplished through forest surveillance.

Surveillance of forest health is monitored by means of formal surveys of the land (Carnegie, Cant, & Eldridge, 2008). The Forest Health Protection program is devoted to monitoring forest health ("Programs," 2011). The program provides technical assistance on forest health matters, especially related to disturbance agents such as pests, pathogens, and invasive plants that threaten forest resources. The most efficient and cost-effective technique related to invasive species is the prevention of their establishment and spreading within a forest area ("Forest Health Protection," 2011). The forests in the United States are monitored to obtain information over time about the health of the forest in order to determine if there are detrimental changes or improvements (Bennett & Tkacz, 2008). In order to achieve this goal, it is necessary to obtain views of large areas of land. Aerial surveys are used in surveillance as a method to determine the status of forest health (Woodall, Morin, Steinman, & Perry, 2010) and have played a key role in facilitating the goal of forest health management, from the perspective of forest health and fire management ("Aerial Application," 2009). Therefore, the use of aircraft contributes to achieving the mission of the Forest Service by providing access to large areas of land. The high resolution images that are needed for forestry are costly and difficult to obtain by either satellite or traditional airborne data collection using pilots and technicians (Grenzdorffer, Engle, & Teichert, 2008). Despite the benefits of aerial support for forest health monitoring, these programs are often targets for cost-cutting (Becker, 2004).

As with any government agency, the Forest Service is tasked with decreasing operational costs ("Budget," 2011). The Budget for FY 2012 contained a three percent reduction for Forest Health Management-Federal Lands ("FY 2012 budget justification," 2011). The cost related to using aerial support for forest surveillance adds to the organizational budget (Rasker, 2010). However, a recent survey involving attitudes of managers suggested that Forest Service wildfire managers consistently ranked the cost of their efforts as the least important factor in their decision-making process (Wibbenmeyer, Hand, & Calkin, 2012).

The addition of unmanned aircraft system (UAS) technology could be one key part of the solution in reducing cost and improving forest health management, as well as other programs such as fire, wildlife, and timber management. The organizational change involved to implement this innovative technology would be facilitated by the support of management within the forest health programs, as well as by employees who will use the technology within the organization (Fernandez & Rainey, 2006). However, organizational change and acceptance of new technology can be difficult to achieve (Chew, Cheng, & Petrovic-Lazarevic, 2006).

Currently, about one-third of the US is forested making it the fourth largest forest estate in the world and the Forest Service manages about 25 percent of those forested lands (Blay & Dombeck, 2013). The agency is organized into nine geographical regions illustrated in Figure 1 and each region has a forest health program manager and at least one individual who collects forest health data ("About us," 2011).

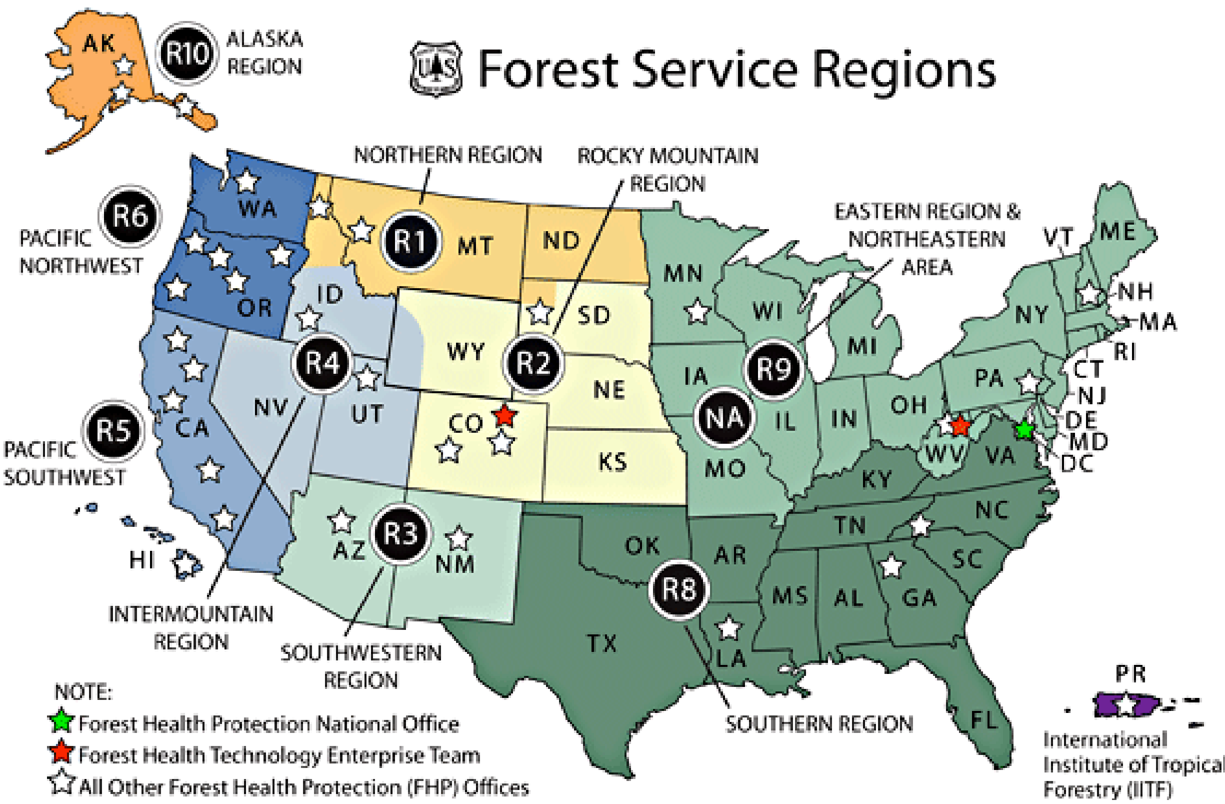

Figure 1. Regions of the US Forest Service

This figure illustrates the nine regions of the US Forest Service including Northern Region (R1), Rocky Mountain Region (R2), Southwestern Region (R3), Intermountain Region (R4), Pacific Southwest Region (R5), Pacific Northwest Region (R6), (note there is no R7), Southern Region (R8), Eastern Region (R9), and Alaska Region (R10) presented at http://www.fs.fed.us/foresthealth/resources/images/FS_regions.gif

Statement of the Problem

The Forest Service is challenged to provide forest health management at a lower cost. Forest Service aviation needs, which play a large role in forest health surveillance and fire management, have been assessed many times; however, the conclusions of these studies in terms of type, quantity, and cost differ (Bracmort, 2013). Even the most recent of these studies (Keating et al., 2012) does not consider UAS technology, despite the fact that studies suggest that UAS technology has the potential to provide effective surveillance to maintain forest health, while at the same time allowing for a reduction in cost (Grenzdorffer, Engle, & Teichert, 2008; Marenchino, 2008; McCormack, 2008; & Meszaros, 2011). Regulations were expected to be in place by 2020 to govern UAS operations ("Unmanned Aircraft Systems," 2008), but with the "Small UAS Notice of Proposed Rulemaking" having gone forward in February (Federal Aviation Administration, 2015), this is now more likely to be in 2016 or 2017, at least for small UASs (those under 55 pounds). The introduction of UAS technology has the potential to be part of the solution to improve forest health surveillance; however, the acceptance of this new technology will involve change. Because managers are very influential in promoting organizational change (Ryan, Williams, Charles, & Waterhouse, 2008), the attitude of program managers about UAS technology and their understanding of its potential use in their programs is crucial. At the same time, the implementer will be the individual who will actually put the innovation to use (Rogers, 2003) and therefore, data collectors also play a significant role in acceptance of this new technology. Because the perceptions of key forest health personnel about UAS technology are unknown, the need for a qualitative study exploring the attitudes and knowledge of these individuals about the use of UAS technology has emerged.

Purpose of the Study

The purpose of this descriptive qualitative case study was to explore the attitudes of the forest health program managers and data collectors about the use of UAS technology and their knowledge level of this technology in relation to their programs.

Theoretical Framework

The Diffusion of Innovation Theory (Rogers, 2003) was used as the theoretical framework. This research falls under the category of organizational behavior as it involves members of the organization to implement a new innovation as part of the standard practice. However, it also involves social psychology in that individual and cultural factors affect the acceptance of innovations (Tolba & Mourad, 2011). The Diffusion of Innovation Theory has its roots in social psychology. The history of conceptual and empirical study of this theory is extensive and the robustness of the theory is the result of studies that have been conducted from many disciplines and fields (Dearing, 2009). Rogers' theory is appropriate for investigating the adoption of new technology and, in fact, Rogers often used the words technology and innovation interchangeably (Sahin, 2006). The current use of the theory is evident in research involving acceptance of new technology (Blau & Hameiri, 2010; Casanovas, 2010; Greenhalgh et al,, 2008; Peslak, Ceccucci, & Sendall, 2010; Tolba & Mourad, 2011; & Vaccaro, Ahlawat, & Cohn, 2010).

Rogers (2003) developed the theory in an effort to understand what factors influence a person's willingness to accept or reject new technology. The theory was developed in terms of the social context in which individuals exist. The four main elements of the theory are the innovation itself, communication channels, time, and the social system. The guiding principle is that in the process of diffusion, the innovation is communicated through channels over time within a social system (Sahin, 2006). The assumption of the theory is that in any given sample of individuals or organization faced with accepting new technology, this process will occur.

According to Dearing (2009), diffusion of innovation theory is evolving into a science of dissemination driven by new technologies and needs of government agencies. Dearing believes this science is being shaped by researchers in various fields of study, including forestry. Dearing also pointed out that the adopter of the innovation is not necessarily the one who will use it. The implementer will actually put the innovation to use.

The social system in Rogers' theory may be represented by an organization. According to Rogers, the individual and the social system in which they exist may be affected by the innovation. In a literature review regarding the adoption of online education in universities by Casanovas (2010) concluded that the organizational culture will influence whether the innovation is accepted.

This study was guided by the Diffusion of Innovation Theory because adopting UAS technology represents a change for individuals as well as organizational change. Within the context of the theory, the program managers represent the adopters, the data collectors the implementers, and the Forest Service the social system.

There are five main diffusion characteristics that influence the rate of adoption including relative advantage, observability, compatibility, complexity, and trialability (Rogers, 2003). The presence of these five factors is consistent with faster adoption of the innovation. Rogers stressed that adopting a new innovation is difficult and that the theory of diffusion will continually evolve over time. In a study by Vacaro, Ahlawat, and Cohen (2010) regarding adoption of the Apple iPhone, the researchers contributed to the theory by extending the list of diffusion characteristics to include cost, uncertainty, social relevance, and marketing design.

The model postulates that in any given sample, the subjects will fall into one of five adopter categories illustrated in Figure 2. Few (16%) are in the innovator and early adopter category, the majority (68%) falls into the early and late majority, and the final 16% fall into the laggard category (Rogers, 2003). The theory enables the researcher to predict that in the group of managers and data collectors, there will be individuals who will represent characteristics of each of these groups in a similar distribution.

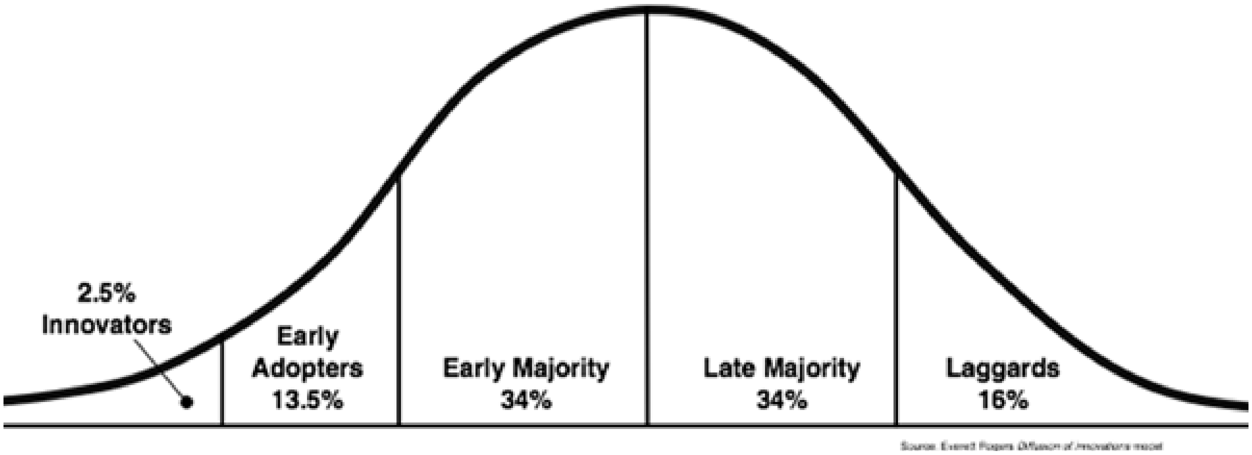

Figure 2. Bell-curve distribution for Roger's Diffusion of Innovation Theory

This figure illustrates the distribution of the five categories for any given sample.

Many studies suggest that UAS technology can provide quality data for forest health surveillance at a lower cost; however, there is an unanswered question whether individuals, such as program managers and data collectors, in the Forest Service would accept the technology. Therefore, the use of a theory related to diffusion of innovation of new technology was appropriate for this study.

Research Questions

The purpose of this descriptive qualitative case study was to explore the attitudes of the forest health program managers and data collectors about the use of UAS technology and their knowledge level of this technology in relation to their programs. The central research question was what perceptions do program leaders have on the use of Unmanned Aircraft Systems in their Forest Health Management programs? The five research questions that guided the inquiry are listed below.

Q1. What is the attitude of managers and data collectors regarding the future use of UAS technology in their programs?

Q2. What reasons exist to contribute to the attitude of the managers and data collectors about future use of UAS technology in their programs?

Q3. What is the knowledge level of managers and data collectors regarding how UAS technology would be used in their forest health programs?

Q4. What is the level of understanding that managers and data collectors have regarding how UAS technology would affect the cost of their forest health programs?

Q5. What is the level of understanding of managers and data collectors about how UAS technology might affect the quality of data collected through aerial surveillance?

Research Methods and Design

In this descriptive qualitative case study the attitudes of forest health program managers and data collectors were explored regarding the use of UAS technology in their programs. This was done in order to examine their inherent knowledge of the technology and its potential use in improving forest health surveillance with an emphasis on increasing the quality of the data collected and lowering the cost of the program. To accomplish this objective, interviews using open-ended questions were conducted with program personnel in order to gather the data. This interview technique is used when the researcher is principally interested in descriptive, explanatory or exploratory appraisal in order to obtain subjective data, such as attitudes (Patton, 2002).

A qualitative design was appropriate for this study because the attitude of program managers and data collectors about the concept of UAS technology is unknown. A case study is used to capture the complexities of a single case; however, the single case can be made up of multiple cases (Yin, 2014; Patton, 2002). In this research, the multiple-case study design was used in which multiple cases (18 interviewees) contributed to the overall qualitative data. The reason this design was chosen is that, unlike single case design, multiple-case design provides the possibility of direct replication and a strong start to theoretical replication which will strengthen the findings (Yin, 2014). The researcher was able to maintain the personnel consistency of manager and data collector as the interviewees, while at the same time, providing the diversity within the sample consisting of personnel from all nine regions of the country. The multiple interviews served as the case of analysis studied. The qualitative analysis centered on the presentation of thematic analysis across the cases (Patton, 2002). The justification for choosing an interview approach for this particular study was based on the fact that both the participants and the researcher would have the ability to take the interview in a variety of directions for the purposes of data collection. The open-ended questions used within the study were primarily guided by the research questions established by the researcher and Diffusion of Innovation Theory. The interview style was informal conversational interviewing. The research questions were directed at how the managers view UAS technology and how much they know about its potential use in their programs. A pilot study was conducted in order to test this entire process on two individuals not involved with this research. One individual works as a wildland fire training officer and the second individual is a program manager for the Forest Service state fire assistance program. Institutional Review Board (IRB) approval from Northcentral University (NCU) was obtained for the pilot study alone and then later obtained for the core study.

Population

The population in this research study included individuals who are responsible for forest health protection within the Forest Service. This group includes those individuals in management positions related to the forest health program as well as those individuals who carry out assessments and data collection. Forest health oversight is influenced by decisions made by high level leaders in the Forest Service to program managers in each region to those individuals who actually collect data regarding forest health. This population was appropriate for the study because it is the attitude of these individuals about the value of UAS technology that will determine if it will be used, since these individuals will be most affected by its use.

Sample

The purposive, convenience sample (Marshall, 1996) was pre-determined by the regions of the Forest Service and consisted of 18 participants. The sample consisted of the one program manager and one data collector from each of the nine geographic regions. There is some word of caution on even using the term “sample” within a case study (Yin, 2014), since the use of the term may mislead others to think the case comes from a larger population of like cases. The researcher did not wish to imply that assumption. This sample was chosen because it represents the nine regions nation-wide and included those individuals with the closest involvement with forest health activities.

Recruitment consisted of the researcher contacting the managers and data collectors from each of the nine regions. These regions were already established and identified as well as the individuals who serve in these positions. All 18 individuals were invited to participate in the study and were informed that participation was voluntary.

Materials/Instruments

The interview questions were guided by the Diffusion of Innovation Theory. The concepts of the theory were used to develop the questions in relation to the five research questions. These questions were derived from the researchers’ desire to explore attitudes and knowledge level of managers and data collectors about the use of UAS technology in their programs. There were a total of 10 interview questions. Each participant was allowed as much time as was needed to answer the questions. Prior to full study data collection, the interview instrument was pilot tested with two individuals who are in similar positions as the full study participants in the Forest Service, but were not a part of the full study sample. One individual works as a wildland fire training officer and the second individual is a program manager for the Forest Service State Fire Assistance Program. Based on the results of the pilot study and input from the reviewers, the researcher made revisions to the interview questions. The researcher revised the interview to include open-ended questions with follow-up questions to eliminate the possibility of simple yes or no answers. The questions also reflected a greater clarification asking the participants to explain their knowledge of UAS technology. Based on reviewer input, a question regarding aerial surveys was added as well as a question regarding safety. The question related to a timeframe when the Forest Service could be ready for implementation of UAS technology in forest health was changed to allow for an open-ended answer rather than the specific year. Finally, a way of debriefing participants was added by asking them if they had any questions about the study.

Data Collection, Processing, and Analysis

There were six steps in the data collection process. (1) Each participant completed an informed consent form. (2) The researcher conducted one interview with each individual by telephone. (3) One hour was allotted for each interview. (4) Because the questions were open-ended, each interviewee also had an opportunity to ask questions or take the interview in a different direction in order to share his or her ideas regarding the topic. (5) If any program manager would have been uncomfortable with this method, other data collection accommodations would have been made, such as traveling to meet with that individual personally; however, this situation did not occur. (6) With the permission of the participants, the interviews were digitally recorded. If the participant would have been uncomfortable with the interview being recorded, the researcher would have taken detailed notes from the interview. However, this situation did not occur.

After the data was collected, the digitally recorded interviews were transcribed by an individual not affiliated with the study. The transcribed data was reviewed manually by the researcher and two professional colleagues not involved in the research project.

Thematic analysis was used to identfy themes. This process is a form of pattern recognition achieved by careful reading and re-reading of the data in order to identify emerging themes (Fereday & Muir-Cochrane, 2006; Patton, 2002). The three evaluators manually reviewed the data separately, but in the same manner. Having multiple evaluators review the transcripts enabled the different individuals to form themes from the data (Golafshani, 2003) and served as a form of investigator triangulation in an effort to balance the subjective influences of individuals (Jupp, 2006). Each reviewer received paper copies of the transcribed interviews and was instructed to manually review the data using coding, sifting, sorting, and identifying themes (Lichtman, 2013). As such, it was expected that by utilizing the process of reading and re-reading the data, emerging themes within the collected data sets could be identified. For example, the assigned code of [decreased risk to personnel] was present in all 18 responses regarding potential benefit of UAS technology. Thematic analysis can help the researcher to demonstrate rigor (Fereday & Muir-Cochrane, 2006), an important factor in conducting case study research (Yin, 2014). When research is performed in a rigorous manner it can lead to more effective practices than decisions based mainly on intuition, personal preferences, or common sense (Anderson, Lievens, Van Dam, & Ryan, 2004). With such an analysis, the findings were obtained in an unbiased manner.

The reviewers identified categories and themes derived from the data, and identified the main common themes. It is based on this information that the researcher utilized the data garnered through the interviews, along with data from the literature review, in order to develop a sufficient platform from which effective, and above all accurate, conclusions were created.

Results

A total of 18 individuals were invited to participate in the study and all accepted. The sample consisted of the one program manager and one data collector from each of the nine regions of the Forest Service for a total of 18 participants. The demographics of the sample are presented in Table 1. The average age of the program managers was 54 (M=54.89, SD=6.41) and 46 (M=46.00, SD=7.53) for the data collectors. Eight of the nine program managers and seven of the nine data collectors were male. Of the nine program managers, eight were caucasian and one was African American. Eight of the nine data collectors were caucasian and one was Native American. Of the nine program managers two had a bachelor’s degree, five a master’s degree, and two a doctoral degree. Of the nine data collectors one had some college, four had a bachelor's degree and four had a master's degree. The mean years of service for the program managers and data collectors was 26 (M=26.39, SD=12.15) and 17 (M=17.33, SD=7.95), respectively.

Table 1

Demographics of Sample

Characteristics	Subgroup	Program Manager (n=9)	Data Collector (n=9)
Age	M (SD)	54.9 (6.4)	46.0 (7.5)
	Range	42-62 yrs	37-57 yrs
Years Service	M (SD)	26.4 (12.15)	17.3 (7.95)
Gender	Female	1	2
	Male	8	7
Race/Ethnicity	African American	1	0
	Asian American	0	0
	Caucasian	8	8
	Hispanic	0	0
	Native American	0	1
	Other	0	0
Education	High School	0	0
	Some College	0	1
	Associate Degree	0	0
	Bachelor's Degree	2	4
	Master's Degree	5	4
	Doctoral Degree	2	0

Seventeen themes were identified illustrated in Figure 3 including overall acceptance of the technology, reasons for favorability and concerns about the technology, overall knowledge level as well as educational needs, uncertainty of cost effect, and overall belief that this technology will improve data quality.

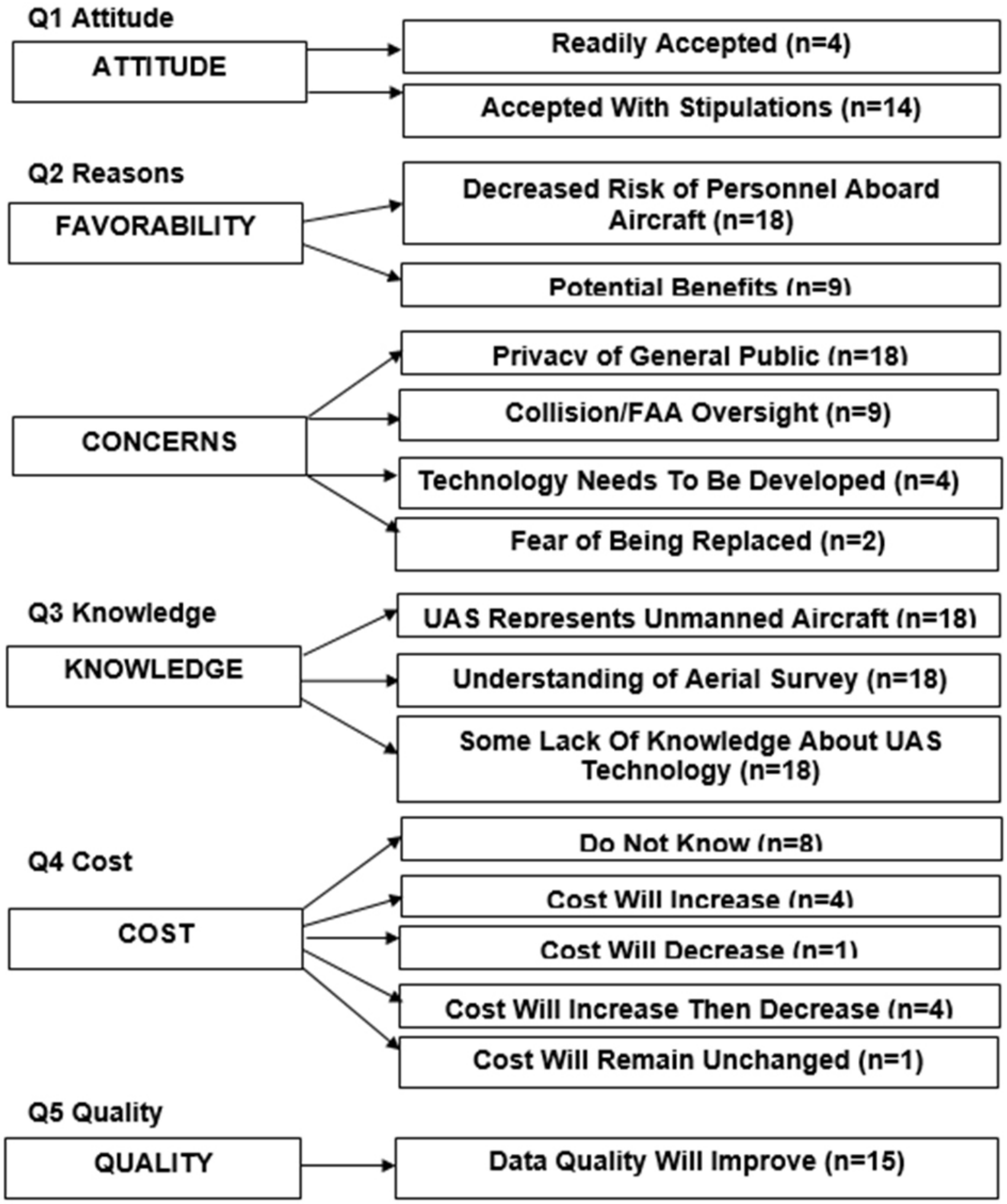

Figure 3. Flowchart created by the author illustrating the 17 themes identified through data analysis in relation to the five research questions.

Accepted with stipulations. While several participants expressed that the technology would be readily accepted, most participants expressed that UAS technology would be accepted with stipulations including the development of a communications plan, a training plan, a strategy for implementation, and organization-wide policies. This information will be especially helpful to those individuals within the organization planning education and training of personnel on UAS technology.

Most of the participants categorized themselves on the early adoption side of Rogers' Theory. This factor is important because, according to the theory, the adopter will make the decision whether to invest in the innovation (Rogers, 2003). Fifteen of the 18 participants placed themselves in the category of innovator, early adopter, or early majority. Support for UAS technology at the level of the managers is a good predictor of its acceptance within the organization. The literature supports the fact that organizations must be innovative to adapt to changing circumstances (Yukl & Lepsinger, 2004) and in the public sector, such as the Forest Service, organizational change requires support of top level civil servants (Fernandex & Rainey, 2006).

Table 2

Categories of Participants within Roger's Theory

Categories	Program Managers (n=9)	Data Collectors (n=9)
Innovators	3	3
Early Adopters	4	2
Early Majority	1	2
Late Majority	1	0
Laggards	0	2

Decreased risk of personnel aboard aircraft. All the study participants expressed that UAS technology would improve safety simply by keeping personnel out of the air. One of the many benefits of UAS technology is less risk in flight compared to traditional manned aircraft (Martinsanz, 2012).

Potential benefits. Most participants expressed that UAS technology will benefit their programs. The literature supports the participants belief and contains multiple sources that suggest UAS technology will improve surveillance over large areas of land, whether that be for forest health monitoring (Ollero & Merino, 2004), inspecting forestry operations (Grenzdorffer, Engel, & Teichert, 2008), glacier monitoring (Whitehead, 2010), avalanche control (McCormack, 2008), natural disaster monitoring ((Al-Tahir, Arthur, & Davis, 2011), forest fire monitoring (Everaerts, 2008), and collecting low-altitude imagery over difficult areas (Jones, Pearlstine, & Percival, 2006).

Privacy of general public. All participants expressed that the use of UAS technology will create privacy concerns for the public. Several addressed the big brother concept and that some members of the public will worry that they are being watched by the government. Some stated that this may be more prevalent in certain areas of the country than others. The literature supports the fact that civil liberty and privacy groups have concerns about misuse of UAS technology and limited oversight by the FAA in this regard (Elias, 2012). Many participants in this study expressed that a proactive approach by the organization would be best when implementing UAS technology into their programs and regions. This important data finding can be very useful to the organization in planning a proactive approach to public education of UAS technology in its forest health program.

Collision/FAA oversight. Several participants expressed concern that UASs may collide mid-air with other aircraft. Many participants also expressed not only the need for FAA oversight, but that they want the direction and guidance of the FAA regulations. Participants pointed out that the Forest Service is an organization in which personnel are familiar with rules and regulations and they want similar guidance to address the use of the new technology. The FAA is working closely with the UAS community to develop standards including how UASs will sense and avoid other aircraft. Part of this effort is the UAS Traffic Management (UTM) system, being led by NASA for the FAA so that small UAVs and other aerial platforms can co-exist, especially in airspace that will primarily be used by UAVs (National Aeronautics and Space Administration, 2015.)

Technology needs to be developed. Several participants stated they believed UAS technology will need to be further developed before it could be useful in their programs. One researcher found that despite the advancing use of UAS technology in photogrammetry, the availability of these systems is limited and development is needed in relation to the sensors and the Global Positioning System (GPS) unit of the guidance system (Meszaros, 2011). However, as manufacturers become aware of the requirements needed for UASs to complete aerial survey images, the way will be paved for UAS technology development in this area (Grenzdorffer, Engel, & Teichert, 2008).

Fear of being replaced. Two participants expressed concern that they may be replaced by this new technology. They enjoy flying and they do not want to see that part of their job eliminated. However, the literature supports the fact that UAS technology will not eliminate jobs; a UAS is not without a pilot and in many cases, there may be more crew members needed than with traditional aircraft (Everaerts, 2008).

Some lack of knowledge about UAS technology. While all participants had a clear understanding of aerial surveys and UAS technology in general, most expressed that they do not know enough about it to know how it will affect their Forest Health programs. Under the Diffusion of innovation Theory, the first of the five stages of acceptance of new technology is knowledge; there must be knowledge and understanding of the concept in order to achieve acceptance (Rogers, 2003).

Desire for multiple methods of learning. Most participants expressed that they want to learn more about UAS technology and that they want to have multiple methods of training in order to gain that knowledge. This information can be very beneficial for leaders within the organization as they plan education programs for learning about UAS technology.

Cost-benefit uncertainty. Participants had a wide range of responses related to the potential cost benefit of UAS technology in their programs. All participants expressed their opinion of what would happen with cost; however, most all participants stated that they did not really know for certain how the new technology would affect their program costs. The literature suggests that aerial surveying can be conducted using UAS technology in forestry and can provide the same high quality data as conventional methods at a much lower cost (Grenzdorffer, Engle, & Teichert, 2008; Marenchino, 2008; Rango et al,, 2009; Wallace, Lucieer, Watson, & Turner, 2012; & Whitehead, 2010).

Improved quality. All participants expressed the belief that UAS technology would improve the quality of data collected in their programs. This belief is related to the fact that the data would be more standardized, human subjectivity would be removed, and interpretation would be more objective. The literature supports the participants' belief that conducting forestry surveillance using UAS technology will improve quality of the data (Lu, Li, & Tang, 2010; & Lucieer, Robinson, & Turner, 2010).

Evaluation of Findings

Q1. What is the attitude of managers and data collectors regarding the future use of UAS technology in their programs?

The overall attitude of the participants was positive regarding the future use of UAS technology in their programs. However, only a few participants stated that the technology would be readily accepted. The majority of participants said the technology would be accepted with stipulations including the development of a communication plan, training plan, strategy for implementation, and an organization-wide policy.

Participant Ma stated:

"I feel pretty positive about the technology. I'd really be a champion if we're going to this new technology."

Nearly all participants felt safety would be improved simply by keeping personnel out of the air.

Participant Ma stated:

> "I don't have much of a safety concern about using the drones. . . . . the safety aspect I see is protecting the lives of our pilots and spotters who go up into the air on this monitoring for hundreds of hours every summer season."

All of the participants addressed the belief that public privacy concerns will be an issue, the concept of big brother watching over the public, the need for a social license to use this technology, and the need to be proactive in educating the public.

Participant Ma stated:

> "I think we'll need some social license to do this work . . . and I think it's our responsibility to do that."

Q2. What reasons exist to contribute to the attitude of the managers and data collectors about future use of UAS technology in their programs?

The overall attitude was positive and one might postulate that the participants felt this way because many placed themselves in the early innovator category and that they believe the organization will benefit from this new technology. The participants offered positive reasons in favor of the technology including decreased risk to personnel and potential benefits. They also offered concerns that contributed to their attitude. These reasons included concerns for privacy of the general public, for collision and need for FAA oversight, for the need for technology development, and for fear of being replaced in their jobs by the technology.

Q3. What is the knowledge level of managers and data collectors regarding how UAS technology would be used in their forest health programs?

While all participants knew what UAS technology meant in terms of the aircraft being unmanned and had an understanding of aerial survey, most expressed at some point in the interview that they do not know enough about the technology, especially in relation to how it can be used to benefit their forest health programs.

Q4. What is the level of understanding that managers and data collectors have regarding how UAS technology would affect the cost of their forest health programs?

Many participants simply did not know how the technology would affect the cost of their program and data collection. However, many discussed how they thought it might influence cost, whether that would be to increase, decrease, increase over time, or remain unchanged.

Q5. What is the level of understanding of managers and data collectors about how UAS technology might affect the quality of data collected through aerial surveillance?

Most participants felt the quality of data would improve. The benefit of computer technology was compared to that of the human eye as being more precise and accurate. The benefit of the ability to review the data multiple times from the UAS recorded data was also addressed. Currently, when aerial surveys are completed, the person performing that survey interprets the observations and completes a sketch map. This action involves the observation of that individual and interpretation to be placed on a map. There is no opportunity to repeat that view. If this activity were to be completed with the use of UAS technology, the imagery could be captured by a single image, continuous imaging, or videography, depending on the type of sensor used. This raw data will not contain individual subjectivity of interpretation and would provide historical data that would be available for unlimited review by many individuals at unlimited time-points.

Participant Ma stated:

> "Well, of course you could remove some human error. You can't take your eyes off the target and I would think drones would not. And even human beings could look to the ground, even professionals, and think they see damage this year, when it was really damage from last year. So I do think there's some opportunity to avoid those skips in detection . . . . and maybe avoid some of the errors in professional judgment."

Summary

The Forest Service is a conservation organization that has existed for more than a century (Williams, 2000) that faces many challenges in a changing global community with the complexities of public opinion, ecosystem management, and declining budgets (Kennedy & Quigley, 1998) to continue its mission to care for the land. The benefits of forests to the nation and the global ecosystem are significant in terms of clean air and water, recreation, renewable resources, and jobs (USDA-Forest Service, 2012). Research supports the use of aerial surveys to assess forest health (Woodall, Morin, Steinman, & Perry, 2010). The role of the Forest Service in managing the health of 193 million acres of forest and grass lands through surveillance by aerial photography and mapping carries risk and high cost (Becker, 2004; & Carnegie, Cant, & Eldridge, 2008). Budget cuts and flat existing budgets threaten the ability of the Forest Service to adequately monitor forest health (Becker, 2004). UAS technology is one tool that may provide the possibility of monitoring large areas of land, including forests, as a safer, cost-saving alternative to traditional manned aircraft (Grenzdorffer, Engel, & Teichert, 2008), especially with the ability it provides to fly at low altitudes (Everaerts, 2008). In order to use this tool, the Forest Service would have to accept this new technology. Organizational change, especially within the public sector, can be difficult (Fernandez & Rainey, 2006). The introduction of a major innovation within an organization can cause resistence to that change, even from the leaders (Yukl & Lepsinger, 2004). Top-management support and committment are crucial in bringing about change within an organization (Fernandez & Rainey, 2006). Perceptions of managers is a key element in an organization to support change and innovation, as well as effective communication and employee attitudes (Chew, Cheng, & Petrovic-Lazarevic, 2006). The use of Rogers' Diffusion of Innovation Theory (2003) can be helpful in determining the adoption process of new technology.

Implications

The results of this research study have contributed to the understanding of attitudes and knowledge level of managers and data collectors, or potential users, regarding UAS technology within the Forest Service. Knowing the attitudes and perceptions provides individuals planning to introduce this new technology with a foundation on which to build the innovation process. The results of this study show that key personnel who will be responsible for initiating this technology have a basic understanding of the technology and a desire to learn more, are favorable to its use in their program, have knowledge of some of the potential problems such as public concern for privacy, believe in taking proactive steps to minimize these problems, and believe that the technology can improve cost and quality of data necessary for their forest health programs.

Limitations include the fact that despite the participants representing managers and data collectors from all nine national regions of the Forest Service, the results from this small sample cannot be generalized to other populations, especially those individuals representing non-government organizations (Fernandez & Rainey, 2006).

Additionally, one of the interview questions asked the participants to place themselves into one of Rogers' categories regarding acceptance of innovation. Both the researcher and the external reviewers pointed out that this question was confusing and difficult to interpret. However, most particpants expanded enough on their answer that the researcher and the external reviewers were able to determine the appropriate category into which the participants placed themselves.

Recommendations

Several recommendations emerged from this study including the need for a proactive plan for public education about UAS technology concerning privacy issues, the need for multiple methods of education and training of personnel to introduce the new technology, the need for education of personnel on what research has been completed regarding UAS technology and forest management, the effect this technology will have on current budgets, potential personnel needs regarding the use of this new technology, and education on how the technology can improve cost and quality of data.

Most all of the 18 participants expressed that the public will have concerns about unmanned aircraft flying over private and public property. Many felt that the Forest Service will need to have a proactive plan to educate the public prior to the implication of UAS technology.

Participant Ma stated:

> "I think we would have to approach it very gently and gradually and have a public awareness campaign; maybe even a demonstration. I would want to work with our communications professionals and see how we did roll this out publically and develop some support."

All of the 18 participants told how they would like to learn about UAS technology. There were multiple methods mentioned including webinars, videos, field demonstration, hands-on training, experience-sharing by others, classroom, and written material. Most participants said they would like to receive the education by more than one method.

Participant Db stated:

> "A good place to discuss this with folks nationally would be at an aerial survey working group meeting; have this be a discussion item with an individual presenting who really knew the ins and outs, the regulatory, and some of the practical applications. Then have follow-up discussion with the group."

Participant Dc stated:

> "I tend to do better if something is presented to me in a classroom style setting, where I'm introduced to it and I learn all the functions and how to operate it."

Participant De stated:

> "I would be interested in testing it out in a kind of hands-on manner. Actually going out with a UAS and checking out, you know doing a little mock survey and seeing what type of data we get out of it. . . . I would also like to see how other people are using it and using the data, both in forest heath and in related fields."

Participant Df stated:

> "I guess I would like to see an application for webinars to cover general topics and how people are using UAS in the forest health arena, And then I would like to see some practical, hands-on application type data – to be able to kind of kick the tires with it a little bit just to see what it can do and how it can be used in the program and then, as a last phase, share our experience with others in the field to see if this technology would be useful or applicable to other programs."

Participant Di stated:

> "Well, by using it. I think that's the best way for us to learn is to just get out and do it in a limited sense."

Participant Mb stated:

> "I think some hands-on examples of maybe even some case studies specific to forest health issues and how they were resolved . . . . I believe maybe results of case studies presented in a workshop-type of format where people could ask questions would probably be kind of an ideal way to market it."

Participant Me stated:

> "Certainly materials that can be read are very good, videos that demonstrate how the technology is used or how it can be used would be great . . . eventually some form of hands-on demonstration or training to learn about it."

Participant Mf stated:

> "I would wish to learn from pilot testing in certain regions, different cover types of vegetation to see how the mapping turned out under different scenarios."

Many study participants also expressed the desire to know what research has already been done with UAS technology in relation to forest management. This information can be very helpful in the program planning for the introduction of UAS technology. The programs planned will need to include multiple learning methods and a thorough coverage of what research has been done with UAS technology, both within the Forest Service and in private orgainzations, in relation to forest health management.

The implementation of this new technology will most likely affect the allocation of current budgets. When the FAA has the regulations in place that will enable the organization to implement the use of UAS technology, funds will need to be allocated to purchase the UASs. The decision will need to be made as to whether there will be a pilot use of the technology or whether it will be simultaneously used in multiple areas of the country.

Participant Ma stated:

> "Honestly, if the Forest Service was looking for a region to give it a test drive, I'd be willing to raise my hand."

The implementation of this technology will also require management of these changes within the organization. It will need to be decided if existing managers can adequately handle the implentation of such a change. Perhaps there will be a need for one person to provide oversight of the program on a national basis.

Finally, the study participants had beliefs about how UAS technology will affect the cost and quality of data in their programs. While all participants had ideas on how the technology will affect cost, most were not sure and admitted to only guessing about its effect. The literature supports the fact that UAS technology can reduce cost on surveillance of large areas of forested lands (Grenzdorffer, Engle, & Teichert, 2008; Marenchino, 2008; Rango et al., 2009; Wallace, Lucieer, Watson, & Turner, 2012; & Whitehead, 2010) and this information will need to be included in the training programs offered.

While most participants expressed the belief that UAS technology would improve the quality of their data, they were not certain about this prediction. Research has shown that this technology can provide improved quality of data collection for forest health monitoring over large areas of forested lands (Casbeer, Kingston, Beard, & McLain, 2005; Everaerts, 2008; Grenzdorffer, Engel, & Teichert, 2008; Jones, Pearlstine, & Percival, 2006; Lu, Li, & Tang, 2010; Marenchino, 2008; McCormack, 2008; Meszaros, 2011; & Morris, 2007) and this information will need to be included in the training programs offered.

Recommendations for future reseach include the possibility of other quantitative and qualitative studies involving other samples and other questions. A potentially beneficial quantitative study design may include comparison of existing cost of data collection by manned aircraft vs. collection of the same data using UAS technology. This same study design could be used to compare quality of data. A potential qualitative study could involve interviews or questionnaires of members of the public on privacy concerns, especially land owners near the sites of aerial surveys. Additional questions that could be asked may include the nature of their privacy concerns, whether these concerns do not exist with manned aircraft surveys, and would they be willing to pay higher taxes to maintain the traditional methods of aerial surveys of public forest lands.

Conclusions

In conclusion, the results of this study have added to the literature regarding implementing new technology into a government organization. The literature contains fewer references on organizational change in the public sector (Fernandez & Rainey, 2006). The perceptions of managers is a key element in an organization to support change and innovation, as well as effective communication and employee attitudes (Chew, Cheng, & Petrovic-Lazarevic, 2006). The perceptions identified in this study of managers and data collectors who will use the technology are crucial information to be used in planning the technological innovation of UAS technology within the Forest Service to assist with forest health and, ultimately, ecosystem management.

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PEER-REVIEWED PAPER

HEURISTIC NEAR-OPTIMAL UAS PATH PLANNING ALGORITHM FOR CONVOY OVERWATCH

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Abstract

The optimal path to fly a small unmanned aerial system (SUAS) for convoy overwatch was calculated, heuristically approximated onboard a SUAS autopilot, and demonstrated with hardware in-the-loop simulations and flight test. The optimal path minimized a cost functional consisting of the SUAS's control effort and deviation from a desired slant range. Due to several hardware and software limitations, the SUAS autopilot was incapable of implementing the optimal controller onboard. This paper introduces a novel heuristic-based algorithm developed in three steps and implemented onboard the autopilot to approximate the optimal solution. The first step manipulated the autopilot loiter logic to allow target tracking. The second step identified three parameters in the loiter logic that were tuned using a Design of Experiments (DOE) methodology. Lastly, a finite state machine (FSM) was created based on the DOE results to further optimize the real-world convoy overwatch algorithm. Each step was tested to evaluate how well it approximated the optimal path. The final algorithm using the FSM exhibited a 65% improvement in tracking performance and demonstrated an implementable, near-optimal convoy overwatch algorithm.

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Heuristic Near-Optimal UAS Path Planning Algorithm for Convoy Overwatch Nomenclature

α = Cost functional weight factor
ϕ, θ, ψ = Roll, Pitch, and Yaw angles, deg
$\dot{\phi}$= Roll rate, deg/s
ψw = Wind direction, deg
f = Update frequency, Hz
g = Gravitational acceleration, m/s^2
h = SUAS altitude (AGL), m
J = Cost function value
J_{th} = Cost function threshold
SR = Slant range, m
SR_D = Slant range desired, m
t_0 = Initial time, sec
t_f = Final time, sec
t_{look} = Look-ahead time, sec
V = SUAS airspeed, m/s
V_G = SUAS ground speed, m/s
V_w = Wind speed, m/s
X_{GV}, Y_{GV} = Ground vehicle components in inertial frame
X_{SUAS}, Y_{SUAS} = SUAS components in the North, East, Down (NED) inertial frame

Introduction

Unmanned aerial systems (UASs) constitute a rapidly developing platform of American military air power. Since 2002, the number of operational UAS has increased over 40 fold and now UAS comprise an astounding 41% of the military's aircraft inventory (Gertler, 2012). Currently, both manned and unmanned platforms are used to provide real-time, video surveillance of friendly vehicle convoys in wartime environments. The Air Force Research Lab's (AFRL) goal is to demonstrate autonomous convoy overwatch using small unmanned aerial systems (SUASs) that can stream continuous, full motion video to the convoy commander without any direct input from the ground station operator. Using autonomous SUAS platforms for convoy surveillance allows for improved allocation of personnel and resources, saving the Air Force time, money, and lives. In addition, the technology has applications to search and rescue operations, armored car overwatch, wildlife tracking and monitoring, and border patrol applications.

Accomplishing the feat of autonomous target tracking with a SUAS is not without its challenges. The specific surveillance requirements for successfully performing convoy overwatch, coupled with the limited processing power of the onboard autopilot and power supply of the SUAS provide the greatest obstacles. To best achieve autonomous target tracking, first the optimal flight path for the SUAS must be determined. The subsequent challenge is to fly the optimal path onboard a real SUAS. If the optimal path cannot be determined and flown in real time, then a heuristic-based approximation of the optimal path should be demonstrated and compared.

A variety of research has been done using optimal control to develop flight paths for unmanned tasks. Smith, Cobb, Pierce, and Raska (2013) used optimal control to generate paths for UAS collision avoidance. Kim, Oh, and Tsourdos (2013) used optimal control to develop a nonlinear model-predictive coordinated standoff tracking of a moving target. Their optimal path formulation was compared with the Lyapunov vector field approach presented by Frew, Lawrence, and Morris (2008). The optimal solutions more accurately maintained the desired standoff distance from the target and kept the desired separation between the SUASs. Geiger et al. (2008) incorporated optimal control for a SUAS to track a moving ground vehicle. Their research used a fixed orientation camera and their cost functional maximize the SUAS time on target for simplified ground vehicle paths. Jodeh, Coon, Masternak, Cobb, and Agte (2014) used optimal control to plan a path for maximizing the ground coverage of unattended ground sensors. Pre´vost, Th´eiault, Desbiens, Poulini, and Gagnon (2009) developed an extended Kalman filter to predict the future path of a moving target and generated an optimal path based on that information. All of these optimal path formulations required a cost functional, optimizer, and future knowledge of some kind. The processing time required to determine the optimal solutions often exceeds the mission time, therefore disqualifying them from real-time applications.

There have been numerous research efforts accomplished that use unmanned platforms to track moving targets that are applicable in a real-world environment. Rysdyk (2006) developed a path planning algorithm used for target observation in the presence of wind. His guidance law was developed using "good helmsman" techniques, which output a relative course heading as a function of cross-track error. Yoon, Park, and Kim (2012) developed a guidance law that used multiple SUAS to perform coordinated standoff tracking. Similarly, work done by Frew et al. (2008) and Lawrence, Frew, and Pisano (2008) performed target tracking by creating globally stable, Lyapunov vector fields that allowed a SUAS to autonomously and efficiently track a moving target. Quigley, Goodrich, Griffiths, Eldridge, and Beard (2005) improved the Lyapunov vector field approach through introducing a Hopf bifurcation method. This specific type of limit cycle has a faster convergence rate to the circular orbit than the Lyapunov approach and was implementable real-time onboard the SUAS. Each one of these methods represent a sub-optimal, target tracking algorithm that were efficient enough to execute real-time onboard the SUAS autopilot.

The two objectives of this research were: develop an optimal path planning algorithm and demonstrate a real-world execution of it for autonomous convoy overwatch. An optimal flight path algorithm is presented that calculates the necessary SUAS control inputs for any given ground vehicle path. More specifically, the algorithm determined the minimum control inputs required for a SUAS to maintain a desired slant range from the ground vehicle. This algorithm used future knowledge of the exact ground vehicle location to calculate the optimal path. The path planning capability was demonstrated through computer simulations using time-stamped, GPS locations of a ground vehicle driving along a path. Secondly, the optimal path algorithm was approximated onboard the SUAS, demonstrating a real-world, near-optimal tracking capability. The finalized heuristic method did not rely on future knowledge of the ground vehicle information, instead it was able to adjust and track based on current ground vehicle information. The heuristic approximation was developed using a three step process built upon the preexisting loiter logic of the SUAS autopilot.

Optimal Path Formulation

The first objective was determining the optimal SUAS flight path to perform convoy overwatch for a given ground vehicle profile. In the optimal path formulation, the ground vehicle profile information was known prior to solving the optimization problem. Therefore, the resulting optimal path was used as a metric to compare the accuracy of the heuristic-based approximations. This section presents the SUAS equations of motion, a multi-objective cost functional to minimize the slant range error with the minimal amount of control input, and the optimal control algorithm used to determine the optimal path.

Equations of Motion

The SUAS was modeled as a modified 2D Dubins (Dubins, 1957) airplane and included a level turn assumption. It was also assumed that the SUAS automatically used the required pitch control to maintain a constant altitude, reducing the degrees of freedom in the optimal control problem. The aircraft's roll rate ($\dot{\phi}$) was the only control variable used in the optimization. Assuming the SUAS only executed level turns allowed the roll angle to dictate turn rate and effectively described the SUAS's lateral-directional motion. For the optimization the SUAS and ground vehicles' ground velocity was an important parameter. While the SUAS's airspeed was fixed at the velocity corresponding to maximum endurance. However, the presence of wind (V_w) impacted the SUAS's groundspeed thus the SUAS groundspeed had to be calculated according to Equation 1:

$$V_G(i) = \sqrt{\Big[V\cos\psi(i) - V_w(i)\cos\psi_w(i)\Big]^2 + \Big[V\sin\psi(i) - V_w(i)\sin\psi_w(i)\Big]^2} \tag{1}$$

The SUAS equations of motion are defined in Equations 2-5:

$$\phi(i+1) = \phi(i) + \dot{\phi}(i)\,\Delta t \tag{2}$$

$$\psi(i+1) = \psi(i) + \left[\frac{g}{V_G(i)}\tan\phi(i)\right]\Delta t \tag{3}$$

$$X_{\text{SUAS}}(i+1) = X_{\text{SUAS}}(i) + \Big[V_G(i)\cos\psi(i)\Big]\Delta t \tag{4}$$

$$Y_{\text{SUAS}}(i+1) = Y_{\text{SUAS}}(i) + \Big[V_G(i)\sin\psi(i)\Big]\Delta t \tag{5}$$

The equations of motion were discretized based on a fixed time step, $\triangle t$. For a fixed $\triangle t$, these equations were used as first-order approximations to find the state information at the succeeding time step. The discrete form was consistent with the form sent to the optimization algorithm discussed later. The locations of the SUAS and the ground vehicle were required for calculating the slant range at each time step. Since the ground vehicle was friendly, as is the case for convoy overwatch, the exact location was known. For the optimal control algorithm, the location history of the ground vehicle was an exogenous input, passed directly into the optimizer. During flight test, the ground vehicle GPS coordinates were transmitted directly to the SUAS. The slant range at the current time step is defined as:

$$SR(i) = \sqrt{\Big[X_{\text{GV}}(i) - X_{\text{SUAS}}(i)\Big]^2 + \Big[Y_{\text{GV}}(i) - Y_{\text{SUAS}}(i)\Big]^2 + h^2} \tag{6}$$

Note that the SUAS altitude was held constant and the ground vehicle path was flat *(h(i) = h)*, which meant that a 3D slant range maps directly to a 2D standoff distance.

The cost functional:

$$J = \sum_{i=0}^{N}\left[\alpha\left(\frac{SR(i) - SR_{\text{desired}}}{SR_{\text{desired}}}\right)^2 + (1-\alpha)\left(\frac{\dot{\phi}(i)}{\dot{\phi}_{\text{max}}}\right)^2\right]\Delta t \tag{7}$$

was the summation of the cost at each step. The optimal control was characterized by the control vector ($\dot{\phi}$) that minimized the scalar value J in Equation 7. This effectively minimizes control effort while maintaining sufficient slant range for the mission objective.

A weight factor (α) was used to gauge the relative importance placed on each term and ranges from 0 to 1. A low value of emphasized minimizing control effort, while a high value of favored reducing deviation from the desired slant range. The main goal of the convoy overwatch was to maintain the desired slant range from the ground vehicle as closely as possible. Not penalizing control effort resulted in aggressive, stop-to-stop saturated control inputs, correlating to erratic SUAS flight paths and decreased endurance. Therefore, α was set to 0.95 for the convoy overwatch scenario, which struck the balance between maintaining the desired slant range while still considering control effort. This level of α produced trajectories that were smooth enough to be tracked but still prioritized minimizing the deviation from the desired slant range.

For this optimal control problem to be representative of the real-world convoy overwatch scenario, the mathematical formulation included system constraints. The equations of motion, defined in Equations 2-5, are called dynamic constraints and act as equality constraints, forcing the optimizer to satisfy each state equation at each time step. Specific to this optimization, several path constraints were placed on the system to model the dynamics of the real-world flight test SUAS, discussed in detail later. Table 1 highlights the path constraints for roll angle (ϕ) and roll rate ($\dot{\phi}$). The roll angle was constrained to match the actual minimum turn radius of the flight test SUAS. Given the level turn assumption, constraining the roll angle simultaneously constrained the SUAS turn radius. Lastly, the maximum and minimum roll rates were determined based on real-world telemetry data. The roll rate constraint was rarely active because of its inclusion in the cost functional.

Table 1

Path Constraints for Optimal Control Problem

Variable	Min	Max
ϕ	$-40°$	$40°$
$\dot{\phi}$	-100 deg/s	100 deg/s

The optimizer used a finite time horizon method, named the "look-ahead" algorithm, for generating the optimal paths. In the look-ahead algorithm, shown in Algorithm 1, a finite time history of the ground vehicle's future path was made available to the optimizer. The number of nodes (N) were determined by multiplying the update frequency (f) by the look-ahead time (t_{look}). The look-ahead method started at the SUAS's initial conditions. The optimal control solution was only computed for the time interval specified by t_{look}. Then the SUAS state equations are propagated forward for $\triangle t$ seconds ($\triangle t = 1/f$) until it reached the next node. Next, a new solution interval was created using the same t_{look} and used the current states of the system as the new initial conditions. This process was repeated at each node until reaching the final time (t_f). It is important to note that the new optimal path could be solved at some multiple of $\triangle t$ if more computational time was required. In this case, there would be multiple nodes between the solution intervals.

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Algorithm 1 : Look-ahead Algorithm

Determine total number of nodes: $N = t_{look} \times f$

Set initial conditions

for $t_0 : \Delta t : t_f$ **do**

  Acquire ground vehicle path and wind information (used as fixed parameters)

  Guess control vector ($\dot{\phi}$)

  Propagate state equations forward (Eqns 2 - 6)

  Optimizer:

    Find $\dot{\phi}$ that minimizes cost functional (Eqn 7)

    Satisfy dynamic constraints (Eqns 2-5)

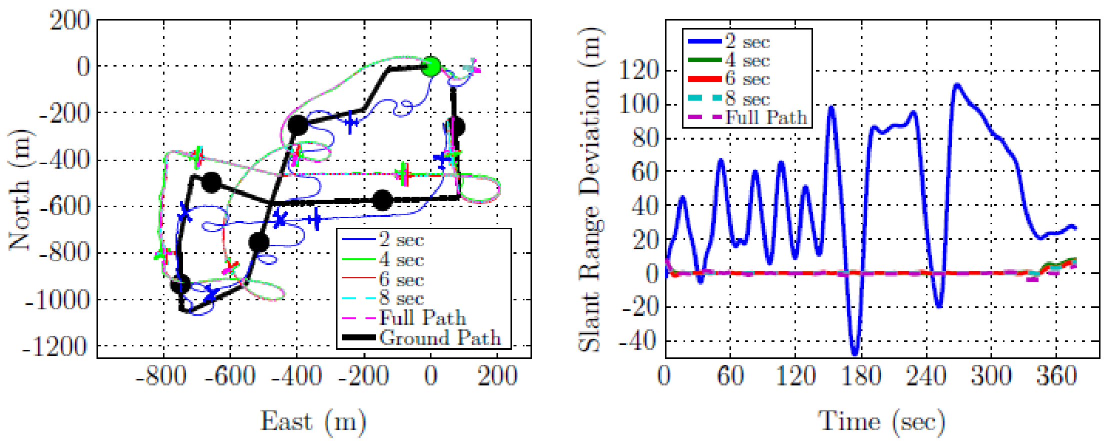
    Satisfy path constraints (Table 1)

  Set optimal states at 2^{nd} time step as new initial conditions

end

Result: Optimal control and states correspond to the initial conditions of each time step from $t_0 : \Delta t : t_f$

The optimal control algorithm assumed the availability of the ground vehicle's path for a finite time horizon (t_{look}) and planned the optimal path based on that knowledge. Understanding how different values of t_{look} affected the optimal solution aided in algorithm selection for eventual implementation. There was a tradeoff between t_{look} and the realism of the model. In reality, the future path of the ground vehicle was not known with perfect certainty and therefore an estimate was required. A shorter t_{look} correlated with a more realistic estimate of the ground vehicle's location. Conversely, larger values of t_{look} typically resulted in a lower cost but were less feasible because of the uncertainty related with predicting the ground vehicle's path. To determine the appropriate t_{look}, several different look-ahead times are plotted and compared in Figure 1. Every optimal flight path was calculated using the same ground vehicle profile, zero wind speed, and the same initial conditions. MATLAB 2012b was the software package used to solve the optimal path using the fmincon function.



(a) Optimal Path Comparison (b) Slant Range Deviation Over Time

Figure 1 : Comparison of Optimal Paths Using Different Look-ahead Times and Full Path Information

In Figure 1a, an aircraft is plotted every 60 seconds to represent the location of the SUAS and a black circle is plotted to represent the ground vehicle location. The green circle represents the ground vehicle's starting point and the desired standoff distance from the ground vehicle was 150 meters. Figure 1b shows the slant range deviation over time. The x-axis is incremented by 60 seconds to correspond with the SUAS locations in Figure 1a. For each t_{look} value, Table 2 displays the corresponding cost, number of nodes, update rate, and run time per update.

Evaluating the flight paths in Figure 1a and 1b revealed a distinct difference between the optimal path calculated with $t_{look} = 2$ seconds and the flight paths created using a $t_{look} \geq 4$ seconds. Table 2 shows that the cost of the 2 second solution is over 480 times greater than all of the other solutions. Figure 1b portrays how the slant range of the 2 second optimal path immediately deviated from the desired slant range and grew in amplitude with time. Given the initial starting position and orientation, 2 seconds did not provide sufficient future knowledge for the optimizer to account for the ground vehicle behavior.

t_{look} (sec)	Cost (J)	# of Intervals	Δt (sec)	Interval Run Time (sec)	Total Run Time (sec)
2	47.12	554	0.67	0.13	72.0
4	0.098	554	0.67	0.17	94.2
6	0.075	554	0.67	0.25	138.5
8	0.071	554	0.67	0.31	172.7
Full Path	0.067	1	—	1845.6	1845.6

Table 2. Optimization Results for Figure 1

The required time for path convergence to the optimal path occurred for a lookahead time greater than 4 seconds. In fact, the paths with t_{look} ranging from 4 seconds to full path knowledge were nearly equivalent. This finding was critical because for $t_{look} \geq 4$ seconds the optimal path was not improved with additional increases in look-ahead time. The proximity of the various optimal path solutions suggested that the solution space near the global minimum was flat. The convergence criteria of the optimizer were not specific enough to discriminate between the solutions near the optimal path. This explained why the optimal paths look nearly identical in Figure 1a but had slightly different cost values in Table 2. A flat solution space was desirable because it allowed minor deviations to still result in the near-optimal flight path.

The timeliness of the solution was as equally important as its accuracy. The update frequency used for calculating the optimal solution was 1.5 Hz, meaning that $\triangle t = 0.67$ seconds. To be viable in real-time, the solution must converge to an optimal path at a rate faster than the update frequency. As a general rule of thumb, speeds twice as fast as the update frequency were desired because it allowed time for the autopilot to implement the controls. Therefore, t_{look} ranging from 4 8 seconds constituted viable solutions because of their speed and accuracy.[1] This meant that the look-ahead algorithm had the potential to determine the optimal path for convoy overwatch onboard the real-world, time-sensitive environment of a SUAS. Despite the speed of the look-ahead algorithm, the required advanced knowledge was not available to the SUAS in a real-time, dynamic environment. Therefore, a heuristic-based approximation of the optimal path devoid of prior knowledge of the ground vehicle information was developed.

Heuristic Approach

The second objective of this research was to demonstrate a near-optimal convoy overwatch in real time. A tracking algorithm called "follow-me" was engaged to execute a real-world, ground target tracking solution, agnostic to any notion of path optimality. The follow-me mode was native to the ArduPilot Mega (APM) 2.5, the flight test autopilot. This mode was the initial step in approximating the optimal path generated by the lookahead algorithm. Follow-me worked by collocating the current SUAS loiter point with the current GPS location of the ground vehicle. Successfully tracking a moving ground vehicle established a baseline performance and guaranteed feasibility of the problem. The next step was to identify parameters within the follow-me logic and determine which affected the optimality of the flight path. A Design of Experiments (DOE) was used to evaluate the impact of the selected parameters. Finally, to better decrease the cost of the heuristicbased path a Finite State Machine (FSM) was constructed to allow for dynamic path planning depending on the state of the SUAS.

Parameter Definition

Examinations of the existing APM fixed-wing aircraft firmware yielded three parameters, existing or readily implementable, directly utilized by the follow-me navigation logic. These parameters represent the effort to minimize roll rate and deviation from a desired slant range (Equation 7). The loiter radius, loiter range, and the navigation point lead time, were the three parameters used to build the heuristic approximation.

Loiter radius was the horizontal distance from the target point that the SUAS attempted to maintain. For a stationary ground vehicle, this represented a circular loiter. When the ground vehicle was inside or on the loiter radius, updates to desired heading (which were subsequently fed into lower level control loops) accounted for the ratio of the current target distance to the desired distance. The level of effort applied to achieve that distance directly represented the balance between control effort and slant range.

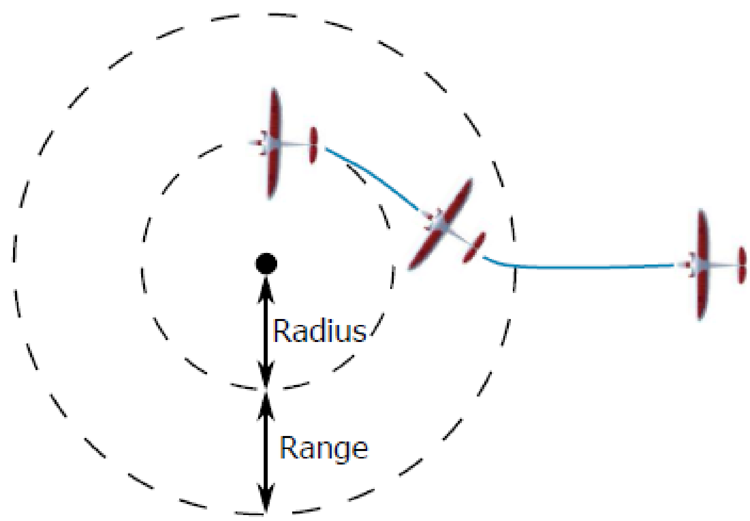


Figure 2 : Definition of Loiter Radius and Loiter Range

Loiter range was an additional distance beyond the loiter radius inside which the SUAS began a gradual transition from straight flight towards the target point to circular flight around the target point. Similar to the effects of loiter radius, control effort was directly based on a ratio representing relative SUAS position inside the range. Therefore, the loiter range parameter was a direct factor in control effort determination which impacted the optimality of any given flight. Figure 2 demonstrates the role of both loiter radius and range in the APM navigation logic.

Finally, the point to which the SUAS was navigating towards must be considered. An additional APM firmware modification called "lead time" was incorporated to allow for a simple estimation of the ground vehicle future location. The parameter represented a time constant that was multiplied by the ground vehicle velocity to adjust the navigation point ahead of the ground vehicle. The lead time was similar to t_{look}, in that it only considered a finite portion of the ground vehicle's future location. The lead time parameter, which was evaluated along with loiter radius and loiter range, defined the three parameters that were experimentally tuned to approximate the optimal path for ground vehicle tracking.

Finite State Machine Construction

The last step was to develop navigation logic in the FSM that was responsive to real-time SUAS conditions. The existing performance was examined to identify any com- bination of SUAS and ground vehicle states that warranted alternative behavior. However, rather than performing this analysis on data from the unmodified follow-me mode, it was important to first adjust any relevant system settings to maximize the flight path's opti- mality. Flight data garnered from these settings resulted in a more appropriate determina- tion of state definitions.

Test Setup

SUAS Testbed The SUAS used to flight test the heuristic approach was the Sig Rascal (Figure 3). The aircraft had a 110" wingspan, was 75.75" long, weighed 11 pounds empty, and was propelled by an electric motor. The motor was powered by three, 4-cell batteries which allowed for 40 minutes of flight time. The video surveillance payload, shown in the inset of Figure 3, was located underneath the Rascal's fuselage which allowed the camera to have an unimpeded 360◦ of pan and 90◦ of tilt. The camera placement maximized the camera's possible field of view, giving the SUAS increased flexibility for performing surveillance and reconnaissance missions.

A HackHD camera was used for gathering the video data during flight test. The camera recorded video in 1080P high definition, stored it onboard a Micro-SD card, and was outfitted with the stock 160◦ wide angle lens. The Hack-HD was attached to the pan- tilt gimbal, powered by two Hitec servos, and was commanded to continuously point at the current GPS coordinates of the ground vehicle.

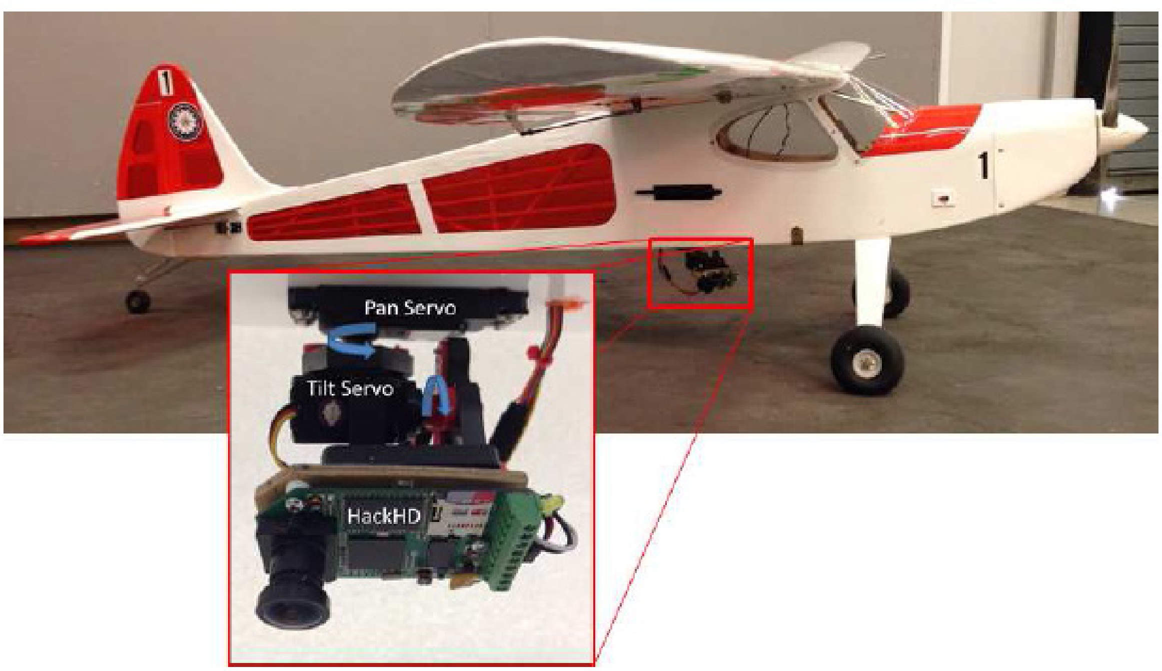


Figure 3 : Gimbaled Camera Apparatus Affixed to SUAS Testbed

The APM was the autopilot used for the hardware in-the-loop (HIL) simulations and flight tests. APM was a full-featured, open source autopilot that incorporates all of the necessary functions for a variety of flight modes. The autopilot included a 3-axis accelerometer, rate gyros that measured the orientation changes of the aircraft, a 16 MHz Atmega328 processor onboard and could control 8 different channels. The APM 2.5 had a variety of flight modes that could be engaged through the MissionPlanner ground station software interface. The follow-me flight mode served as the launching point for the heuristic approximation algorithm. Because all of the APM 2.5 source code was available, the native follow-me code was used as a template to create both the DOE and FSM mode.

Flight Test Location

All flight tests were conducted at Camp Atterbury Joint Maneuver Training Center, IN. This Army installation had restricted airspace, which did not require a FAA issued certificate of authorization for SUAS flight test. Camp Atterbury had extensive ranges and multiple launch sites for SUASs, which made the location prime for flight test. The range had numerous roads that allowed for simulating real-world convoy operations. Figure 4 shows a view the SUAS airstrip and the ground path driven to simulate a convoy path.

The path had a "figure 8" configuration that featured both left and right turns, as well as straightaways. This path was specifically chosen because of its complexity and variation in ground vehicle behavior. The goal was to develop a heuristic-based approximation based on an overtly complex convoy route, with the assumption that tracking performance would naturally improve with simpler ground vehicle paths.

Figure 4 : Camp Atterbury Test Range, Indiana. Base Image: ©DigitalGlobe, IndianaMap Framework Data, USDA Farm Service Agency, ©2015 Google

The heuristic-based approximation of the optimal path was evaluated through a mixture of flight test and HIL simulations. The purpose of using HIL simulations was to supplement the flight test efforts, not to replace them. Therefore, the HIL environment was constructed to mimic the flight test setup as closely as possible. The HIL simulations featured an APM 2.5 and its MissionPlanner ground station software controlling a virtual Sig Rascal flying in the FlightGear simulator. A representative ground vehicle profile was driven on the same path used for the flight tests. A wind environment typical to Camp Atterbury was used in the simulation and the same wind conditions were used for each of the HIL simulated flights. Lastly, validation flights were conducted to ensure the similarity of control effort between the real-world and the virtual Sig Rascal. Reducing these independent variables to known quantities allowed the cost functional values from each HIL simulation to be directly compared. HIL simulations were essential due to the logistical constraints of flight test, the quantity of data required to build the heuristic approximation of the optimal solution, and reducing the variability of the wind conditions and ground vehicle path. There was confidence in the HIL results because of the ability to test the custom autopilot firmware modifications in a representative, high fidelity environment.

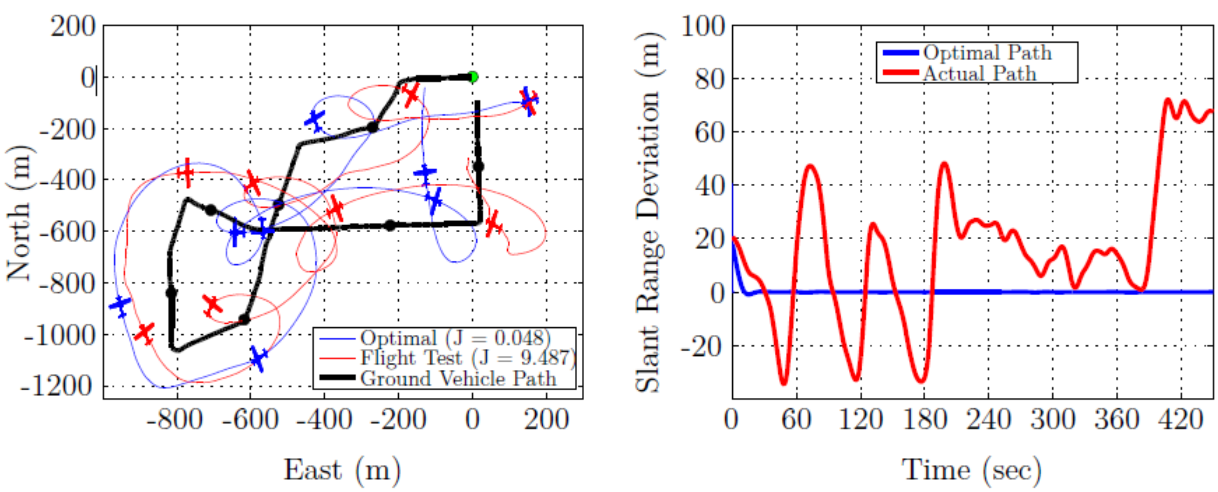
Results

The results of the flight test and HIL simulations are discussed in this section. The progression from the follow-me mode, to the DOE results mode, to the FSM mode are shown and their impact on the path optimality is discussed. The results displayed in this section are generated from both flight test and HIL simulation data. The optimal path was calculated with the look-ahead algorithm (Algorithm 1) and used the same ground vehicle profile, initial conditions, wind speed, wind direction, and SUAS airspeed measured by the autopilot during the flight test. The goal was to create an optimal solution that incorporated all of the specific test conditions experienced by the SUAS during the flight test. This allows a realistic comparison between the flight test and simulation result with the optimal path. Finally, all three modes are compared and analyzed to determine their ability to approximate the optimal path generated using the look-ahead method.

Follow-Me Mode

The first vehicle tracking function implemented onboard the SUAS was the followme mode. In this mode, the SUAS loiter point was set to be the ground vehicle's location. The flight test results, shown in Figure 5, compare the performance of the flight tested follow-me mode with its corresponding optimal path.

During the flight test, the autopilot controlled the SUAS to maintain a 150 meter loiter around the moving ground vehicle as it drove the "figure 8" ground path. The loiter radius was chosen based on engineering judgment.



(a) Path Comparison (b) Slant Range Deviation Over Time

Figure 5 : Results from the Follow-me Flight Test Compared to Optimal Path

The performance of the follow-me mode was sensitive to the initial conditions of the SUAS. Therefore, the ground vehicle began driving when the SUAS was located behind the vehicle at a similar heading angle. The starting SUAS configuration minimized the initial amount of control effort required to achieve the desired slant range. In Figure 5a, an aircraft is plotted every 60 seconds to represent the location of the SUAS for both the optimal and the flight test paths and a black circle to represent the ground vehicle location. The starting ground vehicle location is represented with a green circle.

Figure 5b compares the slant range deviation of the optimal path versus the flight test path as a function of time, showing how close the follow-me mode was to maintaining the desired slant range. The time intervals are set at 60 seconds to correlate with the aircraft locations in Figure 5a. A 0.1 Hz low-pass filter was used on both slant range data sets to eliminate the higher frequency noise.

Comparing the performance between the two paths reveals drastic differences and inadequacies of the flight-tested follow-me mode. The values of the cost functional, displayed in the legend, show a discrepancy between the optimal path cost and follow-me mode, which cost 200 times greater. Due to the multi-objective nature of the cost functional, the specific cost values do not have physical meaning and therefore are not intuitive. However, the magnitude of the cost functional difference reveals the disparity between the optimal path and the follow-me mode. This discrepancy between the optimal and follow-me paths can be largely attributed to the simplicity of the follow-me mode.

Using the follow-me mode, the SUAS successfully tracked the moving ground vehicle. However, there was a substantial difference between the optimal path and the path created by the follow-me mode. This makes sense because the optimal path specifically minimized slant range error and control effort, while the follow-me mode only sought to loiter about a moving point. For the first 240 seconds, the SUAS continually overshot the desired slant range as it aggressively tried to maintain the desired standoff. The following 120 seconds showed the SUAS flying closer to the desired slant range with less overshoots. This region of performance occurs when the ground vehicle turns to head east and drove straight for 800 meters. Coincidentally, the subtle slant range deviation defining this period occurred when the SUAS predominantly had a tail wind. The benefit of the tail wind for this period degraded the SUAS performance after the ground vehicle made the final turn. The ground vehicle's final left-hand turn occurred while the SUAS begins a righthand loiter. Immediately before the turn, the SUAS was at the desired standoff, but immediately following the turn its slant range error jumped significantly. To continue loitering around the ground vehicle, the SUAS had to turn back into the wind. The head wind drastically reduced the SUAS ground speed, causing a drastic increase in slant range error. In the optimal path, after the SUAS converged to the desired slant range there were no deviations because the future location of the ground vehicle was available to the optimizer.

The initial flight test successfully demonstrated the follow-me autopilot function. However, this method insufficiently approximated the optimal path and the two orders of magnitude difference between the costs highlighted the need for a better approximation. The goal of the following heuristic method iteration was to minimize the slant range error over the entire flight path through statistical analysis.

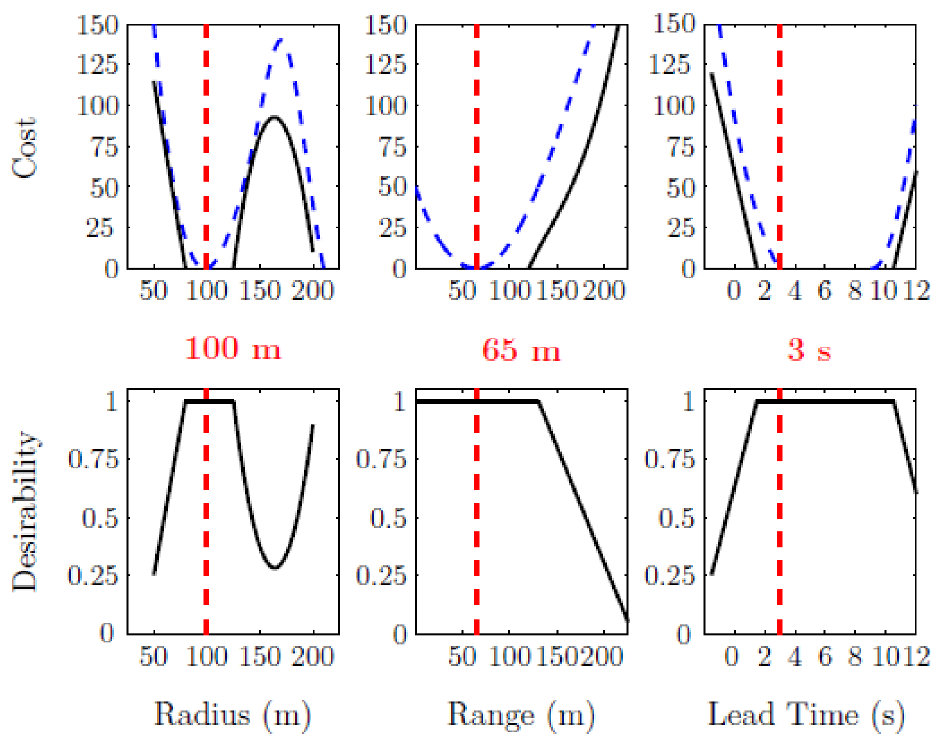


Figure 6 : Factor Profiler for Combined Regression Model during DOE

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Design of Experiments Results Mode

A DOE was used to determine the best parameter values for the follow-me tracking task. A total of 26 HIL simulations run at various loiter ranges, loiter radii, and lead times were used to build a traditional regression model. Each of the simulated flights were run using the same ground vehicle profile, with the exact same wind model. All of the test points were entered in as non-coded (engineering) units and an analysis of variance was performed on all of the significant terms using the statistical software JMP.

A factor profiler, shown in Figure 6, was constructed for the model to determine the best combination of parameter settings. Figure 6 shows the relative cost and desirability for each of the parameters at a range of values. The desired parameter values minimized the cost, which simultaneously maximized the desirability. Each of the recommended parameters was highlighted graphically in Figure 6 with a vertical, red dashed line. The recommendations from the combined regression model were 100 meter loiter radius, 65 meter loiter range, and 3 second lead time. In this case, all three parameters were determined significant at the 0.05 level. Since the DOE was tuned for a specific path, it was unknown how these parameters would change for another ground vehicle path. This uncertainty was the motivation for using the "figure 8" path, with the assumption that tuning the algorithm to a complex ground vehicle path would allow for robustness towards simpler paths.

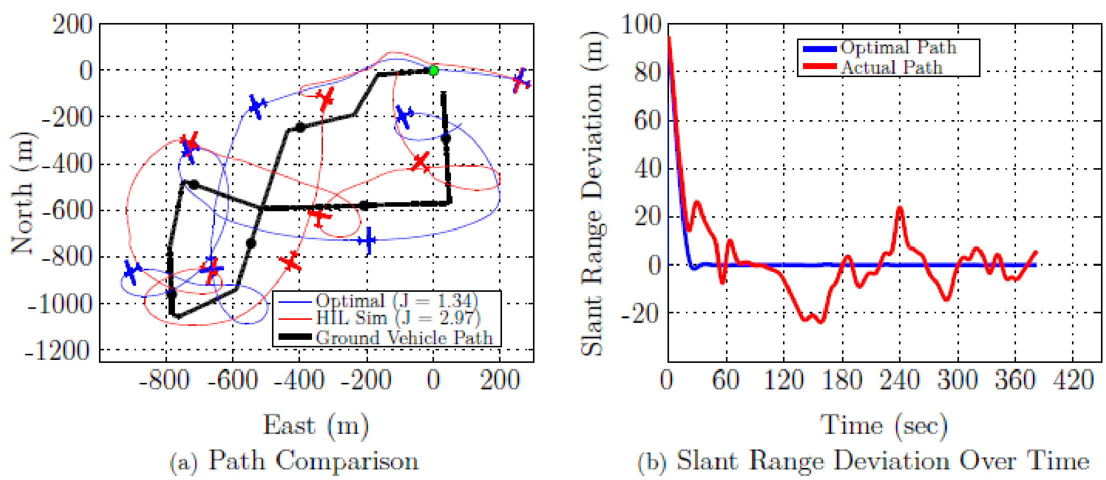


Figure 7 : HIL Simulation Results of DOE Suggested Parameters Compared to Optimal Path

A HIL simulation was performed at the DOE recommended lead time of 3 seconds, loiter range of 65 meters, and loiter radius of 100 meters. Figure 7a shows the path comparison of the HIL simulated DOE results and the optimal path. Figure 7b shows the slant range as a function of time. Higher frequency noise was eliminated from the data sets using a 0.1 Hz low pass filter.

The cost functional values for both paths are shown in the legend in Figure 7a. The cost of the HIL simulated path was only twice the cost of the optimal path. This was a substantial improvement from the follow-me mode shown in Figure 5a. Additionally, comparing the slant range behavior with time in both Figures 5b and 7b, demonstrates how the results from the DOE allowed the SUAS to adhere more closely to the desired slant range. Despite all of the improvements, there were still several noticeable overshoots in slant range deviation. These deviations resulted from the lack of future knowledge avail able to the APM. The sharp ground vehicle turns at 150 seconds and 240 seconds constituted drastic changes in the ground vehicle's direction. The DOE mode had the lead time parameter, which is a simple linear estimator, but was unable to account for these sudden turns. Contrast this performance with the optimal path generated using the look-ahead method which had perfect future knowledge. The optimizer anticipated sharp vehicle turns and adjusted the SUAS's roll rate accordingly to maintain the desired slant range throughout the entire ground vehicle profile. The perfect, future knowledge of the ground vehicle path assumption makes the optimal path infeasible to fly in real-time, but it serves as a best case for judging the optimality of the heuristic algorithm.

Finite State Machine Mode

The greatest increase to the path cost occurred during large deviations from the desired slant range. Setting the cost functional weight factor to α =0.95 heavily emphasized minimizing slant range error. Adding logic to supplement the existing DOE tuned parameters minimized the negative impact caused by large slant range error. The FSM added two additional parameters to the flight firmware and categorized the SUAS performance into three different states. The two additional parameters added were an instantaneous cost threshold ($J_{\text{threshold}}$) and a loiter radius buffer ($\triangle LR$). The slant range error ($SR-SR_{\text{desired}}$) and the instantaneous cost (J_i) were the two variables that dictated the active state within the FSM. Depending on the values of these two variables, the SUAS was in one of the three states: Standard tracking, High Range tracking, or Low Range tracking. Figure 8 shows a graphical representation of the FSM.

Standard tracking was the predominant state flown in simulation and was active when J_i was less than J_{th}. In this state, the DOE suggested parameters were flown. The High Range tracking state activated when J_i and SR were greater than J_{th} and SR_{D} respectively. In this instance, the loiter radius was reduced by $\triangle LR$. The smaller loiter radius increased the turn rate of the SUAS, allowing for the SUAS to quickly reduce the slant range error. The Low Range tracking state activated when J_i was greater than J_{th} and SR was less than SR_{D}. In this state, the SUAS was too close to the ground vehicle and as a result its loiter radius was increased by $\triangle LR$. The High and Low Range tracking states were designed to temporarily adjust the desired loiter radius, enabling the SUAS to quickly reacquire SR_{D} and fall back under J_{th}. Once the SUAS was under J_{th}, it would return to the Standard tracking state.

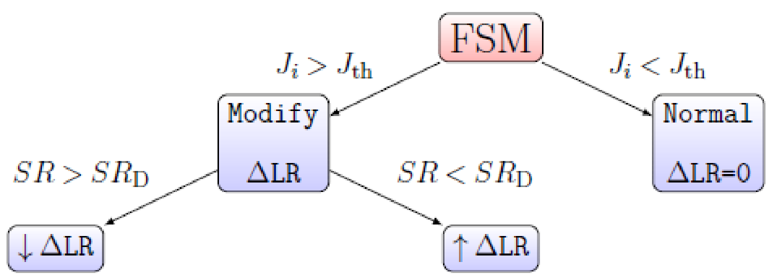
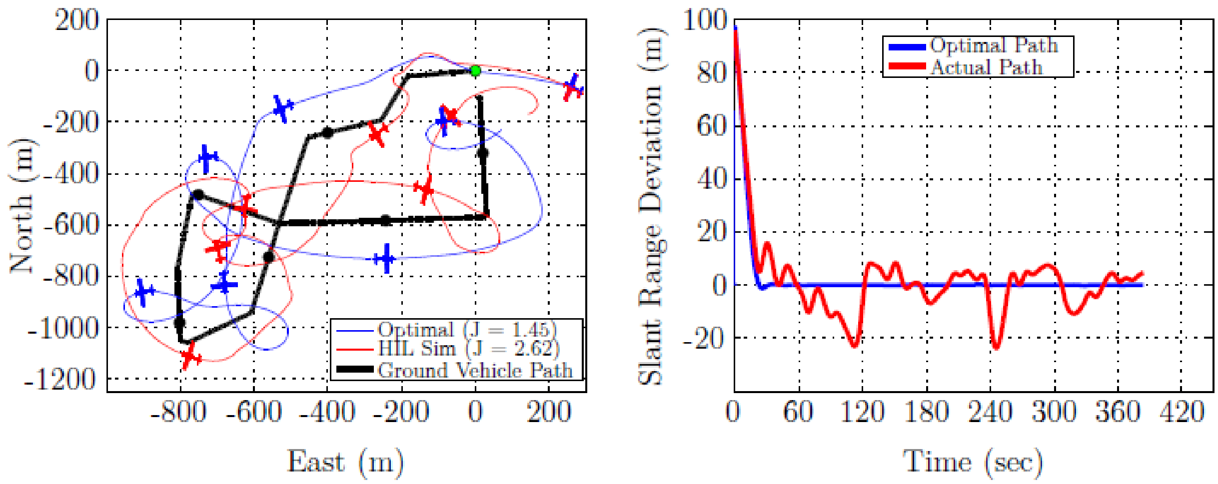


Figure 8 : Flowchart representing the logic that creates the FSM.

For the HIL simulations, the FSM was implemented on the APM with $J_{\text{threshold}}$ set to 0.003. This $J_{\text{threshold}}$ value activated the FSM logic when the to a slant range error was greater than 9 meters. $J_{\text{threshold}}$ was tuned based on analysis of a J_i profile and aimed to execute state transitions when necessary but not excessively. The loiter radius buffer ($\triangle LR$) was set to 35 meters, which represented a ±23% change of the loiter radius parameter. $\triangle LR$ was determined using engineering judgment with the intent to affect measurable changes while avoiding unsafe behavior if flown in real life. Figure 9a compares the flight path generated during a HIL simulation of the FSM mode to the optimal path calculated using the look-ahead algorithm. Figure 9b shows the slant range as a function of time for both the FSM simulation and the optimal path. A 0.1 Hz low pass filter was used on both slant range data sets to eliminate the higher frequency noise.



(a) Path Comparison (b) Slant Range Deviation Over Time

Figure 9 : HIL Simulation Results of FSM Compared to Optimal Path

Comparing the costs for the DOE results flight to the FSM flight reveals only a marginal improvement in performance. However, the benefit of the FSM is observed when comparing Figures 7b and 9b. Both the DOE and FSM flights had noticeable overshoots around 120 seconds, 240 seconds, and 300 seconds. These overshoots occurred because the SUAS reached the desired loiter radius attached to the ground vehicle (see Figure 2) and started to loiter. This was problematic because as the SUAS turned to loiter, the ground vehicle continued traveling along its path. The spikes in slant range error occurred during the short time when the ground vehicle and SUAS were traveling in opposite directions. With the FSM enabled, the SUAS quickly reacted to the high slant range error, increased its turn rate, and returned back to the desired slant range. The aggressive turning resulted in shorter duration spikes in slant range. The FSM behavior is seen graphically in Figure 9b by the distinct spikes that plunge away from the desired slant range, but quickly return. Without the FSM enabled (Figure 7), the SUAS was slower to reacquire the desired slant range, therefore decreasing the optimality of the flight path. The optimal path avoided the slant range overshoots encountered in both the DOE results and FSM mode by flying ahead of the ground vehicle and then turning around. By passing the ground vehicle instead of turning once the desired loiter radius was reached, the optimal path maintained the desired slant range throughout the turn. This optimal behavior was only possible because of the future ground vehicle path knowledge made available to the look-ahead algorithm.

Analysis of Each Mode

The second objective of this research was achieved through the development and simulation of the FSM mode. The FSM was developed iteratively starting with the followme functionality.

The graphical representation of both the flight paths and slant range deviation charts in Figures 5, 7, and 9 are beneficial for model verification. However, the improvement from the follow-me mode to the DOE results to the FSM is difficult to discern from simply comparing Figures 5, 7, and 9 to each other. Table 3 compares the cost functional values of the three different modes of the heuristic-based algorithm.

Replicate	Follow-Me Cost (J)	DOE Results Cost (J)	FSM Cost (J)
Initial test	9.732	2.967	2.620
1	6.747	5.249	1.966
2	5.656	2.799	2.513
3	4.915	1.985	2.361
Average	6.763	3.250	2.365
Std Deviation	2.118	1.400	0.286

Table 3
HIL Results for Follow-Me, DOE Results and FSM

The follow-me mode, the DOE settings mode, and the FSM mode were all simulated four times in HIL. Each of the 12 flight paths used the same ground vehicle profile, similar initial conditions, and the same wind profile. Controlling all of these factors allowed for each of the cost functional values to be directly compared to one another. The 2nd to last row of Table 3 displays the average cost functional value for each mode. The last row shows the standard deviation of the costs from the HIL tests. Both the average cost and the corresponding standard deviation decreased significantly from the followme mode to the FSM mode. Completing the DOE and accepting the suggested settings yielded an average cost reduction of 52%. Incorporating the FSM logic further increased the algorithm's optimality by another 27%. The final algorithm that used the FSM logic on top of the DOE results accounted for a 65% increase in performance compared to followme.

The variation between the different replicate data points is largely caused by the slight differences in the initial conditions. To appropriately capture the variance of the data, Figure 10 displays a 95% confidence interval for the cost of each mode and their corresponding optimal paths.

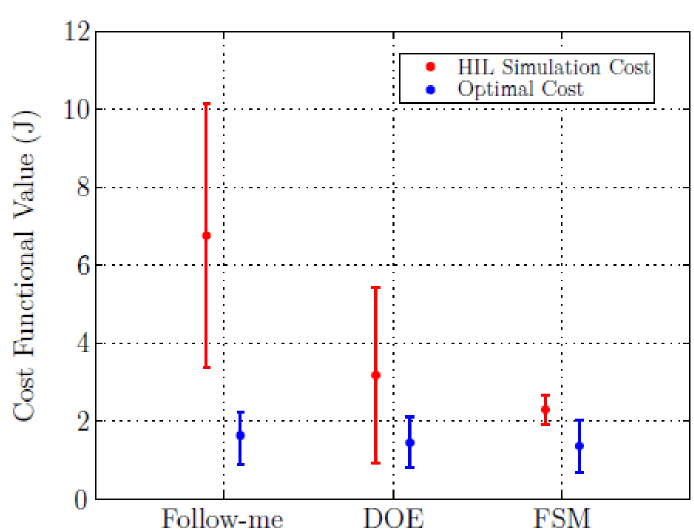


Figure 10 : 95% Confidence Intervals for Each Heuristic Algorithm Mode with Corresponding Optimal Paths

There are two important results shown in Figure 10. First, the iterative nature used to develop the algorithm successfully decreased the average cost and lowered the variation of the cost functional values. The order of magnitude decrease of the standard deviation from the follow-me mode to the FSM revealed a significant increase in the algorithm robustness. The FSM's superior performance, coupled with a lower standard deviation increased the confidence in the final version of the algorithm. Secondly, the proximity of the FSM results to its corresponding optimal path indicated that it accurately and consistently approximated the optimal solution for the given ground vehicle path.

The progression from follow-me to the DOE results to the FSM resulted in a closerto-optimal path planning algorithm. This trend validated the logic used when refining the algorithm because the DOE was used to narrow in on specific parameter values that correlated to a closer-to-optimal loiter logic. Additionally, incorporating the FSM increased the robustness of the path planner using the DOE suggested parameters.

Conclusion

A novel approach to autonomous convoy overwatch was presented that used optimal control-based techniques to build a heuristic algorithm. First, a cost functional was developed to model the optimal behavior of a SUAS tracking a cooperative, moving ground vehicle. The multi-objective cost functional primarily focused on minimizing the deviation from a desired slant range, while also considering the control effort. Using the look-ahead algorithm, the optimal path was developed for a given ground vehicle path. This algorithm was not able to be implemented onboard the SUAS and therefore a heuristic-based algorithm was developed to approximate the optimal path. Developing this algorithm consisted of three primary phases: the follow-me mode, the DOE results mode, and the FSM mode. The progression from the follow-me mode to the DOE results to the FSM resulted in a 65% increase in optimality. This trend validated the logic used when refining the algorithm because the DOE was used to narrow in on specific parameter values that correlated to an improved optimal loiter logic. While some of the flights were completed during flight test, the majority of the data were collected via HIL simulations. Therefore, it is recommended to flight test the three modes to validate the results shown in Figure 10.

The FSM was able to approach the cost of the optimal path without the benefit of perfect, future knowledge of the ground vehicle's location. The relatively low cost of these flights coupled with the considerable performance increases over default capabilities indicate that near-optimal flight paths for convoy overwatch are operationally feasible using a real-time, heuristic strategy implemented onboard the autopilot.

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Notes

[1]All solutions computed on a Samsung ATIV Smart PC pro (Intel i5 processor) using MATLAB 2012b under default settings

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TECHNICAL PAPER

STITCHED PANORAMAS FROM LOW-COST AIRBORNE VIDEO CAMERAS

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Abstract

Effective panoramic photographs are taken from vantage points that are high. High vantage points have become easier to reach as the cost of camera-equipped quadrotor helicopters has dropped to nearly disposable levels. The low-quality video recorded by these cameras can be converted into still panoramas, whose quality and resolution are comparable to images captured from remote-controlled aircraft that are much larger and thus have much greater flight risks.

Introduction

High-quality panoramic photographs (5 to 10 megapixels, with good contrast, sharpness, and gamut) can now be acquired from aircraft under 100 grams. Such aircraft pose much less risk than aircraft carrying higher-quality cameras. An aircraft under 250 g that impacts a bystander has a less than 1% chance of inflicting injury at or beyond severity score 3 of the Abbreviated Injury Scale (Gennarelli & Wodzin, 2008; FAA, 2016). On the other hand, a typical quadrotor carrying a popular airborne camera such as those manufactured by GoPro (75 g to 150 g) has a flying weight of at least 450 g to 900 g, based on a payload fraction of 0.17 to 0.2. (For commercial rotorcraft, this payload fraction holds over three orders of magnitude (Khromov & Rand, 2006, fig. 10), or over five orders of magnitude when considering DARPA's goal for UASs under 10 g (Hylton, Martin, et al., 2012).) Such "category 2" aircraft need safety constraints not needed by lighter aircraft: formal tests to verify that, in likely failure modes, impact energy is less than a set threshold; an analysis of rotor impact; and an operating manual that includes requirements for flight near bystanders, at least 6 m above or 3 m laterally away from them (FAA, 2016). The categories for even heavier aircraft have correspondingly stricter constraints, such as operator qualifications, restrictions on flying over crowds, and creating and following a risk mitigation plan. In short, aerial photography can now present little risk to both bystanders and the UAS itself, which can be inexpensive enough to replace outright if it is lost or damaged.

Capturing video from sub-100 g quadrotors is commonplace (Chen, 2015), but no reports have been published about capturing still images. This paper offers a complete set of techniques for acquiring high-quality panoramas from such aircraft. In order, the sections of this paper describe how to extract still frames from these videos; maneuver effectively to avoid motion parallax; suppress artifacts due to poor camera quality; cope with strong winds and motion blur; and record simultaneously from multiple cameras (on multiple quadrotors) to broaden a panorama. These techniques are all suitably simple and inexpensive.

Although many aerial tasks rely on cameras, other payloads are not unknown. Insofar as the techniques presented here generalize beyond cameras, they may inspire others to try lighter, simpler sensors on lighter, simpler aircraft. Taken together, all of this reduces the risks inherent to flight, widens a task's range of deployment, and makes aerial sensing more accessible to grassroots movements, nonprofits, and organizations in developing countries.

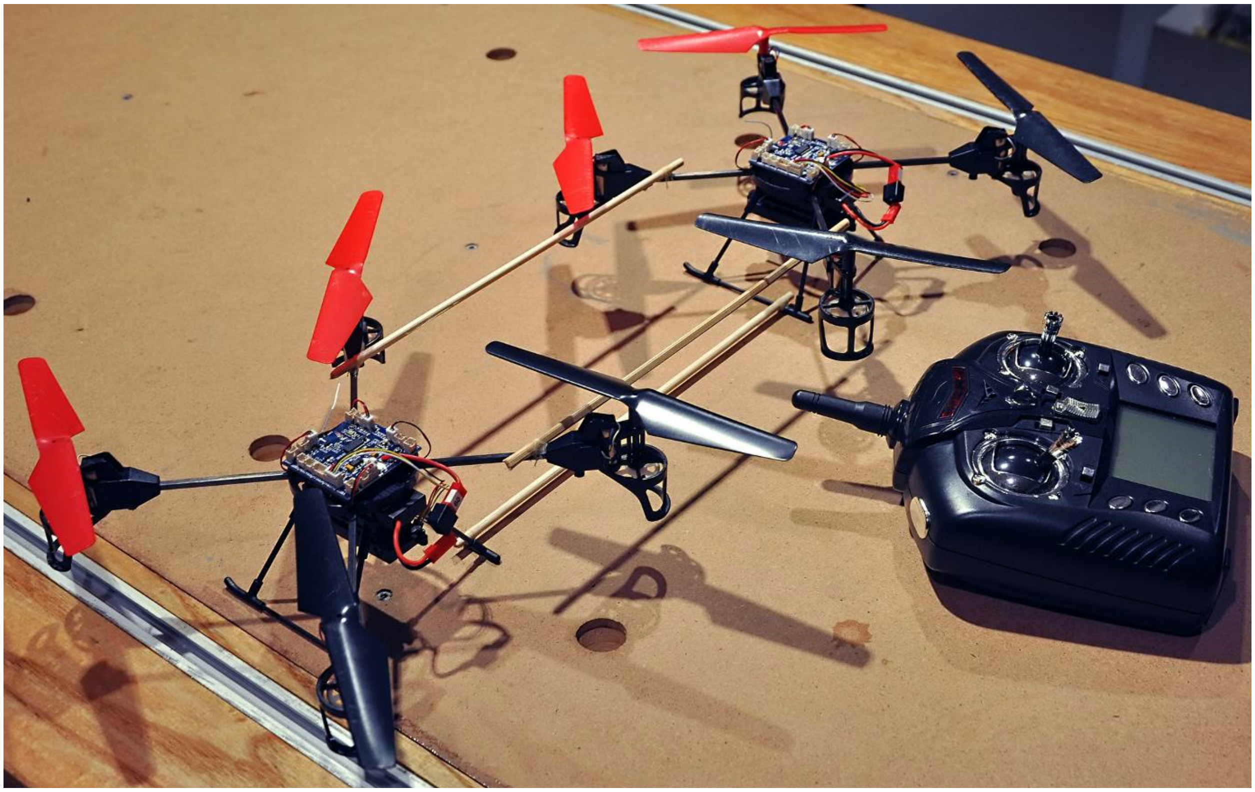

Figure 1. Two videocamera-equipped quadrotors, with a shared radio-control transmitter.

Quadrotors

During the 1990's, electric power for radio-controlled aircraft improved to match the power of piston engines. At the same time, electric drivetrains kept their advantages of reliability, low vibration, and mechanical simplicity. Electric power became mainstream. Over the next decade, the enduring consumer preference for mechanical simplicity then led to the quadrotor helicopter, with only four moving parts on the entire aircraft. Pushing almost all of the aircraft's complexity into software made it inexpensive, maintenance-free, and crash-tolerant. On e-commerce web sites, the price of sub-100 g camera-equipped quadrotors, such as those in fig. 1, has fallen below USD 15.

Quadrotors in the range of 100 g are inconspicuous and quiet. Although quadrotors as light as 12 g have become widely available in the past two years, reviews in hobby magazines agree that they are overwhelmed by winds stronger than a few knots. Thus, a flying weight near 100 g may remain optimal for some time. Besides offering stealth, small size also lets the aircraft be carried around more often, to capture images at unplanned opportune moments (fig. 2).

Figure 2. Full 360 degree panorama. Trenton, Ontario, 2013-08-19.

Converting a Video to a Panoramic Image

Panoramas can be extracted from many kinds of video recordings, of course, but particular issues apply to videos recorded by cameras on small quadrotors.

In nonaeronautical contexts, the camera often found on small quadrotors is called a keychain camera or an "808" (Lohr, 2016). Its specifications change monthly, but are roughly: mass 8 g, pixel resolution 640x480 to 1280x800, microSD card storage, 30 or 60 frames per second, fixed focus, and depth of field 10 cm–infinity. Its 2 mm diameter lens performs poorly in low light, so flying at dusk or indoors should be avoided. The lens's narrow field of view means that the pixel resolution matters less than one might think. For example, fig. 2 includes plenty of detail, despite being stitched from a video whose resolution is only 640x480. The final panorama has eight times more pixels than any individual frame from that video.

Keychain cameras save a video file in motion-JPEG format, which is just a sequence of individual JPEG images that happens to be synchronized to a soundtrack (Library of Congress, 2012). Because this format does not exploit inter-frame redundancy, it produces files 3 to 10 times larger than those made with a modern codec. This large size is tolerable, though, because it does not constrain recording—videos of a dozen 5-minute flights easily fit on a modest 8 GB card. In fact, a camera with stronger file compression would drain the aircraft's battery faster, paradoxically decreasing the duration of both a flight and its recording.

Individual frames from the video file can be extracted with software ranging from idiotproof smartphone apps to elaborate Swiss Army knives like FFmpeg (2016). For the latter, a typical command is `ffmpeg -i infile.mov -vcodec png -f image2 %04d.png`. This produces image files named `0001.png, 0002.png`, ..., . (Alternatively, if image quality needs no further improvement , the original JPEG frames can be instantaneously extracted: `ffmpeg -i infile.mov -vcodec copy -f image2 %04d.jpg.`)

The resulting collection of video frames usually needs some preparation before stitching. Dropped or missing frames occur with some camera-card combinations, or when the camera's CPU is momentarily too slow for even the simplistic motion-JPEG format. Naive extraction of frames "reconstructs" these missing frames by repeatedly duplicating the previous frame, but such duplication slows down image stitching. Many of these consecutive duplicate frames can be removed by specifying the option `-vsync 0` to FFmpeg. Removing all duplicate frames requires a duplicate-file finder, of which dozens are available for free online. Because these finders use file size as a quick first test for duplication, they are much slower with formats such as `.bmp` and `.ppm` that give every frame the same file size. The `.png` format does not suffer from this, and is thus preferred.

These image files may be further improved as needed by applying the tools discussed later in this paper. When they are ready, they are sent to an automatic image stitcher, such as the free programs AutoStitch (Brown, 2015; Brown & Lowe, 2007) and Image Composite Editor (Microsoft, 2016). The stitcher then produces a single panoramic image (figs. 2, 3, and 8).

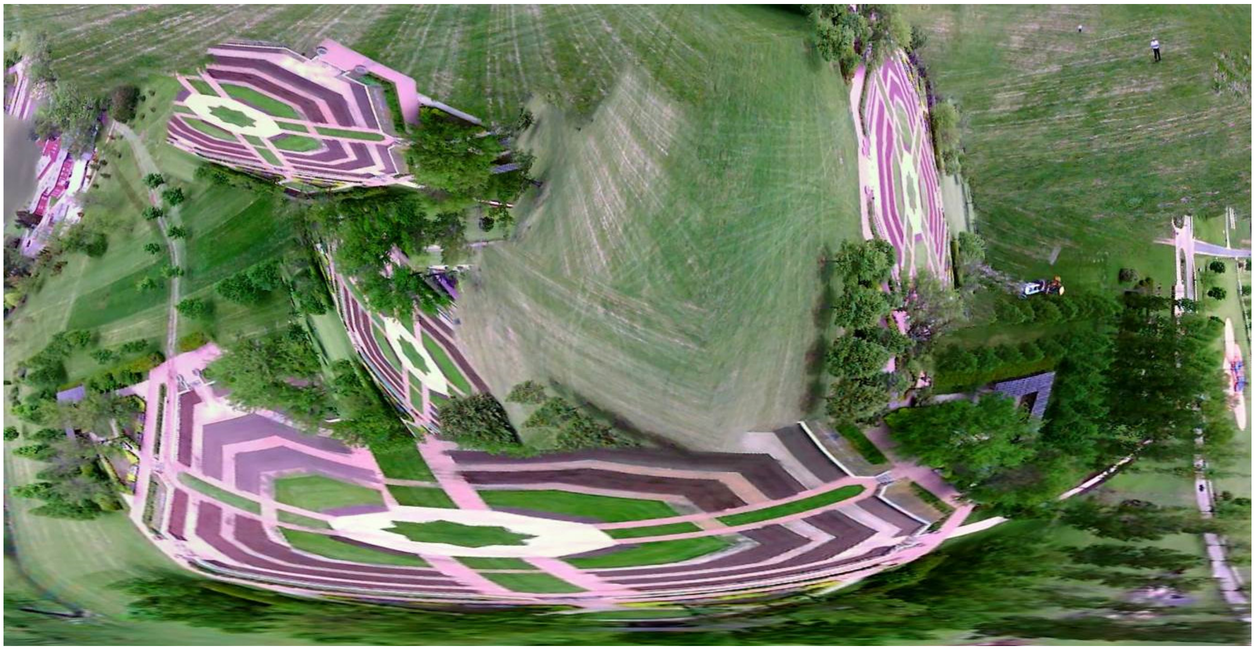

Figure 3. Mis-stitching due to camera movement. UIUC Arboretum, Urbana, Illinois, 2013-05-16.

Flight Paths Optimized for Stitching Images

Stitching software assumes that the images it is given were captured from a single viewpoint. Because a lightweight quadrotor is hardly a stationary tripod, this assumption is spectacularly violated by stitching the video recording of an entire flight (fig. 3). For a coherent panorama, only a subinterval should be stitched.

A convenient way to capture a stitchable subinterval is to pirouette the quadrotor, yawing about a vertical axis while avoiding other rotations or movements (in cinematography, this is the very definition of a pan shot, the abbreviation for panorama). Some drifting is tolerable if the subject is more than about 20 m away, and if the pirouette is less than a full circle. Stitching gains accuracy when frames have more overlap, which happens with slower yaw. The slowest practical yaw for a 100 g quadrotor is about 0.4 rad/s, or 16 s for a full pirouette. Even slower stationary yaws would require more mass or a GPS-enabled autopilot to resist wind gusts. Because 0.4 rad/s is still fast enough to avoid stitching artifacts such as ghosting (Chen & Huang, 2012b; Uyttendaele, Eden, et al., 2001), it is preferred.

Choosing a Stitchable Subinterval

After landing, the video is viewed on a computer to find a brief interval that shows the desired subject. To maximize the panorama's coverage, one stretches the interval's endpoints as far as one can, while restricting it to a single pan (without reversing direction) from a single viewpoint. Although several back-and-forth pans would cover the subject more thoroughly, in practice each pan would be from a slightly different viewpoint, introducing seams like the one in fig. 8 just left of the red truck. The more these viewpoints differ, the more obvious the seams are (fig. 3).

Video Downlinks

After reviewing the videos from a few flights, most pilots develop an intuition for what the quadrotor's camera is seeing. But if the quadrotor's height exceeds that used to capture fig. 2, about 30 m, it becomes almost too small to orient in flight, to aim its camera. (Its body is less visible than a baseball at home plate as seen from first base.) If aiming is a concern, a live video downlink can be added to the quadrotor. But this extra equipment, and lightening of the stock parts to compensate for this payload, costs ten to twenty times more than the original aircraft (Gaffoor, 2013). Also, the many single points of failure of such first-person view (FPV) flight add risk, counter to the whole point of using this kind of aircraft. Even for a 100 g aircraft, the prudent FPV pilot flies nearby enough to revert to line-of-sight control, and maintains situational awareness with a spotter assistant. When flying much more than 30 m away, with or without FPV, it becomes safer to instead fly an aircraft that is large enough to be visible at that distance.

Suppressing Camera Artifacts

A keychain camera's image quality may be poor in several ways: varying brightness, rolling shutter, moire bands, and compression blockiness. Fortunately, these artifacts can be suppressed or eliminated.

Reducing Variations in Brightness and Color

Brightness and color variations in a video are due to the camera's automatic exposure compensation and automatic white balance (Uyttendaele, Eden, et al., 2001). When the view changes suddenly from bright cumulus to shaded terrain, the camera takes a few seconds to correct its exposure. Similarly, when a view of only grass suddenly tilts up to include some sky, a full second elapses before the white-balanced grayish grass becomes bright green again. Frames from such transitions may not be usable for stitching. Reducing such variations requires slower aircraft rotation. After flight it may be too late to correct the transitional frames if color is out of gamut, or if shadows or highlights are clipped (lost detail, in pure black shadows or pure white highlights).

Minimizing Artifacts due to Rolling Shutter

Small cameras often use a "rolling" shutter, which captures an image one scanline at a time, instead of all at once. In other words, different parts of the image correspond to different instants in time. Therefore, moving the camera relative to the subject produces visible warp and skew. As with varying brightness, the first cure is slower aircraft rotation. Also, balancing the propellers with flecks of adhesive tape reduces the mechanical vibration that causes "jello" in video (Graham, 2013).

Unlike varying brightness, though, rolling shutter can be suppressed after flight (Baker, Bennett, et al., 2010; Grundmann, Kwatra, et al., 2012). Rolling shutter repair is included in commercial video software such as Adobe Premiere Pro and Adobe After Effects, and in free video software such as the Deshaker plug-in for VirtualDub (Thalin, 2014; Lee, 2013). However, these tools specialize in inter-frame smoothness, which is not needed for panorama stitching. Worse, they may crop the image (which shrinks the panorama's coverage) or add a black border (which confuses the stitcher). If the border's color can be made transparent, however, commercial stitchers such as Adobe's Photomerge may succeed. Better yet, Deshaker can fill the border with pixels from previous or successive frames, or, when those are unavailable, with colors extrapolated from the current frame.

Avoiding Moire Artifacts

The artifact called a moire pattern consists of undesired bands of hue or brightness (fig. 4), seen in a subject with repetitive detail that exceeds the camera's resolution. If the stitcher tries to match such stripes or bands, which shift from frame to frame as the camera moves slightly, stitching quality deteriorates. This is particularly so for stitchers that match image features by hue as well as by brightness, because a camera sensor's Bayer filter mosiac produces strong hue bands. The pattern is due to foldover at the camera's Nyquist frequency. Better cameras suppress this with anti-alias filters. To avoid moire patterns, then, one must either fly quite far from such a subject, or fly so close that each stripe is at least two pixels wide (for a keychain camera, at most a few hundred stripes visible at once).

Figure 4. Different magenta-cyan moire patterns on three identically corrugated roofs. The roofs differ only in their distance from the camera. UIUC Dairy Cattle Research Unit, 2013-08-01.

Removing Blockiness due to JPEG Compression

Some JPEG frames may be compressed so strongly that a grid appears at the boundary between 8x8 pixel blocks. As with moire patterns, this noise varies from frame to frame, distracting the stitcher from matching common elements across frames. Such grids are also distracting in the final panorama. This artifact is suppressed by the UnBlock algorithm (Costella, 2006; Goudeseune, 2014), which smooths over the boundaries between blocks, but only aggressively enough to reach the same distribution of discrepancies across the block boundaries as is found in the block interiors (fig. 5). The algorithm's tuning-free design prevents it from introducing other visual artifacts.

Tethering a Quadrotor to a Kite

In winds too strong for a lightweight quadrotor, it can nevertheless be given a high vantage point by hanging it from a toy delta-wing kite (span 1.3 m, cost USD 5). Even with the aircraft's four booms removed to prevent the rotors from getting fouled in the kite's tether, the aircraft still operates as a power source and remote control for the camera (fig. 6).

An elaborate Picavet camera suspension (Picavet, 1912; Beutnagel, Bieck, et al., 1995) is inappropriate: building and testing one takes several hours, while a commercial unit costs many times more than the entire quadrotor. On the other hand, just dangling the camera from the kite's tether shakes the camera so much that fewer than one frame in a hundred is stitchable (fig. 7). Happily, the shaking can be dampened by hanging the camera from not one but two points on the tether, at the bottom of a "V." Then one frame in ten has acceptably low motion blur. But this then poses the problem of how to find these still rare frames.

Culling Motion-Blurred Images by Automatic Sorting

Manual culling of frames blurred by camera motion is impractical. To automate this, one can measure how blurred each frame is, and then sort the frames by blurriness. A frame's blurriness is measured simply and thus robustly by re-saving it in JPEG format, with and without first applying a Gaussian blur. The smaller the ratio of the sizes of the two resulting JPEG files, the less effective the Gaussian blur was, and thus the blurrier the original frame was. Because calculating a blur is slow, downsampling beforehand by a factor of four or so greatly speeds up the processing of thousands of frames. (Downsampling also attenuates sharp pixel-block boundaries such as those in fig. 7. This is desirable because those sharp boundaries reduce how well the Gaussian blur approximates the original motion blur—they hide the smooth motion blur behind artificial crisp edges.) One can then build a list of pairs of frame-filenames and blurriness values. After sorting this list by increasing blurriness, the start of the list then yields a set of least blurry frames. A more elaborate deblurring method, culling any video frame that has few sharp edges compared to its neighbors (Chen and Huang, 2012a), fails in the presence of duplicate frames, which we have already discussed.

Of course, a Gaussian blur only approximates a motion blur. But the exact motion blur is a combination of axial rotation and panning, which is too expensive to measure for this quick first pass that culls almost all of the frames. Later passes can use advanced algorithms (Li, Kang, et al., 2010; Cho, Wang, et al., 2012), which not only detect but even remove mild blur by estimating camera motion from consecutive frames—although these again fail for duplicate frames. Such advanced deblurring can also improve videos taken without the help of a kite.

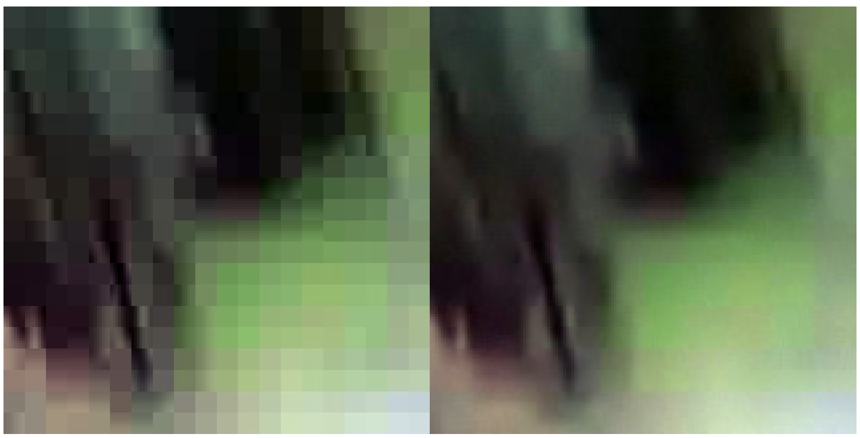

Figure 5. Detail (160x160 pixels) from top right of fig. 7. Left: original. Right: processed by the UnBlock algorithm.

Figure 6. Kite hoisting a rotorless quadrotor-camera (a "nullicopter"), while capturing fig. 7.

Figure 7. Strong motion blur from a kite-suspended camera. Evergreens 5 m to 15 m tall, Okanogan-Wenatchee National Forest, 2013-05-22.

Multiple Cameras

Terrain hillier than what is shown in fig. 2 may need more vertical coverage than what one camera can provide. The same holds for panoramas that need coverage of nearby foreground as well as distant background (fig. 8). In this case, a quadrotor may have enough thrust to carry more than one camera, with each camera pointing in a slightly different direction. This has been proposed for Parrot's AR.Drone quadrotor (400 g, USD 300) (Chen and Huang, 2012a), but no implementations to date have used aircraft under 100 g. More typical is DARPA's ARGUS-IS cluster of several hundred cameras (Vaidya, 2011).

Figure 8. Top: panorama stitched from one camera's frames. Bottom: second camera's frames added. UIUC Large Animal Clinic, 2013-10-09.

If the quadrotor's maneuverability suffers with the extra payload of more cameras, another novel solution is to laterally combine two or more (figs. 1 and 9). (Buying multiple aircraft is an inexpensive way to get spare parts.) The transmitter is unaware that it is controlling more than one quadrotor. The composite aircraft is less maneuverable because the stabilizers in each quadrotor fight each other, and because roll authority is reduced. But the more important controls—pitch, yaw, and thrust—have no reduced authority. As with multiple cameras on one quadrotor, each camera points at a different angle.

Figure 9. Two-camera octorotor, just before capturing fig. 8.

Conclusions and Extensions

High-quality panoramic photos can be captured with a videocamera-carrying quadrotor of startlingly small size and cost, thanks to multiple stages of software post-processing. These stages can be applied to whichever aspects of a particular panorama need improving.

Multiple cameras can record stereoscopic video, especially when widely spaced on an octorotor. The audio recorded with each camera's rudimentary microphone suffices to synchronize the individual monoscopic video recordings.

A stereoscopic panorama can be made with only one camera, by recording two partial pirouettes from nearby locations. A typical sequence of maneuvers would be a half pirouette, forward flight for a few seconds, and then a half pirouette in the opposite direction. Each half pirouette is stitched into its own monoscopic panorama; these two are then combined.

Although the data recorded by lightweight sensors carried by lightweight aircraft may be inferior to what is recorded by standard equipment, post-flight software can ameliorate this. Furthermore, in some cases the reduced cost and reduced flight risks of lightweight equipment may make it the only practical way to collect data at all.

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