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DEVELOPMENT AND TESTING OF AN UNMANNED AIRCRAFT SYSTEM FOR

ENVIRONMENTAL SCIENCE

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2011

DEVELOPMENT AND TESTING OF AN UNMANNED AIRCRAFT SYSTEM FOR

ENVIRONMENTAL SCIENCE

By

JERALD JAMES BRADY, BSCS

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

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Abstract

For some environmental science applications, Unmanned Aircraft Systems (UASs) are increasingly recognized for their capacity to collect remotely sensed data in a safer, more efficient and effective manner than is permitted with manned aircraft and satellite remote sensing platforms. To date, however, technological, human, and other challenges have constrained adoption of UASs in the environmental sciences. This study developed and tested a new UAS for an archetypical environmental science research group (stakeholder) composed of non-UAS experts. Specifically, this thesis: 1) Assessed the research and operational needs of the stakeholder to determine the optimum UAS platform; 2) Developed an Unmanned Aerial Vehicle (UAV) and sensor payload; 3) Developed a new software tool for UAV operation planning, control, and optimized data acquisition; and 4) Tested the operational performance of the newly developed UAS.

A powered paraglider was selected as the optimal UAV platform for the stakeholder. Development and testing of the UAS overcame many technical, human, and other challenges. A relatively stable and useful UAS with a 30lb payload was engineered and appears to meet the needs of the stakeholder. A new scalable operational software tool was engineered that integrates operation planning, UAV and sensor specification, and map based real time flight optimization with a relational database.

An assessment of the Unmanned Aircraft System was performed by asking four different pilots, ranging in pilot skills from skilled to novice, to perform two flights (one unassisted and one assisted with the newly designed operational software) to best capture photographic coverage of an experimental area (200 x 400 meters) within a fifteen minute time limit.) . The capacity of the operational software to improve the spatial coverage of data acquisition was also assessed. Coverage of aerial photography was enhanced 4.41% to 35.76% when the operational software was used when compared to non software

assisted flights, and the Unmanned Aerial Vehicle spent between 3.75% and 12.29% more time in the predefined sampling area when guided by the operational software. An experienced pilot outperformed inexperienced pilots but still benefitted from the guidance offered by the operational software.

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Table 1: Acronyms Used

Term	Meaning
COTS	Commercial Off The Shelf
ES	Environmental Science
FAA	Federal Aviation Administration
HALE	High Altitude Long Endurance
NAS	National Air Space
PP	Powered Paraglider
PPUAV	Powered Paraglider Unmanned Aircraft Vehicle
QAQC	Quality Assurance Quality Control
RC	Radio Control
RPM	Rotations per minute
UAS	Unmanned Aircraft System (Includes the Vehicle and additional software components)
UAV	Unmanned Aerial Vehicle (Only includes the vehicle and not any attending systems)
VTOL	Vertical Take Off and Landing

1. Introduction, Related Work, and Objectives of this Paper

1.1 Introduction

Global change, which includes climate change, is affecting the provision of ecosystem goods and services (Millennium Ecosystem Assessment, 2005). Tracking and monitoring animal movements, detecting and ameliorating infestations of introduced species, assessing the impact of pollution, and monitoring wild fires are among the most prominent challenges in the environmental sciences. Recent developments in technology such as remote sensing applications (remote image capturing, spectral and gas analysis, and even radio signal repeaters for animal tracking) are allowing researchers to gather data at faster rates, over larger areas and in more extreme environmentsthat were not possible previously. Yet there are still limitations with these methods. Radio repeaters require valuable man-hours to track down and tag animals (Rango, et al., 2006), while spectral and gas analysis is limited to the researcher's immediate area of accessibility (Diaz, et al., 2010). Remote image capture is expensive, and satellite imagery is impacted severely by cloud cover in many areas such as the Arctic. These shortcomings have largely underpinned the development of Unmanned Aircraft Systems (UASs) and the utilization of Unmanned Aerial Vehicles (UAVs) to gather data in the environmental sciences.

By using UASs, researchers can collect data in a less dangerous, less expensive, and less labor intensive manner that allows for a smaller carbon footprint than traditional aircraft and satellite remote sensing platforms. UAS platforms allow data to be collected in remote or dangerous places and with a more flexible time schedule, can span a larger area of coverage, and make measurements at a higher resolution compared to other methods. While UASs provide many obvious benefits to environmental science remote sensing applications, there are still several challenges to be resolved. Some of the challenges preventing general adaption as a sensing platform include the need for transmitting flight telemetry data in real time, quality assurance and quality control of streamed data, and optimizing the

ease of flight control and operation of the UAV. While specific challenges are being addressed, most studies focus on designing/customizing UAVs for highly specific research needs rather than trying to address the general needs of the academic UAS using community. This thesis begins to addresses this gap and provides a viable solution for these challenges.

1.2 Background and Rationale

1.2.1 Unmanned Aircraft Vehicles and Unmanned Aircraft Systems Defined

Unmanned Aircraft Vehicles or UAVs are robots with the capacity to fly and that have control systems ranging from a remote human pilot (not onboard) in constant control with the UAV to complete autonomy where instructions are pre- programmed and the UAV completes entire missions unassisted by a human pilot. New technology has been integrated into UAVs, which has increased both the complexity and utility of UAVs. To emphasize the increasing complexity of UAVs, a change in the nomenclature was recently introduced by the Federal Aviation Administration (FAA) to refer to UAVs and their attending systems as UASs or Unmanned Aircraft Systems. A UAS includes the UAV, the payload sensors contained onboard, any flight software working onboard and on the ground, and the additional flight crew that are needed to allow the aircraft to fly successful missions (Dorr, Fact Sheet - Unmanned Aircraft Systems (UAS), 2010). Historically UASs have been in development in parallel with regular aircraft. As the technology underlying general flight for manned aircraft has improved and become more miniaturized, UAVs have undergone increases in payload size and volume (Chin and Sern, 2009).

1.2.2 History of UAV Development

The first recorded use of a UAV was in 1849 when Austrians developed a pilotless hot air balloon to drop bombs on the city of Venice. In this case, a copper wire connecting the balloon to the launch site

was electrically charged to open a clasp that would release the bomb (More About Balloons, 1849). Although not a plane or other vehicle in the traditional sense, these hot air balloons are widely considered a precursor to the more modern UAVs as they introduced the concept that remotely controlled aircraft could be used without endangering operators and to provide improved efficiency and mobility.

After the invention of the airplane by the Wright Brothers in 1906, development of UAVs became possible through the invention of radio controlled technologies in the beginning of the 20th century by Nikola Tesla (Tesla, 1898). Tesla developed the first remotely operated apparatus by using a radio transmitter and receiver to control a small boat. After this the first major development of remote control radio technologies was developed by Elmer A. Sperry who engineered a gyroscope for the US Navy during World War I (WWI) (1913) (Pearson). The advent of the gyroscope allowed for an electronic evaluation of aircraft orientation. Although commissioned to develop the “flying bomb”, a full sized unmanned plane filled with explosives that could be remotely controlled or flown autonomously to drop bombs on far sites, his completed planes were never used on the battlefield in WWI. Later, however, Sperry’s technology was used as the precursor to guided missile technology developed during World War 2 (WW2) (Pearson).

Between WWI and WW2, the British military decided to expand upon Elmer’s work and create one of the first cruise missiles - the LARYNX. The LARYNX was a monoplane aircraft that could fly on autopilot and was launched from a warship. Intended to destroy Zeppelin bombers and attack ground targets, the plane had limited success and was not used in any conflicts (Goebel, 2010). At around this same time, the first radio controlled planes were sold for commercial use. These were developed by Reginald Denny. A former pilot in WWI, Denny became interested in radio technology and opened a company that sold the Denny plane. This plane was primed by spinning the propeller with a rubber

band. There were several servos onboard that controlled the rudder and ailerons that the pilot could control from a radio controller on the ground. Flight time was severely limited, but this aircraft was widely popular. This design represented the first miniaturization of radio control (RC) transmitters for public use and initiated the development of model aviation as a hobby (Naughton, 2005). With the success of his earlier models, Denny later designed and built RC aircraft as training aids for the military. These RC models were used in flight practice for inexperienced U.S. soldiers and anti aircraft (AA) gun training at the start of WW2. This development further engrained UAVs in military operations and technology development (Naughton, 2005).

With the successful application of UAV's in the military, the U.S. Navy continued the use of UAVs as training tools during WW2 and expanded their usage to weapons deployment during WW2 through the development of the aerial torpedo, an unmanned airplane used to attack enemy installations. An aerial torpedo was made by adding remotely piloted radio controls to obsolete aircraft that were loaded with an explosive payload. Two pilots would launch the plane and then parachute from the plane shortly before reaching the mission's target. By using television cameras on board the aerial torpedoes, RC pilots could control the aircraft and hit a remote target. Although this project, codenamed "Operation Aphrodite", had limited success during WW2, it was significant in that it marked the first time UAVs were used in a combat situation that were also enabled with the first wireless transmission from onboard unmanned airplanes to remote operators (Fahrney, 1980).

At the start of the cold war, spy planes were regularly used to collect information on opposing countries. However the risk of a spy plane being shot down and/or a pilot being caught by an opposing side was a primary concern to the countries involved. Subsequently, UAV research and development progressed rapidly during the 1950s. One of the UAVs developed at this time was the Ryan Model 147 Lightning Bug series (Wagner, 1992) a common drone of the US Navy. Drones at the time were remote

controlled planes that were used as training aids for anti aircraft gun training and were later modified to be used for reconnaissance. The Ryan Model 147 series flew missions in North Vietnam, Communist China, and North Korea with great success during the 1960s and 1970s. At the outset of the Vietnam War, the U.S. Navy put into use a new model based of the Ryan to conduct intense surveillance of the Vietnam conflict. Although this model flew more than 1,651 missions (Wagner, 1992), UAVs were not being used in active combat because of the time lags in data transfer to ground forces. As the UAV's distance from a staging area increased, the lag time for data response also grew causing remote pilots to take longer and longer to respond to incoming stimuli. There was also an upper cap to UAV reconnaissance distance from the staging area as radio signals cannot reliably travel around the curvature of the Earth without being absorbed or dispersed. This limiting factor hindered the development of UAVs for combat over the next few decades (Wagner, 1992).

The availability of reliable satellite communication networks in the late 1980s and early 1990s extended remote piloting capabilities and allowed for the control of aircraft flying on the opposing side of the globe to the pilot. Miniaturization of computer technologies also continued through the 80's and 90's, and the performance of hardware and software also improved, allowing UAVs to harbor complex computer programs on board for the first time. These innovations allowed for substantial improvements to UAV autonomy, requiring manual piloting only when aircraft needed to be operated in or near high risk situations. UAVs developed for Operation Iraqi Freedom (March 20th 2003 to present) include the MQ-1 Predator, which has been used extensive for military intelligence and reconnaissance missions (Tomkins, 2008). However the recent reduction in cost of UASs has made them approachable by the general public as well. The last 10 years has seen a surge in the use of UASs in academia as well as the public sector in general. Figure 1 provides a timeline to illustrate major innovations to UAS design that has led to UAV platforms being used for environmental monitoring. These platforms are

increasingly being recognized by the environmental science community as a useful tool for remote sensing of environmental phenomenon.

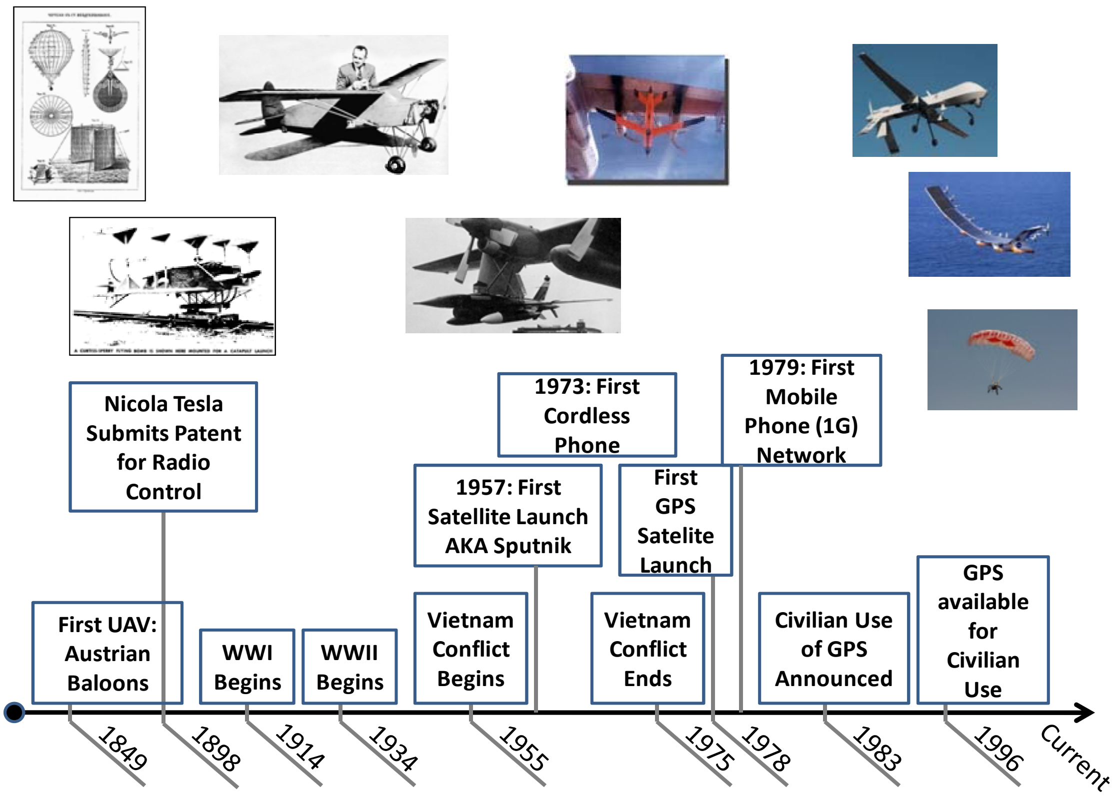

Figure 1 - Timeline of UAV and technology development, highlighting how various military applications have facilitated the development of these technologies (More About Balloons, 1849; Pearson; Naughton, 2005; Fahrney, 1980; Brass, 2004)

1.2.3 Academic Utility and Applications in Environmental Science

As the development of UAVs continued throughout the 20th Century, their utility eventually drew academic interest. Inexpensive reusable UAVs that fly into dangerous orremote areas and can remotely sense and telemet environmental data without putting pilots and other personnel in harm's way are appealing to researchers. Development has also allowed untrained personnel to set up and launch craft quickly in the field. This fact has made them invaluable to research projects that would otherwise rely on expensive manned aircraft containing highly trained pilots to collect data. With the adoption of technology from the RC community and as the US military continued development with vehicles like unmanned helicopters, blimps, and planes, academics transferred knowledge gained from successes and failures alike to design their own UAVs for their own research areas. Researchers began developing UAVs for studying a wide array of areas including active volcanoes and rangeland wildfires to extremely violent tornados and hurricanes. In general UAS use in academia collects data on naturally occurring phenomena in the hopes to better understand the environment.

1.2.3.1 **Ecosystem Monitoring**

Some of the earliest forms of ecosystem monitoring probably occurred with the use of comparative photography. Photography taken at the same position and angle over different time frames can show ecosystem change over time (Kull, 2005). In order to achieve the best results, early photos had to be taken from strategic locations to cover the most area or to obtain large views of the landscape. However by doing so, photos were limited to specific views of the study area that were not always representative of the entire site. This problem made aerial photography an interesting solution as it provided a unique vantage point that could encompass the entirety of study areas.

Figure 2 - Photo from an early kite UAV of San Francisco after the great quake of 1906

Aerial photography acquired with the use of UAVs has become more common over time. The most famous early use of unmanned kite aerial photography is probably George Lawrence's photo of the aftermath of the San Francisco earthquake in 1906. Using a kite with a large camera attached, he was able to take a panoramic photo of San Francisco from 2000 feet above ground. Aerial photography was greatly enhanced in the 1960s with the advent of aircraft that could attain high altitudes including extension to space. Cameras would regularly be attached to rockets prior to lift off and then take photos as the rockets ascended into space (Bird and Morrison, 1964). Photography would be stored onboard and retrieved from capsules upon landing.

More recently as the size, weight, and cost of sensors (including cameras) has continued to decline, it has become feasible to attach lightweight sensors to UAVs to record data. Balloon and blimp unmanned vehicles have seen an increase in use in the last few decades due to their low cost (Murden and Risenhoover, 2000). Balloon/Blimp systems have been used in forest ecosystems to measure photosynthetically active radiation - PAR (Parker, 1996) and transmit readings down the length of the tether in dense canopies. Kite UAVs have been used to acquire high altitude (over 1000 meters) aerial photography using light weight cameras. These kite UAVs typically have camera mounts that have the capacity to reorient themselves in flight utilizing electronic servos that adjust its positioning. With radio control from servos, it is also possible to remotely trigger the camera to take photos from high altitudes (Aber et al. 2008). However there are several drawbacks to using tethered balloon/blimp and kite UAVs for environmental monitoring. Blimps/balloons and kites are usually tethered and require human interaction for movement of the UAVs in flight. This implies that the pilot may have to stand in the ground-based sampling area below the UAV. Also, these UAVs can only be used with relatively light winds (balloon and blimp) and/or specific ranges of wind speeds. Relative to their size, they also have extremely limited payloads. This has motivated many environmental scientists and technologists to focus their development on fixed wing or airplane UAVs, vertical takeoff and landing (VTOL) UAVs, and/or helicopter UAVs.

The trend to include UASs in environmental research for the acquisition of aerial photography for landscape management has increased in recent years (See Figures 3 & 4). Fixed wing UAVs have seen great success in the monitoring of environmental variables at the landscape to regional levels as they provide a fast way to sample relatively large areas. It has been shown that these platforms can be made from commercial-off-the-shelf (COTS) parts in an inexpensive manner (less than $2000) and be used as a practical tool for ecological studies (Hardin and Jackson, 2006). Furthermore, with the aid of Geographical Information Systems in conjunction with aerial photography it is possible to acquire air-

borne photography and classify different land cover types in resulting imagery (Rango, et al., 2006). The analysis of imagery from UAVs such as VTOLs has also successfully identified invasive species (Blumenthal D. et al. 2007). VTOLs were used for aquatic weed surveillance in Australia where live video of the ground is analyzed by machine learning algorithms to determine species classifications and show the percentage of weeds versus regular vegetation (Goktogan et al. 2010).

With the inclusion of new sensors, such as video, UASs have been successfully used for the study and observation of wildlife (Jones, Pearlstein, and Percival, 2006). Researchers at the University of Florida, for example, used a FoldBat UAS that allowed remote monitoring of wildlife with video and camera systems in the Florida everglades. The UAS was quiet enough to not interfere with wildlife and they concluded that the UAS was a useful tool for their needs. The same research group has since improved upon their original design by collaborating with the Florida's Micro Air Vehicle Laboratory to customize another UAS (Watts, et al., 2008). Their newly designed UAS has autonomous GPS flight control and a continuous record of attitude and pitch, which they use post flight to orthorectify imagery.

1.2.3.2 **Atmospheric Observation**

Atmospheric observations are of great interest in environmental science as they provide a way to research and monitor key events that have the capacity to affect society. A good example is the monitoring of gaseous and ash plumes from volcanic eruptions, which are detrimental to manned aircraft, human and ecosystem health, and property. Several studies have been conducted utilizing UASs in and around volcanic eruptions to circumvent the danger of using manned aircraft in such areas. The analysis of gas plume composition from the Turrialba Volcano in Costa Rica with a custom designed portable mass spectrometer collects useful data that helps to determine when the next eruption is likely to occur. Researchers there are developing their own electric UASs to reduce cost and prevent risk to manned pilots flying through the volcanic plumes (Diaz, et al., 2010). Another group in Italy from the

“Dipartimento di Ingegneria Elettrica, Elettronica e dei Sistemi” has also monitored volcanic gas plumes around Mount Etna to determine eruption likelihood and gaseous contents as well. Initially, the group designed a plane system that was completely autonomous and based on COTS products. Their design allowed for high altitude flight up to 4,000 meters, had a range of 3 kilometers, and could fly autonomous flight for 30 minutes (Caltabiano et al. 2005). Their initial choice of an electric engine limited the altitudinal range and length of the flight, which was corrected by switching to a gas engine. Other studies focused on sampling around volcanoes (Longo et al. 2007) have shown the benefit of multiple working robotic systems collecting data in conjunction with a UAV. By utilizing an unmanned ground vehicle (UGV), a fixed wing UAV, and a wall climbing robot, the group demonstrated that a team of robots could be used to safely and remotely conduct reconnaissance and acquire data during a volcanic eruption as well as large scale industrial accidents (Longo et al. 2007). A typical difficulty encountered with UAVs studying volcanoes is the need for autonomous flight due to the inability of pilots to see the craft while flying in volcanic plumes. To address this difficulty, a UAV was constructed for this specific purpose at the University of Catania, Italy. Their work included the design of the hardware control mechanisms onboard the aircraft that allowed for autonomous flight to be turned on and off (Astuti et al. 2009).

Meteorological research has also benefitted from the use of UASs. The Aerosonde is a fixed wing UAV that has been in development since 1992 and has successfully flown long range missions to better understand meteorological changes in Australia and the Arctic (Holland, et al., 2001). This system has a flight range of 4000 kilometers and has a 40-hour endurance. The engine was custom designed and is the world’s smallest fuel injected engine, which allows for a fuel economy in excess of 2000 mpg (Holland, et al., 2001). Sensors relay air temperature, wind speed, air pressure, and humidity to the ground station as well as details on aircraft performance such as engine temperatures, revolutions, voltage, etc. Wind speed around the Aerosonde is computed by using a proprietary algorithm that

requires an ‘S’ type turn with constant gps, and airspeed values during the maneuver are being used to calculate the wind speed (Holland, et al., 2001). Since its inception in 1992, the design has been continuously improved. It has also been used for monitoring changes in arctic sea ice extent off the coast of Barrow, northern Alaska (Inque, Curry, and Maslanik, 2008). Sea ice studies demonstrated that data from the UAV gave better results than satellite microwave products. In Florida, UAVs have been used to measure lightning optical pulses during severe weather and provide data used to determine the length of lightning flashes in storms (Mach, et al., 2005). Meteorological studies using mini UASs with highly customized sensors (sensors record air pressure, humidity, and air speed at 40 hertz) and processing algorithms have been used to determine wind speed (Kroonenberg and Martin, 2008) through the normalization of air speed, with respect to the airflow of the UAV in flight. Balloon UAVs have also become well recognized for their capacity to aid meteorological research – particularly for their capacity to maintain fixed altitudes and for measuring vertical profiles of ozone, particulates, and solar radiation, for example. Using data from ground based sensors, the authenticity of data collected from aerial balloons was verified, which demonstrated that balloons were practical applications that gave the same expected results and provided a greater coverage area for data collection then traditional ground based observations (Greenburg, Guenther, and Turnispeed, 2009).

1.2.3.3 **Emerging UAS/UAV Technologies relevant to environmental science**

Over the past decade especially, there has been a focus to miniaturize UAVs. Small UAVs are now being labeled as micro UAVs. They can be hand launched and are extremely portable (Schafroth et al. 2009). Some micro UAVs have been designed based on flight characteristics of insects and birds (Howard, 2007). Companies such as Aerovironment are developing UAVs as small as birds and insects that will work in swarm configurations to monitor relatively small places such as buildings in urban warfare situations where the small UAVs will collect data and relay this to larger bird shaped UAVs flying

outside of the buildings that will then relay data to control stations. As miniaturization to UAV platforms and sensors continue to address military needs, the academic community will likely reap the benefits of this research and development as it provides more inexpensive smaller sensors that can be used to monitor a wider array of environmental properties. Swarm UAV computing is becoming a hot topic in academia as it would allow wireless sensors networks to be mobile, inexpensive, and effective at collecting diverse information of a single event or location (Ilaya, Bil, and Evans, 2008).

At the same time, there has also been research to make UAVs more energy efficient and lengthen the duration of flight (Goraj, Frydrychiewicz, and Winiecki, 1999). These UAVs need to use regenerative energy sources such as solar power arrays and lightweight batteries in order to maintain flight. One of the first successes for these UAVs was realized with the NASA Pathfinder Plus and Helios models (Brass et al. 2004). These models used very large wingspans (15 meters or 50 ft) that are covered in solar panels. The solar panels charge a series of electric engines that keep the UAV aloft. Despite early success, the Helios crashed when strong winds caused the structure to destabilize. The motivating concept behind these energy efficient UAVs is to use them as a alternative to satellites because they could be launched and programmed to fly at high altitudes and serve as a relay for radio communication with UAV or ground based sensor systems. These models also could provide environmental science with mobile weather stations that provide real time weather data around globe allowing them to relay valuable data about atmospheric change.

Novel developments of UASs for applications in the environmental sciences have largely focused on the development of cyberinfrastructure that promote not only advances to UAS hardware engineering, communication and control systems but also embedded sensor systems. For example, new sensors on UAVs have been used to monitor pathogens in fields of potatoes with the use of sophisticated modeling techniques (Aylor et al. 2011). This study showed that the use of UASs could improve crop yields

through the early location of treatable disease. Some studies have also introduced swarm control of multiple UAVs for environmental monitoring and analysis (Roberts et al. 2008). New simulation software has even been created to test algorithms designed to handle multiple UAVs flight paths and to help optimize their data collection (Goktogan and Sukkarieh, Distributed Simulation and Middleware for Networked UAS, 2009).

1.2.4 Research and Implementation Challenges

While UAS development and use within the environmental sciences has increased dramatically in recent years, several key challenges remain. Front and foremost, and in response to public safety concerns, the US Federal Aviation Administration (FAA) currently defines UAVs as ”an unmanned aircraft” that is “remotely operated” (Unamnned Aricraft Systems(UAS), 2011). The document defines that a UAS can ranges in size “wingspan as large as a Boeing 737 or smaller than a radio-controlled model airplane.” (Dorr, Fact Sheet - Unmanned Aircraft Systems (UAS), 2010). The FAA does note in their current fact sheet that radio control model fliers are outside the current jurisdiction of UAS from a memo (Vuren, 1981) issued on the subject. This memo also stipulates that model operators can fly as long as they stay below 400 feet and collaborate with nearby airports by yielding the right of way to manned aircraft. More recently, the FAA has expanded their website to explain the methodology for the inclusion of UASs into national air space (NAS) (Kalinowski, 2010) as new policy changes are introduced. These policy changes were openly discussed at a meeting at the American Geophysical Union in 2008 that I attended. At the meeting FAA advisors asked researchers to describe their desires for future policy changes and UAS research. Many groups expressed concern over the FAA making changes to the current regulations as it would restrict UAS research and warned that strict regulations would deter labs from conducting research with UASs. Furthermore some at the meeting suspected that the new regulations were going to hamper UAS growth in the United States academic community,

which would result in lag as new FAA policy changes were introduced. The FAA introduced their changes in 2009; however, publications utilizing UASs have continued to grow (Figures 3, and Figure 4).

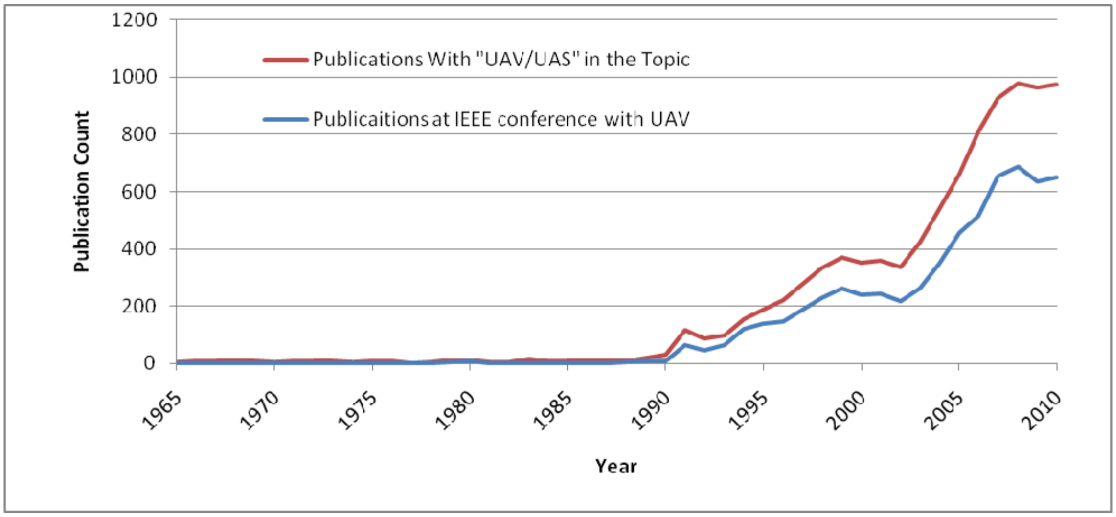

Figure 3 - Publications per year with topics including the words "UAV/UAS" over the past century (Data taken from ISI Web of Knowledge) are in red. Publications per year in the IEEE conference containing the words "UAV/UAS" in the topic over the past half century are in blue.

With respect to the utility of UASs in the environmental sciences, developmental trends in flight, data capture, and transmission capacities have increasingly attracted the interest of the research community (Figure 4). Payloads have continued to increase for UAVs and are expected to do so for the next eight years (Red, 2009)(Figure 5). Computational power has continued to grown for the last 40 years (Figure 6) and is predicted to continue to grow also (Chin and Sern, 2009). For environmental science researchers this conveys that the capacity for UAV autonomous control and data collection and optimization will also continue to grow. However development needs to be sustained and focused on usability and broader applications.

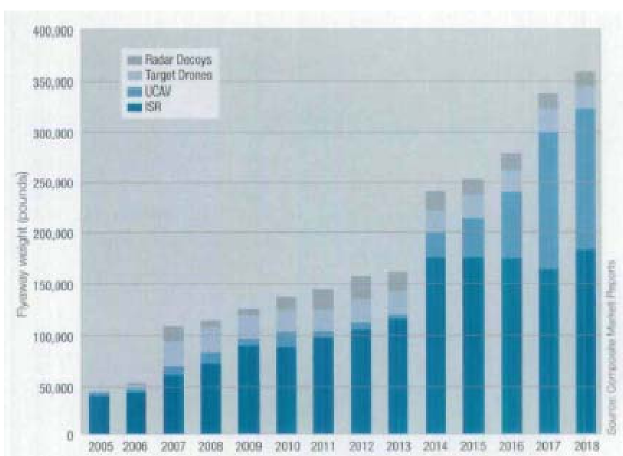

Figure 4: Estimated aero structures flyaway weight or payload capacity until 2018.

This is an exciting time for environmental science as the UAS field is ripe with new possibilities for future research and will continue to be so as technology advances. As researchers continue to use more advanced technology, data collection speed will likely increase allowing higher rates of data collection from a wider range of localities. In turn models of climate change and predicted weather patterns will become more accurate as more and more data is included. Eventually researchers could even know the current status of the world's ecosystem by viewing the latest real time data collected via unmanned systems in the air, water, and ground. To the average ES lab, the complexity of UAS development is overwhelming and the COTS technology is beyond their means. Improving upon UAV control and data collection is a necessity for the use of the system by academia.

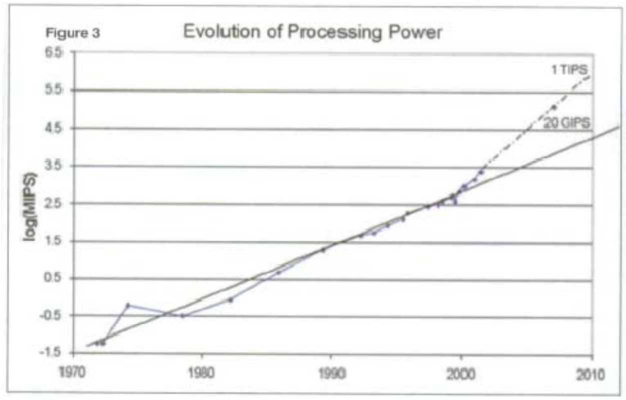

Figure 5 - Changes in the computation power of central processing units over the last 40 years.

1.3 Goals and Objectives

This project was motivated by a combination of the unmistaken benefits UASs can bring to environmental science and the overwhelming challenge most environmental scientists encounter in the development, refinement and application of UASs in their research. The overarching goal of this study was to develop a new UAS for an archetypical environmental science research group (referred as the stakeholder hereafter) composed of non-UAS experts who wish to add a UAS to their existing suite of environmental monitoring tools. The candidate stakeholder group chosen was, the System Ecology Lab (SEL), at the University of Texas at El Paso. The SEL is a perfect stakeholder for this study because i) They conduct research in climatically diverse landscapes in the Arctic and Chihuahuan Desert that could

greatly benefit from the addition of a UAS; ii) SEL is a relatively small lab situated within an academic research-training environment with a high turnover of students and staff; and iii) SEL personnel have little prior expertise in electrical engineering, piloting, and mechanical engineering associated with UASs.

The following objectives will be addressed in order to meet the overarching goal of this thesis outlined above:

1. Assess the research and operational needs of the stakeholder to determine the optimum UAS platform for its needs.
2. Develop a UAV and sensor payload to meet the hardware needs of the stakeholder.
3. Develop software for UAV operation planning, control, and optimized data acquisition.
4. Test the operational performance of the newly developed UAS hardware and software components with the stakeholder and assess how the operation of the UAV is benefited from the software components outlined above.

Each of these four goals has been addressed in chapters 2 (user needs), 3 (UAV and sensor development), 4 (software etc), and 5 (assessment of system etc) respectively.

2. Assessing the Requirements of the Stakeholder for UAS Design and Selection

The process of choosing the optimal UAS for the stakeholder used elicitations for requirements, an analysis of different UAV models, a comparison with how well each model met the elicited requirements, and an evaluation comparing the importance of the requirements with the compatibility of each UAV model to those requirements. Initially it was important to determine what requirements the stakeholder had for the UAS. During this phase, requirements were divided into two main categories to facilitate prioritization of stakeholder needs. The stakeholder was asked to answer the following.

a. What are the operational requirements?
b. What are the research requirements?

An importance rating, from 1 to 5, was assigned to each requirement by the stakeholder as well. A range of UAVs were compared against the elicited requirements and scored from Incompatible (0) to Excellent Compatibility (6). Utilizing this analysis and importance rating for each sub requirement an algorithm was defined to optimize the choice of UAV. Once the UAV model was selected, respective advantages, disadvantages, and limitations of each UAV model were presented to the stakeholder. This chapter details the process of assessing stakeholder needs, optimizing the choice of UAV, and documenting the relative benefits and disadvantages of each UAV option, as outlined above.

2.1 Operational Requirements of the Stakeholder

The operational requirements of the stakeholder were summarized into six main components: technical skill necessary, portability, setup and maintenance cost, flying conditions tolerable for flying, ease of crash recovery, and flight handling characteristics. Operational requirements were defined

through interviews with the stakeholder as well as prior knowledge gained while working with the stakeholder and are outlined in Table 2.

Table 2: Operational requirements put forth by the stakeholder. These requirements help to highlight the capabilities the UAV must address to be functional for the stakeholder. Sub requirements are divisions of a given requirement and were also put forth by the stakeholder. Criteria identified by the stakeholder provide more detail on specific items they are interested in for a sub requirement and were used to determine the optimum UAV for the stakeholder in section 2.3. The importance value assigned to each sub requirement was used to quantify the requirement's value.

Operational Requirement	Operational Sub Requirement	Criteria identified by the stakeholder	Rationale and General Comments	Importance (5 highest)
Suitability for Inexperienced Operators (2.1.1)	**Low Level of Expertise Required from Operators**	• UAV needs to be stable in flight • UAV need to be simple to fly	Operators are likely to be inexperienced and from broad ranging disciplines (computer science, electrical engineering)	4
	UAV Operation Requires Less than Four People	• Number of flight crew needed for transport and operation is less than four people	Field sites are often remote and visited by small field teams due to logistic constraints, therefore, the system needs to be operated by a flight crew of a maximum of a four people	5
	Expertise Required Only for One or Two Operators in Flight Crew	• Only operator requires expertise • UAV preparation, maintenance, and flight control can be performed by inexperienced persons	The stakeholder conducts interdisciplinary research where the personnel constraints may be limited to only one operator with a high level of expertise	5
	Experience Needs to be Gained Quickly and Easily	• Time needed to transition from inexperienced to experienced operator is short (several days) • Partitioning of flight crew responsibilities is possible	Stakeholder has a high turnover of students who would be expected to operate the UAS and therefore operators and field crew need to be trained quickly and easily	5
The UAS Needs to be Portable (2.1.2)	**UAV can be Transported in Backpack or Helicopter**	• UAV light enough to be carried by backpack • UAV dimensions can fit within a helicopter	Stakeholder has field sites in the arctic tundra as well as remote areas of Chihuahuan desert that do not always provide access to roads	5

	UAV can be Readily Shipped as Cargo	UAV is robust and can be packaged to resist damage from mishandling and the size of the package fits within a crate no bigger than 1 cubic meter	The stakeholder's research requires the shipping of equipment to remote localities. UAVs sent to these environments must be light enough to meet freight requirements but rugged enough to endure this travel as well.	5
The Cost of Operating and Maintaining the UAV must be Inexpensive (2.1.3)	**The Operating Budget for Outset Purchase Must Be Less Than $25,000**	• The training of flight crew must be included in the purchase cost • The more inexpensive option between pre-built systems and custom developed UAVs needs to be selected	In the interest of stretching grant monies as far as possible, the purchase cost of the UAV should be relatively low.	4
	The Annual Maintenance Budget Must Be Less Than $2,000 a Year	The maintenance costs need to include repair to faulty parts, replacement of faulty ports, transportation of the UAS, and normal operational expenses	The nature of academia limits sustained funding, so maintenance and shipping costs should be as low as possible.	5
The UAV must be able to Tolerate Moderate Wind and Temperature Conditions (2.1.4)	**The UAV can tolerate wind speeds at research foci**	The UAV can still fly correctly in wind speeds ranging from 0 to 5 m/s during flight	The wind speeds at the main research foci for the stakeholder require an UAV that can handle operating within these conditions.	4
	The UAV can function within temperature ranges at research foci	The UAV can function normally within temperature ranges of 0 to 50 C	The temperature extremes of the research foci necessitate an UAV that can operate within these conditions.	3
UAV must be Repairable Following Light to Moderate Crashes	**UAV crashes should not occur often due to equipment failure and should not**	• Crashes with the UAV should occur less than in 100 flights due to equipment failure • Recoverability of UAV from	The stakeholder has very sophisticated sensors that would obtain interesting data from the field if mounted onboard the UAV. However these sensors are also very costly and are delicate. Furthermore, additional costs associated with crashes from the	5

(2.1.5)	**completely destroy or damage the UAV**	failures should of possible •	UAV, cannot severely exceed operating budgets set forth by the stakeholder.	
The UAV should be able to Obtain Flight Under Select Field Conditions While still Providing for Moderate Area Coverage (2.1.6)	**Wind speed should not be completely necessary or unnecessary for flight**	UAV should be able to fly in windless and windy conditions.	Due to the remoteness of field sites that the stakeholder visits, repeat visits to sites may not be possible. Therefore windy conditions cannot completely rule out flight operations.	5
	The length of flight for the UAV must be reasonable for data acquisition	The flight time for the UAV must be at least 25-30 minutes with a full payload	Data collection from sensors onboard should be complete and through as possible. A flight of 25 minutes allows the stakeholder to gather enough data from the air to make time consuming sensor mounting for the flight viable.	5
	The area of coverage from sensors onboard should be reasonable	The UAV must be able to cover at least four hectares during flight	The flight speed of the aircraft should be reasonable (around 10 m/s) for data acquisition to occur at a steady rate and over new areas. A four hectare range is suitable for novice pilots to gather enough data for analysis.	4
	Takeoff and landing of the UAV should be possible in the research foci	The UAV should be able to take off and land in the field with limited or no runway	Due to the research locations where the stakeholder works, there is no guarantee that paved or extensive runways will be present. To circumvent this, the UAV needs to be able to launch with the least amount of runway possible.	5

2.1.1 **Suitability for Inexperienced Operators**

The suitability for inexperienced operators included the following sub requirements: low level of expertise required for operation, UAV operation requires less than four people, expertise required for only one or two of the flight crew, and the experienced needs to be gained quickly and easily. This was a important requirement for the stakeholder as the nature of academia makes for a very dynamic workplace. Students typically graduate after 3-4 years and these changes can create the potential for a loss of 'institutional memory'. Of all the operational requirements specified by the stakeholder this category was deemed the most important (Table 2).

The stakeholder's expertise for UAS development is somewhat limited and this is their first UAS development project. The nature of the stakeholder's discipline deemed it unlikely that users would have an electrical engineering, computer science, or piloting background so model choice for the UAV needed to address this. To help minimize the potential for crashes and improve recovery from pilot error and/or uncontrolled flying states, the UAV also needed to be stable, slow flying and respond in a relatively docile but reliable manner. Furthermore the UAV needed to be relatively easy to fly so users with beginner piloting skills could learn to fly in a timely manner. The stakeholder requested the UAS for remote area use so the UAS also had to be easy to trouble shoot and simple enough for maintenance to be conducted in a timely and efficient manner with limited access to spare parts.

The criteria describing the number of participants necessary for successful operation of the UAS considered the number of flight crew necessary for takeoff, the number of operators that would be using the UAS, and the number of participants necessary for transport. The candidate field site for the stakeholder is an hour and a half drive and includes 30 minutes of walking. This necessitated a low number of flight crew for operation. The number of flight crew necessary for transport had to remain minimal. A maximum of two individuals was requested for the transport of the UAV and another 1 to 2

people was requested for any additional equipment such as tools, spare parts, sensor packages etc. This transportation sub requirement is directly linked to the portability requirement (see section 2.1.2).

Due to the education-training environment the stakeholder maintains, a high user turnover rate is expected. Furthermore, additional training costs must be minimized as there are time constraints on student's schedules, (i.e. classes, homework, etc.). The training schema proposed by the stakeholder would have senior level graduate students training incoming graduate Environmental Science and Biology students to maintain corporate memory. Considering this, the training, operation and maintenance of the UAS must be simple, relatively cheap, and intuitive. A UAS with these traits would allow users to transition from being complete novices to experts in relatively short period of time and decrease the chance and consequence of error on the part of new users.

2.1.2 **Portability**

The requirements for portability issued by the stake holder were somewhat more flexible than the technical skill necessary for other operation sub-requirements. The stakeholder was willing to give concessions in this area to help meet other requirements. Portability requirements focused on the distance from a staging area to a remote field site and shipping concerns.

The stakeholders overall best case and worst case field site locations were assessed for UAS operations. In the best case scenario, a field site was very close to the staging area (such as a laboratory in Barrow, Alaska). Even if the staging area has adequate infrastructure there will be a need for conversion of a nearby area into a launch/landing zone. It was considered impractical to build landing/launching zones at every remote study site to facilitate this. As in the case of Baffin Island where some field sites were miles away from camp, the UAS needed to be light enough for transport by 2-3 people (see section 2.1.1) yet rugged enough for transport by helicopter. This also presented the problem of having no guarantee that the site would have a flat launch/landing area and required the

UAV to have a low amount of maintenance necessary in the event of breakdown (i.e. replacing parts with relatively inexpensive new ones).

Tied to these two sub requirements is the need for shipping. The stakeholder regularly ships sensors and equipment across the US and internationally for field research. The UAS must be portable enough to fit within freight size and weight specifications yet rugged enough to withstand transport in this manner. A lower weight was requested to reduce the cost of regularly shipping the UAS.

2.1.3 **Cost**

The cost requirement for the UAS was considered as important as the suitability for inexperienced operators requirement. The stakeholder generally acquires funding from research grants. Thus, purchase, maintenance, and repair costs for the UAS needed to be inexpensive and manageable within the typical budget of an environmental science research grant. The budget for the purchase of the UAV was limited to approximately $25,000 (excluding maintenance). To consider the best option for the stakeholder an analysis was made to determine if it was more cost effective to purchase a RC Model and place sensors on board, or purchase a pre packaged UAS built by a commercial vendor, or to build a custom UAS.

The first option considered was to purchase a radio controlled vehicle or a UAV from a commercial vendor and then place sensors onboard for data collection. This option is a relatively inexpensive approach (several hundred to a couple of thousand dollars), as it allows the stakeholder to benefit from mass-production and take advantage of shared research and development costs typically absorbed within such products. With inexpensive craft this is ideal for very small scale one time projects. However once the scope of the project increases the complexity required from a given UAS also increases. Depending on the desired specifications this option can include the need for electrical engineers, computer scientists, and/or trained pilots. Without the development of a customized UAV,

mass produced commercially available systems generally lack scalability as their payloads are typically limited.

A preferred option for the stakeholder was to purchase a commercially available UAS(s). An obvious benefit to a COTS UAS is there is a lesser need for trained professionals in multiple disciplines as the vendor is selling a commercial product that has been tested and quality checked. Furthermore, COTS systems overcome much of the challenge of integrating systems components, which are prone to software and hardware interoperability conflicts and require explicit expertise or prolonged testing to ensure proficiency. There are some disadvantages to this option however. Besides the greater cost, the buyer becomes dependent on the company for: pilot and operator training, maintenance and repair, and replacement of failed custom components. This solution was not considered viable to the stakeholder primarily because of the expense of this option (around $80,000).

The other option was to build a UAS from the ground up. Developing a UAS from “scratch” would allow the stakeholder to save substantially on costs for component parts. Custom built UASs allow for training to take place while normal operations are in play as users do not have to wait for training from a commercial vendor (section 2.1.1 technical skill necessary). The primary disadvantage to this approach is the high level of expertise required and the lengthy research, development and testing needed to produce a field-usable UAS. The stakeholder felt they did have the required expertise or time to consider this option.

2.1.4 The Ability of the UAV to Tolerate Weather Conditions

Limitations to the operational flying conditions were weighted heavily by the stakeholder (see section 2.2.4 research focal areas). Factors considered for this sub-requirement included the dominant wind speed, precipitation, and temperature at the stakeholder’s primary field sites. Wind speed was the most important consideration because of its direct limitation to most UAV operations. The stakeholder

conducts research primarily near Barrow, Alaska in summer and in the Chihuahuan Desert near El Paso, Texas year round. The UAV has to fly in the majority of wind conditions present at these locations so as to be effectively utilized by the stakeholder. Therefore UAV model choices that required calmer winds were not generally considered viable solutions. Minimum wind speeds necessary for takeoff were also considered as both field locations on average never had a time of day with low wind speeds (Figure 7 and 8).

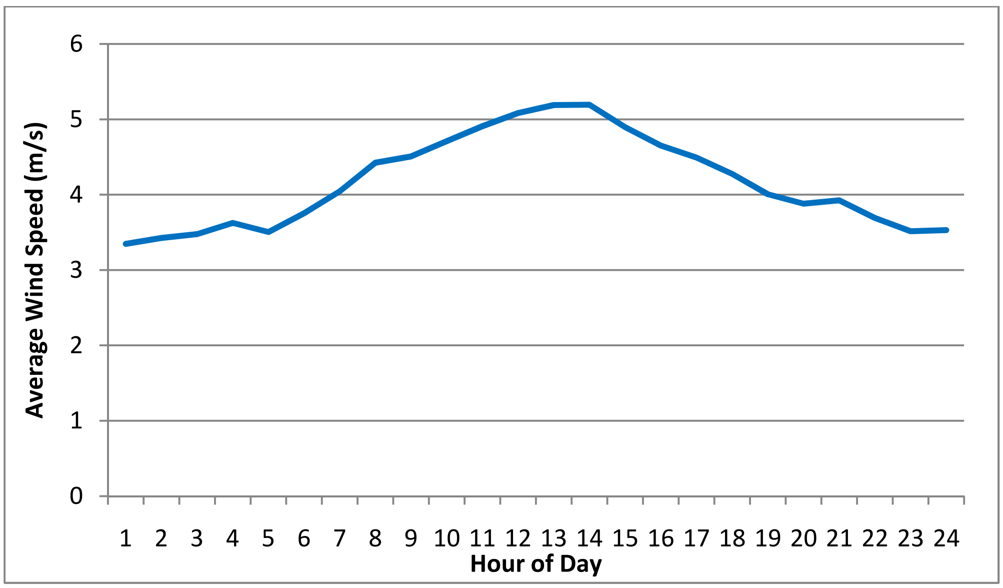

Figure 6 - Averaged wind speed for wind data collected from all of July 2010 near Barrow, Alaska. Data presented was collected from the stakeholder at research sites near Barrow.

Barrow is located on the coast of the Arctic Ocean in Northern Alaska. The city usually experiences moderate winds throughout the summer. Figure 7 shows that the average gust for a day in the field season peaks at over 5 m/sec around 2 PM and is lowest around midnight (Figure 7). Gusty winds can cause problems even for an experienced pilot. While monitoring of the Chihuahuan desert is conducted year round at the USDA Jornada Experimental Range, the stakeholder was interested in wind conditions during the summer months, when plant growth is most prolific. The stakeholder had already established a substantial array of infrastructure at Jornada including: sensor networks, phenocams, robotic tram systems for measuring hyperspectral reflectance, and an eddy covariance tower. Data

collected from the eddy covariance tower in summer 2010 was used to determine wind speeds in the summer months.

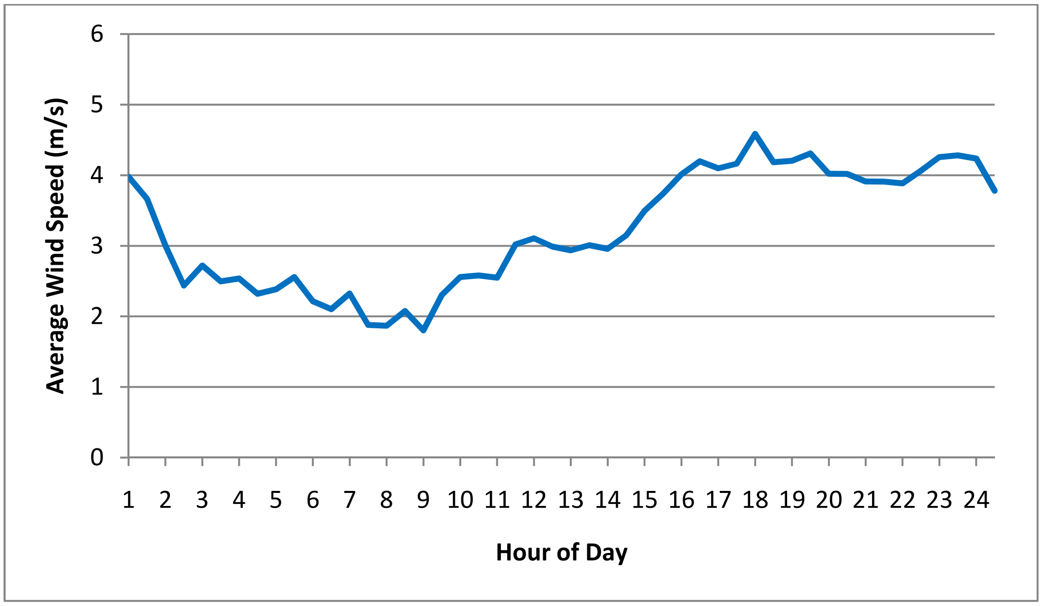

Figure 7 - Averaged wind speed data collected over the month of July in 2010 near the stakeholder's eddy covariance tower site at the USDA Jornada Experimental Range. Data shows that peak winds are in the late afternoon early evening and continue on until midnight.

Averaged data for July 2010 shows that the wind speed peaks at around 4.5 meters per second (Figure 8). Although no wind gust data was collected, the average wind speed data demonstrates that wind conditions require UAV flight to be very stable. Wind data demonstrates that a UAV that requires wind conditions to launch was acceptable as most days experienced some wind. Peak times of flight would have to occur early morning to prevent exposure to turbulence during flight and thereby increase the stability of flight.

The stakeholder was concerned about temperature as an operational requirement for their UAS. Low temperatures can promote icing on the wings, and cause problems with engines and moving parts. Furthermore consistent high temperatures can make sensors and control units malfunction. Fortunately, temperature readings for Barrow during field seasons are slightly above freezing (Figure 9).

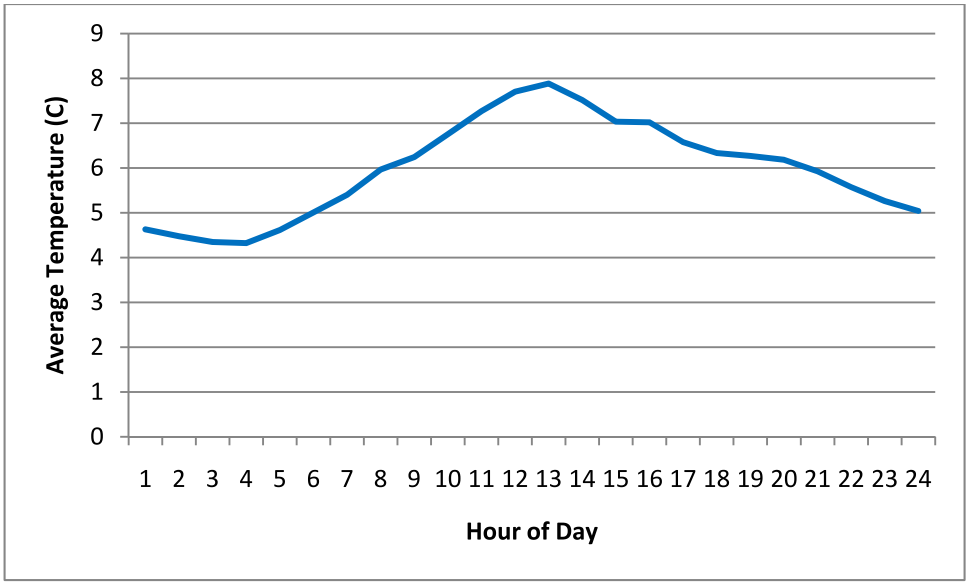

Figure 8 - Averaged temperature data collected in July of 2010 over the course of a day near Barrow, Alaska.

As the temperature stays relatively warm, even when considering wind chill with flight, during the field season there is no real concern that UASs would have trouble functioning (Figure 9). In the Chihuahuan desert however the temperature is much higher during the field season (Figure 10). Temperatures can get very high in the desert during the day so the stakeholder expressed concern that sensors may not function properly and certain components might over heat. Even though the temperature can get very high it is nowhere near the extremes where commercially available electronics will not function. Furthermore, extreme processing of large data sets will heat up processors so components should be restricted to smaller simpler processors (Longo et al. 2007).

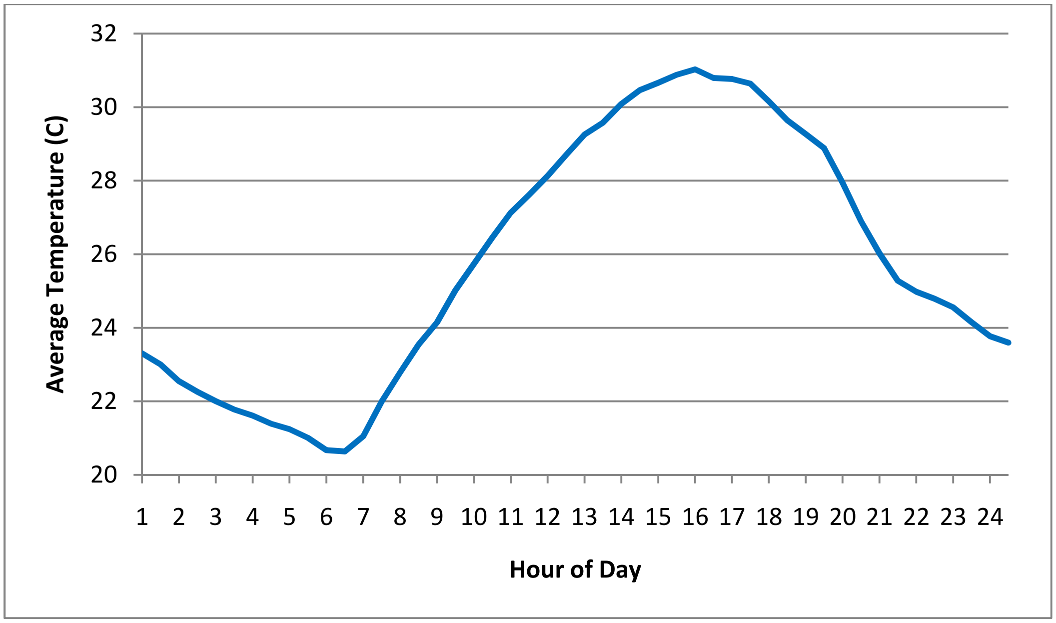

Figure 9 - Averaged temperature data in July of 2010 over the course of a day at the Jornada Experimental Range.

2.1.5 Crash Recovery and Manageability

Another requirement was for the UAV to be relatively “crash friendly” and recover quickly from erratic flight conditions and pilot error because students with limited piloting expertise would be the primary users of the UAS (see section 2.1.1. suitability for inexperienced operators), and the stakeholder would have limited funds and down-time to recover from crashes (see section 2.1.3 cost). The UAV needed to be very stable while in flight, behave in a predictable manner, and be somewhat sluggish in regards to control so as to give users time to acclimate to its method of flight. The main concern for the stake holder however was for the potential sensor payload that could be onboard during a crash as this payload could represent a significant financial investment to the stakeholder. Therefore, the sensor packages had to be well protected in order to survive a crash.

2.1.6 **Flight Characteristics**

Stakeholder operational requirements culminated with the elicitation of the UAV's flight characteristics. Flight characteristics were considered to be factors associated with flying the UAV including length of flight, takeoff and landing requirements, and the area of coverage.

Flight time and the area of coverage for a UAV were also given major consideration. The stakeholder specified the flight time of the UAV to be at least 20-25 minutes during which, the flight speed average approximately 5 m/s. This time was determined by the stakeholder and allowed for the pilot time to ascend to a cruising altitude of 122 meters (400 ft) and collect image data spanning an area of four square hectares during a single flight, or fly a total distance of around 4 kilometers before needing to refuel.

The UAV requirements specified for landing and takeoff were strongly limited as most of the stakeholders field sites require short take off and landings on unprepared surfaces amongst dense networks of water bodies (in the Arctic) and shrubs (in the Chihuahuan Desert). Therefore it was essential for the stake holder to have a UAV that could launch with limited or no runway.

2.2 Research Requirements of the Stakeholder

Research requirements of the stakeholder were generally much easier to elicit than operational requirements and focused on how the UAV would be used for research. To compartmentalize stakeholder needs in a manner that could be targeted towards UAS development and testing, research requirements were grouped into the following research sub-requirements: sensor payload needs, exchangeability of the sensor payload, the need for real time data, and the main research focal areas (Table 3). Sub requirements were not necessary for this table as most requirements were not complex. Requirements were determined through interviews through with the stakeholder, and inspection of various workflows and working ideas presented by the stakeholder.

Table 3: The table below highlights research requirements put forth by the stakeholder. Sub requirements were not included in this table as the complexity behind most requirements did not necessitate it.

Research Requirement	Criteria Identified by the Stakeholder	Rationale and General Comments	Importance
The Sensor Payload Needs to be Light Weight and Require Little Energy (2.2.1)	The sensors that collect operational data need to be lightweight (< 2 kg) and require low amounts of power (< 500 mA)	In order to allow for a larger exchangeable sensor payload the stakeholder required that operational sensors be miniaturized. This included the batteries necessary for operation of the sensors.	5 out of 5
The UAV's Exchangeable Sensor Payload must be able to Carry Several Sensors (2.2.2)	The UAV must be able to carry a payload for the exchangeable sensor package of at least 11 kg (25 lb)	The stakeholder has sensors that weigh several kilograms by themselves so to include 3 or 4 onboard would require a suitable payload requirement.	3 out of 5
The UAV must have Real Time Data Transmission from Sensors Onboard (2.2.3)	Data transmission from onboard must have a bandwidth of up to 10 Mb/s and at least 10 Kb/s and the range or transmission must be at least 1 km	The stakeholder determined that transmission from several sensors could reach up to 10 Mb/s but was willing to sacrifice bandwidth for operation data to 10 Kb/s.	5 out of 5
Sensors must be relevant to the Stakeholder's Research Foci (2.2.4)	Sensor operation within research foci must allow for dust protection, and moisture buildup	Due the Chihuahuan desert's arid nature, sensors onboard the UAV must tolerate damage. Outside Barrow, Alaska moisture build up is common, so sensors had to be designed for this as well.	5 out of 5

2.2.1 **Sensor Payload Needs**

In order to better describe the sensor payload, requirements were divided into sensors needed for the operation of the UAV, and sensors used to acquire data for research. It has been suggested that most UASs stream real data sensor output for altitude, GPS, pitch, angle and tilt of the UAV as operational data (Chao, Cao, and Chen, 2010). Therefore it was considered that these sensors would be used to determine the UAV's condition and see if the flight path is "correct". However the weight of the operational package needed to be minimized so that the UAV could carry heavier exchangeable sensor payloads. Additional payload considerations included the power supply needed for it onboard.

2.2.2 **Exchangeable Sensor Payloads**

The capacity for an exchangeable sensor payload was requested by the stakeholder to expand the range of sensor packages that could be flown on the UAV. Ideally, the sensor payloads could be easily configurable and attached and detached in the field with up to three different sensors packages being flown on each day of flight. With the exception of a camera, the stakeholder did not mandate specific sensors for every flight but was more interested in the ability to remove and attach different types of sensor. The range of sensor packages being considered by the stakeholder included sensors for measuring spectral reflectance, trace gas analysis, and microclimate. Based on these sensors, it was deemed necessary for the UAV to have a payload of at least 11 kg (around 25 lbs).

2.2.3 **Need for Real Time Data**

The stakeholder required transmission of data for each sensor within 1 kilometer of the operator. The amount of bandwidth required for this transmission was minimal for operational data such as GPS, orientation, and altitude (< 1Kb/s). When considering the exchangeable sensors however transmission needs were calculated as high as 10 Mb/s. In order to better accommodate this, the

sensors should be placed on separate transmitting frequencies depending on their function. Flight critical sensors could be placed on the frequency with the farthest range and lower bandwidth usage and sensors purely used for research could communicate on a frequency with a higher bandwidth and a shorter range. The likelihood of frequency conflict was not an important issue for the stakeholder, as the use of the UAS was going to be conducted in remote areas where wireless frequencies were not in active use (see section 3.2 for more information). Quality control of data was not considered an important requirement as data downloaded from optional sensors could be re-downloaded directly from the sensor upon landing by the flight crew and post processed accordingly.

2.2.4 **Research Foci**

Barrow Research had several research requirements from the user that were of the utmost importance. The research focal areas have been already covered in detail earlier (see section 2.1.4 Flying Conditions), however, it was important to address specific requirements for sensors operating in these places onboard the UAV. Sensors utilized in Barrow needed to be able to tolerate a certain amount of moisture and mist from regular cloud cover. Due to the nature of the Chihuahuan desert, sensors onboard required dust protection. Landing and launching sites were not be guaranteed to be clear of obstructions to make landing and takeoff practical in the desert so the UAV needed to be compensate for this.

2.3 Determining the Best UAV for the Stakeholder?

The operational (Table 2) and research requirements (Table 3) of the stakeholder were compared to the operational, flight and payload characteristics for a wide variety of UAV models before the selection and purchase of the UAV. The compatibility of each UAV model was compared against the operational and sensor payload requirements outlined by the stakeholder. Compatibility values were categorized subjectively based on technical specifications as: excellent, very good, good, average, poor, very poor, or incompatible. Any UAV model that received a rating of incompatible for any of the stakeholder requirements was removed from the final choice list. UAV models included in this analysis are fixed wing UAVs, vertical takeoff and landing (VTOL) UAVs, Balloon and/or dirigible UAVs, kite UAVs, and powered paraglider UAVs. These are discussed in detail below.

2.3.1 Fixed Wing UAVs

To better achieve complete customizability of sensor packages there was a necessity for a payload of around 11 kg (25 lbs), which is heavy for a non military UAV. Fixed wing models can achieve large payloads but the size of the UAV, and therefore the complexity of the UAV matches this closely. For example, a payload of 15 kgs (around 30 lbs) typically requires a wingspan of more than 4.5 meters (15 feet) (Watanabe and Ochi, 2007). The stakeholder cannot support a hanger or storage area large enough to accommodate such a UAV, which would also require expensive shipping costs.

Fixed wing UAVs flight characteristics (Table 4) also made it a poor choice for the stakeholder because they generally require high launch speeds and thus an improved runway for take offs and landings. Some smaller fixed wing UAVs can be launched using a vehicle or trailer-based catapult system however (Rango, et al., 2006). Most of the stakeholder’s research sites are not accessible by road and do not have improved runways nearby, thus fixed wing UAVs were considered a very poor choice for the stakeholder.

Table 3: Compatibility of the fixed wing platform with the stakeholder by each requirement put forth by the stakeholder. The requirement column for this table includes both research operational requirements detailed in section 2.1 and requirements highlighted in section 2.2. Note that the portability of the fixed wing platform was rated very poor.

Requirement	Pro's	Con's	Comments	Compatibility
Suitability for Inexperienced Operators	• Car Launchers • Simple Design • Ease of Training	• The number required for transport is very high for larger models	Fixed wings provide a lot of simplicity	**Good**
Portability	• Smaller models are portable	• Wing Length • Storage • Shipping	Greatest drawback to this platform due to poor portability for large platforms	**Very Poor**
Cost	• Inexpensive for lower-end models • Maintenance cheaper	• Requires launcher or high speed take off	Overall cost is average for UAVs but is relatively expensive for larger models	**Good**
Ability to Tolerate Weather Conditions	• Somewhat Stable	• Icing on wings • Wind sensitive	Average category although icing on wings can be problematic	**Average**
Crash Recovery and Manageability	• None	• Not Crash Friendly • Sensor Destruction	This impacts heavily on fixed wing UAVs	**Very Poor**
Flight Characteristics	• Great area coverage • Can fly in calm to mild wind conditions	• Runway special launching needs	The runway needs/special launch considerations far outstretch the potential benefit	**Very Poor**
Sensor Payload	• COTS Telemetry packages available	• GPS signal degradation inside chassis	GPS has been known to have interference inside chassis	**Average**
Exchangeable Sensor Payload	• None	• Need to be centrally weighted • Tight mounting space	Not a lot of existing systems to look at.	**Poor**
Need for Real Time Data	• Extensive testing has been done by RC community	• Enclosed may dampen signal strength	Verified possible by academia man times	**Good**
Research Foci	• Fixed wings can tolerate winds at speeds specified although not as well as other platforms	• Need for flat runways or vehicles for launching and landing	Car launchers can help to circumvent problems of vegetation in desert	**Average**

2.3.2 **Vertical Take Off and Landing UAVs**

VTOLs were considered in depth due to their launch and landing capabilities that do not require specially prepared runways. VTOLs also have a higher payload capacity compared to similar sized fixed wing UAVs (Table 5). Furthermore, some VTOLs allow for their propellers to be folded while not in use which improves storage and transportability. Lastly, VTOLs allow for stable flight compared to other UAV models. Disadvantages include low fuel efficiency, which limits payload size. Mishaps while landing and crashes are more likely to result in both the UAV and sensor payloads being damaged and/or destroyed (Schafroth et al. 2009). Finally, the dual propeller design of most VTOLs inherently adds to the complexity of piloting the vehicle which in turn adds to the learning curve for new pilots. The stakeholder requested that the UAV provided an ease of training and piloting, neither of which are characteristic of VTOLs.

Table 4: The table below highlights the compatibility for the VTOL platform as a UAV when compared to each of the stakeholder's requirements. The platform performs well when considering flying conditions the research foci as it is strengths address those areas well. However the technical skill necessary and cost really made the stakeholder reconsider this platform.

Requirement	Pro's	Con's	Comments	Compatibility
Suitability for Inexperienced Operators	• Very Stable • Number of people low	• Difficult to learn to fly	The difficulty to fly the craft is high	**Very Poor**
Portability	• Detachable propellers • Small storage space	• Need flat area (no vegetation) to launch and land	Landing area is small so suitable launch/landing areas are easily found in research foci	**Good**
Cost	• None	• Outset cost very high • Maintenance cost very high	The cost is highest among platforms due to amount of moving parts and complexity of platform	**Very Poor**
Ability to Tolerate Weather Conditions	• Very Stable in Windy conditions	• None	Great consideration with flying conditions imposed	**Very Good**
Crash Recovery and Manageability	• Crash likelihood lower with a trained pilot	• Crashes are devastating • Recovery from piloting errors is difficult	Sensor cost as well as UAV replacement cost made this category its worst point	**Very Poor**
Flight Characteristics	• Great Area Coverage • Topography is no concern • No winds necessary	• Low flight time vs. payload • Higher fuel cost	An average platform once all items are considered.	**Average**
Sensor Payload	• Systems Exist	• Sensors are not enclosed	Working systems exist but are very limited	**Good**
Exchangeable Sensor Payload	• Very Stable	• Sensors are not enclosed	Additional sensors may be problematic	**Average**
Need for Real Time Data	• Existing Systems well tested	• None	More control over position allows for better transmission given orientation of aircraft	**Excellent**
Research Foci	• Work well in both areas	• None	High mobility allows for pinpoint landing and prevents moisture build up	**Excellent**

2.3.3 Balloon and/or Dirigible UAVs

The stakeholder's requirements ruled out balloons and dirigibles. Balloons and/or dirigibles are capable of motion but require large amounts of gas and/or fuel to sustain flight (Table 6). Due to the remoteness of study areas, transportation of adequate gas and/or fuels would be difficult if not impossible. Furthermore due to their flight characteristics, balloon and dirigible UAVs are limited to flight in extremely low wind speeds. Launching requires large amounts of pressurized gas to be brought out to the field that is logistically difficult and costly. Landing considerations in the desert with abundant cloth piercing shrubbery would make finding adequate space for initial inflation of the aircraft difficult in addition to the ponds near Barrow would make locating dry empty spaces difficult to locate as well. All of the aforementioned characteristics made balloons and dirigibles incompatible with the stakeholder's requirements.

Table 5: Compatibility of the Balloons/Dirigibles aircraft and specific stakeholder requirements is listed below. Typically the compatibility requirements of the platform scored very well or very poorly. The platform failed due to the flight characteristics of the platform however.

Requirement	Pro's	Con's	Comments	Compatibility
Suitability for Inexperienced Operators	• Training is simple • Flight is very simple	• 3-5 people for start up of UAV	Great platform for containing corporate memory	**Very Good**
Portability	• Collapsible Craft • Easily Transported	• Requires the carriage of fuel • Transport of filling medium		**Good**
Cost	• Initial cost is very Inexpensive	• Helium is very expensive • Repairs to fabric are costly and regular due to surface area		**Average**
Ability to Tolerate Weather Conditions	• Stable • Tolerates weather well	• Very susceptible to winds		**Average**
Crash Recovery and Manageability	• Likelihood of crashes are very small • Sensors onboard will survive most crashes	• A rupture of the craft is devastating and cannot be recovered but very unlikely		**Very Good**
Flight Characteristics	• Long flights and good fuel expenditure	• Ground coverage is very poor • Launches needs a clean relatively flat area • Poor control of direction of craft		**Incompatible**
Sensor Payload	• Additional Weight can be added	• Need an enclosure	Small lightweight sensors can be mounted	**Average**
Exchangeable Sensor Payload	• Additional Weight can be added	• Need an enclosure	Mounting heavier sensors would be difficult	**Average**
Need for Real Time Data	• Prototypes Exist	• None	Direct line of sight and limited electronics onboard help with transmission	**Very Good**
Research Foci	• None	• Remote areas that require fuel to be transported and well as filling gasses • Plant life can puncture and rip fabric easily		**Very Poor**

2.3.4 **Kite UAVs**

Kites have excellent compatibility with some of the stakeholder's requirements but were incompatible with others (Table 7). Kites allow for research to be conducted in the research focal areas, are very portable and light, and are inexpensive relative to other UAV models but primarily permit static views of site areas. Furthermore users typically have little or no control over motion and thereby limit the area of interest captured by sensors. Kites can easily crash, require strong winds for flight, in instances require trampling of the field site in order to position the kite over target areas, and typically cannot achieve the payload necessary for the scalability requirement put forth by the stakeholder. Kite systems, therefore, were considered incompatible with the needs of the stakeholder.

Table 6: Compatibility of kite platforms with specific requirements elicited by the stakeholder is shown below. The aircraft was incompatible with several requirements including the exchangeable sensor payload, crash recovery, and flight characteristics.

Requirement	Pro's	Con's	Comments	Compatibility
Suitability for Inexperienced Operators	• Simplistic Training • Small number (2) for launch and retrieval	• None	Very simple system to run and maintain	Excellent
Portability	• Small and Collapsible • No fuel so more portable • Easily Packageable	• None	Extremely portable	Excellent
Cost	• Very Inexpensive • Enclosures are available for some sensors • Low Maintenance Costs	• None	Cheapest platform available	Excellent
Ability to Tolerate Weather Conditions	• Can fly in high winds	• Cannot tolerate rain or lightning • Highly susceptible to winds	Does not fly as much as it hovers over a given area	Very Poor
Crash Recovery and Manageability	• Easy to recover from crash	• Likelihood of crash is very high • Sensors are likely to be damaged or destroyed	Cannot recover from crashes or piloting error easily without ensuring sensor damage or destruction	Incompatible
Flight Characteristics	• No fuel consumption • Can launch from anywhere	• Need strong winds for flight • Small area of coverage during flight (dependent on operator)	Totally dependent on winds for flight and cannot move over research areas without direct human interaction	Incompatible
Sensor Payload	• Working systems exist	• Payload is very small	Small payloads for operational sensors exist	Poor
Exchangeable Sensor Payload	• None	• Kite size has to be very large for good payloads	Large payload of 11 kg (25 lbs) are unrealistic	Incompatible
Need for Real Time Data	• No signal interference from moving parts	• Payload makes wireless communication limited	Throughput is lower because batteries have to be small	Poor
Research Foci	• Works well in a stakeholder research areas	• None	Tolerates moisture and can fly in areas well due to height of canopy	Excellent

2.3.5 **Powered Paraglider UAVs**

Powered Paragliders (PPs) UAVs have few poor compatibility ratings to the requirements elicited by the stakeholder (Table 8), and thus they are the best match for the stakeholder. The most disadvantageous characteristic of PPs is that the flying conditions under which they perform best are not ideal for all of the requirements stipulated by the stakeholder. PPs operate best in 4.47-6.70 m/s (5-10 mile/hour) winds. As seen in section 2.1.1.4, the winds at the research sites specified by the stakeholder are on average around this level. They also do not operate optimally in gusty wind conditions. Both of these requirements may be somewhat manageable with additional practice on the part of the pilot and selecting flight days when optimal weather conditions prevail. Typically, UAV weight and size to payload ratios for these craft are very low and easily meet the stakeholder's requirements. PPs have collapsible wings that allow for easy transportation and the simpler design (compared to VTOLs) and docile response to pilot commands allows for less-steep learning curves for pilots in training. Furthermore in the event of a loss of control of the engine and/or steering lines, powered paraglider UAVs have a higher chance of landing unaided and undamaged relative other UAV models (Thramm, and Judex, 2006). Although the flight time of PPs is dependent on payloads and wind strength, they have a much better fuel consumption to payload ratio compared to VTOLs (Watanabe and Ochi, 2007). While PP UAVs need some type of flat surface to take off and land, these surfaces do not need to be completely level or require special preparation as long as the ground is reasonably firm. Depending on wind conditions and speed they can launch from anywhere between 5 to 17 meters.

Table 7: Compatibility of each requirement for powered paraglider UAV platform are listed below. In general this platform did very well as it provided for an extra payload as well as met with major requirements put forth by the stakeholder.

Requirement	Pro's	Con's	Comments	Compatibility
Suitability for Inexperienced Operators	• Stable flying • Relatively simple flying	• Flight crew needed is high 3 to 4	Simple aircraft to fly and maintain	Good
Portability	• Can be stored and shipped easily	• Needs a small car or three people to transport	Can be ported easily as the "wing" is collapsible and craft is small	Good
Cost	• Outset cost is within parameters	• Canopy replacement is expensive	The most effected requirement based on compatibility as cost is high for replacement canopy	Poor
Ability to Tolerate Weather Conditions	• None	• Stability issues during flight • Gusty wind susceptibility	The platform can begin swinging during flight that might throw off sensors onboard	Poor
Crash Recovery and Manageability	• Parachute provides built in crash check • Very rarely crashes will occur • Parachute can help with recovery • Sensors will likely survive crashes	• None	With no control the UAV will glide to the ground preventing most damage to sensors	Excellent
Flight Characteristics	• Covers a considerable amount of area with good winds and a sufficient amount otherwise • Great flight time for a payload	• Slow flying • Winds are not necessary for flight but help • Topography Considerations • Gusty winds • Not as stable	An average platform based on this stakeholder requirement	**Average**
Sensor Payload	• Payload requirements easily met	• Parachute may cause sensor interference	A very small change of operational sensor interference	Excellent
Exchangeable Sensor Payload	• Payload requirement easily met	• Parachute may cause sensor interference • Enclosure for Sensors	Enclosures need to be attached but payload allows for it	Excellent
Need for Real Time Data	• Real time data streaming possible	• Moving parts can cause interference	Interference is only slightly higher than fixed wings due to large servos for parachute control	Very Good
Research Foci	• Moisture (in small quantities) is not a problem	• High amount of UV light can degrade parachute faster • Plant life can tear canopy		Good

2.3.6 **UAV Model Choice**

For research groups typified by the stakeholder in this study, choosing the right UAV model for their research is not a simple task. Unfamiliar terminology, detailed technical specifications, and the lack of a model system to aid such decision making is commonly found to be overwhelming. To partly address this problem, this study employed a method to elicit requirements from the stakeholder and match these against a range of operational and payload characteristics of several different UAV models. In order to determine semi-quantitatively, the best choice of UAV for the stakeholder, an index of suitability for each model of UAV (Suav) was developed (Equation 1). Suav explains how well a given UAV model met the requirements put forth by the stakeholder. Results are given in Tables 9, 10, and 11.

Equation 1: Suav = ((SR*ER) / M %

Equation 2: M = SR * Max(ER)

Suav – Index of suitability for a given model of UAV, expressed as a percentage

SR – Average of the stakeholder's assigned importance value for each requirement (from Tables 2 & 3) ranges from 1-5.

ER – Expert assigned compatibility value for each stakeholder requirement (from Tables 4-8) ranges from Very Poor to Excellent or 1-6. Note that a ranking of incompatibility was not used in this analysis.

M – Maximum Values of ER assigned to each requirement to represent a "perfectly" compatible UAV.

Fixed wing UAVs had an overall suitability index of 43% (Table 9) with three requirements reducing its suitability: portability, crash manageability, and flight characteristics. The fixed wing's wingspan, which affects ease of transport and storage, also reduced the suitability of this UAV. The chance for sensors to survive a crash was minimal and dropped its score as well. Lastly requirements for an open and flat launch or landing area also made fixed wing UAVs a less optimal solution.

Table 8: The overall ability to satisfy the stakeholder's requirements by utilizing a fixed wing model is shown below. The final Suav is calculated below in the bottom right.

	SR - Stakeholder's Importance Value	ER – Expert's Compatibility Value	Suav – Suitability Index
Suitability for Inexperienced	4.75	4.00	19/28.5
Portability	5.00	1.00	5/30
Cost	4.50	4.00	18/27
Tolerate Weather Conditions	3.50	3.00	10.5/21
Crash Recovery	5.00	1.00	5/30
Flight Characteristics	4.75	1.00	4.75/28.5
Sensor Payload	5.00	3.00	15/30
Exchangeable Sensor Payload	3.00	2.00	6/18
Need for Real Time Data	5.00	4.00	20/30
Research Foci	5.00	3.00	15/30
Suav Sum			118.25/273 or **43%**

VTOLs had a slightly better 57% suitability index (Table 10) and were limited by the technical skill necessary to pilot the vehicle, cost, and crash manageability requirements. VTOL UAVs also have a high initial cost. Recovery of sensors following a crash is also highly unlikely.

Table 9: The overall ability to satisfy stakeholder's requirements for VTOL models is shown below. The final Suav is calculated below in the bottom right.

	SR - Stakeholder's Importance Value	ER – Expert's Compatibility Value	Suav – Suitability Index
Suitability for Inexperienced	4.75	1.00	4.75/28.5
Portability	5.00	4.00	20/30
Cost	4.50	1.00	4.50/27
Tolerate Weather Conditions	3.50	5.00	17.5 /21
Crash Recovery	5.00	1.00	5/30
Flight Characteristics	4.75	3.00	14.25/28.5
Sensor Payload	5.00	4.00	20/30
Exchangeable Sensor Payload	3.00	3.00	9/18
Need for Real Time Data	5.00	6.00	30/30
Research Foci	5.00	6.00	30/30
Suav Sum			155/270 or **57%**

Powered paraglider UAVs had the best suitability index of 71% (Table 11). Powered paragliders met most requirements with the exception of cost, and climatic conditions. PP UAVs have a limited range of wind speeds in which they can be safely flown but are susceptible to high maintenance costs if parachutes are damaged or are in need of replacement. However the model that best suits the stakeholder's elicited requirements is the powered paraglider UAV and was subsequently chosen by the stakeholder. The benefits and limitations of powered paraglider UAVs are discussed in detail below.

Table 10: The overall ability to satisfy the needs of the stakeholder or the Suav index for the powered paraglider platform is presented below. This platform won over the other platforms as it was able to obtain the highest Suav rating.

	SR - Stakeholder's Importance Value	ER – Expert's Compatibility Value	Suav – Suitability Index
Suitability for Inexperienced	4.75	4.00	19/28.5
Portability	5.00	4.00	20/30
Cost	4.50	2.00	9/27
Tolerate Weather Conditions	3.50	2.00	7 /21
Crash Recovery	5.00	6.00	30/30
Flight Characteristics	4.75	3.00	14.25/28.5
Sensor Payload	5.00	6.00	30/30
Exchangeable Sensor Payload	3.00	6.00	18/18
Need for Real Time Data	5.00	5.00	25/30
Research Foci	5.00	4.00	20/30
Suav Sum			192.25/270 or **71%**

2.4 **Review of Powered Paraglider UAVs**

After comparing products from several different PPUAV providers, the purchase of a PPUAV was completed through Atair Aerospace. Atair is largely funded through Department of Defense contracts to develop parachute-related technologies for the military. PPUAVs are among their product line. The model chosen for purchase was the Micro LEAPP (Long Endurance Autonomous Powered Paraglider) (see Figure 11) which was originally developed for military surveillance operations in remote areas by ground soldiers or through deployment from manned aircraft. The purchase agreement included onsite training in New York.

Figure 10 - Early Design Concept of the Micro LEAPP Provided by Atair Aerospace

Powered paraglider UASs have been utilized previously in the military and the academic sector (see Section 1.2.2) so their limitations and utilities are relatively well known. A powered paraglider system is dependent on a parachute and most models utilize a pusher propeller engine configuration. PPUAVs maintain flight using the parachute as a wing and the propeller for thrust. While in flight, the chassis hangs below the parachute. Launching of the UAV is conducted with at least three people including one pilot and two assistants. The pilot starts the engine and tests for any abnormalities by engaging the engine from high to low several times. After the check is performed, they inform the two assistants that the UAV is ready to launch. Once the launch starts, the pilot will run away from the front of the

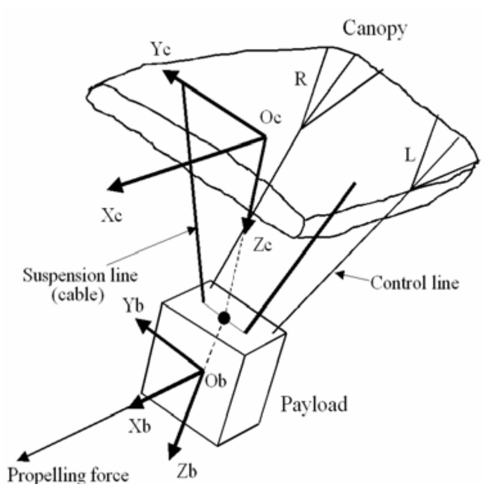

Figure 11 - Model Figure Demonstrating Forces Involved with a PPUAV in Flight (Watanabe and Ochi, 2007)

UAV to the side while the assistants begin to run forward. The assistants' main objective during launch is to locate the parachute's orientation directly above the chassis and once this occurs releases their hold on the parachute after which the pilot will have to maintain the parachute's orientation directly above the chassis for flight to occur. Flight control is managed using a weight-shift system similar to that used by helicopters whereby thrust from the engine forces the chassis upward resulting in added resistance to the upper wing, and therefore, lift. Additional lift can be generated from a steady mild wind which acts to increase airspeed and the resistance gradient of the wing. This is why PPUAVs launch more easily in relatively calm steady winds than in conditions where there are no winds at all. Steering uses a set of break or control lines connecting the chassis to the parachute outer edge of the parachute. When pulled taught, these lines cause the aircraft to turn in the same direction of line pull (i.e. pulling the left line results in the PPUAV turning left). Turns typically reduce air speed, which may result in a loss of altitude. Following take off, engine speed is typically reduced to level flight. Landing is achieved through lowering engine speed and steering the PPUAV toward a desired landing target. Landing must take place with the PPUAV moving up or down wind as cross winds result in the tires gripping the ground, which can result in flipping the aircraft.

The stakeholder required a payload of approximately 11 kilograms (around 25 pounds) (section 2.2.2.). Payloads for PPUAVs can vary from a few kilograms to several thousand depending on the power of the engine and the size of the parachute. To lift around a 14 kg (30 lb) payload Atair Aerospace determined the model needed to weigh around 18 kgs (40 lbs) with a 9.15 meter (30 foot wingspan). The Micro LEAPPs specifications fulfilled the requirements put forth by the stakeholder in terms of cost (see Section 2.1.3) and payload (see Section 2.2.1-2.2.2) and are

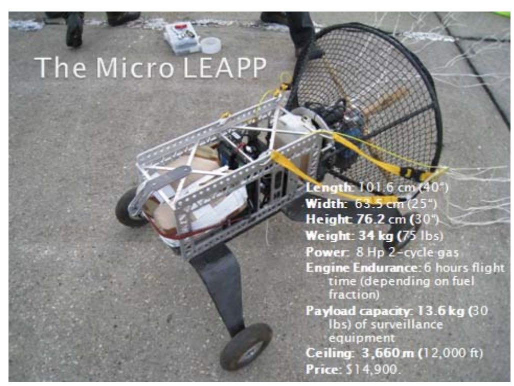

Figure 12 - The Micro LEAPP specifications from Atair Aerospace are presented above.

listed in figure 13. The Micro LEAPP can fly to altitudes of 3,660 meters (12,000 feet) and the endurance on the engine is specified as six hours with no payload. The dimensions of the Micro LEAPP were also within a statisfactory range for the stakeholder. Due to the power of the engine (8 hp) the Micro LEAPP could take off in steady wind conditions with relatively low engine speeds.

There are several disadvantages to PPUAVs however. Powered paragliders require flight in relatively calm wind conditions 2.20-6.70 meters per second (5-15MPH) with little or no turbulence (i.e. stable wind conditions) (Goin, J, 2008). Parachutes require a higher level of maintenance than regular fixed wings due to UV degradation of the parachute fabric. Parachutes need to be packed in a precise manner and should me manually inspected for holes and tears frequently. The hours of use for a parachute need to be carefully recorded to better determine when a replacement will be necessary. Replacement of parachutes can lead to infrequent but high maintenance costs, especially with very intensive use. The Micro LEAPP has a slow flight speed of around 6.70 meters per second (15 mph). Furthermore their overall speed and travel distance declines significantly when flying into strong headwinds.

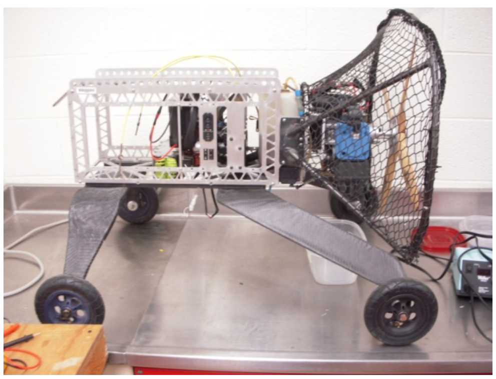

Figure 13 - The Micro LEAPP inside the stakeholder's laboratory.

3. Developing a UAV and Sensor Payload to Meet the Needs of the Stakeholder

Developing the UAV and sensor payload to meet the stakeholder's requirements was a challenging task. As with most UASs a significant amount of flight testing and modification of the UAV was necessary. However, the PPUAV presented technical, design, and logistic challenges that were not expected by the stakeholder. This section addresses these challenges and presents solutions to demonstrate to other parties the amount of labor and planning required for the development of an operational and useful UAV. Flight testing and modification of the UAV is first considered, followed by the development of the sensor package.

3.1 Flight Testing and Modifications of the UAV

The UAV or the Micro LEAPP was purchased from Atair Aerospace (see Section 2.4) as they provide some of the larger commercially available PPUAVs on the market. Atair Aerospace regularly produces PPUAVs for the military so their commercially available PPUAVS are in high demand and were recommended. The purchase of the Micro LEAPP was finalized in March of 2008 with completion of the UAV, training, and delivery predicted for July 2008. Atair Aerospace was interested in expanding their business into academic research and was willing to accommodate the stakeholder by reducing overall cost of the UAV (free training, parachute, etc.). However, due to higher priority department of defense contracts, the Micro LEAPP delivery date was postponed several times over the course of 2008. Final completion of the Micro LEAPP was in late 2008 with a training session held in New York in early January of 2009. The training session provided an opportunity for the stakeholder to work with the engineers who built the Micro LEAPP and to receive training from expert pilots on the operation and maintenance of the aircraft. Several small modifications to the Micro LEAPP were requested at the time of training and final delivery was made in March 2009.

Following delivery, the engine on the Micro LEAPP required two days of adjustments to account for changes in elevation and humidity between New York and El Paso. Preliminary flight testing was conducted near El Paso at a turf farm and at the Radio Controllers of El Paso club's flight field. Flight testing was between 4-5 hours of field time 1-3 times a week (depending on weather conditions). New flight crew were proficient within 1 or 2 flight days. A total of nine members were trained.

Several replacements of onboard components were needed for the UAV to function properly. After several weeks of initial flight testing problems were discovered the landing gear. Wheel axles began to lock during rotation causing the UAV to pull to the left during takeoff and landing. This was problematic as typical launches of PPUAVs require orientation and launching into the wind. After some initial research on the part of the stakeholder, a suitable replacement was found using a modified wheel assembly from off-road skates. Atair Aerospace agreed to replace the UAVs wheels with the new skate wheels at no extra charge as it was a flaw in the original design. It is important to note that by considering replacement parts that are produced in abundance by commercial vendors of outside of regular UAV and RC stores; the stakeholder was able to greatly reduce the cost and time of designing a custom engineered solution.

Later, complications arose due to an electronics malfunction that caused a small short onboard. Diagrams were provided by the stakeholder to Atair Aerospace illustrating wiring damage and proposed solutions to fix the damaged wires. Although the damage was repaired with the help of Atair employees, it was unclear to both parties what would cause the short to occur. After repairs were made, there was an increase in the frequency at which electronics were burning out or malfunctioning. The stakeholder completed a wiring diagram (Figure 15) of the electrical systems onboard to better determine where the problem was located. Eventually, with the creation of an electrical wiring diagram of the affected channels, it was discovered that the initial electronic design had a flaw that provided too

much voltage and current to the electronic ignition system on board. A new electrical wiring solution was implemented to circumvent this problem and after installing it no further electronic malfunctions have occurred to date. It is recommended that regardless of the

UAV design, that parties utilizing these systems complete a working electrical wiring diagram of the entire system to verify commercial copies of the same diagram and check for inconsistencies between the two..

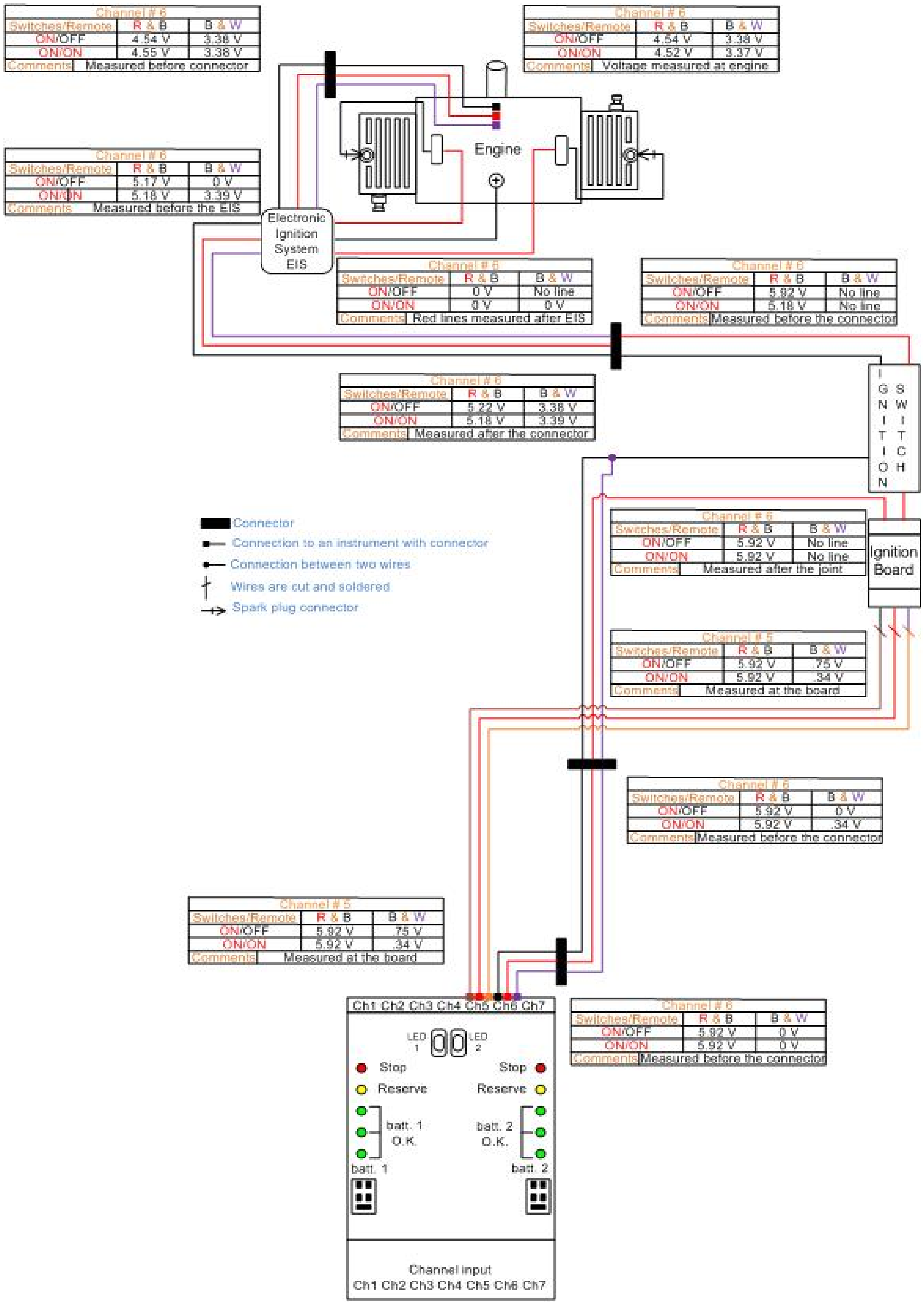

Figure 14 - Electrical wiring diagram of channels 5 & 6 for the Micro LEAPP.

At one point, the engine became increasingly difficult to start. After some investigation it was discovered that the piston chambers in the engine had become scored, decreasing compression. The problem was solved by purchasing a new engine, which was cheaper than refurbishing the old engine. The older engine had been previously used for testing and was likely used extensively under harsh operating conditions and possibly damaged in this process. With the new engine, a process of tracking engine performance and maintenance was introduced, and few unforeseen problems have been encountered since.

A housing for the large electric starter battery was constructed to better protect the battery (Figure 16). Previously the starter battery had to be removed after starting the engine at every launch. This required the presence of an extra flight crew member. The placement of the battery onboard improved efficiency of flight days by reducing flight launch time and reduced damage to electrical cables through repeated connections. Approximately 2.27kg (*ca.* 5lbs) of payload was lost, however.

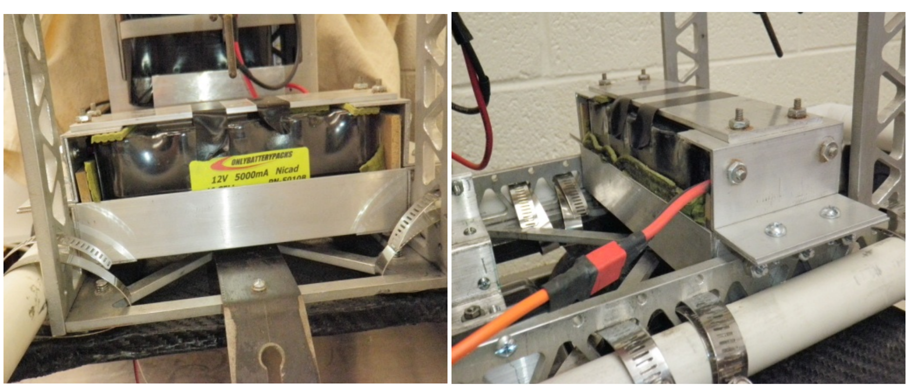

Figure 15 - Electric starter battery housing onboard the Micro LEAPP. The left picture is a front view of the Micro LEAPP and the right picture is a view from the right side of the aircraft.

Several other components onboard have been replaced or removed. The timing module sensor, which alerts the electronic ignition system to spark the spark plugs, malfunctioned. With the aid of the electrical wiring diagram it became possible to quickly narrow down which part was faulty (Figure 15). Furthermore the receiver required replacement from a 52 MHz to a 2.4 GHz frequency due to

interference with other radio signals in flight testing areas. The old receiver was still functioning correctly and the stakeholder retained the part for future use. It is important to plan for this eventuality when utilizing a UAS as one frequency may not always be available at all locations.

Human error on the part of the pilot has also led to some unfortunate problems during flight testing. Several rough landings have sheared screws and broken other parts that required replacement. Developing a very through checklist that verifies reoccurring problems post flight helped to alleviate unnecessary downtime and stockpiling of regularly needed parts.

Although flight testing necessitated several modifications to the UAV, it can be said that attention to detail, keeping detailed flight and maintenance log books (flight time, parachute hours, etc), and thoughtful planning will help mitigate the amount of down time experienced when using UAVs. It is also important to note, however, that to maintain this attention to detail does require active personnel who utilize the UAV frequently. These personnel can note which parts and equipment are more likely to fail and are key to redesigning such features to improve operational performance. Without these personnel it is possible that development time spent during flight testing will greatly exceed projected expectations and will minimize constrain development of research sensor packages or even collecting research data.

3.2 Sensor Package Development

Development of two different sensor subsystems or packages – one for normal flight operation and one for research data collection were required. The operation and research sensor packages onboard were initially separated to provide a more robust platform in the event of communication failure and to help ease bandwidth requirements for the research sensor package. Following the unexpected delays experienced in flight testing and modification of the PPUAV, the research sensor package was not developed to the degree initially hoped for but nonetheless presents a baseline from

which further development can be scaled. This section describes the initial design considerations and development of these two sensor hardware systems for the Micro LEAPP UAV.

3.2.1 Operational Sensor Package Development

Initial design considerations for the operational sensor package included the need for GPS, x orientation, y orientation, z orientation, air speed, ground speed, and altitude. These sensors needed to be centrally located for weight and balance issues and easily accessible. An additional constraint was the need for low power consumption to prevent space limitations with large batteries on board. The wireless system's communications needed to be relatively long range (exceeding 1 km or 0.62 mile) for a small bandwidth (< 1 kBps).

Selection of the operational sensor package was dependent on the choice of the main control unit, which needed to package data to be transmitted wirelessly to the base station (see section 4.1). Several different control units were considered, including a high level object oriented programmable control unit named Pico, control units that operated using an open source autopilot (Paparazzi), and an autonomous open source flight control software provided by DIY Drones (Ardupilot). Initial considerations were to use Pico however the control unit's hardware features were too limited and did not allow for all sensors required by the stakeholder. Paparazzi was briefly considered although it was not chosen due to an abundance of hardware that required extensive customization. Ardupilot eventually was chosen for the operational sensor package control unit as it had pre-configured hardware solutions and robust software control for the autonomous package.

The sensors listed in Table 12 were included in the final flight operation package. These sensors and their interactions with the Ardupilot control unit were supplied with open source software. The source code for the control unit was modified based on autonomous software provided by DIY Drones.

This modification was necessary to address several stakeholder requirements and is discussed in more detail in Sections 3.2.2 and 4.2.

Table 11: Operational sensor package onboard the Micro LEAPP.

Sensor	Measurement/ Purpose	Sampling Rate	Power	Sampling Error/Accuracy
GPS	Latitude, Longitude, Altitude, Ground Speed	1 Hz	4.5V – 6.5 V DC 44 mA	10 m(lat/lon), 5 m(alt), 0.1 m/s(speed)
Integrated Silicon Pressure Sensor	Air Speed	Not Available (Est. > 1 Hz)	4.25-5.25V DC 10 mA	+- 1.5 %V
AttoPilot XYZ Horizon Sensor	XYZ Orientation	Not Available (Est. > 1 Hz)	4.5V – 6.5VDC 15mA	+- 5 degrees for each orientation
XBee-Pro XSC009	Wireless Communication	Transmission: 9600 kBps	3V – 3.6V 265 mA Tx 65 mA Rx	Range: Up to 9.32 kilometers or 15 miles

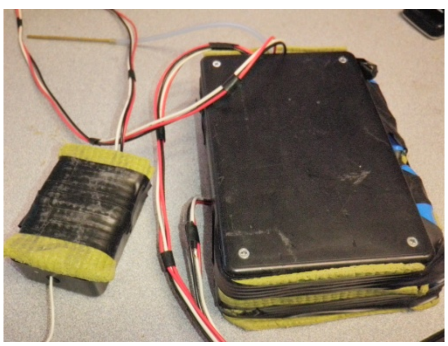

Figure 16 - Photo of the flight telemetry or operation sensor package onboard the Micro LEAPP the left box houses the wireless communication while the right box houses the remaining sensors.

A suitable housing for the operational sensor package was constructed to allow the sensors to be mounted onboard. The larger housing as seen in Figure 17 contains the GPS, Air Speed, and the orientation sensors (Table 12) while the smaller housing contains the wireless communication device (Figure 17). By constructing the housings for the flight operation package the sensors will be better able to survive a crash and sustained use.

3.2.2 **Research Sensor Package Development**

As mentioned above, the research sensor package development was one of the last to take place and subsequently did not reach the levels initially requested by the stakeholder. Original design considerations for this package included a small laptop with software to communicate with the base station software. Prior to flights, users could specify the sensors onboard the UAV in the software and through a handshake type process the two pieces of software would communicate and set up data recording. The research sensor package would communicate to the base station software through the use of a 2.4 GHz router. The wireless range for this system would be extremely limited without a custom antenna (line of sight 300 meters), so burst communication could only occur when the UAV was close to the launching area.

As the project progressed it was eventually decided to focus on one specific sensor - a photographic camera. Selection of the camera was based on the wireless capabilities available in “point and shoot” cameras in 2009. Two cameras were eventually purchased as they provided wireless capabilities at affordable prices. These two cameras were the Nikon Cool Pix S52c and the Canon Power Shot SD430. However, it was realized shortly after purchase that the while their wireless capabilities functioned properly, photos could not actively be transmitted without human interaction with the camera. As this human interaction was not possible mid flight it was eventually decided to use the auto shoot functions of the cameras to take photos onboard. A protective housing for the cameras was necessary to enable their use onboard the UAV.

A small Pelican Case was modified to construct and housing for the camera. This was mounted on the belly of the Micro LEAPP (Figure 18). A servo was installed inside the camera housing to trigger the camera to take photos (Figure 18). The servo was activated by software added to the control unit.

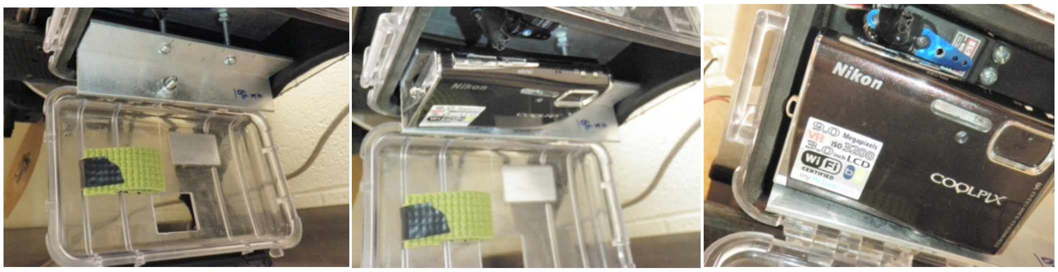

Figure 17 - The camera bay mounted on the belly of the Micro LEAPP. The three pictures from left to right include the camera housing bay, the camera mounted in the bay, and the servo that triggers the shutter.

After installation of the camera bay, it was discovered during routine flight testing that photos were blurry (Figure 29). The cause for this issue was traced to engine vibration. In order to alleviate this vibration, absorption materials were added to the inside of the camera housing. Although several different materials were tried, a yoga mat provided the most success in removing vibration (Figure 29). Further anti-vibration mitigation is required, which will likely require using rubber mounts on the engine and more sophisticated vibration-resistant mounting solutions for the camera.

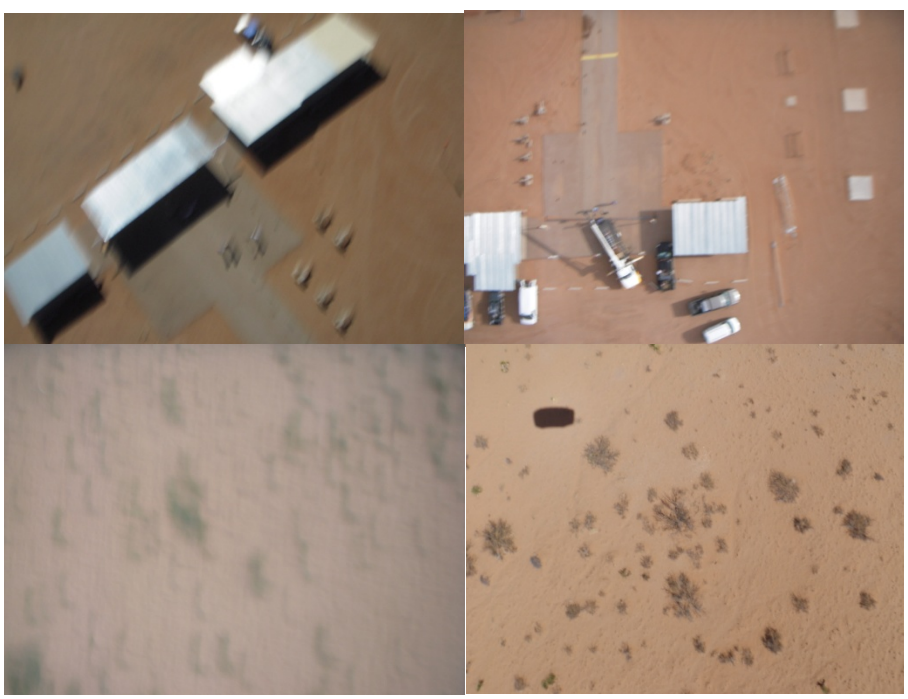

Figure 18 - Photography taken from the UAV. Photos on the left illustrate photos prior to vibration reduction while photos on the right show photography after vibration reduction.

4. Development of software for UAV operation planning, control, and optimized data acquisition

Although there has been a great deal of work on the utilization of UASs for research (Astuti et al. 2009) (Aber et al. 2008) (Jones IV, Pearlstine, and Percivial, 2006), most studies do not address key problems with relatively cheap and entry level UASs that would be the typical choice of the stakeholder in this study. In smaller and low-tech labs that do not specialize in UAS engineering but instead use UASs as a research tool, a frequent concern is how to optimize flight time, flight operation, and data collection without the additional investment of skilled pilots and teams or high-end autopilot and communication systems. The UAS software presented here is designed to address these shortcomings. This chapter describes the high level design of the UAS software and then proceeds to explain how each piece of software interacts with one another. The development of the software was focused on being scalable, simple, open source, and adaptable to multiple UASs and payload options.

Three pieces of software were developed and maintained for the stakeholder including: the base station software, the flight telemetry software controlling the flight telemetry onboard the UAV, and an analysis tool that visualizes data collected from the base station software for a given flight. The analysis tool was not specifically requested by the stakeholder, but was introduced to assess flight and UAS performance during performance testing (section 5.2). This chapter provides an overview of each piece of software and its database (if applicable) before describing the software design and layout in more detail.

4.1 Base Station Software

This software is installed on the base station laptop and uses Microsoft Access as its database. The software connects to the database that is preconfigured prior to the installation of the software. The entity relationship diagram (Figure 20) and the actual database design are shown below (Figure 21).

The main entities (Figure 20) in this database include functionality for managing flight logbooks and data, defining and editing profiles of UAVs, sensors and measurements, naming of field names in data tables. The logbook entity represents a specific flight. The (Figure 20) UAV entity represents an Unmanned Aircraft Vehicle in the database and can include any type of UAV. A sensor entity represents equipment used to collect data onboard the UAV. In order to configure data collected from sensors, the measurement entity (Figure 20) is used to describe the type of data collected and the respective units of this data. The measurement entity can also be expanded for future scalability. The fields entity (Figure 20) allows users to define a field name (column heading) within a data table for each sensor and measurement, which is potentially useful when multiple sensors of the same type are flown on the UAV but are positioned to collect data in different ways (e.g. upward and downward looking optical sensors of the same type). The data entity (Figure 20) represents the total amount of data collected from all sensors during all flights.

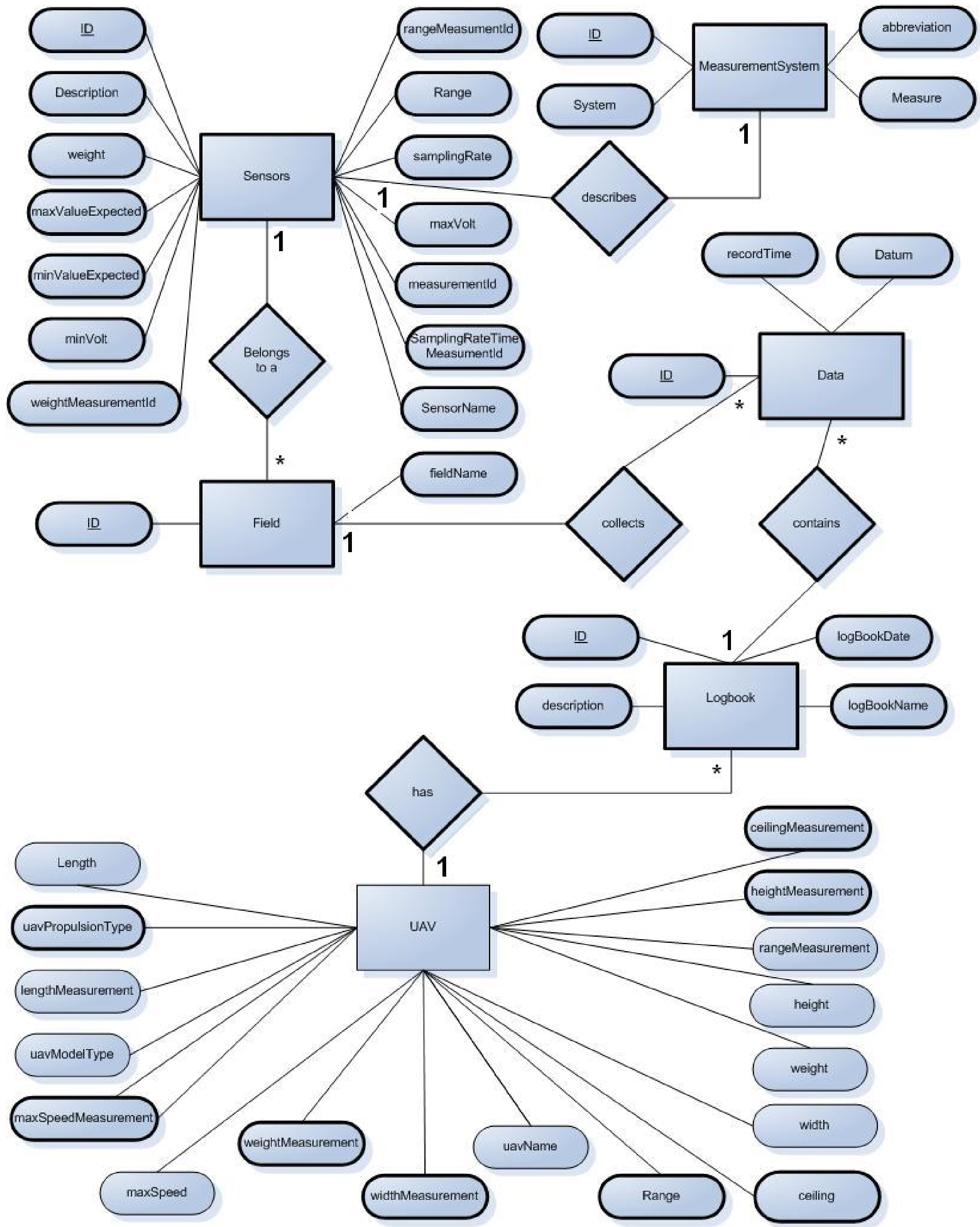

Figure 19 - An Entity Relationship(ER) diagram illustrating how the various entities in the base station software database interact with one another. ER Diagrams are high level representations of items in the database. In the diagram squares represent entities while ovals represent attributes of each entity. Diamonds demonstrate relationships between entities and how they interact with one another in the database. The asterisk and numbers further define relationships and their parameters - * indicates where there are many instances of a given entity (e.g. 1 sensor could have multiple fields); 1 indicates where there is only one instance of a given entity (e.g. 1 UAV has many log books).

The relationship diagram presented in Figure 21 demonstrates how the different tables are related to each other in the database. Compared to the ER diagram (Figure 20), the relationship diagram is very similar, but includes several look up tables that illustrate the potential for customization in the future. These tables allow the user to specify the UAV model type, the UAV's propulsion type, different systems of measurement, and different objects of measurement, for example. Relationships between tables in the database are based on unique identification numbers assigned by Microsoft Access upon entry into the database (Figure 20 & 21).

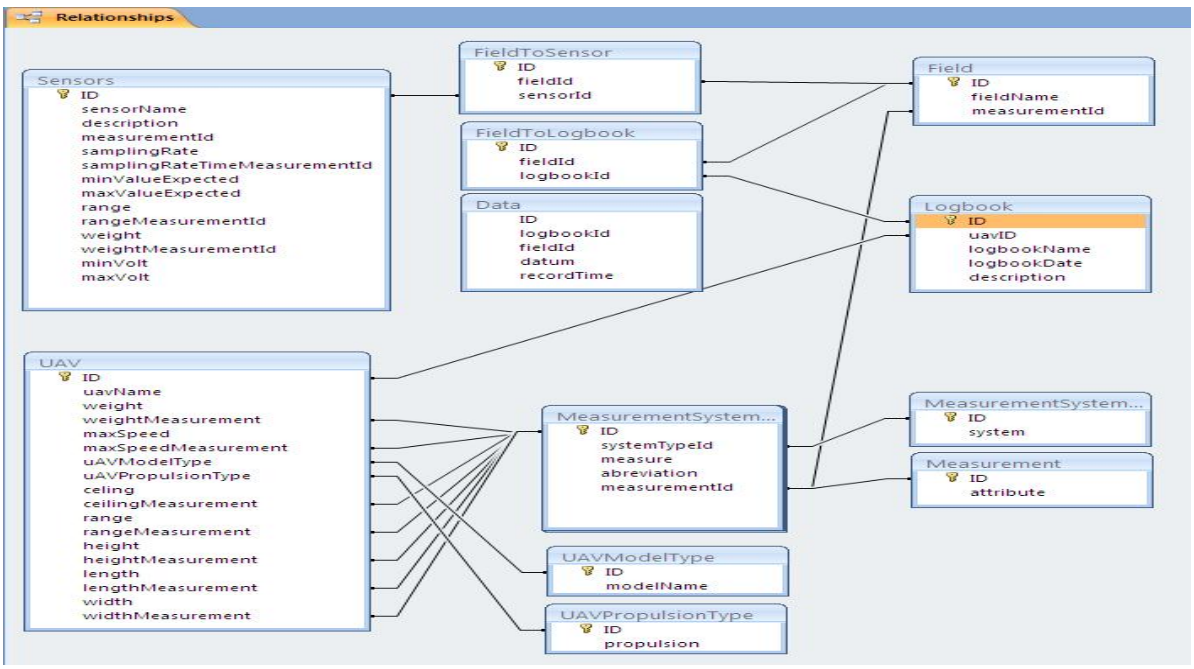

Figure 20- Actual relationships between the various tables in the base station software database. This relationship diagram includes several tables (or entities) that were not included in the original ER diagram as they are simple look up tables. Sensors, fields, logbooks, UAV, measurements, and data entities are still included in the final database.

4.1.1 Base Station Software GUI Layout

The base station software graphical user interface (GUI) is divided into six main screens. After launching the software the user is presented with these six options (Figure 22). The left five options in allow users to enter data into the database for each of the entities (with the exclusion of Field) as described above (Figure 20). These operations include adding flights (logbook) into the database,

reviewing past flights, adding or editing attribute information for different UAVs, adding or editing sensors, and adding measurement attribute information into the database. The rightmost choice allows users to "Start" or launch a flight.

Figure 21 - Main Menu of Base Station Software

4.1.2 GUI Layout - Creating a Flight

By clicking the "New Flight" button (Figure 22) the "Create a New Flight" (Figure 23) screen will be displayed. The "Create a New Flight" (Figure 23) screen allows users to specify which UAV and fields are linked to the UAV for a given flight. The UAV choice and choices of field names selected determine what sensor readings are stored in the data table and are viewed in the "Flight Window" screen (section 4.1.7.2). Once a name, a date, a UAV, and various fields for the new flight are specified, the information configuration for the new flight (logbook) can be saved into the logbook table by clicking on the "Create" button (section 4.1).

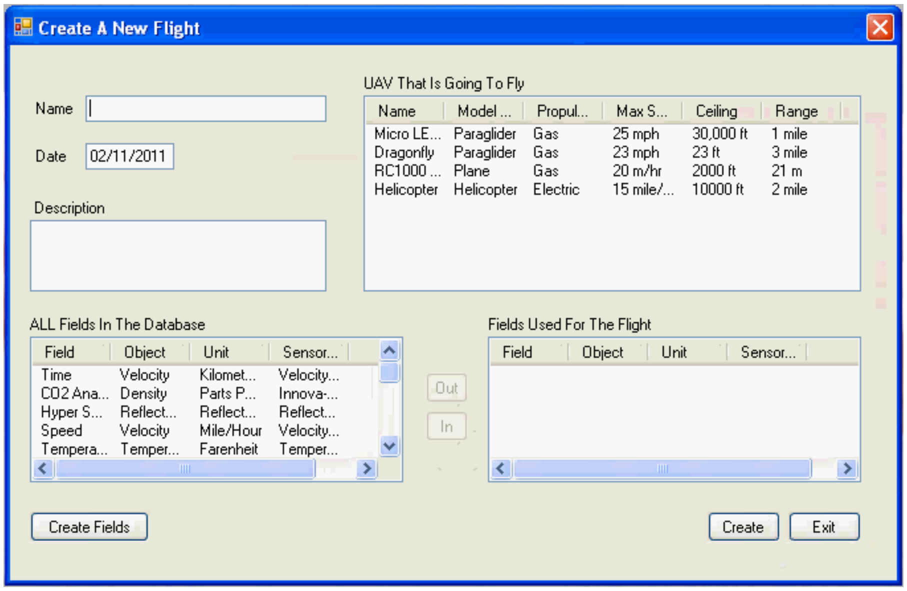

Figure 22 - Create a Flight Screen in base station software.

4.1.2.1 Creating/Editing Fields

By clicking on the "Create Fields" button on the "Create A New Flight" screen (Figure 23) the user will reach the "Create and Edit Fields" screen (Figure 24). This screen allows users to link sensors to a measurement and to give it a preferred name. This approach was requested by the stakeholder as there could be certain fields in a flight that would be common throughout multiple flights. Given that a user may want to run the exact same two sensors on a flight with one being positioned in a different way than another, it is necessary to assign user-defined names to keep the two data streams separated in different fields within the database. Once the "Name", "Sensors", and "Measurements" are specified for the new field, the new field can be created by clicking on the "Create" button (Figure 24). Editing existing fields is also possible by selecting a field of interest from the "Current Fields" list, and modifying the "Name", "Measurement", and "Sensors" information as required, and then clicking the "Edit" button. Note that the "Create" button changes to "Edit" on all screens when attributes are selected.

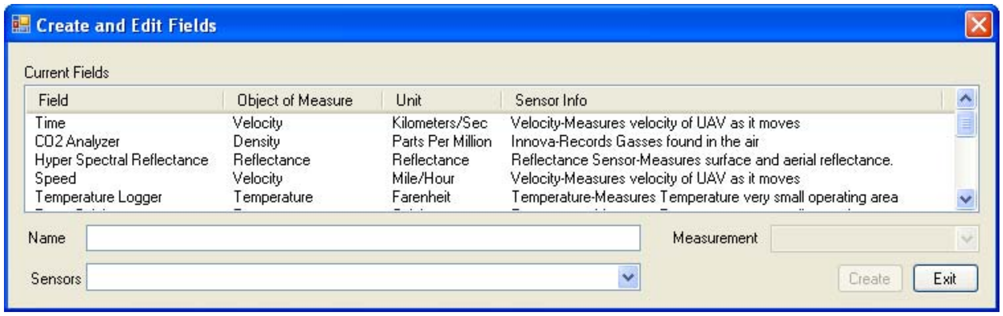

Figure 23 - Creating/Editing a Field screen within the base station software.

4.1.3 GUI Layout - Reviewing a Flight

By clicking on the “Review Flight” (Figure 22) button the “Review Flight” screen (Figure 25) is displayed. By reviewing a flight (Figure 25) users are able to see what data they have collected from their flights and also edit the “Flightbook Name”, the “UAV Name”, the “Date”, and the “Description” in the database. After selecting a flight, the software loads relevant data associated with that flight including any data that may have been recorded on the “Start a Flight” screen (Figures 29-32). The “Save” button (Figure 25) allows users to make changes to the flight selected from the “Flights in the Database” list. The “Export” (Figure 25) button allows users to export all data associated with a flight into a Microsoft Excel spreadsheet or as a comma delimited .txt file.

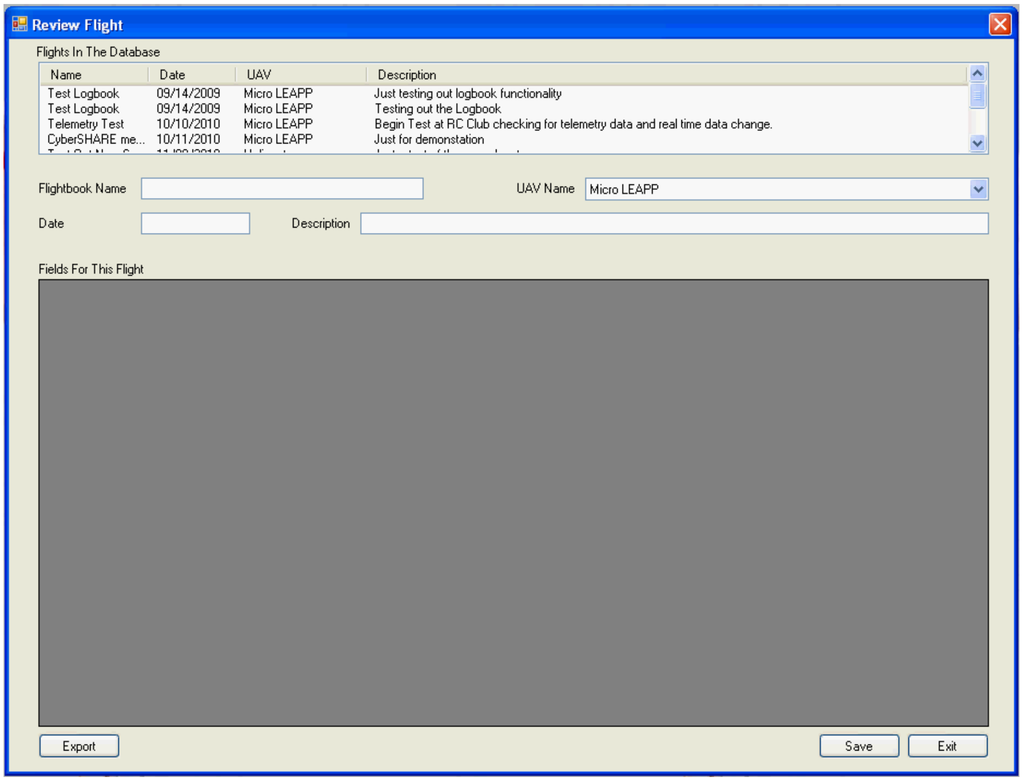

Figure 24 - Reviewing a Flight inside the base station software.

4.1.4 GUI Layout - Adding or Editing Unmanned Aerial Vehicles

By clicking the “Add/Edit UAV” button (Figure 22) the “Add or Edit Unmanned Vehicle(s)” screen (Figure 26) is displayed. Adding or editing UAVs is performed in the “Add or Edit Unmanned Aerial Vehicle(s)” screen (Figure 26). By entering the UAV’s “Name”, “Weight”, “Max Speed”, “UAV Model Type”, “UAV Propulsion Type”, “Ceiling”, “Range”, and “Dimensions”, and clicking the “Save” button (Figure 26) users can add a new UAV profile to the database. By selecting a UAV from the list “Current List of UAVs” at the top of the screen (Figure 26) and clicking the “Save” button, users can edit UAV profiles already stored in the database. The “Manuals” button (Figure 26) allows access to user manuals for a respective UAV in the “Current List of UAVs”. The “Clear” button removes all text in any field on the “Add or Edit Unmanned Vehicle(s)” screen (Figure 26).

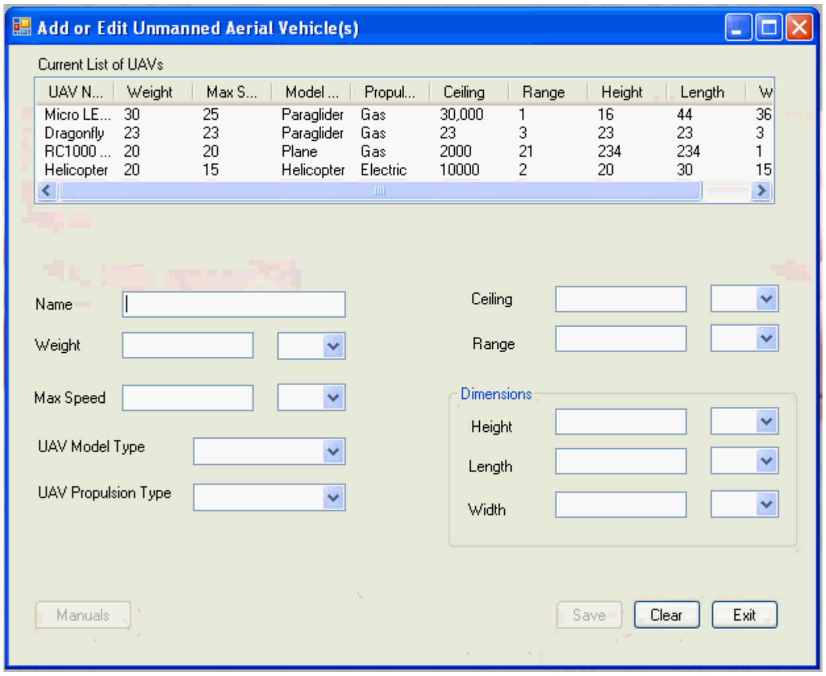

Figure 25 - Adding/Editing an UAV to the base station software screen.

4.1.5 GUI Layout - Adding and Editing Sensors

The “Creating a new sensor” screen (Figure 27) allows users to add or edit sensors in the database and is displayed by clicking on the “Add/Edit Sensors” button (Figure 22). Sensors entered in this form (Figure 27) can then be attached to fields for a given flight in the “Create and Edit Fields” screen (Figure 24). By entering the “Name” of the sensor, the “Weight”, the “Sampling Rate”, the “Range” of the sensor, selecting the measurement that aligns with the sensor from the “Measurements Sensor Makes (Select One)” list, and clicking the “Create” button the user can add new sensors to the database (Figure 27). The “Description”, “Minimum/Maximum Volt”, and “Minimum/Maximum Value” in figure 26 are optional fields added to allow for optimizing data collection for certain sensors. By selecting a sensor from the list at the top of the screen, modifying fields, and clicking the “Create” button, it is possible to edit the information associated with a given sensor.

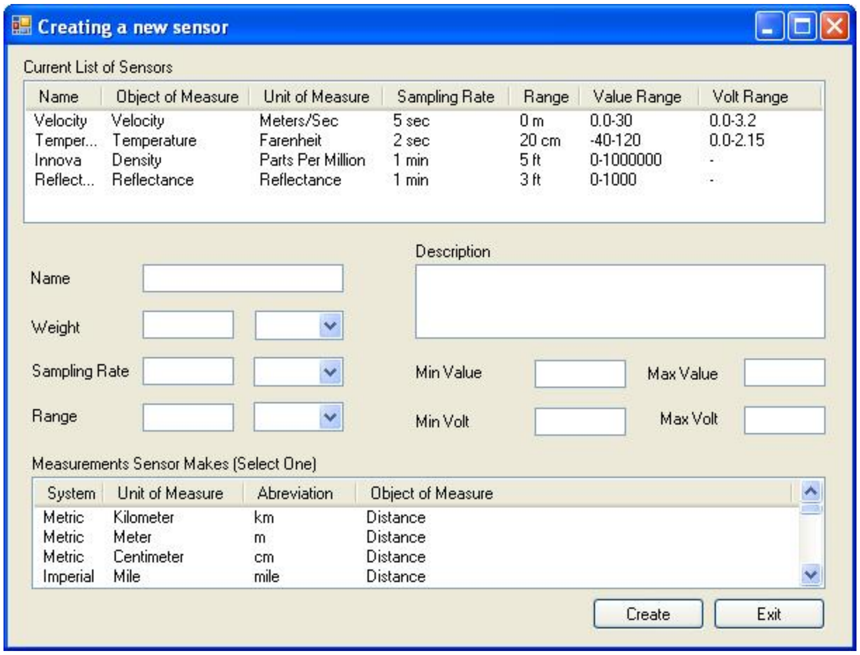

Figure 26 - Adding/Editing a sensor screen in the base station software

4.1.6 GUI Layout - Adding and Editing Measurements

The “Create a New Measure” screen (Figure 28) allows for new measurement profiles to be entered into the database and is displayed by clicking on the “Add Measures” button (Figure 22). Measurement attributes include the system of measurement (i.e. Imperial, Metric, etc), the unit of measure (i.e. meter, second, kilogram, etc), an abbreviation for that unit, and the object of measure (i.e. distance, volume, time etc.). New measurement profiles can be added to the database by entering data in the “Unit of Measurement”, the “Type of Measure”, the “Abbreviation”, and the “Measurement System”, and by then clicking the “Save” button (Figure 28). To edit measurements in the database, the user needs to select a Measurement profile from the “Measurements” list, make changes, and then click the “Save” button (Figure 28).

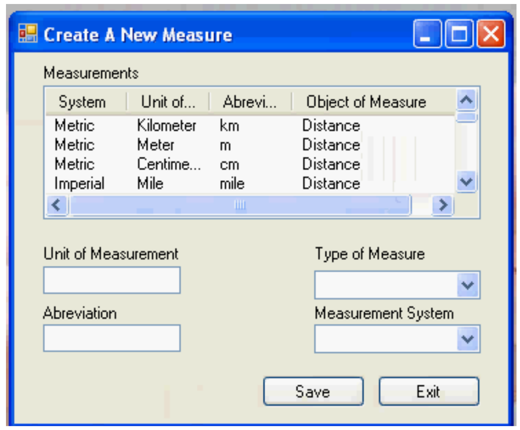

Figure 27 - Adding/Editing a Measurement in base station software

4.1.7 GUI Layout - Starting a Flight

The "Flight Window" screen (Figures 29-32) is displayed when users click the "Start a New Flight" button (Figure 22). The "Flight Window" screen (Figures 29-32) allows users to record data for a given flight profile in the database. The screen is split into four tabs; each tab configures the software to display real time data and prepares the database to record data being transmitted from the UAV. The tabs include: "Basic Sensors" or flight telemetry setup, "Optional Sensors" or sensors that are linked to a respective flight, "Layer and Area" tab that allows for geographic specification of the desired flight area and GIS imagery loading, and the "Start Flight" tab that shows data collection in real time.

4.1.7.1 Starting A Flight – Basic Sensor Setup

This tab (Figure 29) allows users to specify the UAV they will be using in the flight and setup the serial communication (COM port) with incoming flight telemetry readings from the operational sensor package (section 3.2.1). After a connection is established, the text boxes and speed dials on the right side of the GUI (Figure 29) are populated with real time data. If the connection is invalid or not established an error will alert the user. The "Next" button (Figure 29) displays the next tab "Optional Sensors" (Figure 30) while the "Cancel" button (Figure 29) returns the user to the main menu screen

(Figure 22). The “Save Screen” button (Figure 29) allows users to take a screen shot of the current screen and save it in a jpg format.

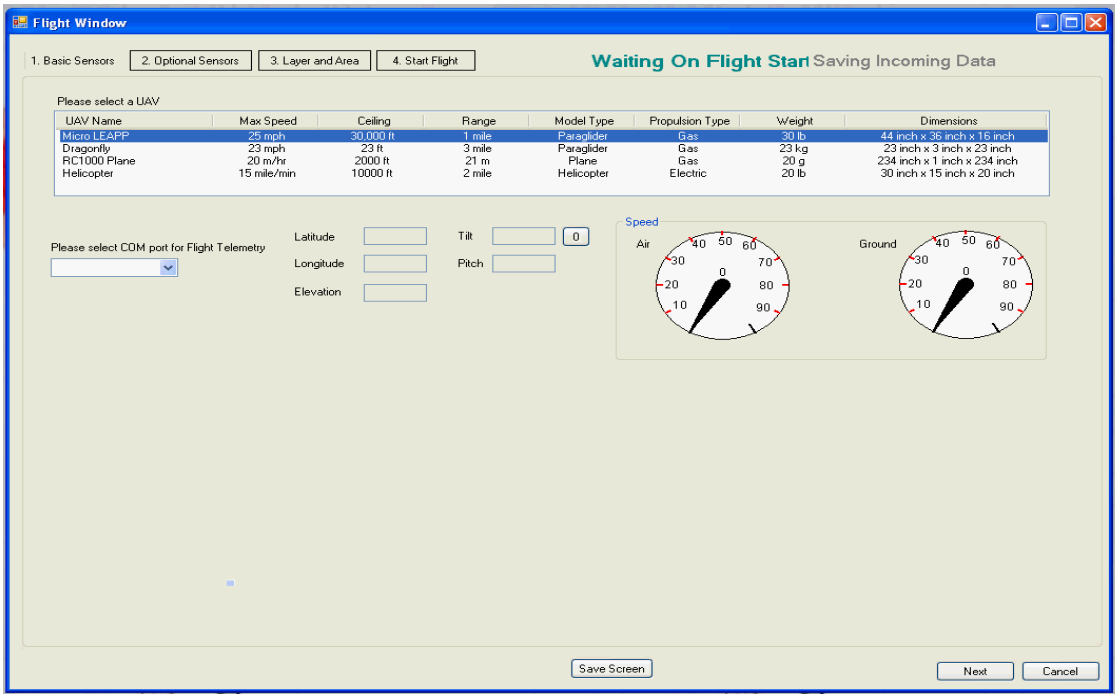

Figure 28 - Launching a Flight - Basic Sensor Setup or tab 1 in the base station software.

4.1.7.2 Starting A Flight – Optional Sensor Setup

This tab (Figure 30) allows the user to configure the flight as described earlier in section 4.1.2. Flights shown on this tab are based on the UAV selection made in the previous tab (section 4.1.7.1). By choosing a flight from the “Current flight setups for this UAV (Please select one below)” list, users assign which flight profile (logbook entry) they will be using to save data to the database. Aside from this choice, current functionality for this tab is somewhat limited at present. It is intended that this tab will be customized to accommodate the user’s needs in the future (see section 3.3.2 for more information). The “Start” button (Figure 30) serves no functionality at this time. The “Next” button (Figure 30) advances the “Flight Window” screen to the next tab for “Layer and Area” specification (Figure 31) while the “Back” button (Figure 30) returns the user to the “Basic Sensors” setup tab (Figure 29).

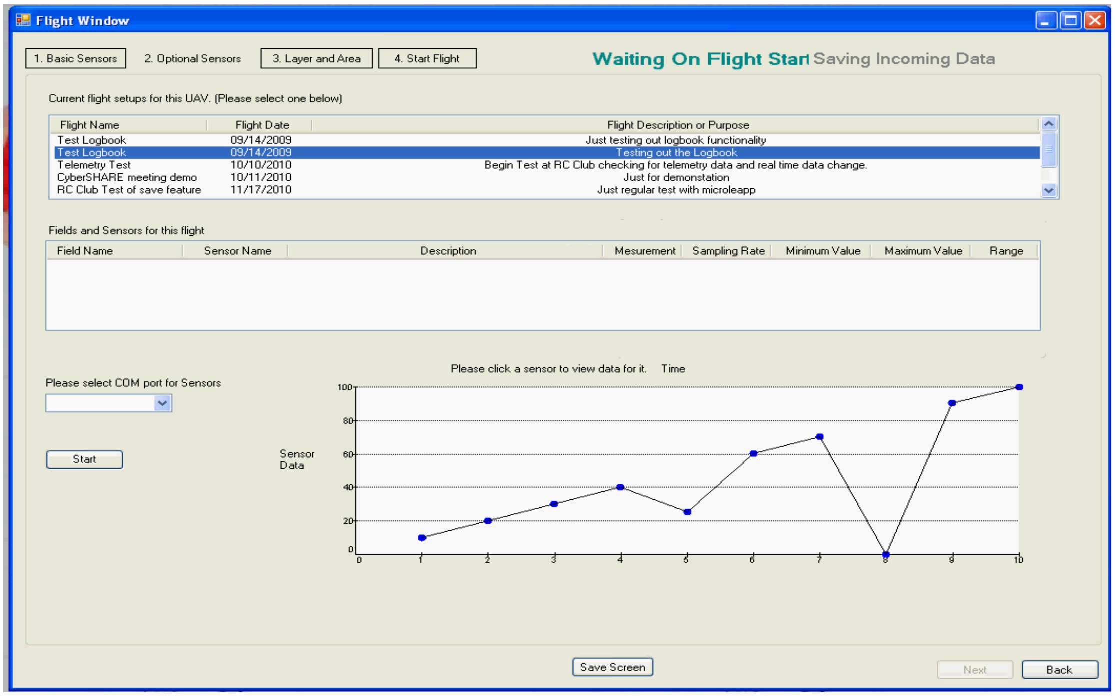

Figure 29 - Launching a Flight Optional Sensor Setup or tab 2 in the base station software.

4.1.7.3 Starting A Flight – GIS Layers and Area Specification

This tab (Figure 31) allows users to add GIS data to the GUI to better visualize their study area and data collection using the UAV. The "Load Shapefile" button (Figure 31) allows users to add GIS layers in the form of shape files. The "Load DEM" button (Figure 31) allows users to input digital elevation models for the given area they intend to sample. The "Zoom In", "Pan", and "Zoom Out" buttons (Figure 31) provide functionality on the "Layer Viewer" once GIS imagery is uploaded. The "Update Area" button (Figure 31) allows users to specify the bounding coordinates of the flight area. The "Save Values" (Figure 31) button allows users to specify the range of acceptable data input and limit recording of data from sensors based on the orientation and altitude of the aircraft. The "Next" button (Figure 31) advances the "Flight Window" screen to the "Start Flight" tab (Figure 32) while the "Back" button returns the user to the "Optional Sensors" tab (Figure 30).

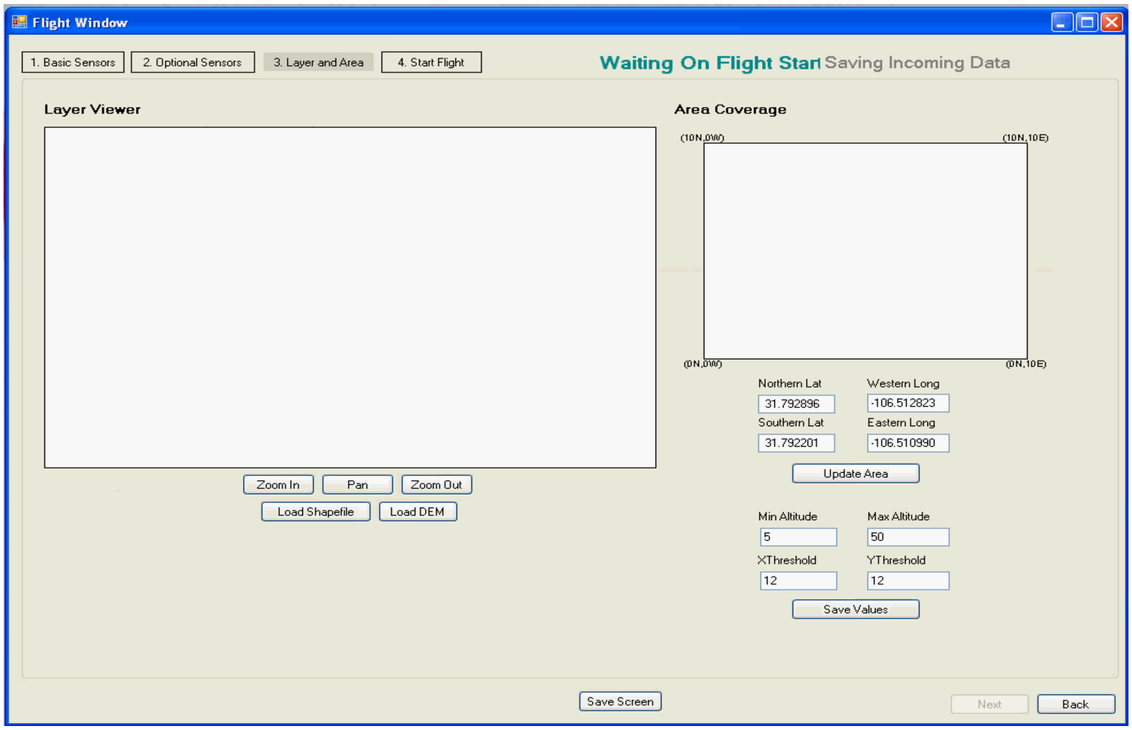

Figure 30 - Launching a Flight GIS Layer and Geographical Area Specification or tab 3 in base station software.

4.1.7.4 **Starting A Flight – Start Flight**

When users are ready to begin their flight they will advance to the "Start Flight" tab (Figure 32). This tab shows all data selected for streaming from the UAV in real time. The "Flight Telemetry Data" in the top left of the screen (Figure 32) displays data seen in the "Basic Sensor Setup" tab including: latitude, longitude, altitude, tilt, pitch, air speed, and ground speed (see section 4.1.7.1). The "Onboard Sensors" list (Figure 32) displays all sensors onboard the UAV, and by choosing a specific sensor the user can see a graph of the last 20 entries recorded for the selected sensor. The bottom half of the tab (Figure 32) shows the "GIS imagery in the Layer Viewer", which includes layers loaded from the "Layers and Area" tab (see section 4.1.7.3). The bottom half of the GUI (Figure 32) also shows the study area in the form of a map (top down or plan). As sensor readings are transmitted to the base station, boxes representing the "sampling area of a given sensor" are drawn to show the "sampled area" in the "Area Coverage" GUI (Figure 32). This feature allows users to visualize their data collection (blue boxes) during

a flight and determine which areas are adequately or inadequately sampled. This tab only starts recording to the database when a user clicks on the “Start Flight” button at the bottom right of the screen (Figure 32). Once this is clicked data is recorded based on the flight selection made earlier (see section 4.1.7.1) and the “Flight Time” text box begins counting the mission time. The “Reset Picture” button allows users to clear the current sampled area from the “Area Coverage” GUI. The “Zoom In”, “Pan”, and “Zoom Out” buttons have the same functionality as the “Layers and Area” tab (Figure 31), except that now they effect the “Layer Viewer” GUI on the “Start Flight” tab (Figure 32).

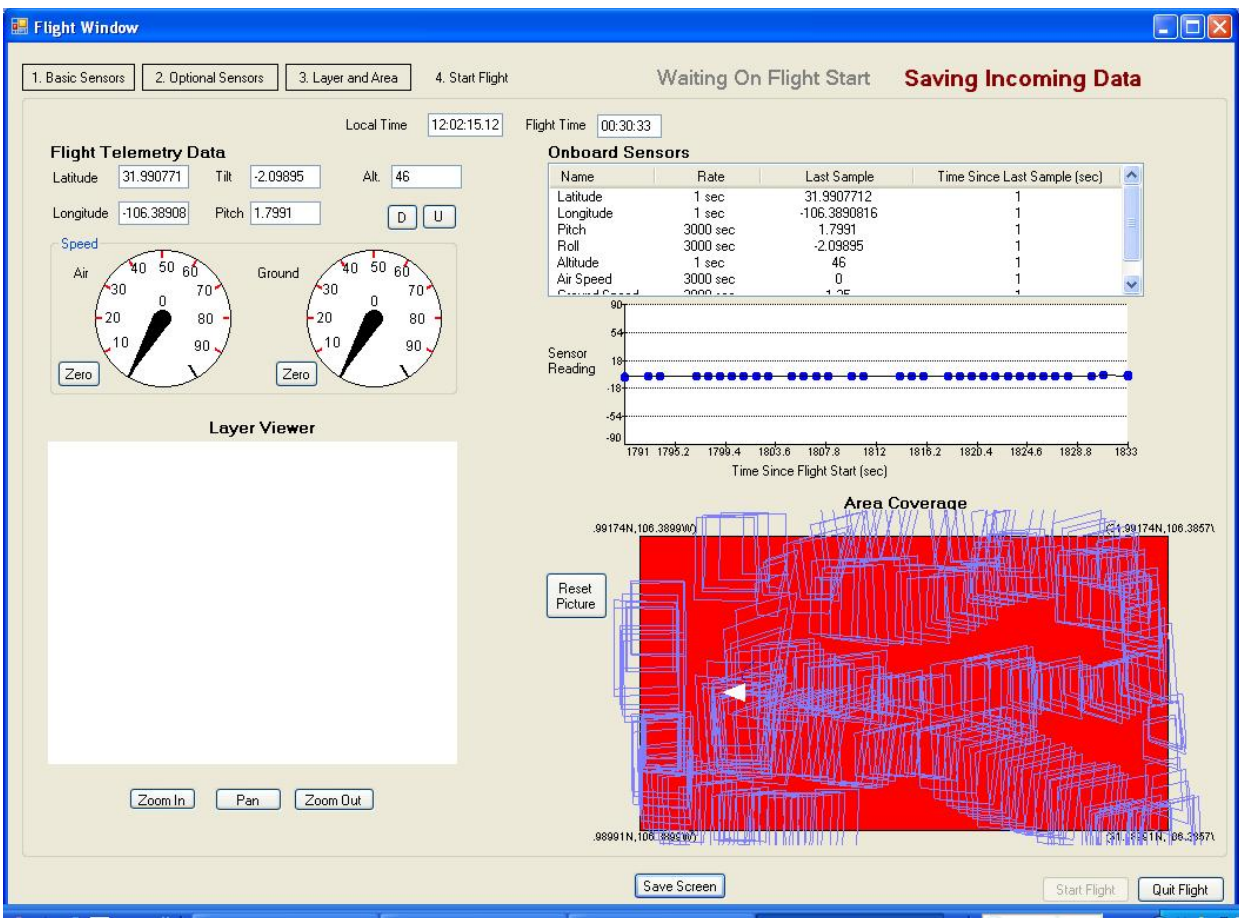

Figure 31 - Launching a Flight - Start Flight or tab 4 in base station software. Above is a simulated flight completed at UTEP. The proximity and overlay of the boxes denotes a moving “vehicle” or in this case a graduate student walking around a parking lot that was used for testing the operational sensor package and this software.

4.2 Flight Telemetry Software

The flight telemetry software is downloaded onto the control unit hardware in the operational sensor package (see section 3.2.1 for more information). This unit coalesces all telemetry data and prepares it for wireless transmission to the base station. The hardware and software for the telemetry package is based on an open source project from DIY Drones (Anderson, 2010). The open source project included a piece of software that allowed for autonomous control of a radio controlled airplane that was modified to be used with the operational sensor package. The modifications included the addition of transmission functions that packaged telemetry data to optimize data quality as well as changes to interrupted service routines for custom control of servos connected to the control unit (see section 3.2.2). The code editor (Figure 33) is commercially provided by the manufacturer of the Ardupilot control units. Typically, downloads to the control unit were made on the day before a flight.

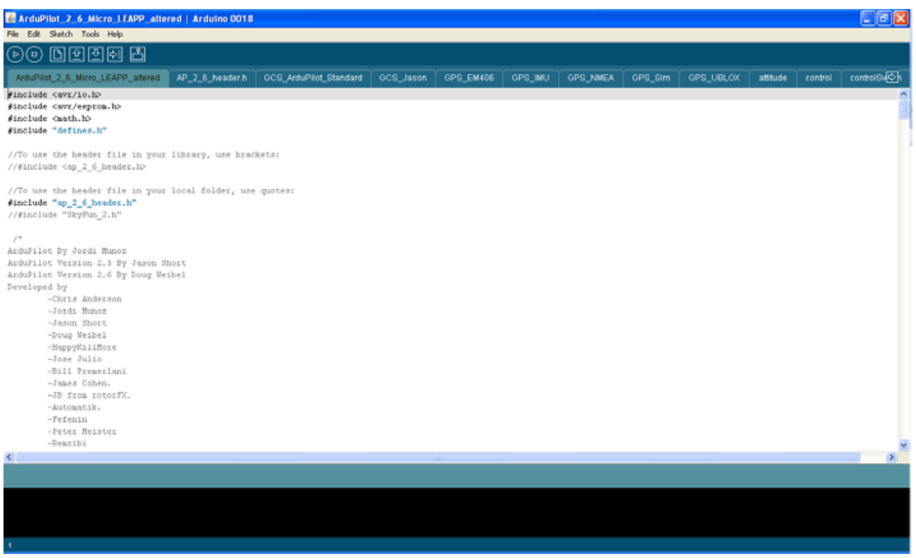

Figure 32 - Screenshot of the control unit's source code editor. The code shown is the actual code used during flight operations.

4.3 Analysis Tool

The analysis tool was developed to process flight data collected from the base station software. The tool recreates a given flight path based on data recorded during flight. It was initially implemented to help with the analysis of data collected during the testing of the UAS and the base station software (see section 5.1 and 5.3.2), but now has enough versatility to be included in the base station software.

Currently, the tool allows users to evaluate how well flight data was collected from a photographic camera onboard. By selecting a specific flight date from the "File Path" text box (Figure 34) the software redraws the flight path followed by the UAV along with boxes representing the time and location photos were taken onboard. After a redraw is complete the "Determine Area Coverage" button allows users to visualize the percent coverage for the chosen sensor. The various settings under "XY Orientation" and "Altitude Options" allow the user to apply various constraints and modify visualization of the flight path, such as changing the altitude to simulate photographic coverage at different heights and image resolutions, for example. The analysis tool was implemented to help determine ways to optimize piloting of the UAV during data collection by showing which areas had and had not been sampled.

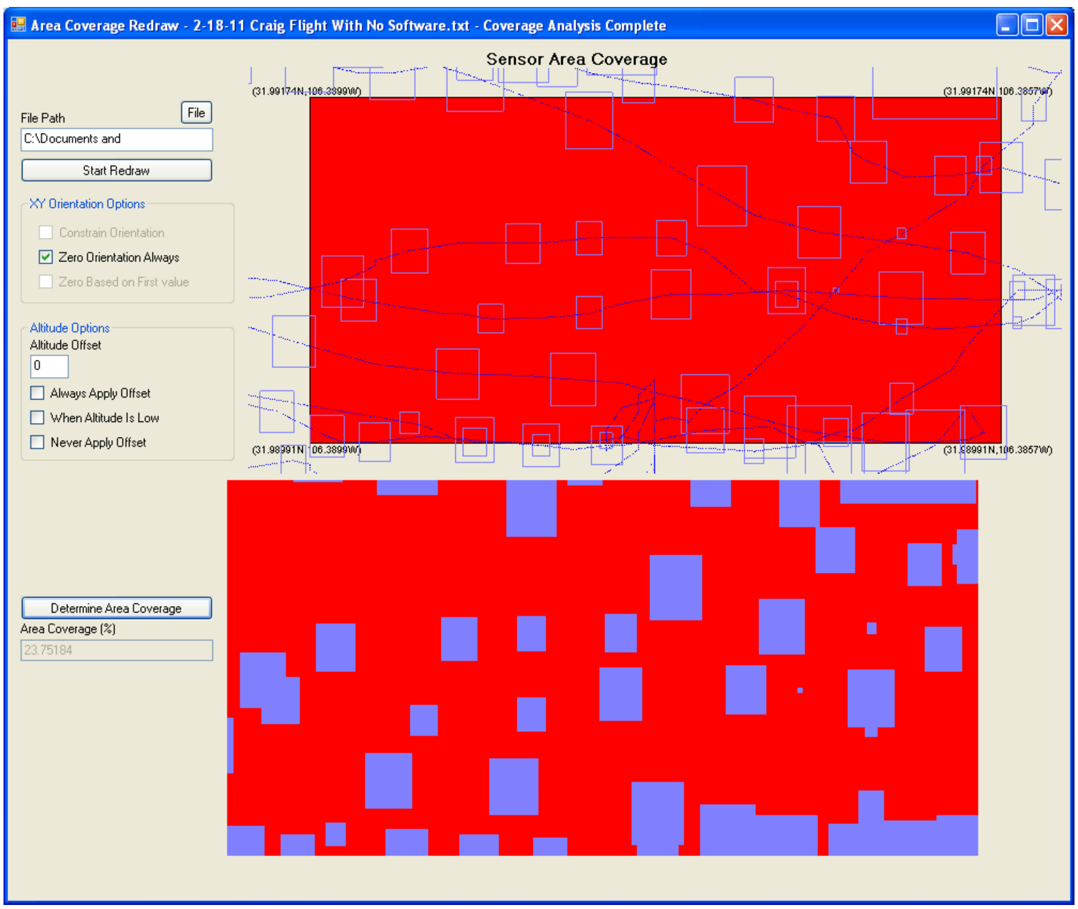

Figure 33 - A screen shot of the analysis tool software that is used to visualize flight information stored in the base station software database. This tool allows pilots to evaluate how well the flight was conducted by determining percent area coverage for the given flight.

5. Assessment of the performance of the UAS and how it meets the needs of the stakeholder.

In order to complete and validate the project, the UAS needed to complete a thorough field test. An experiment was designed to address three main objectives that together, ascertain how capable the platform is for the stakeholder. The main objectives for the experiment were the following:

1. Determine if the UAS can adequately gather data over a predefined and desired research area.
2. Determine whether an untrained environmental scientist can fly the UAV and collect data using onboard sensors.
3. Determine if the UAS operational software improves the areal coverage and quality of data collected during flight.

5.1.1 Background for the Experiment

The stakeholder proposed a standardized sample area that matches the typical sampling footprint of an eddy covariance tower in a desert shrubland. Eddy covariance towers are used to monitor land-atmosphere carbon, water and energy balance by national and international networks such as AMERIFLUX and FLUXNET. In a desert shrubland ecosystem, the sampling footprint of a typical eddy tower ranges from 150 to 500 meters depending on wind strength and surface roughness of the plant canopy (Aline Jaimes personal communication 2011), and the stakeholder wishes to sample this footprint using a UAS with optical sampling devices to improve the scaling of measurements between ground and satellite based sensors.

For this study, we modeled the typical eddy covariance footprint area (200 x 400 meters) from the stakeholders eddy covariance tower that is situated on the USDA Jornada Experimental Range North of Las Cruces, New Mexico (Figure 35).

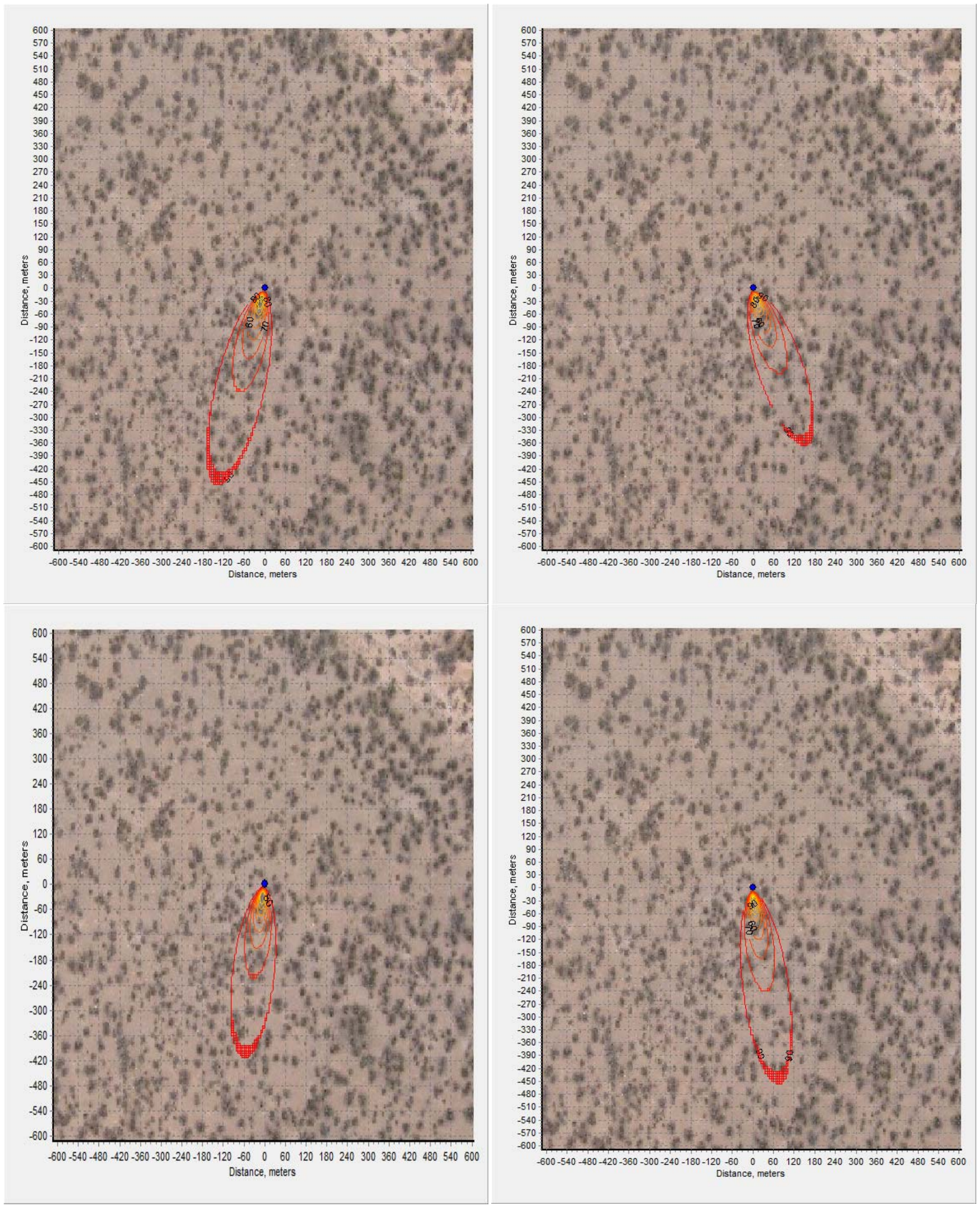

Figure 34 – The Eddy Covariance Tower foot print given by the Stakeholder. The tower is located at the Jornada Experimental Range north of Las Cruces. The footprints from top left to bottom right are for spring, summer, fall and winter.

5.1.2 **Methodology**

The 200 by 400 meter sampling area was selected on land owned by the El Paso Radio Controllers Club (EPRCC) where we conducted the majority of the test and experimental flights for the UAS. The experimental sampling area included the EPRCC runway in the southern part of the marked area and extended north 200 meters (Figure 33). Corner points for the area were located with a hand held global positioning system and marked with wooden poles and orange flagging tape that were viewable from the runway. During the experiment the GPS coordinates for the corner points were input to the UAS operational software to allow visualization of the sampling area for the experiment.

Figure 35 - Marked Flight Area for the Experiment. This location is centered off of the El Paso Radio Controller Club's flight area. Infrastructure located at the flight area is not included due to dated imagery provided by Google.

With the experimental area clearly marked, participants were tasked with capturing aerial photography over the experiment area using the UAS. Pilots were given a few minutes of practice prior to the experiment to allow for familiarization with the controls (i.e. make turns, maintain altitude etc.), after which they began the experiment. The experiment required the participants to fly over the study area and collect data from the camera onboard (see section 3.2.2). The camera system is programmed to take a photograph every 5 seconds and pilots were tasked with maintaining the UAV at an altitude of between 20 to 60 meters to ensure adequate spatial coverage and resolution of the photographs.

Four pilots participated in the experiment. These included:

- **Participant A:** An environmental science student who was an experienced pilot of the UAV, and who helped with flight testing and modification of the UAV.
- **Participant B and C:** Two field ecologists that have experience in the field.
- **Participant D:** A computer science graduate student with no field experience.

The four participants were members of the stakeholders' lab and were chosen for their varying levels of piloting experience. The base station software actively recorded data from all flights for all participants and all data shown in this chapter were collected with the use of that software. A software operator monitored the software during the experiment. This operator was trained in the use of the UAS software prior to the experiment. The experiment consisted of two separate flights for each participant. The first flight or the control flight was labeled as the "unguided flight" where the operator did not interact with participants viewing or managing the software during the flight. Furthermore, during the unguided flight, participants were not allowed to view the base station software. The second flight or the experimental flight was labeled as the "guided flight" whereby the software operator had direct interaction with the pilot during the flight and guided them to unsampled locations and helped them maintain the UAV in the desired flight window (horizontal and vertical). Furthermore, participants were allowed to view the software during the guided flights.

The unguided flight required each participant to collect as much imagery as possible over the study area within a 15 minute period. During this period, the UAS software recorded and visualized data collection. However, the participant was not allowed to utilize the software to assist them in any way during the flight. In addition, the software operator monitoring the progress of the participant was not allowed to guide the participant. The experiment was halted after 15 minutes. The participant was also given the choice of ending the experiment early if they felt they had sampled the area in a sufficient manner. No pilots chose this option, however.

For the guided flight, each participant flew the UAV over the same sampling area for 15 minutes but was given guidance every few seconds from the operator to maximize coverage of the sampling area. Guidance included instructions to alter or maintain heading, altitude and airspeed. The participant was given several minutes of flight time prior to the experiment to familiarize themselves with the control of the UAV, after which the experiment was executed. After 15 minutes of sampling time, the participant was instructed that the experiment had concluded and the software operator halted data recording for the flight. For the control and the experiment, recording of flight performance began when the UAV was over the sampling area and was initiated by instructions from the pilot.

For both unguided and guided flights, results are reported for the time the pilot maintained the UAV within the spatial and altitudinal sampling area, and the cumulative area of coverage sampled within the study area. The performance between guided and unguided flights is compared for each participant to assess the impact of the operational software. Performance between participants is compared to assess the difference between experienced and inexperienced pilots.

5.2 Results

5.2.1 Participant A – Experienced Pilot

Participant A completed the unguided and guided flights on different days. Winds were relatively calm during the guided flight, but were relatively gusty during the unguided flight. Flight telemetry values for the unguided and guided flights are shown in Figures 37 and 38 respectively. During the unguided flight, participant A maintained a mean altitude (Figure 37) of 36.41 meters and maintained the UAV within the altitudinal sampling range 80.69% of the time. Participant A maintained the UAV within the latitudinal and longitudinal extent of the study area 47.36% and 96.4% of the flight time respectively. The percentage of time that the Micro LEAPP stayed within the combined altitude, latitude, and longitude boundaries was 74.82% of the flight (Section 5.3).

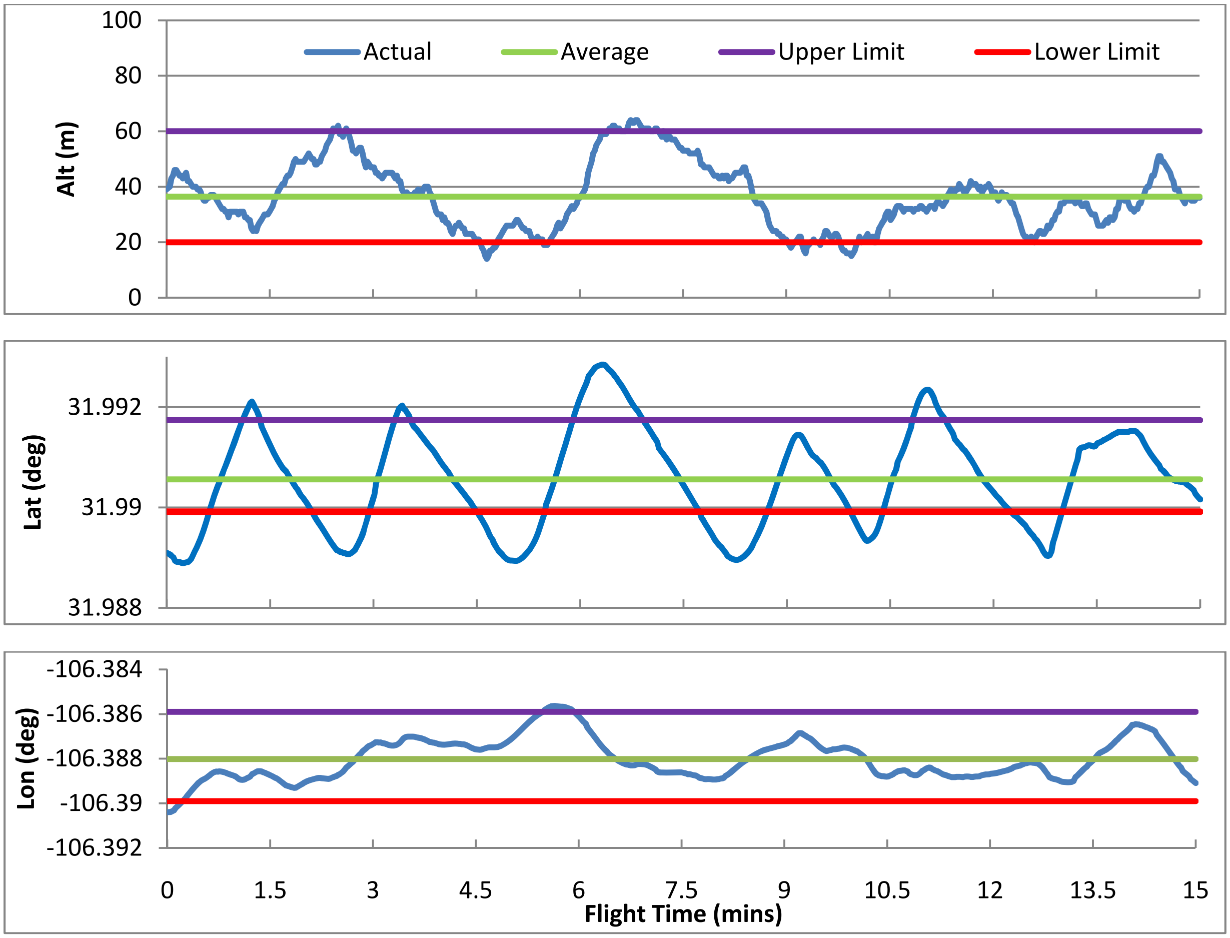

Figure 36- Plots show the position of the UAV during the flight relative to the altitudinal and spatial extent of the sampling area.

During the guided flight, participant A maintained a mean altitude (Figure 38) of 51.06 meters and maintained the UAV within the altitudinal sampling range 84.36% of the time (Figure 38). Participant A maintained the UAV within the latitudinal and longitudinal extent of the study area 61.77% and 89.57% of flight time respectively. The percentage of time that the Micro LEAPP stayed within the combined altitude, latitude, and longitude boundaries was 78.57% of the flight (Section 5.3).

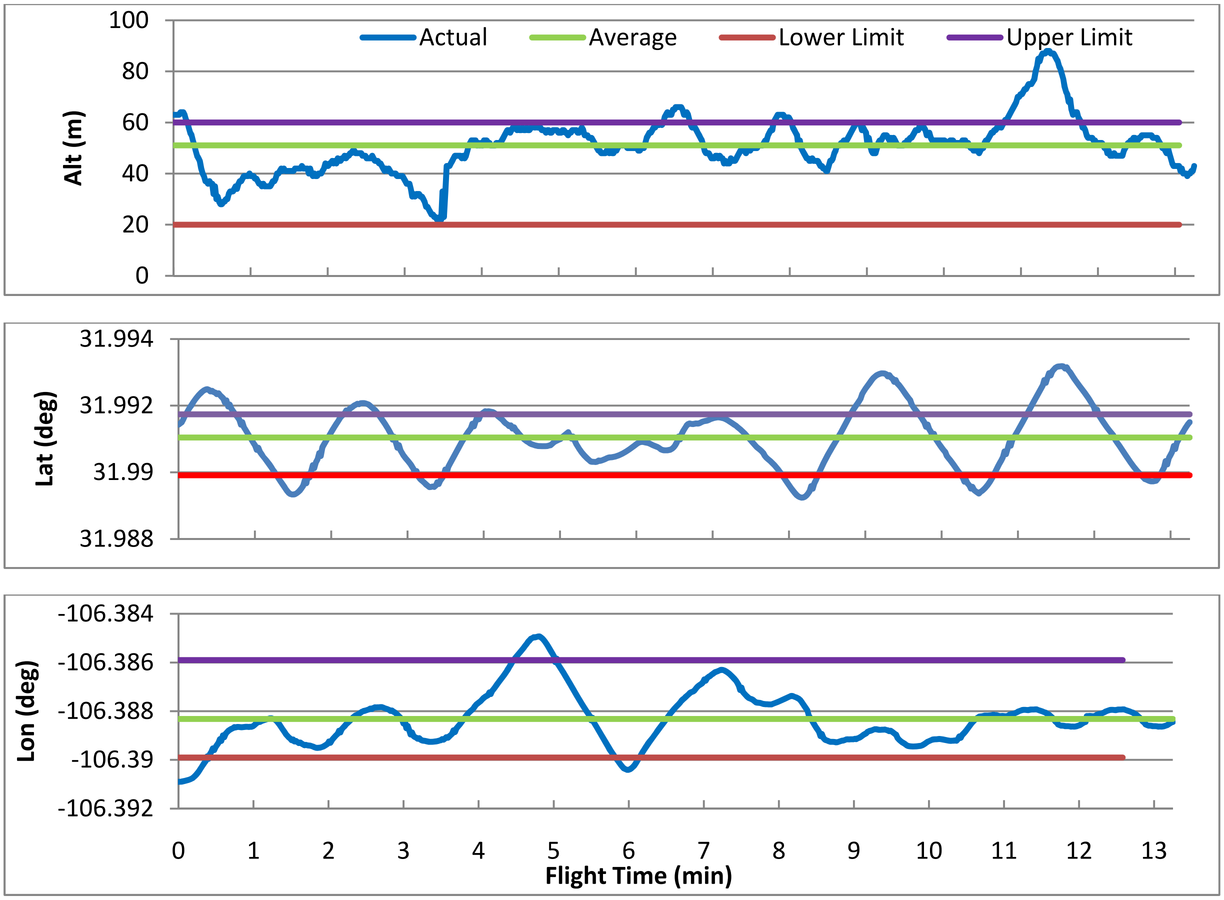

Figure 37- Plots show the position of the UAV during the flight relative to the altitudinal and spatial extent of the sampling area.

The area of coverage for Participant A's unguided and guided flights, and the cumulative coverage over the duration of each flight are shown in Figure 39. The coverage of the guided flight was 33.55% greater in the guided flight compared to the unguided flight and more of the study area was sampled more quickly in the guided flight compared to the unguided flight. The greatest difference between the unguided and guided flights occurred after 9 minutes of flight time.

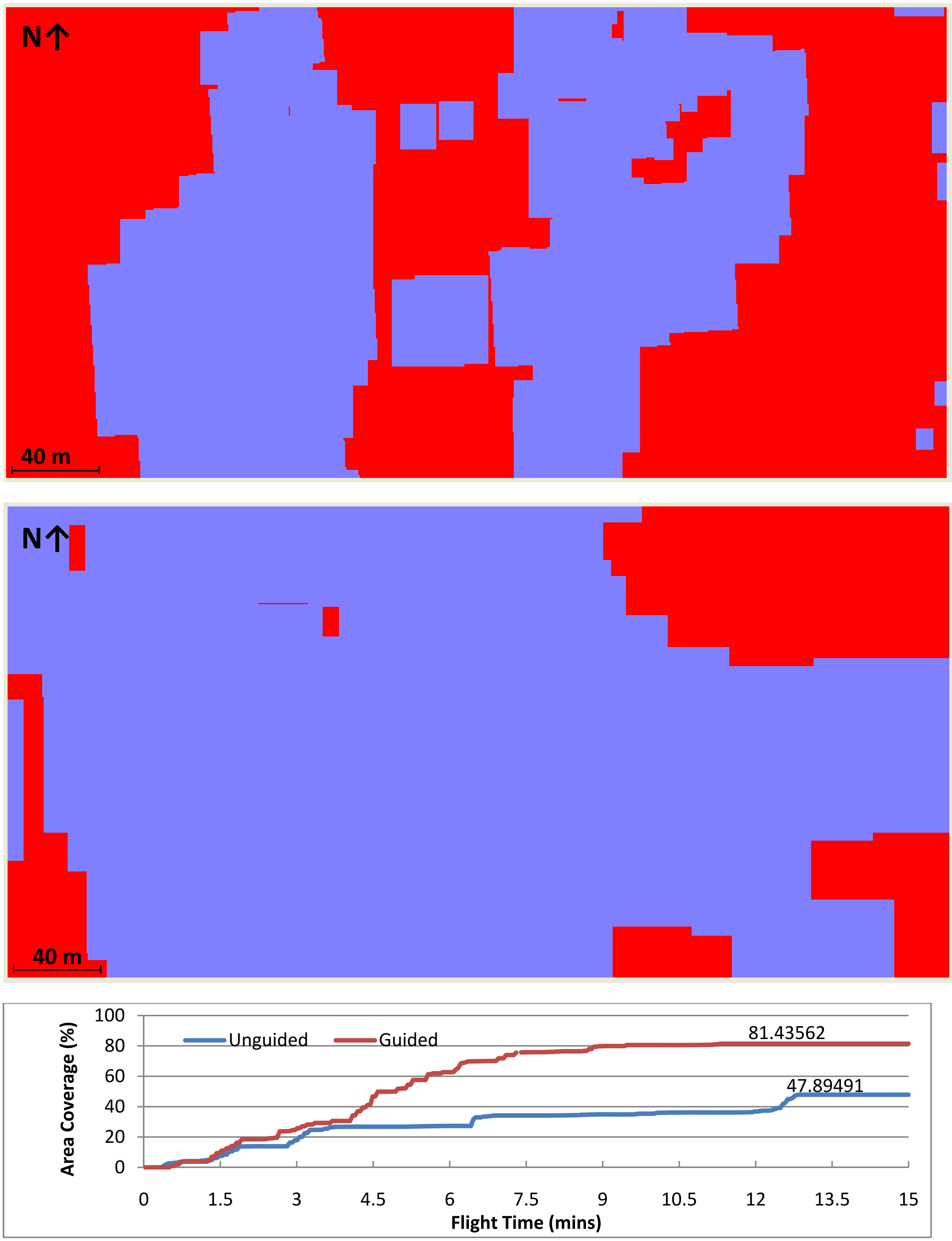

Figure 38 - A comparison of photographic coverage between unguided (top) and guided (bottom) flights followed by the cumulative area sampled over time for unguided (blue) and guided flights (red).

5.2.2 **Participant B – Field Ecologist**

Participant B completed both the unguided and guided flights on the same day. Winds were relatively calm during the flights, which allowed for sharper turns. Flight telemetry values for the unguided and guided flights are shown in Figures 40 and 41 respectively. During the unguided flight, participant B maintained a mean altitude (Figure 40) of 39.93 meters and maintained the UAV within the altitudinal sampling range 64.56% of the time. Participant B maintained the UAV within the latitudinal and longitudinal extent of the study area 89.89% and 92.9% of the flight time respectively. The percentage of time that the Micro LEAPP stayed within the combined altitude, latitude, and longitude boundaries was 82.45% of the flight (Section 5.3).

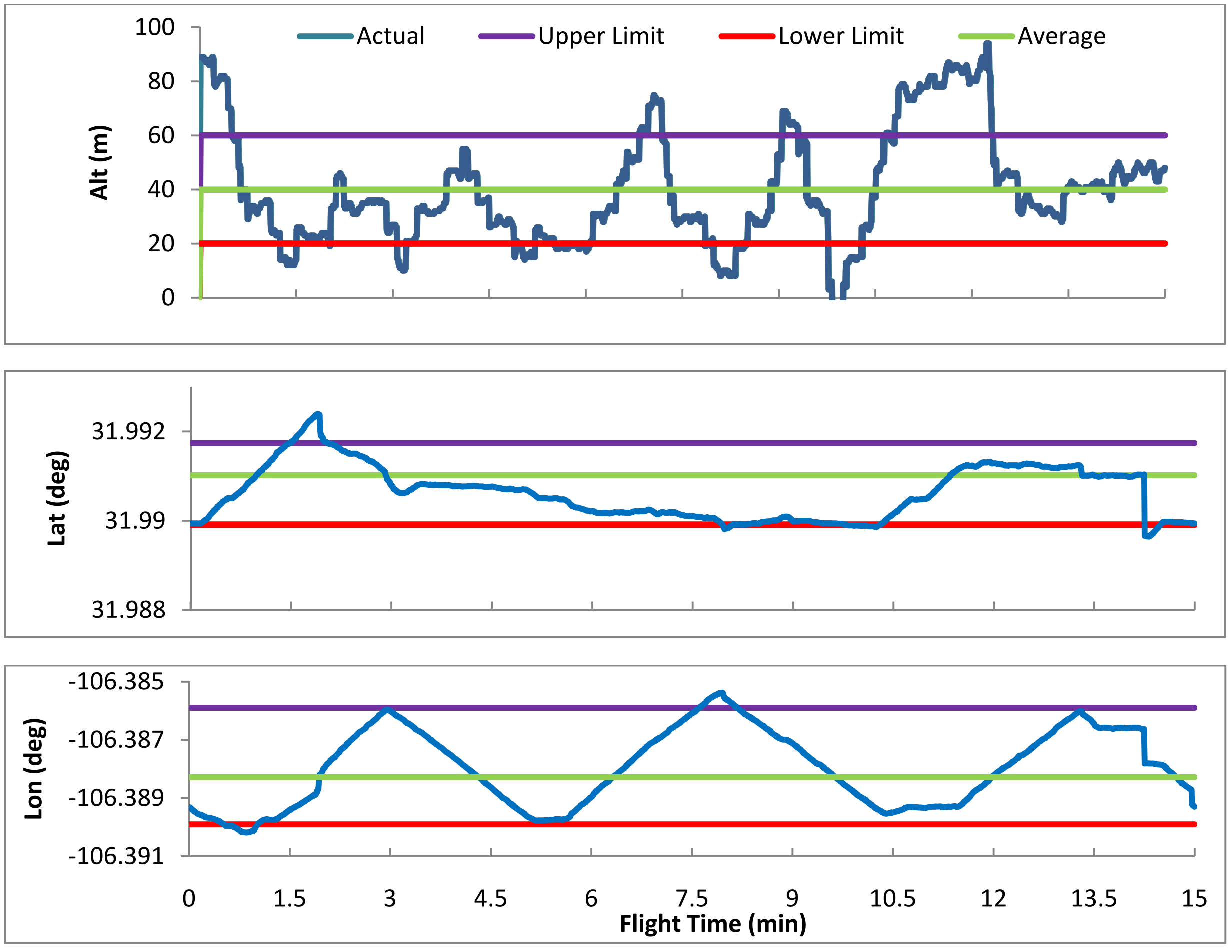

Figure 39 - Plots show the position of the UAV during the flight relative to the altitudinal and spatial extent of the sampling area.

During the guided flight, participant B maintained a mean altitude (Figure 41) of 43.28 meters and maintained the UAV within the altitudinal sampling range 97% of the time (Figure 38). Participant B maintained the UAV within the latitudinal and longitudinal extent of the study area 92.29% and 93.62% of flight time respectively. The percentage of time that the Micro LEAPP stayed within the combined altitude, latitude, and longitude boundaries was 94% of the flight (Section 5.3).

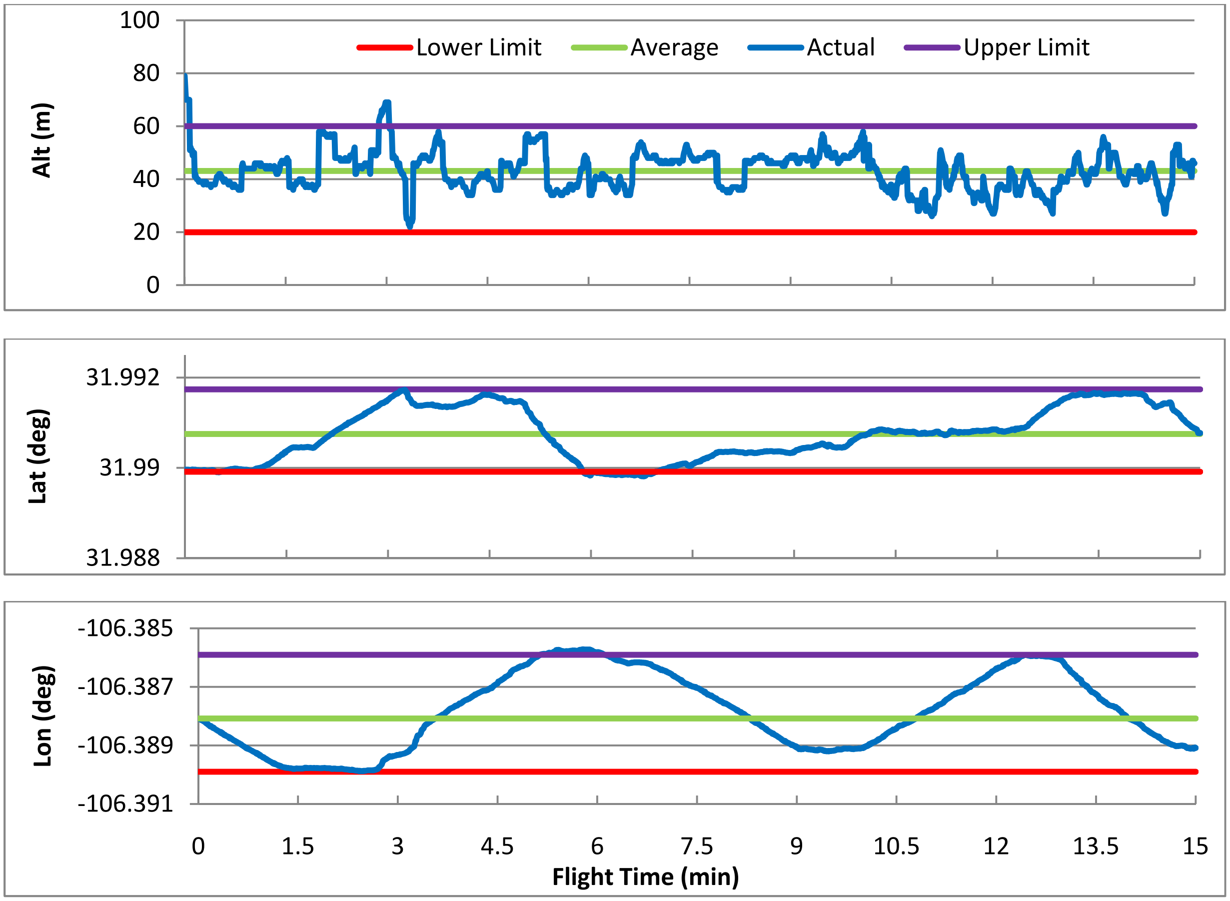

Figure 40 - Plots show the position of the UAV during the flight relative to the altitudinal and spatial extent of the sampling area.

The area of coverage for participant B's unguided and guided flights, and the cumulative coverage over the duration of each flight are shown in Figure 42. The coverage of the guided flight was 29.43% greater in the guided flight compared to the unguided flight and more of the study area was sampled more quickly in the guided flight compared to the unguided flight. The greatest difference between the unguided and guided flights occurred after 12 minutes of flight time.

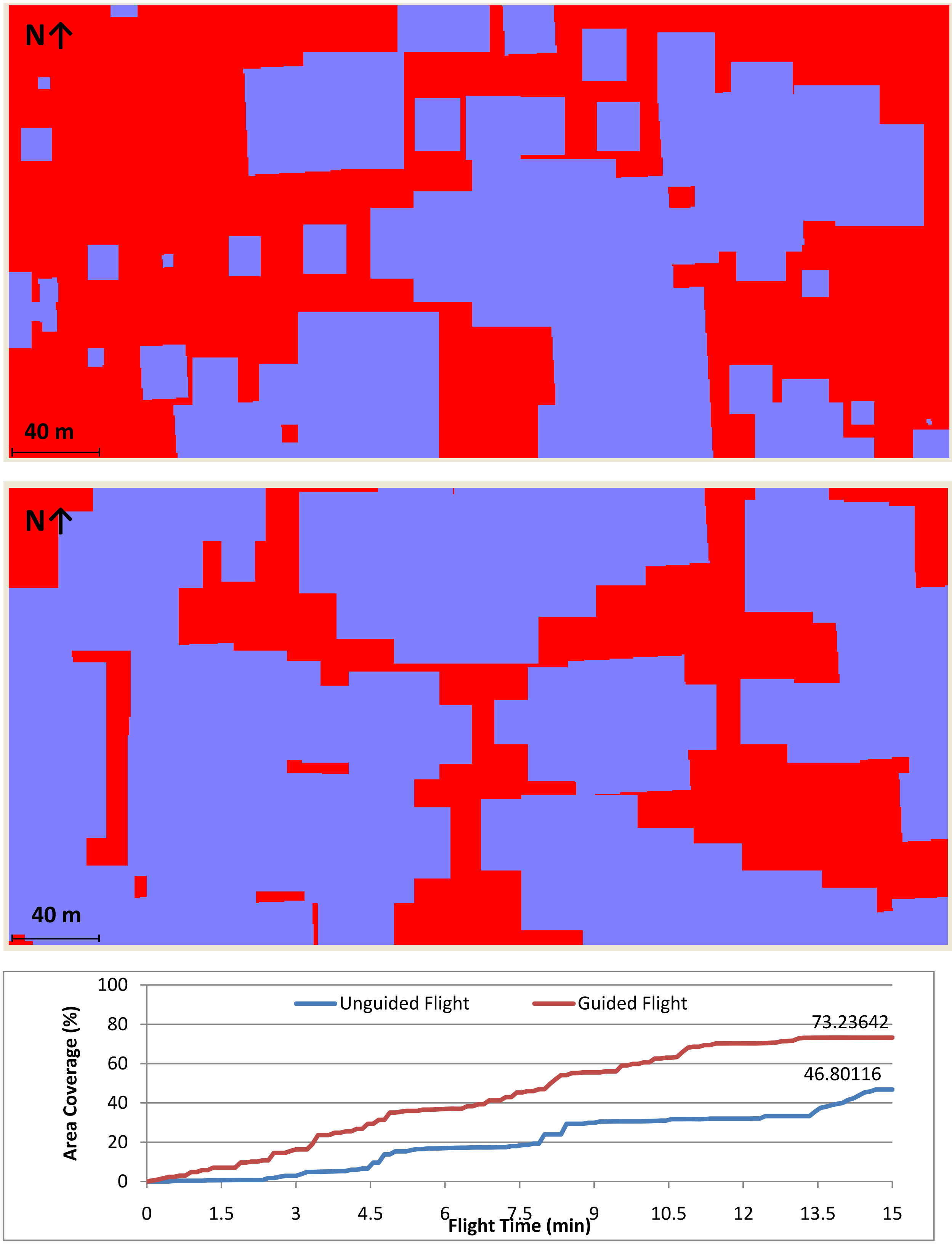

Figure 41 – A comparison of photographic coverage between unguided (top) and guided (bottom) flights followed by the cumulative area sampled over time for unguided (blue) and guided flights (red).

5.2.3 **Participant C – Field Ecologist**

Participant C completed the unguided and guided flights on the same day. Winds were relatively calm during both flights which allowed for sharp turning. Flight telemetry values for the unguided and guided flights are shown in Figures 43 and 44 respectively. During the unguided flight, participant C maintained a mean altitude (Figure 43) of 35.27 meters and maintained the UAV within the altitudinal sampling range 62.99% of the time. Participant C maintained the UAV within the latitudinal and longitudinal extent of the study area 90.05% and 88.41% of the flight time respectively. The percentage of time that the Micro LEAPP stayed within the combined altitude, latitude, and longitude boundaries was 75.05% of the flight (Section 5.3).

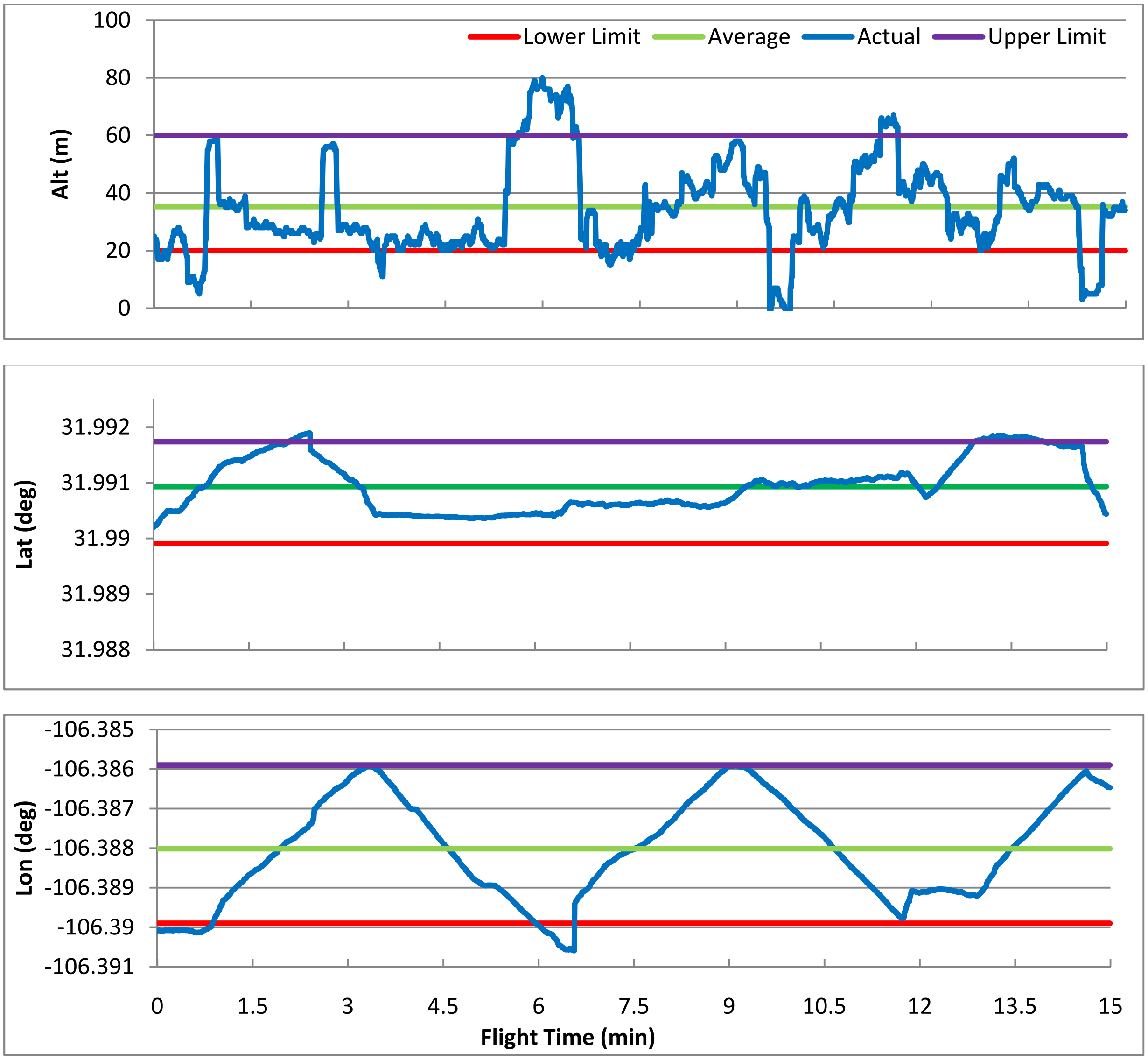

Figure 42 - Plots show the position of the UAV during the flight relative to the altitudinal and spatial extent of the sampling area.

During the guided flight, participant C maintained a mean altitude (Figure 44) of 47.91 meters and maintained the UAV within the altitudinal sampling range 89.54% of the time (Figure 44). Participant C maintained the UAV within the latitudinal and longitudinal extent of the study area 84.77% and 87.72% of flight time respectively. The percentage of time that the Micro LEAPP stayed within the combined altitude, latitude, and longitude boundaries was 76.68% of the flight (Section 5.3).

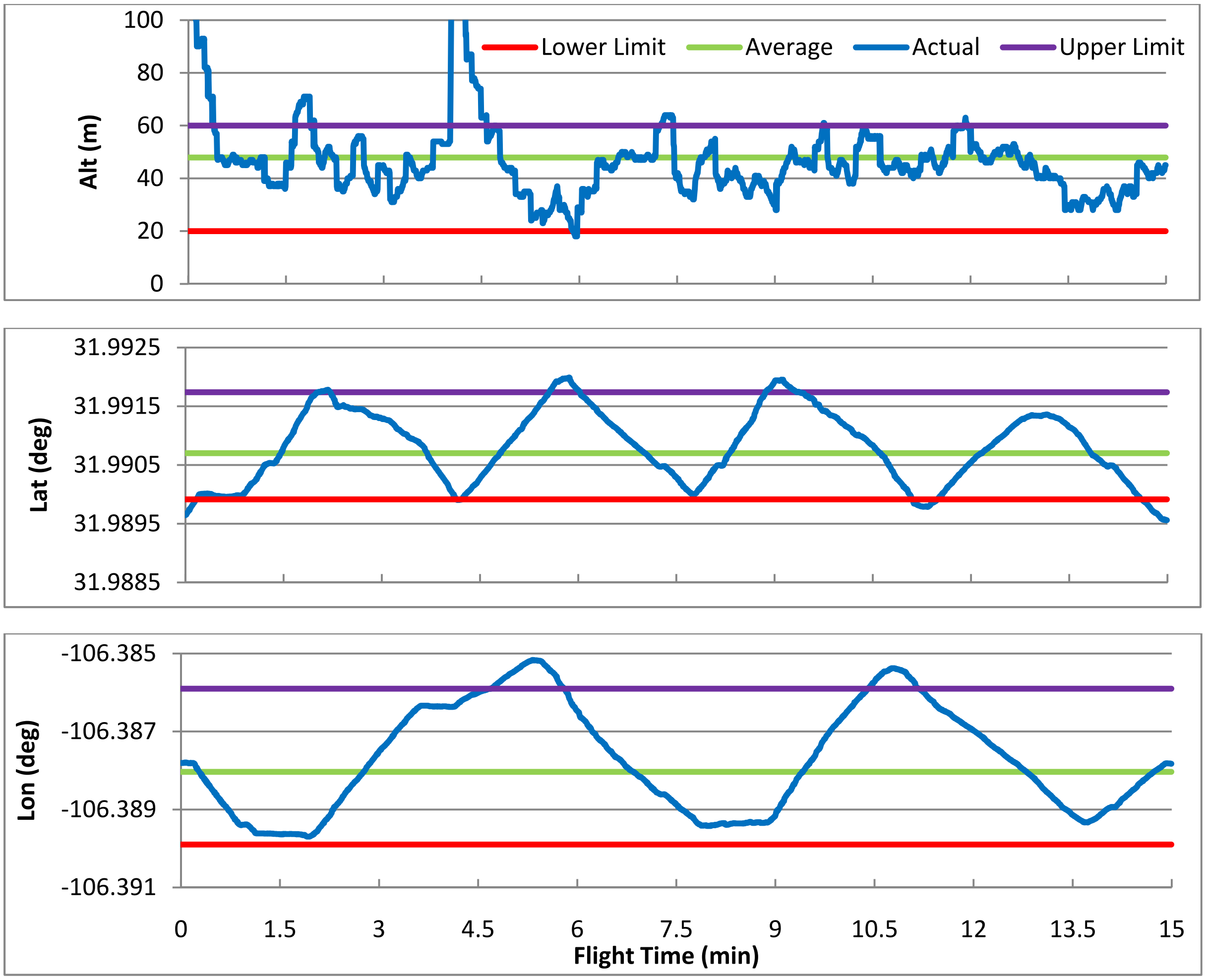

Figure 43 - Plots show the position of the UAV during the flight relative to the altitudinal and spatial extent of the sampling area.

The area of coverage for Participant C's unguided and guided flights, and the cumulative coverage over the duration of each flight are shown in Figure 45. The coverage of the guided flight was 35.76% greater in the guided flight compared to the unguided flight and more of the study area was sampled more quickly in the guided flight compared to the unguided flight. The greatest difference between the unguided and guided flights occurred after 13 minutes of flight time.

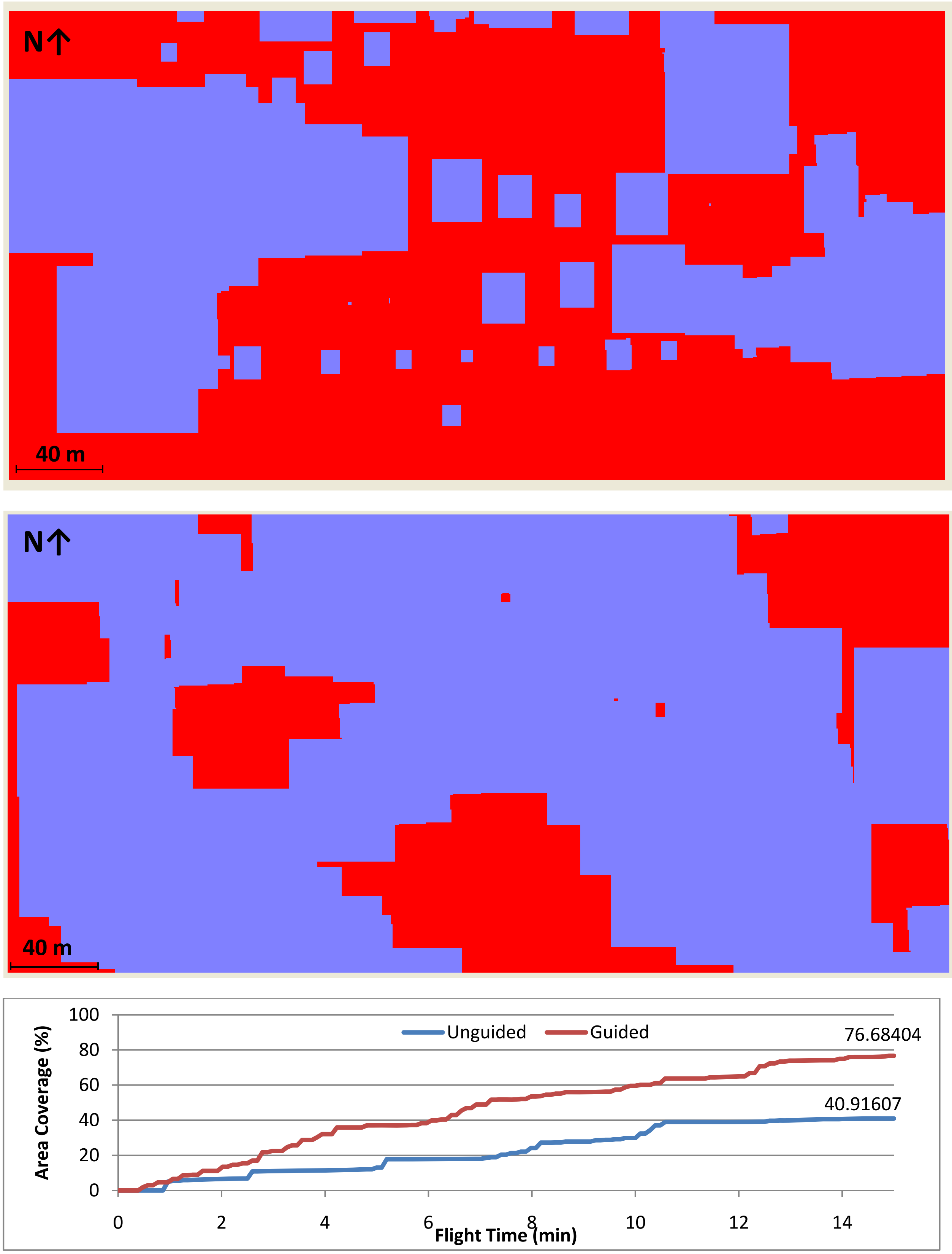

Figure 44 – A comparison of photographic coverage between unguided (top) and guided (bottom) flights followed by the cumulative area sampled over time for unguided (blue) and guided flights (red).

5.2.4 Participant D – Computer Scientist

Participant D completed the unguided and guided flights on different days. Winds were relatively calm during the guided flight, but were relatively gusty during the unguided flight. Flight telemetry values for the unguided and guided flights are shown in Figures 46 and 47 respectively. During the unguided flight, participant D maintained a mean altitude (Figure 46) of 24.59 meters and maintained the UAV within the altitudinal sampling range 53.51% of the time. Participant D maintained the UAV within the latitudinal and longitudinal extent of the study area 40.49% and 90.46% of the flight time respectively. The percentage of time that the Micro LEAPP stayed within the combined altitude, latitude, and longitude boundaries was 61.49% of the flight (Section 5.3).

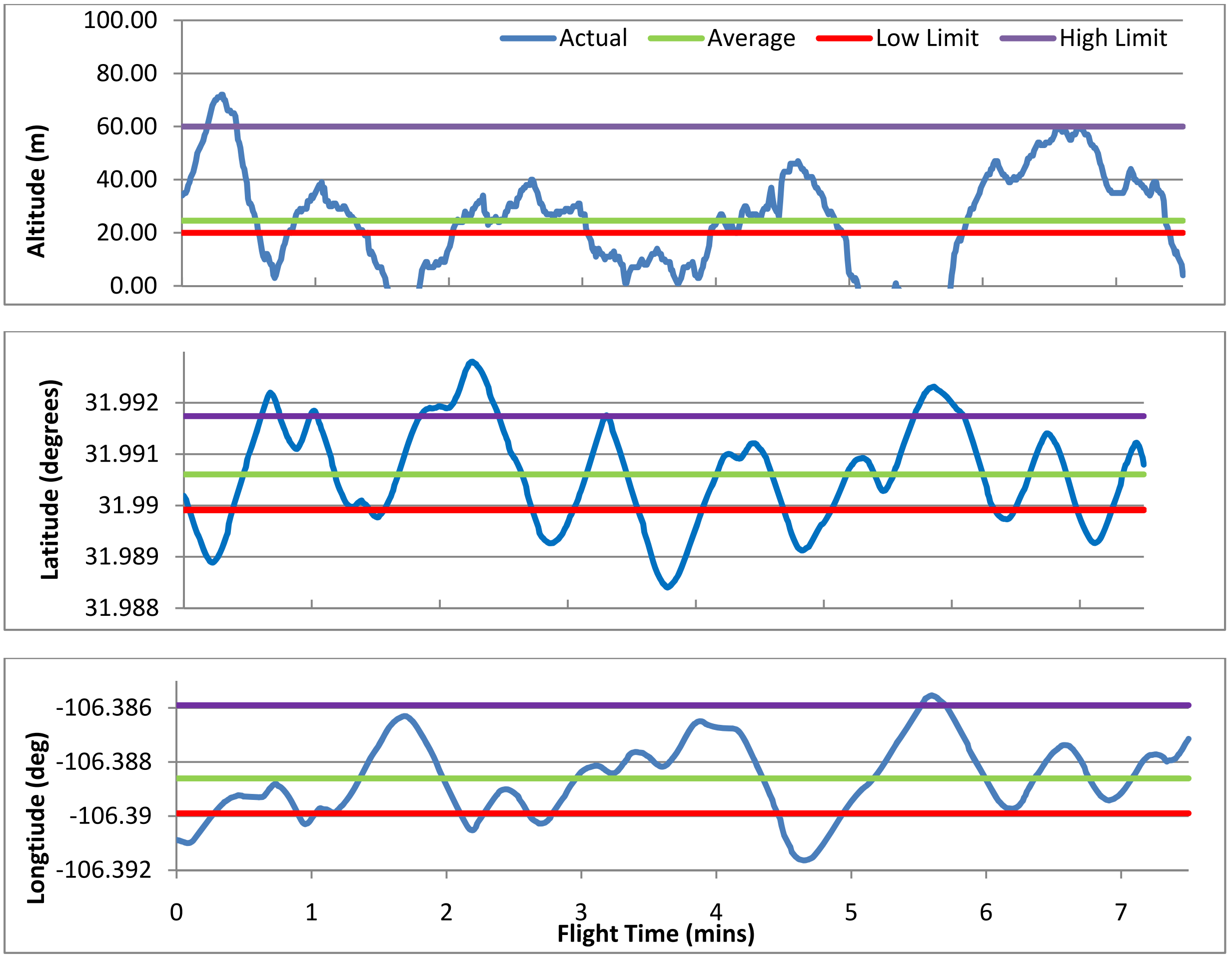

Figure 45 - Plots show the position of the UAV during the flight relative to the altitudinal and spatial extent of the sampling area.

During the guided flight, participant D maintained a mean altitude (Figure 47) of 41.78 meters and maintained the UAV within the altitudinal sampling range 58.54% of the time (Figure 47). Participant D maintained the UAV within the latitudinal and longitudinal extent of the study area 52.1% and 40.49% of flight time respectively. The percentage of time that the Micro LEAPP stayed within the combined altitude, latitude, and longitude boundaries was 66.51% of the flight (Section 5.3).

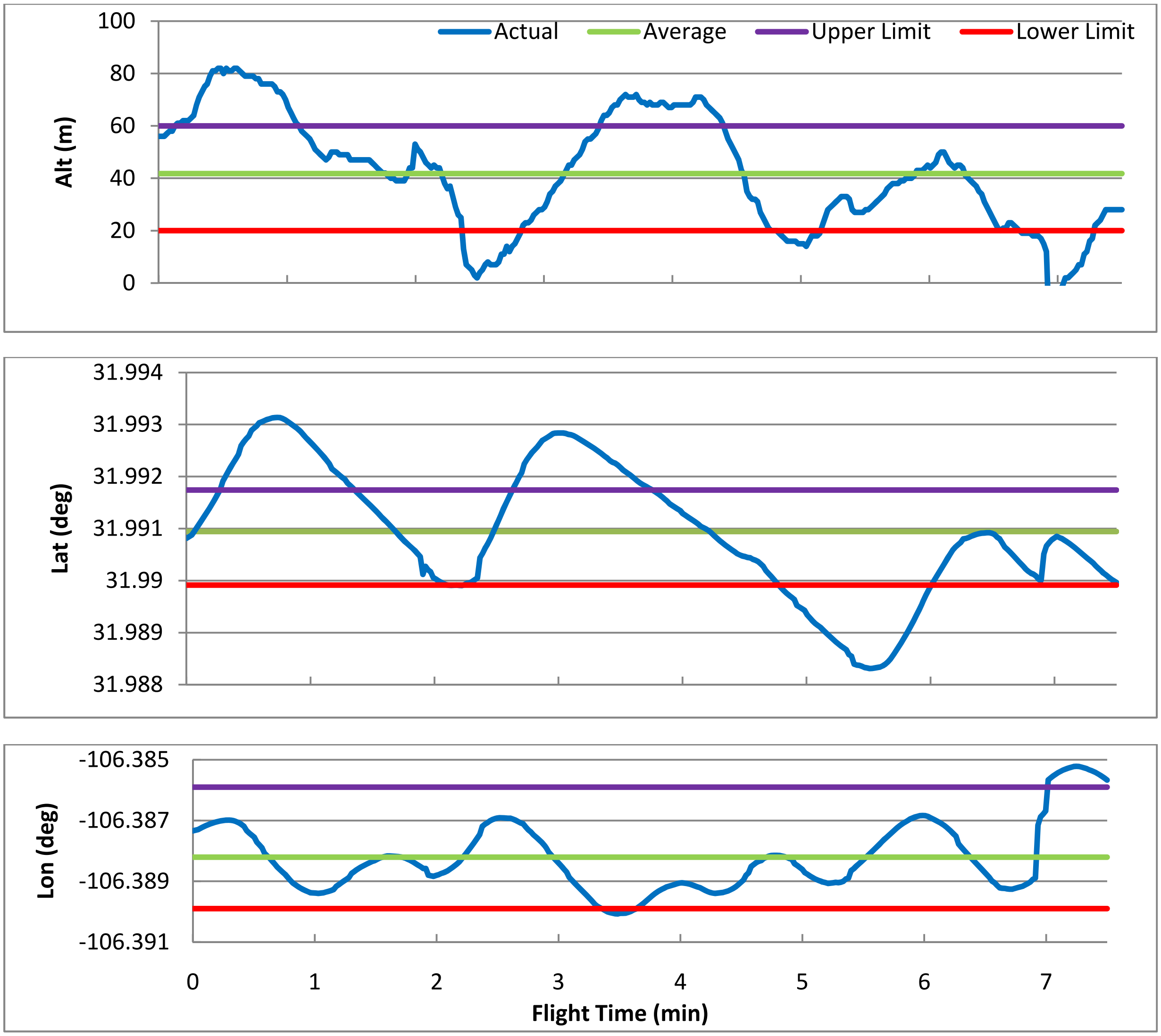

Figure 46 - Plots show the position of the UAV during the flight relative to the altitudinal and spatial extent of the sampling area.

The area of coverage for Participant D's unguided and guided flights, and the cumulative coverage over the duration of each flight are shown in Figure 48. The coverage of the guided flight was 4.41% greater in the guided flight compared to the unguided flight and more of the study area was sampled more quickly in the guided flight compared to the unguided flight. The greatest difference between the unguided and guided flights occurred after 4 minutes of flight time.

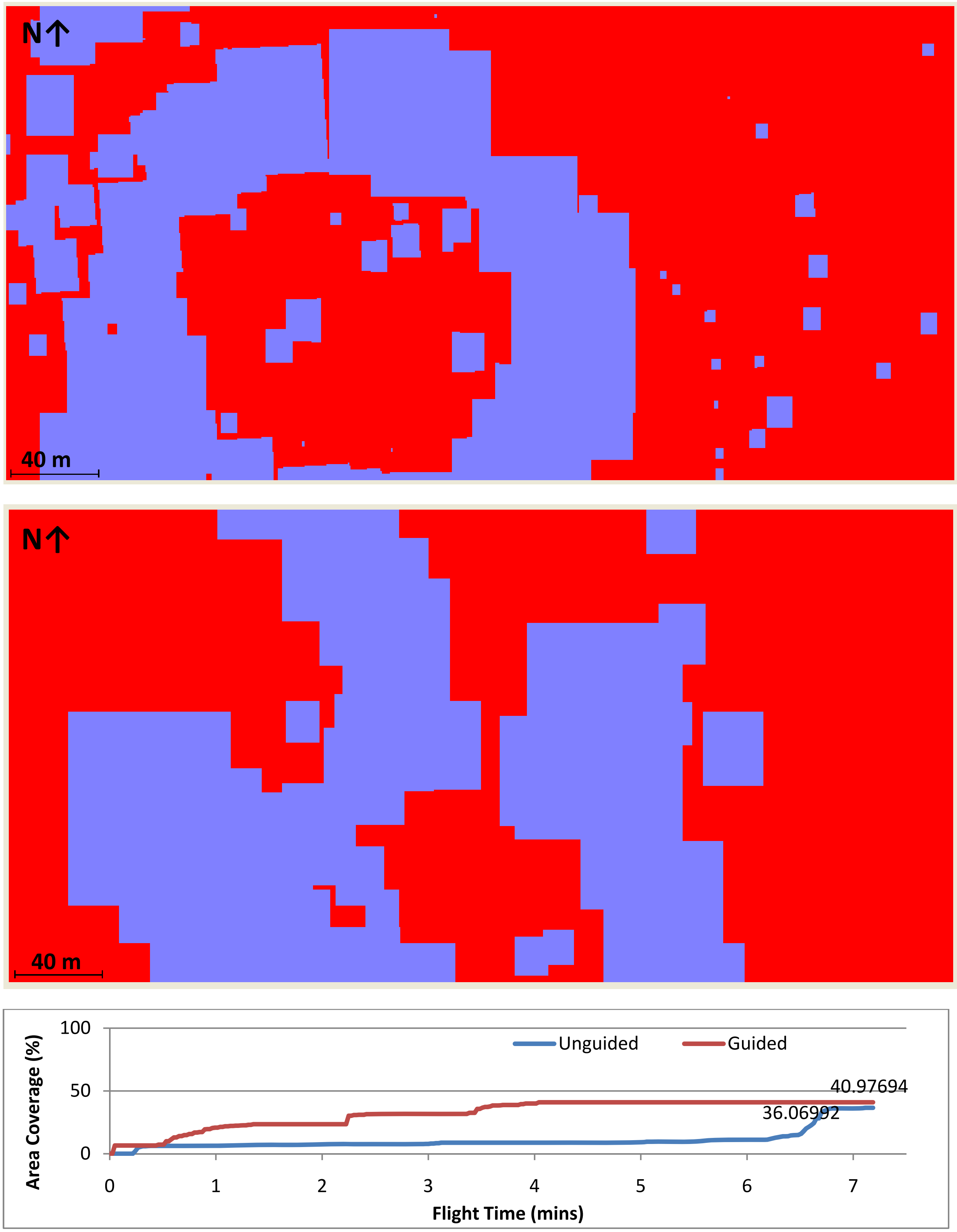

Figure 47 – A comparison of photographic coverage between unguided (top) and guided (bottom) flights followed by the cumulative area sampled over time for unguided (blue) and guided flights (red).

5.3 **Results Summary**

All participants showed an improvement to their photographic coverage of the study area during guided flights (Figure 49). All participants also flew within the boundaries set for the experimental area and altitude a higher percentage of time on the guided flights (Figure 49). The piloting skills of participants ranged from experienced to less experienced (A-D) and this is reflected in the top part of figure 49, which showed that the experienced pilot was more successful in sampling the study area than the other participants. However it seems that the software helped pilots with intermediary skills more than skilled or novice pilots. Although the software improved the percentage of time the UAV was maintained within the combined sampling area for all pilots, there was a greater relative impact of the software in navigating pilots over poorly sampled areas within the study area (Figure 49).

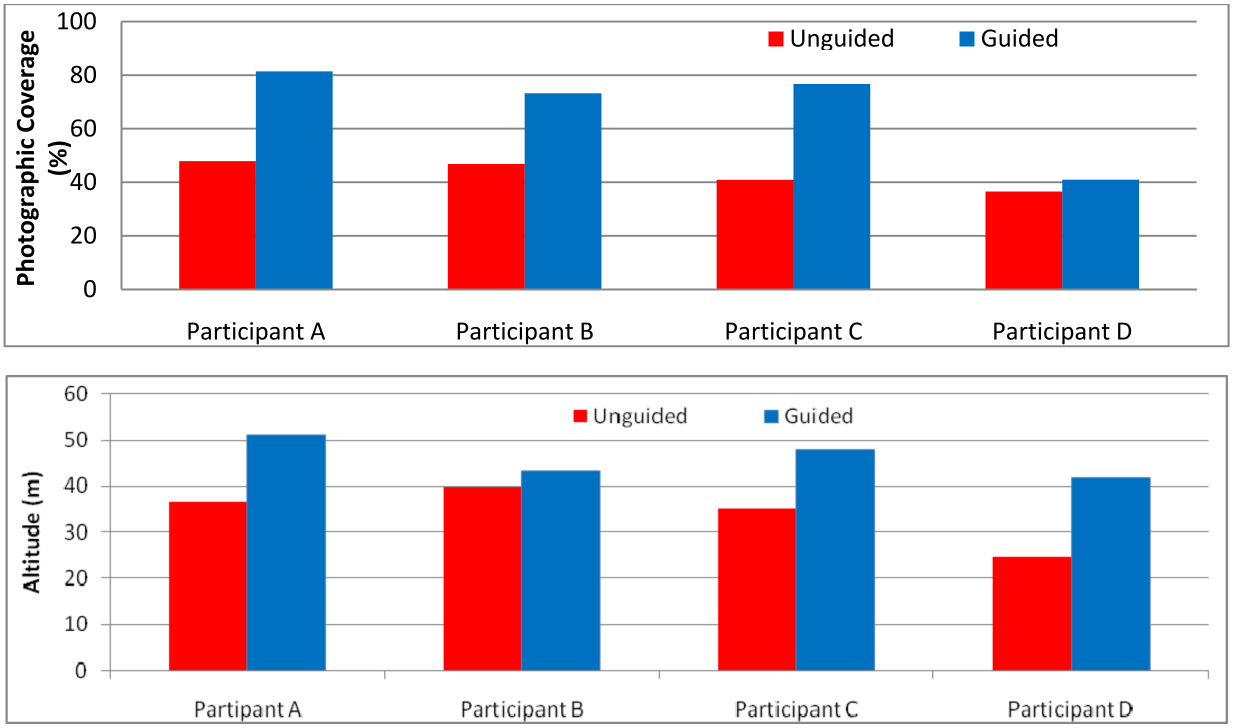

Figure 48 - Photographic area coverage for all participants (top), the average altitude of the UAV over a given a flight (middle), and the percentage of time the UAV flew within the combined boundaries (altitude, latitude, longitude) for all parameters (bottom).

In general data collected from the UAS illustrate that flight performance improved with the aid of the base station software during flight. A detailed summary of all data collected during both guided and unguided flights for all participants is presented in Table 13.

Table 12: This table includes a summary of all parameters collected from the unguided and guided flights for the four participants. The average altitude for each flight is shown along with the percentage of time the UAV was within sampling area boundaries for altitude, latitude, longitude, of both latitude and longitude, and of the combined altitude, latitude, longitude boundaries. The last column displays the percentage coverage of the photographic camera for each flight. Positive net changes are bolded and in green while negative net changes are bolded in red. Boxes highlighted with darker black borders are the greatest net positive change out of all participants.

Participant	Flight Type	Avg. Alt (m)	Alt (%)	Lat (%)	Lon (%)	Lat/ Lon (%)	Lat/ Lon/Alt (%)	Area Coverage (%)
A	Unguided	36.41	80.69	47.36	96.4	71.88	74.82	47.89
	Guided	51.06	84.36	61.77	89.57	75.67	78.57	81.44
Net Change	--------------	**14.65**	**3.67**	**14.41**	**-6.83**	**3.79**	**3.75**	**33.55**
B	Unguided	39.93	64.56	89.9	92.9	91.4	82.45	46.81
	Guided	43.28	97.94	92.29	93.62	92.96	94.62	73.24
Net Change	--------------	**3.35**	**33.38**	**2.39**	**0.72**	**1.56**	**12.17**	**29.43**
C	Unguided	35.27	62.99	90.05	88.41	89.23	75.05	40.92
	Guided	47.91	89.54	84.77	87.72	86.25	87.34	76.68
Net Change	--------------	**12.64**	**26.55**	**-5.28**	**-0.31**	**-2.98**	**12.29**	**35.76**
D	Unguided	24.59	53.51	40.49	90.46	65.48	61.49	36.57
	Guided	41.78	58.54	52.1	89.08	70.49	66.51	40.98
Net Change	--------------	**17.19**	**5.03**	**11.61**	**-1.38**	**5.01**	**5.02**	**4.41**

The average altitude during flight increased from the control to the experiment for all participants with the biggest change documented for participant D (Table 13). The percentage of time the UAV was within the altitude bounds also increased for each participant with participant B having the greatest percentage change. The percentage of time the UAV was within the latitude boundary depended on the participant but the largest changes occurred for participant A. The percentage of time within longitudinal boundary did not change depending on the flight. This might be explained by the experimental area being 200 meters across (north to south) and 400 meters long (east to west). This probably gave all participants more space to perform maneuvers and stay within bounds of the longitudinal experimental area. The percentage of time within the latitude and longitude boundary did increase for most participants but not all. The percentage of time the UAV was maintained within all

boundaries (altitude, longitude and latitude) increased for all participants but more so for participant C. Photographic area coverage increased markedly for all participants with the exclusion of participant D. While participant D's photographic area coverage did improve, it did not change as much as other participants. This could be partly attributed to poor weather conditions on the day of flight and the difficulty in controlling the UAV during gusting winds.

With respect to the objectives of the experiment highlighted in 5.1.1 all the objectives were addressed. The UAS design demonstrated it can gather data for research and then relay operational control data in real time (section 5.1). The experiments illustrate that an untrained pilot cannot only fly the UAV but can collect higher quality more efficiently when using the operational software.

6. General Discussion & Conclusion

The overarching goal of this study was to develop a new UAS for an archetypical environmental science research group composed of non-UAS experts who wish to add a UAS to their existing suite of environmental monitoring tools. Specifically, this thesis:

1. Assessed the research and operational needs of the stakeholder to determine the optimum UAS platform for their needs.
2. Developed a UAV and sensor payload to meet the immediate hardware needs of the stakeholder.
3. Developed a new software tool for UAV operation planning, control, and optimized data acquisition.
4. Tested the operational performance of the newly developed UAS with the stakeholder and assessed how the operation of the UAV benefited from the operational software tool outlined above.

The main objectives this thesis have been addressed in specific chapters, each of which is discussed below.

The selection of an optimum UAV that meets the research and operational needs of the stakeholder is highlighted in Chapter 2. Following enumeration of the needs of the stakeholder, inter-comparison between different UAV platforms was conducted to determine the optimal UAV for the stakeholder. The powered paraglider was chosen as the optimal UAV platform for the stakeholder. Powered paragliders are relatively easy to launch, fly and land; carry a large payload that reduces the need for miniaturization of sensor packages; are easily stored and packaged for transport; and are cost effective compared to other UAV models. Other studies have analyzed and demonstrated powered paragliders as an optimal choice given the constraints of other projects as well (e.g. Thamm and Judex 2006).

Flight testing, modification of the UAV, and sensor payload development is outlined in chapter 3. Unlike most publications, which appear to avoid discussion of such topics as equipment failure, pilot error, and other operational challenges, this chapter highlights such problems. Although some trouble

shooting and repairs were expected for the development of the UAS, the actual problems and challenges encountered far exceeded these. Although some publications also report such challenges Jones IV, Pearlstine, and Percivial, 2006), (Chao, Cao, and Chen, 2010), discussion with experts in the UAS field at a range of national and international meetings where work from this study has been presented (see Curriculum Vitae below), suggests that there is an under appreciation for the time consuming and technical challenges that need to be overcome to develop a usable and useful UASs. Despite the many technical, human, and developmental challenges encountered in this study, a relatively stable and useful UAS has been developed that appears to meet the needs of the stakeholder.

Chapter 4 addressed an overarching need challenging the UAS community – development of software that integrates operation planning, UAS specification, and during-flight operation optimization tools. The system designed in this study targets RC UAS applications in particular, but could be expanded to autonomous systems relatively easily. This tool is generic and has the potential to be applied to other mobile sampling platforms such as unmanned ground vehicles. This software has formed the basis for several additional studies outside of the scope of this thesis, that have developed optimized algorithms to optimize area coverage given a sample area and limited turning radius (Brady et al. 2010). Although several other software tools have been designed to determine flight paths of swarms of UAVs (Ilaya, Bil, and Evans, 2008), this tool appears to be unique and amongst the first to optimize flight paths for RC UAVs.

Operational flight testing using the UAS and software developed in Chapters 3 and 4respectively is documented in Chapter five. Testing examined if the UAS could acquire data for a predefined study area, the capacity of the operational software to improve the spatial coverage and data acquisition of the UAS, and how this depended on the relative experience of the pilot in control. The UAS successfully acquired data that was enhanced by 0.72% to 35.76% when the operational software was used. Pilots also spent between 3.75% and 12.29% more time in the predefined sampling area when guided by the

operational software compared to when this was not used. The largest impact of the operational software, however, was a 4.41% to 35.76% improvement in the coverage of aerial photography acquired for the experimental study area. These successes reinforce the benefits of applied cyber infrastructure development for UASs. An experienced pilot outperformed inexperienced pilots but still benefitted from the guidance offered by the operational software, highlighting the potential gains of experience and improved operational cyberinfrastructure.

Future directions for the project should consider focusing on a redesign of the chassis for the Micro LEAPP. This redesign will help to eliminate recent mechanical failures that were experienced and also allow for a reduction of vibration from the engine. The base station software should be further developed to include additional optional sensor functionality. The inclusion of an optimized flight trajectory tool based on joint research with Dr. Vladik Kreinovich will likely help to further improve flight path optimization (see Appendix A for more information).

The development of UASs has taken place over more than 200 hundred years, with the most rapid development occurring over the past 20 years. The appreciable benefits of UASs to fields such as atmospheric science, agricultural development, and environmental science has largely catalyzed such development and are likely to continue to do this in the future. The large choice of UAVs can be overwhelming to stakeholders new to the field and there has been a distinct lack of decision tools like that presented in Chapter 2 that facilitate this. Stakeholders appear to generally expect technical and other challenges in the development of tailoring of UASs to meet their needs but these are greatly underappreciated and under reported in literature. Although such knowledge may appear to downplay the advances in UAS technologies, it is an important consideration that requires honest and expert evaluation, and could be best documented in a synthesis article comprised of multiple authors with expertise in a wide range of UAV platforms and levels of UAS complexity. The overarching goals of this thesis have been met and new UAS has been successfully developed and tested. The most significant

result of this thesis, however, is that it has shown how a relatively inexperienced research group has been able to greatly enhance their UAS development through the development of such novel tools as a UAV choice protocol, operational optimization software, and a powered paraglider UAV with scalable development potential that can be flown by relatively inexperienced pilots to acquire useful data for the environmental sciences.

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Appendix

A. Tutorial on Set Up of Software

To install the software double click the "setup.exe" file in the "Base Station Software\Installation" folder inside the attached folder with this document. The installation will be automatic. After installation go to your programs folder and select "UAS Control" to start the program. The software comes with a database including sample data. Please note that the software works only on Windows operating systems and with computer that's have Microsoft Access and .NET deployment package 2 or higher.

B. Toward Computing an Optimal Trajectory for an Environment-Oriented Trajectory for an Environment-Oriented Unmanned Aerial Vehicle (UAV) under Uncertainty

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Chapter 1
Toward Computing an Optimal Trajectory for an Environment-Oriented Unmanned Aerial Vehicle (UAV) under Uncertainty

Jerald Brady, Octavio Lerma, Vladik Kreinovich, and Craig Tweedie

Abstract Over the past decade a few but increasing number of researchers have begun using Unmanned Aerial Vehicles (UAVs) to expand and improve upon existing remote sensing capabilities in the Arctic. Due to the limited flight time, it is important to make sure that the UAV follows an optimal trajectory – in which it cover all the points from a given area within the smallest possible trajectory length. Under the usual assumptions that we cover a rectangular area and that each on-board sensor covers all the points with a given radius r, we describe the optimal trajectory. A more complex optimal trajectory is also developed for the situations in which we need to get a more spatially detailed picture of some sub-regions of interest (in which we should have a smaller value r) and it is sufficient to get a less detailed picture (with larger r) in other sub-regions. We also describe the best ways to cover the trajectory in situations in which an UAV missed a spot – due to excess wind or to an inexact control.

1.1 Introduction

Need for environment-oriented UAVs. Arctic observing systems need to be enhanced with improved remote sensing technologies and capabilities – particularly mid-altitude remote sensing using air-borne platforms; see, e.g., [9]. Over the past decade a few but increasing number of researchers have begun using Unmanned Aerial Vehicles (UAVs) to expand and improve upon existing remote sensing capabilities in the Arctic.

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Need for customizable UAVs. Typically UAVs tend to be designed for a specific task or area of operation and so Unmanned Aircraft Systems (UASs) are usually not easily customizable.

It is desirable to develop UASs that allow for customizable sensor packages, reliable communications between ground and aircraft, tools to optimize flight control, real time data processing, the ability to visually ascertaining the quantity of data while the UAV is air-borne, and the ability to launch and land safely in these remote regions.

Our system. We have developed a prototype software system that allows for the customization of UAVs. This software has enhanced communication between ground and the UAV, can synthesize near real time data acquired from sensors on-board, can log operation data during flights, can visually demonstrate the amount/quality of data for a sampling area. The software has been designed to benefit an existing NSF Arctic Observing Network project that will focus on the remote sensing of landscape-scale vegetation structure and function.

Our UAS includes a paraglider UAV that has a suite of sensors suitable for characterizing hyperspectral reflectance and other surface properties. This paraglider UAV allows low and slow flying, has a limited range but a relatively large (ca. 13 kg payload). Sensors on-board relay operational flight data (airspeed, ground speed, latitude, longitude, pitch, yaw, roll, and video) as well a series of customizable sensor packages. Additional sensors can be added to an on-board laptop or a CR1000 data logger; see Fig. 1.1.

Need for coverage. The purpose of the UAV measurements is to describe the values of the environment-related physical quantities such as temperature, humidity, etc., at all possible locations within the rectangular observation area.

Of course, this "all" cannot be understood literally: the observation area has infinitely many points, and it is not possible to measure the value of the quantity is all these points. From the practical viewpoint, it is not necessary to take the measurements in all infinitely many points: usually, we know that the values at nearby points are practically indistinguishable. Specifically, a user usually provides us with a threshold r_0 such that the values of the desired quantity at points P and P' of distance $d(P, P') \le r_0$ are indistinguishable. In this sense, to make sure that we know the value at each point within the observation area, we have to make measurements in such a way that every point from the rectangle is at a distance $\le r_0$ from some point at which a measurement was made – i.e., from one of the points on the UAV's trajectory.

Need to take uncertainty into account. In practice, it is not possible to maintain the exact trajectory of a UAV, we can only maintain the desired trajectory with a certain accuracy r_1. In view of this uncertainty, if we simply make sure that every point P in the area is at a distance $d(P, P') = r_0$ from some point P' on the desired trajectory, the actual trajectory point P'' may

Fig. 1.1 Our UAV in flight

be at a distance $d(P', P'') = r_1$ from P' and thus, at a distance

$$d(P, P'') = r_0 + r_1 > r_0$$

from P. Thus, to make sure that even with this uncertainty, we have the desired coverage (with a distance threshold r_0), we need to guarantee that every point P from the observation area is at such a distance $d(P, P')$ from some point P' from the trajectory that $d(P, P'') \le d(P, P') + d(P', P'') \le r_0$ even when the distance $d(P', P'')$ attains the largest possible value r_1. In other words, we need to make sure that $d(P, P') + r_1 \le r_0$ For this inequality to be satisfied, we must make sure that $d(P, P') \le r \stackrel{\text{def}}{=} r_0 - r_1$.

Thus, to provide the desired coverage under this uncertainty, we need to make sure that every point P from the observation area is at a distance $\le r$ from some trajectory point.

Need for trajectory optimization. Due to the limited flight time, it is important to make sure that the UAV follows an optimal trajectory – in

which it cover all the points from a given area within the smallest possible flight time – i.e., at the smallest possible trajectory length. Such a trajectory is described in this paper.

Comment. Most of our results were first announced in [3, 4].

1.2 Towards an Optimal Trajectory

The problem: reminder. We operate under the usual assumptions that we cover a rectangular area and that each on-board sensor covers all the points with a given radius r (see discussion above).

We are looking for trajectories that provide the desired coverage of the area – i.e., for which every point from the area is located at a distance $\le r$ from some point on this trajectory. Our objective is to come up with the trajectory that is "optimal" in the sense that it is the shortest among the trajectories that provide the desired coverage.

Analysis of the problem. Each trajectory piece of length ΔL_i covers the area $A_i \approx 2r \cdot \Delta L_i$; see Fig. 1.2.

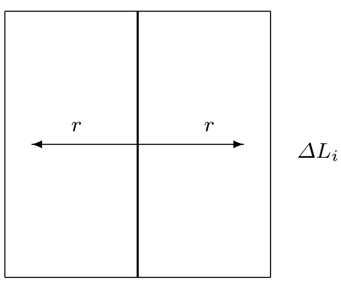

Fig. 1.2 Coverage

So, a trajectory of length $L = \sum_i \Delta L_i$ covers the area

$$A \le \sum_i A_i = \sum_i (2r \cdot \Delta L_i) = 2r \cdot \sum_i \Delta L_i = 2r \cdot L.$$

Thus, to cover a region of area A_0, we need a trajectory of length $L \ge \dfrac{A_0}{2r}$.

Asymptotically optimal trajectory. The following natural trajectory is therefore asymptotically optimal, see Fig. 1.3. Indeed, in the region of area $A_0 = L_1 \cdot L_2$, we have $\dfrac{L_1}{2r}$ pieces of length $\approx L_2$ each. The total length is $L \approx \dfrac{L_1}{2r} \cdot L_2 = \dfrac{L_1 \cdot L_2}{2r} = \dfrac{A_0}{2r}$, i.e., this trajectory is (almost) optimal.

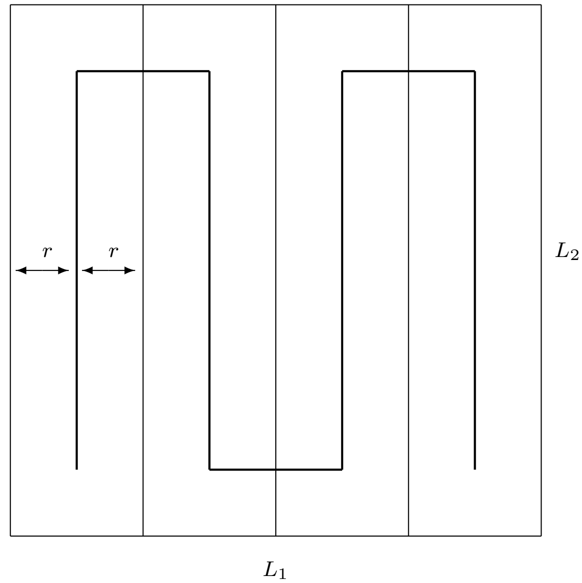

Fig. 1.3 An almost optimal trajectory

The above asymptotically optimal trajectory does not cover all the points. The minor problem with this trajectory is that the corner points (marked bold on Fig. 1.4) are not covered, because the distance from the trajectory to each corner point is $\sqrt{r^2 + r^2} = \sqrt{2} \cdot r > r$.

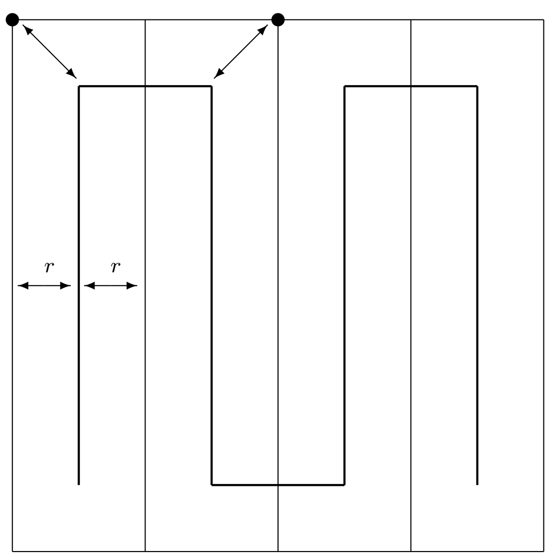

Fig. 1.4 For the asymptotically optimal trajectory, corner points are not covered

Precise formulation of our optimization problem. In this paper, we will consider trajectories which consist of two linear segments in each corner area, i.e., trajectories in which the original linear trajectory coming to the point P_1 is followed by two segments P_1P_2 and P_2P_3 that go into the next "corridor" of width $2r$; see Fig. 1.5.

Under this assumption, the question is how to select the points P_2 and P_3 in such a way that the total path $\ell = d(P_1, P_2) + d(P_2, P_3)$ is the shortest among all the paths that cover the whole corner area (i.e., for which every point from this area is at a distance of $\le r$ from some point on a trajectory).

Practical comment. The restriction to two-segment trajectories comes from *practice*: it is much easier to control the UAV along a linear trajectory, so adding too many segments would make the control difficult to execute in practice.

Mathematical comment. From the purely *mathematical* viewpoint, it may be interesting to analyze which trajectories are optimal among all possible trajectories – not necessarily the two-segment ones.

This problem is similar to the known Kolmogorov's definition of an ε-entropy of a set S (given originally in [6, 7]) as the smallest number of points for which every point in the set S is at a distance $\le \varepsilon$ from one of the selected points. What we are looking for can be viewed as a 1-D analogue of this notion: find the smallest length of a connected curve for which every point in the set S is at a distance $\le \varepsilon$ from one of the points on this curve.

Instead of considering all possible curves, we can also take into account the fact that sharp turns of a UAV are sometimes difficult to execute, and there is usually a bound on the curve's curvature. From this viewpoint, it may be interesting to consider curves whose curvature is bounded by a given value B.

An optimal trajectory: description. To cover the corner points like C, we propose a fin-like modification of the above trajectory; see Fig. 1.5. Specifically, after following the original trajectory up to the point P_1 which is located $2r$ units below the upper boundary, we then go straight to the point P_2 on the line CP' at a distance r from the corner point C. Then, we follow another straight line to the point P_3, etc.

Let us prove that this trajectory indeed covers all the points, and that, among trajectories that cover all the points, this fin-line trajectory is optimal (we will describe in what sense this trajectory is optimal). To illustrate this proof, we will use Fig. 1.6.

Proof that the new trajectory covers all the points. Let us first show that this trajectory indeed covers all the points. Indeed, in the given corridor of width $2r$, every point P below the line P_1P_0 is covered by the trajectory point which lies on the same horizontal line as P. Whether this point P is to the left or to the right of the trajectory, the distance is always $\le r$. A similar

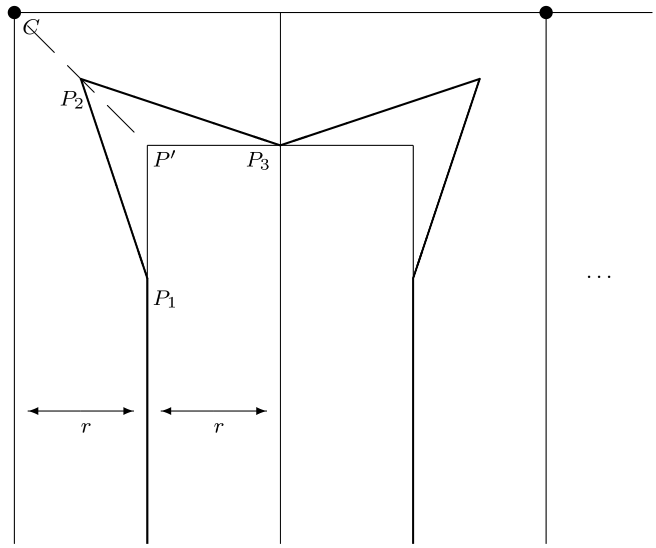

Fig. 1.5 An optimal trajectory

argument can be made about all the other points within this corridor, except for the points within the square $P_0P_1P'P_3$.

To prove the coverage for points from this square, we draw two lines through the point P_0:

- the line P_0P_1' parallel to the segment P_3P_2 of the trajectory, and
- the line P_0P_3' parallel to the segment P_1P_2 of the trajectory.

Both lines are at distance $\le r$ from the corresponding trajectory segments. Thus:

- all the points from the square $P_0P_1P'P_3$ which are above the new line P_0P_1' are covered, because they are at a distance $\le r$ from the segment P_3P_2;
- all the points from the square $P_0P_1P'P_3$ which are to the left of the new line P_0P_3' are covered, because they are at a distance $\le r$ from the segment P_1P_2.

Thus, all the points from the square $P_0P_1P'P_3$ are indeed covered. This completes the proof of coverage.

Proof that the new trajectory is indeed optimal. First, let us take into account that we need to cover points right above the point P_0 (which is $2r$ units below the upper boundary). If P_3 is less than r units away from the

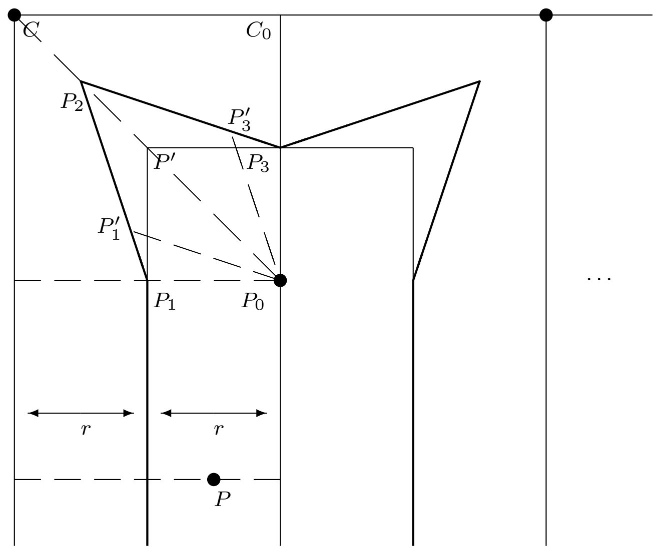

Fig. 1.6 Proof of coverage and optimality of the new trajectory

upper boundary, then these points are not covered. So, P_3 must be at least r units away from the upper boundary.

Similarly, to cover the point C_0 on the upper boundary, we need to make sure that the point P_3 is at a distance of at most r from the upper boundary. By combining these two conclusions, we thus deduce that the point P_3 must be at exactly r points from the upper boundary – i.e., at the same location as for the original trajectory. The only remaining question is where to place the turning point P_2.

For fixed points P_1 and P_3, and for a fixed total length $\ell = d(P_1, P_2) + d(P_2, P_3)$, the set of all the corresponding points P_2 forms an ellipse, with P_1 and P_3 as foci; see, e.g., [2, 5]. At least one of these points of this two-segment piece of the trajectory must cover the corner point C, i.e., it must be at a distance $\le r$ from C. Thus, at least one point from this trajectory must be either within or at the border of the circle of radius r centered at the corner point C. Thus, the circle and the ellipse must intersect. If they are not tangent to each other at the intersection point, then we can decrease the value ℓ, and get a smaller ellipse which will still be intersecting. Thus, for the smallest value, the circle and the ellipse must be tangent to each other at the intersection point. One can show that under this condition, the point P_2 should be on the line PC – at a distance r from the corner point C, i.e., exactly where it is in our arrangement. The optimality is proven.

Comment. It is worth mentioning that the situation is symmetric with respect to reflection over the line $CP'P_0$: under this reflection, P_1 turns into P_3 and vice versa.

Practical comment: how to actually control the UAV. Once the optimal trajectory has been determined, the next question is how to control the UAV so that it follows this trajectory.

- For *manual* control, it is important to provide a good visualization of the past trajectory and of what it has already covered; such a visualization is described, e.g., in [8].
- For *automatic* control, control algorithms are described, e.g., in [1, 10].

1.3 What If We Want Different Coverage In Different Sub-Regions

Formulation of the problem. In some situations, we need to get a more spatially detailed picture of some sub-regions of interest (in which we should have a smaller value r), and it is sufficient to get a less detailed picture (with larger r) in other sub-regions.

Solution: main idea. In this case, it is reasonable to use optimal (or asymptotically optimal) arrangement in each sub-region.

Example: case of four sub-regions. For example, if we need four different values r_i in four different quarter-regions, then we should combine the corresponding optimal trajectories in four subregions as on Fig. 1.7.

In particular, if we use asymptotically optimal trajectory in each subregion, we get the following trajectory; see Fig. 1.8.

General case. The corresponding sub-division can be iterated if within each quarter-region, we have subregions with different desired coverage.

1.4 Tailwind Problem

Idealized case. In the above text, we assumed that a UAV follows the desired trajectory. In this case, we get a full coverage of the desired region.

Tailwind: a problem. In practice, an UAV can deviate from the planned trajectory. As a result, we may not cover some points in the region.

One reason why this may happen is tailwind. In the presence of a strong tailwind, the UAV flies too fast, there is not enough time for sensing.

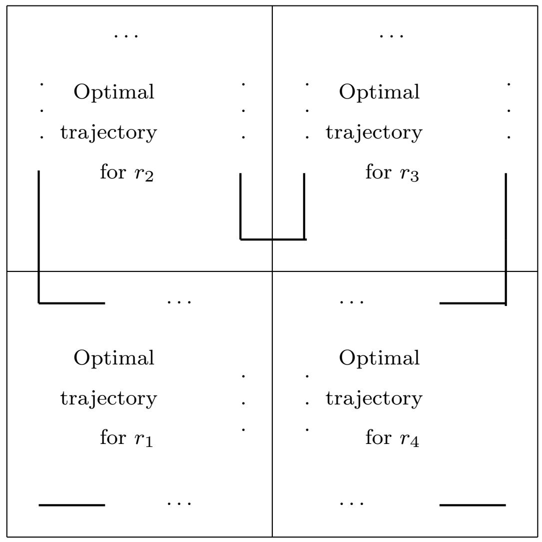

Fig. 1.7 Case when we need different coverage in different subregions

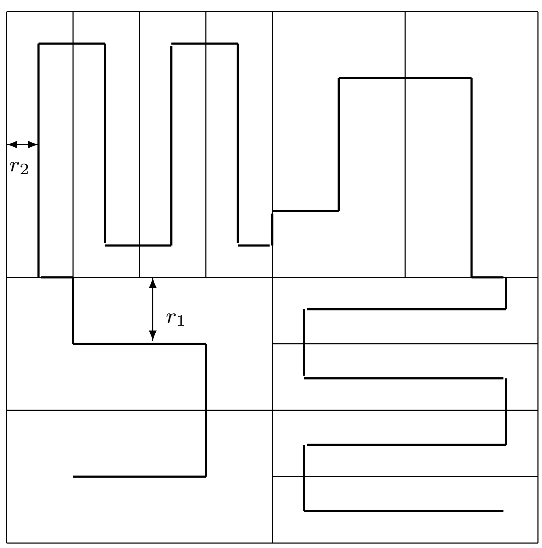

Fig. 1.8 Proof of coverage and optimality of the new trajectory: example

A solution to the tailwind problem. In the case of a tailwind, a natural solution is to change the direction of the trajectory, so that the wind would no longer be a tailwind.

This solution is illustrated below. In Fig. 1.9, we show the original plan. In Fig. 1.10, we show how this plan is disrupted by tailwind. In Fig. 1.11, we show how the change in direction changed the original trajectory.

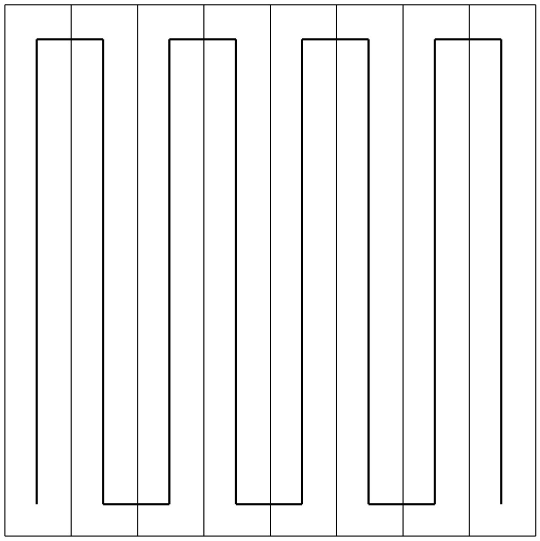

Fig. 1.9 Original plan

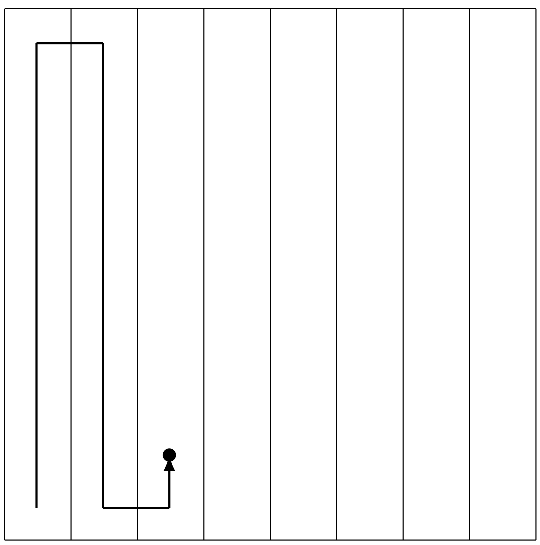

Fig. 1.10 Tailwind problem: plan disrupted by tailwind

1.5 Missed Spot Problem

Missing spot: formulation of the problem. In the ideal case, we should get a perfect coverage of the area; see Fig. 1.12. In practice, however, a sensor may malfunction when the UAV is flying over a certain area. In this case,

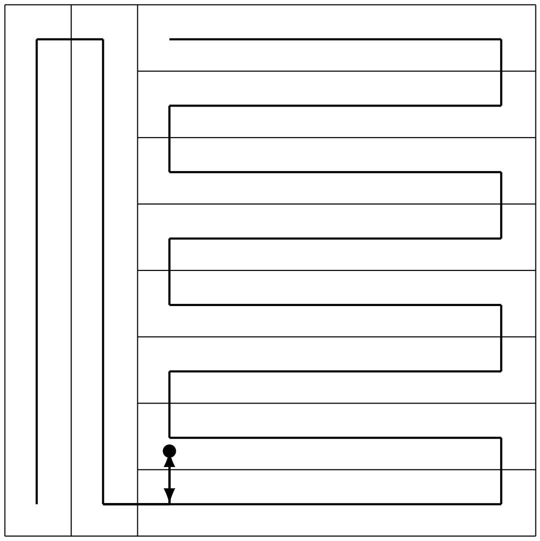

Fig. 1.11 Solution to the tailwind problem: change direction

while the trajectory is still covering the whole area, the measurement coverage misses a spot; see Fig. 1.13.

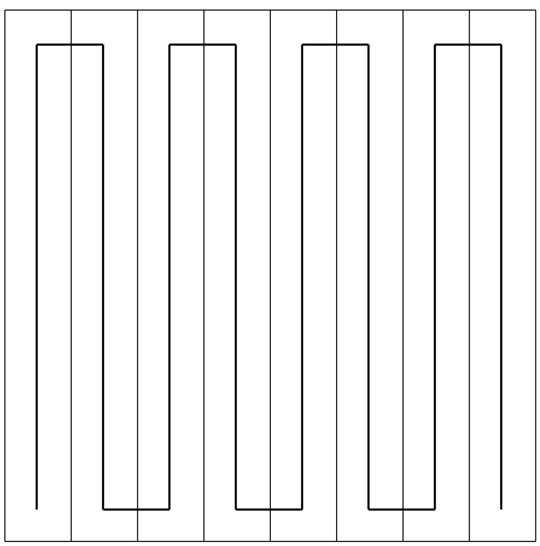

Fig. 1.12 Ideal case: perfect coverage of the area

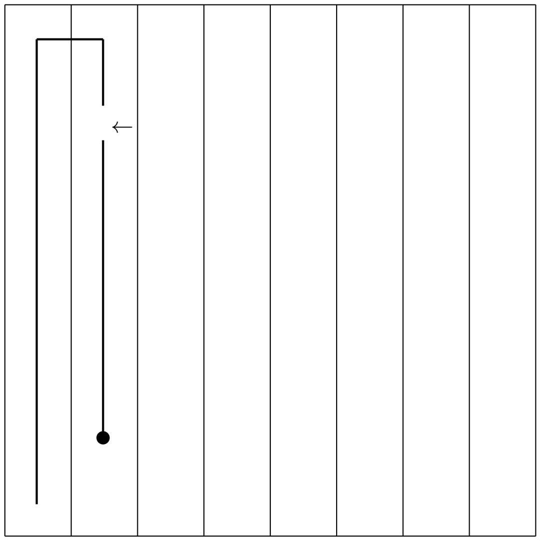

Fig. 1.13 missed Spot problem

Additional problem. The additional problem is that by the time we learn about the disruption, the plane has already moved along the planned trajectory; see Fig. 1.13.

A seemingly natural idea. In this case, if we left a missing spot, a natural idea is:

- to come back, to cover this spot, and then
- to continue along the original trajectory.

This idea is illustrated on Fig. 1.14

Limitation of this seemingly natural solution. The main disadvantage of the above (seemingly natural) solution is that we waste time by covering the same segment AB (see Fig. 1.14) three times:

- when we followed the original path,
- when we go back, from the point A t which we realized that we missed the point, to the point B that we missed; and
- when we go back, from the point B, to the point A, to resume the original trajectory.

A better idea: repair the spot on the next iteration. A better idea – an idea that avoids the above-mentioned waste – is to continue and to re-visit the missed spot on the next iteration; see Fig. 1.15.

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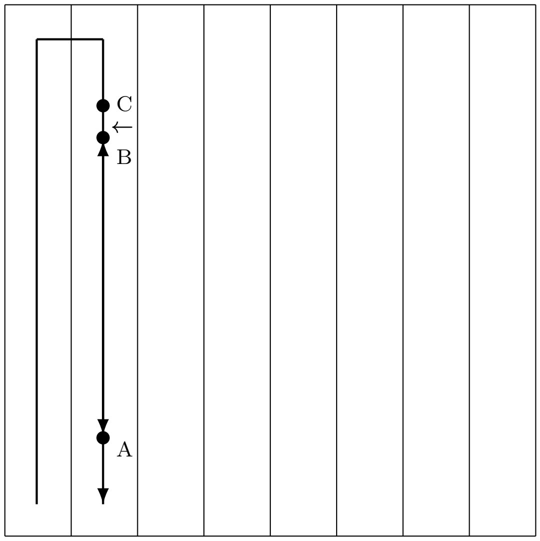

Fig. 1.14 Missed spot problem, seemingly natural idea: come back, then continue

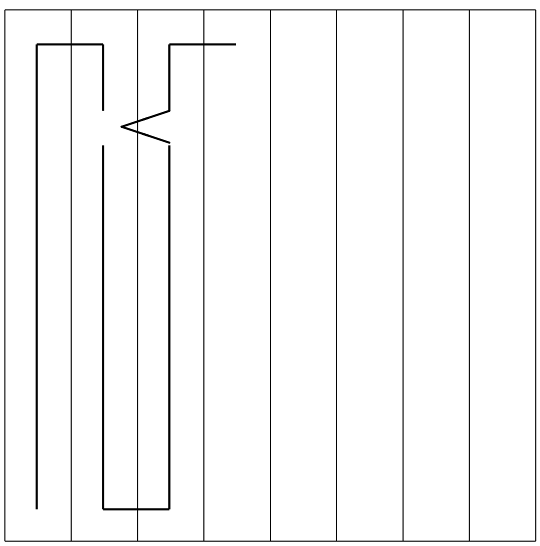

Fig. 1.15 New idea: repair the spot on the next iteration

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Curriculum Vita

Jerald Brady was born in Lincoln, Nebraska. The first son of Jerald Brady and Sharon Brady, he graduated from J.M. Hanks High School in El Paso, Texas, in the spring of 2001 and entered the University of Texas at El Paso in 2002. He pursued a bachelor's degree in computer science and worked at a software development internship with a local company in 2005 where he developed a software suite that the company regularly sells. Later, while working as a teaching assistant in the computer science department he became president of the local Association of Computing Machinery at UTEP and completed his bachelor's with a Major GPA of 3.83. After completing his degree he entered the Environmental Science program student at UTEP as a Master's student while working on a 3D Visualization project planning tool developed for the National Science Foundation named ARMAP 3D. This project along with his work on the Unmanned Aircraft System with the System Ecology Laboratory at UTEP allowed him to present for three years at the American Geophysical Union (2007-2009) as well as at the Society for the Advancement of Chicanos and Native Americans in Science conference for 2007 and 2008. In the spring of 2008, he entered the Graduate School at The University of Texas at El Paso.

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