ABSTRACT

OPEN SOURCE UAV PLATFORM DEVELOPMENT FOR AERIAL PHOTOGRAPHY

By

Daniel L. Richards

Aerial photography is an important layer in Geographic Information Systems (GISs), and generally provides the base layer from which many other digital map layers are derived. Capturing these photos from a traditional full-sized airplane is a complex and expensive process. The recent development of Unmanned Aerial Vehicles (UAVs) and associated technology are providing an alternative to the traditional aerial mapping process. UAVs produced by popular commercial vendors are effective at capturing photos, but are highly expensive to acquire, and equally expensive to maintain.

This research project demonstrates the development and successful implementation of a relatively inexpensive ($2000) unmanned aerial vehicle capable of acquiring high-resolution digital aerial photography. The UAV was developed using open source technology and commercially available components. The methods outlined encompass the platform selection, component inventory, design, construction, configuration, implementation, and testing of the UAV, as well as an analysis of the photography produced by the process. This approach can be used by others to implement similar UAV projects.

OPEN SOURCE UAV PLATFORM DEVELOPMENT FOR AERIAL

PHOTOGRAPHY

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Committee Members:

Suzanne Wechsler, Ph.D. (Chair)
Christopher Lee, Ph.D.
Michael Shensky, M.A.

College Designee:

Amy Bippus, Ph.D.

By Daniel L. Richards

B.A., 1989, California State University, Long Beach

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LIST OF ABBREVIATIONS

AC	Alternating Current
AFS	Active Flight Stabilization
AMA	Academy of Model Aeronautics
API	Application Programming Interface
APM	Ardupilot Mega
ARF	Almost Ready to Fly
AWG	American Wire Gauge
BEC	Battery Elimination Circuit
CA	Cyanoacrylate (Super Glue)
CCD	Charge Coupled Device
CFR	Code of Federal Regulations
CG	Center of Gravity
CHDK	Canon Hack Development Kit
CIA	Central Intelligence Agency
COA	Certificate of Authorization
COM	Communication Port (RS-232 Serial)
COTS	Commercial Off-the-Shelf
DASH	Drone Anti-Submarine Helicopter
DC	Direct Current

DSLR	Digital Single Lens Reflex (Camera)
DVR	Digital Video Recorder
EPO	Expanded PolyOlefin (Foam)
ESC	Electronic Speed Control
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FHSS	Frequency Hopping Spread Spectrum
FPV	First Person View
FTDI	Future Technology Devices International
GCS	Ground Control Station
GHz	Gigahertz
GIS	Geographic Information Systems
GISCI	Geographic Information Systems Certification Institute
GMRS	General Mobile Radio Service
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAD	Hole Accumulation Diode
HD	High Definition
ISM	Industrial, Scientific and Medical (UHV bands)
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LIDAR	Light Detecting and Ranging
LiPo	Lithium Polymer (Battery)

mAh	Milliamp Hour
MAVLink	Micro Air Vehicle Link
MHz	Megahertz
NiCd	Nickel Cadmium (Battery)
NiMH	Nickel Metal Hydride (Battery)
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
OSD	On-Screen Display
PPM	Pulse-Position Modulation
PWM	Pulse Width Modulation
RAM	Random Access Memory
RC	Remote Control
RPV	Remotely Piloted Vehicle
RTF	Ready to Fly
RTL	Return to Launch
SD	Secure Digital
SSD	Solid State Drive
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
UHS	Ultra High Speed
USB	Universal Serial Bus

CHAPTER 1

INTRODUCTION AND BACKGROUND

Autonomous mapping involves the process of capturing photography from a UAV (Unmanned Aerial Vehicle) with a high-resolution camera pointed towards the ground (nadir position). This includes the acquisition of large-scale orthophotography, which has changed over the past few years with the advent of commercial UAVs produced by various companies in the surveying, mapping, and photographic industries. Though these products are effective at capturing photos, they are highly expensive to acquire (between $20,000 and $50,000), and equally expensive to maintain. This document will serve as a reference on how to build a fixed-wing UAV with open source components, so that others who desire to implement this approach to autonomous mapping can learn from the issues encountered during the process.

Significance

The adoption of open standards and the advances of open source projects over the past 15 years are evidence of the maturation of open source technology. The open source model of distribution differs from the commercial model in that the code repositories for open source projects are made readily available at a nominal cost. This generally applies to software, but can be extended to hardware and associated firmware (code embedded in hardware). This model does not work well in many industries, but readily adapts to technology projects due to the cooperative nature of hardware and software developers (Lindberg 2008).

Lowering the cost of entry related to the implementation of UAVs is essential if the technology is to move forward. The full potential of UAVs will be realized once small and large organizations are able to obtain this technology, and leverage their capabilities without breaking their budgets. It is also important to advance open source projects, as these efforts directly benefit entities beyond the technology industry, and provide an opportunity to give back to the community. The open source approach provides an alternative to proprietary solutions, and promotes involvement and education in technology, especially in the field of geospatial science. The open source approach alleviates the limitation of financial means, and promotes the global use of technology to solve the world's complex problems in a cost effective manner (Hiong 2005).

This leads to a discussion of what kind of benefits can result from the use of UAV technology. UAVs allow researchers to study geospatial phenomenon at a spatial scale and temporal resolution not previously capable with satellite and traditional aerial photography methods. UAVs can access locations that full-size aircraft cannot reach, including the inside of volcanos and caves, and other obstructed areas. Most of the products in the marketplace today address the needs of mapping remote or inaccessible landscapes, as current regulations do not permit operating UAVs in populated areas. Lower cost UAVs are being used to map events, and are being flown by many as a hobby.

They can also assist in managing our infrastructure, including utility power line inspection (Gearinger 2014), bridge structural evaluation (Advanced Highway

Maintenance and Construction Technology Research Center 2008), and traffic monitoring (Coifman et al. 2003). Law enforcement agencies are also interested in the technology as a way to provide intelligence for local and national security (Haddal and Gertler 2010). UAVs can provide a detailed, micro level view of our world that cannot be obtained from a ground-based platform. UAVs provide information for decision-making, and are poised to be the next disruptive technology in the geospatial sciences.

Goals

The primary objective of this project is to test the theory that a relatively inexpensive UAV can be developed using open source technology and commercial off-the-shelf (COTS) components with a target expenditure of $2000. By installing an autopilot in a remote controlled (RC) model aircraft, we can determine if such components can actually be used with an on-board camera to capture photos comparable to that of a traditional full-scale, airplane-based aerial photo platform. The results will be measured through an analysis of the performance of the UAV and the quality of the aerial photography. Reaching these goals and objectives will result in the following outcomes:

1. Development of a fixed-wing UAV complete with functioning flight, communication, and photographic systems within specified budget.
2. Implementation of a mission that results in the capture of digital ortho-photography, and applies safety, ethical, and performance criteria.
3. Compilation of a two-centimeter digital aerial photo mosaic and three-dimensional surface model with consistent coverage and quality.
4. Evaluation of open source technology for applications in geospatial analysis.
5. A blueprint for an open source approach to UAV development.

Before proceeding with issues to be addressed before accomplishing these goals, a clear understanding of the terms associated with UAVs need to be established.

Terminology

There are many terms used to describe autonomous vehicles. The term "Unmanned" or "Uninhabited" Autonomous Vehicle will be used to refer to the various systems as well as the one developed for this project. The term "drone" connotes a military association, which is only one aspect of unmanned aircraft. The term drone disconnects the human from the equation, which does not represent the value of human interaction and monitoring in UAV operations. The term "UAV" will be used here to disassociate UAVs from drones, which generally carry with them a negative connotation (KARE 11 Staff 2013). The goal is to create a more positive perception of UAV technology (Dunbar 2012).

To be successful, a project culminating in a viable UAV platform (all of the components needed to complete a successful flight) must take into consideration a number of factors. In addition, these machines are not toys, and should be handled with care, and operated in a manner that will not enforce the negative perceptions of UAVs. Proper use considerations include, but are not limited to, the legality of its use, the feasibility of the technology, liability, and safety.

UAV Use Considerations

Legality

Before any UAV operation is attempted, local laws pertaining to operating UAVs should be researched. Some cities are creating or contemplating outright bans on UAV usage, even though they may operate their own UAVs for specific uses. The Federal

Aviation Administration (FAA) is pursuing regulation of the commercial use of UAVs. A court battle involving the University of Virginia focused on a decision by National Transportation Safety Board (NTSB) law judge Patrick Geraghty, who ruled that the remotely piloted aircraft are not subject to FAA regulations as other aircraft. This ruling was celebrated, but short lived, when the NTSB overturned the judge's earlier ruling, and declared that UAVs meet the definition of "aircraft" under the FAA's regulations. As such, UAVs will be considered to be subject to FAA administration as any other aircraft (Pope 2014).

Even with public opposition, the FAA is actively attempting to shut down commercial operations, and as of January 2015, is only allowing personal use under the "Model Aircraft Guidelines" policy, which includes flying under 400 feet, within line of sight, and not around people or infrastructure (FAA Modernization and Reform Act of 2012 and Advisory Circular 91-57 of 1981). How this applies to government agencies and universities is still a grey area, but the FAA has been directed by Congress to clarify this issue by September 2015. As of this writing, law enforcement agencies and universities can apply for a COA (Certificate of Authorization) with the FAA for specific uses (Federal Aviation Administration 2014).

The California Legislature has also acted to limit the scope of UAV operations by public agencies, especially law enforcement. Assembly Bill 1327 was passed in August of 2014 by both houses, but vetoed by Governor Brown the following month. This bill would have eliminated the use of UAVs by public agencies, and allowed only limited use by law enforcement involving warrants, emergencies involving traffic accidents, park inspections, fires, and environmental disasters, and intelligence gathering involving criminal activity. This bill also referenced the FAA Modernization and Reform Act of 2012, and would have been the first legislation regarding UAVs in California (State of California 2014).

Currently in the U.S., regulations allow flying model aircraft in designated model aircraft fields, or in areas where no people or structures are present. UAVs must also be operated by line-of-sight in complete view of the operator, and must be controlled by the operator at all times. If the operator is not controlling the UAV by line-of-sight, then a spotter must be used to maintain visibility.

Feasibility

UAV technology has matured extensively over the past couple of years, with international brands (for example DJI) moving the technology forward, and reducing the cost of entry. Low cost, preassembled UAVs can be found on Amazon.com for under five hundred dollars, and some models, such as the DJI Phantom, have become common enough to be recognized by the public. In addition to these consumer-grade proprietary UAV models, there is a robust open source community dedicated to UAV development on the Arduino platform, providing an alternative to proprietary models.

Since the UAV operates at altitudes lower than a traditional airplane, a consumer grade camera should be able to produce photos comparable to a specialized, high-end camera mounted in an airplane flying three to four times the altitude. When flying lower altitudes (below 400 feet), factors such as cloud cover, smog, and other atmospheric conditions do not present the same challenges as flying at conventional altitudes (1500 feet and greater). In addition, the difference in photographic quality between consumer-grade and commercial-grade cameras has decreased as camera technology has advanced.

As technology advances, cameras and other components, such as autopilots and communication equipment, have become smaller and lighter, and can fit neatly into a moderate scale (1/6 scale or .60 sized) RC model aircraft. Autopilots now contain GPS, accelerometers, gyroscopes, and other miniaturized sensors. RC aircraft are now being constructed from materials other than traditional balsa and plywood, including foam, carbon fiber, and fiberglass. In addition, communications technology has advanced to include small, low cost, high-powered transmitters and receivers operating in newer frequency ranges, allowing real-time communications between autopilots and monitoring equipment.

Safety

Safety must be the first consideration before sending a UAV into the airspace. The UAV will need to be thoroughly tested to establish a record of reliability. This does not guaranty problem free operation, but testing will provide the opportunity for problem areas to manifest themselves before the UAV is flown. This might include software bugs or mechanical failures due to materials or design errors, or simple operator error when establishing familiarity with new equipment. Before any flights are made, the operator should have a thorough understanding of how all the equipment works. This includes the airframe, communication systems, power systems, or other hardware and software. Knowledge of proper equipment operation can minimize the chance for user error, which is the most common reason for undesirable events. Given all of these concerns, the greatest safety risk is simply not following equipment instructions and common sense safety procedures.

Liability

Before operating a UAV (especially a fixed wing RC type), the pilot should become a member of the Academy of Model Aeronautics, a model aviation association that provides support and insurance for its members. This will provide coverage while flying an RC aircraft, but not necessarily in an autonomous fashion. In order to comply with regulations and insurance provisions, operators should fly away from populated areas, beyond five miles of an airport, and only within line of sight. Fortunately, in California, there exist vast expanses of unpopulated deserts, which make ideal locations to test this technology, as long as this does not take place in a national park or other UAV restricted area.

In Summary

Autonomous mapping with UAVs is a quickly maturing and promising technology, expanding to meet the demands of the geospatial community, with many commercial (Figure 1) and open sources solutions available. Geographic Information Systems (GIS) can incorporate this technology as a way to update changing infrastructure and environmental layers, and traditional flights can be supplemented with current, detailed photography for change detection and analysis. The only barriers to adoption of this technology in non-military applications are the regulatory processes of the FAA. While these regulations are being created, the commercial interest will continue to grow, and scientific uses will assist in improving public awareness of the benefits of UAV technology.

This project will attempt to assess the capabilities of open source technology as it applies to UAVs, and determine if the lower cost components can deliver professional quality aerial photography within a reasonable effort and learning curve. Open source technology may have a lower cost of entry, but generally requires more effort on the part of the adopter. High quality aerial photography forms the backbone of many computer mapping systems, and is important in environmental analysis, urban planning, emergency preparation, transportation modeling, and other areas of application. This project will evaluate the UAV development process, deployment mission, and the photography acquired during the mission.

FIGURE 1. Trimble UX5, a commercial solution launched in the California desert.

CHAPTER 2

LITTERATURE REVIEW

This chapter will review the history of autonomous mapping in the United States. This review places the project, which was completed as part of this research, in the context of historical advances, and sets the foundation for the significance of this project and its contribution to the advancement of this technology.

The History of Autonomous Mapping in the U.S.

UAVs have a long history, much longer than most are aware. Most of the history involves military applications, but scientific and commercial applications have recently emerged. The U.S. government has provided most of the historic funding for the research and application of UAV technology, but this is changing with the advent of smaller, lower cost vehicles. Maturing technology is also a driving factor contributing to the evolving history of UAV applications.

The World War Era

The use of unmanned aerial vehicles in the United States started in the Civil War with the use of Union and Confederate balloons dropping incendiary devices on respective positions (Garamone 2002). The actual use of fixed wing UAVs commenced after the turn of the century, hastened by the prospect of world war. According to the Smithsonian, barely a decade had passed between the first twelve-second flight of Orville and Wilber Wright, and the skies filling with military aircraft, especially in Europe

(Stamp 2013). Perhaps because the United States was not adjacent to the theatre of fighting, it lagged behind in aviation development. This would not last long; by the time the war ended, the United States was experimenting with unmanned aircraft.

The switch to fixed wing UAVs started in World War I with the advent of the Curtis/Sperry “Flying Bomb,” and the Dayton Wright “Kettering Bug,” which were essentially the historical equivalent of modern cruise missiles (Newcome 2004). Engineers designed the Flying Bomb to travel fifty miles, and then dive into the ground. The United States Navy also experimented with UAVs in World War II with the development of the Interstate TDR, a remotely piloted vehicle that was loaded with bombs or torpedoes. Despite successful deployment against Japanese ships in 1944, the Navy cancelled the program due to technical problems and the effectiveness of alternative weapons (Newcome 2004).

On the western front, the U.S. Navy equipped Liberators and B-17 bombers to hold 25,000 pounds of explosives designed to eliminate another UAV threat, the German V-1 Rocket. According to NOVA, pilots flew the aircraft to altitudes of 2,000 feet, and then, after the pilots bailed out of the aircraft, they were navigated by remote control television guidance systems until reaching their intended targets. After the end of the war, the military employed B-17 bombers in the South Pacific for testing the impact of atom bombs. With the success of these programs, the U.S. military invested in UAV technology in the post war period (Krock 2004).

<u>The Vietnam Era</u>

During the Vietnam War, UAV focus switched to reconnaissance when U-2 spy planes were lost over Russia, China, and Cuban locations. The first two programs to incorporate UAV technology were the “Lightning Bug” and “Compass Cookie” efforts, using the Ryan 124 Firebee aircraft ordered originally by the U.S. Air Force for drone target practice, but also modified for high-altitude reconnaissance (Cooper 2003). In 1967, the Navy deployed a remotely piloted helicopter in Vietnam under the DASH program for performing reconnaissance and assisting destroyers with gun aiming. These advanced UAVs were equipped with telemetry feeds and transponder tracking to provide instant intelligence on combatant locations. Overall, UAVs flew approximately 3,000 missions over Southeast Asia during the Vietnam War (Gyrodyne Helicopter Historical Foundation 2013).

The Post Vietnam Era

In the 1950s, the U.S. government utilized high altitude weather balloons during the Cold War for reconnaissance, but transitioned to fixed wing UAVs by the 1960s (Garamone 2002). Though most UAVs were used for target training and sensing in the 1960s, by the early 1970s, the advent of ground based control systems freed the UAVs from direct pilot control. In 1971, the Air Force equipped a Ryan Firebee with a complete remote flight control system, making it a true RPV (remotely piloted vehicle), instead of just a target drone or missile (Shaw 2013). This UAV demonstrated the capabilities of pilotless aircraft against F4 Phantoms, scoring numerous hits in simulation exercises.

In the 1970s, the Army developed a program called the Remotely Piloted Aerial Observation/Designation System, which aimed at getting the RPV to find a target, and keep a bead on it with its laser nose until a laser-guided bomb or missile could home in on the target (Dickenson 1976). UAV development in the 1970s was important in developing the remote sensing capabilities of sensors that gather information related to flight controls, as well as sonic and imagery data.

The 1980s gave rise to the modern era of UAV development, with focus turning to weaponry. The iconic representative of this class of UAVs is the Predator drone, manufactured by General Atomics Corporation. This effort began with the Albatross, a full-scale drone having the ability to stay in the air for fifty-six hours, far surpassing the two-hour limit of existing UAVs. This drew the attention of the U.S. military, who provided the funding in 1988 for the next platform, the Amber. Though this was a capable airframe, it was incapable of sustained long-range flights carrying heavy sensor equipment. The GNAT-750, an improved airframe that integrated GPS for autonomous flight, succeeded the Amber in 1989 (Shaw 2013). This UAV was the first platform to incorporate the sensor turret in a housing mounted below the nose of the aircraft.

The CIA would use the GNAT-750 extensively during this time, but it suffered from range restrictions due to its C-band communications protocol requiring line-of-sight, and poor performance in inclement weather. This gave rise to the Predator, developed for the CIA to replace the GNAT-750. The Predator overcame the range restrictions of its predecessors by incorporating a satellite data link, which freed the UAV from communication relays within line-of-sight. This meant that the communications ground station could be located anywhere in the world, and maintain full autonomous control of the UAV. In 1995, the Air Force also purchased the Predator, and converted the drones to military use, complete with weaponry and sensors. The Predator, along with its sibling Reaper, has seen extensive duty in Iraq, Afghanistan, and other theaters of operation. In contrast, the Northrop Grumman Global Hawk is a completely autonomous vehicle capable of completing a flight plan without user intervention (Shaw 2013).

The Modern Era

Presently, the military is still involved in the use of UAV technology. The U.S. Army utilizes a sUAV (small unmanned aerial vehicle) called the Raven, developed by AeroVironment in 2005. According to the AeroVironment web site, the RQ-11B Raven is the most widely used unmanned aircraft system in the world, though, in this author's opinion, the DJI Phantom (Figure 2) has most likely eclipsed this mark (DJI does not release sales figures). The Raven is a model aircraft complete with an autonomous autopilot capable of flying waypoints up to 500 feet above ground level guided by a GPS receiver. The Raven is equipped with a charge-coupled device (CCD) camera for first person view (FPV), and an infrared camera for night operation. The UAV utilizes a pusher prop configuration to allow an unobstructed view with its CCD camera, and lands on a reinforced belly without damaging the propeller. This UAV has much in common with the UAV developed as part of this project, but costs the Army considerably more, approximately $35,000 for each Raven and $250,000 for the total system (AeroVironment 2015; Kable 2015).

At the turn of the century, however, UAV technology has entered a new phase, with a focus on applications beyond the military. Since the early 2000s, UAVs have taken on more advanced capabilities and airframe types, including rotary as well as fixed wing configurations. On the fixed wing side, advancing technology led to the miniaturization of components and hand launched UAVs. Fixed wing UAVs are also gaining popularity in the hobby arena, with recreational pilots enjoying the remotely piloted flight assisted by FPV cameras. Popular models include the Hobby King Bixler, which incorporates glider-like characteristics for smooth and steady video capture. Models marketed with FPV or UAV intended uses generally incorporate pusher propeller configurations and hand launching.

Newer to the scene are the rotary platforms, or the quad copter. The rotary platforms come complete with a compass, GPS receiver, and gyroscope to allow operators with limited training to fly these machines successfully. Unlike traditional helicopters, these machines are remarkably stable, and can hover in loiter mode for the duration of the battery charge. The advantage of the rotary platform is the ability to hover, a valuable attribute when filming video, as well as the ability to take-off and land in minimal space. Quite possibly, these are the main factors contributing to the immense popularity of the rotary platform. They can be flown almost anywhere by anyone.

Once the domain of well-heeled hobbyists, the Chinese manufacturers have lowered the cost of consumer UAVs, so that anyone can purchase an inexpensive quad copter such as the DJI Phantom (DJI Corporation 2014). It is commonplace to read of a DJI Phantom capturing video of a wedding or sporting event, while drawing the ire of spectators and the FAA (Zhang 2013; Webb 2014). A DJI Phantom recently crashed on the White House lawn, sending the Secret Service scrambling. They later determined that the recreational UAV was being piloted by a National Geospatial-Intelligence Agency employee (Ryan 2015). Though most operators consider the safety of others when piloting these copters, some are flying these with little training and consideration for safety, jeopardizing the continued use of this important technology.

Recently, UAVs have moved from military applications to those that benefit society. UAVs have surveyed tornado damage in Arkansas (Payne, Sutton, and Sayers 2014), and have assisted with fighting fires in New South Wales (Bruce 2015). UAVs are being used to survey crop health and irrigation usage in the American Midwest (Anderson 2014). Along the U.S. border with Mexico, UAVs are used to monitor and collect information to deploy the limited resources assigned to such a large monitoring area (Haddal and Gertler 2010). Even the motion picture industry is utilizing UAV technology to replace expensive and dangerous helicopter based filming (Barnes 2014). Companies are also filming sporting events with UAVs, including the Winter Olympics in Sochi (Feltman 2014).

In the geographical sciences, UAVs allow for the capture of information at spatial and temporal scales not feasible only a few years ago. UAVs are a disruptive technology in the field of geospatial science, as they provide geographers with tools to generate data for cartographic presentation, and process information in real time. With the continued miniaturization of cameras and other components, payload capacities will increase without adding weight to the aircraft, which will allow for longer flight times, or larger sensors. This includes Light Detecting and Ranging (LIDAR) equipment, now produced at sizes that fit into small UAV airframes, which capture high-resolution point clouds capable of producing 3D models of ground surfaces, structures, and vegetation. LIDAR data acquired from a UAV is also useful in rectifying digital aerial photography. The number and types of sensors will increase, mirroring the increase in capabilities of UAVs. High-resolution, multi-spectral, digital imagery, once an impractical desire of geospatial professionals, will become commonplace in the practice of the geosciences.

FIGURE 2. The popular DJI Phantom.

Current Research in the UAV Industry

Due to the highly technical and fast moving nature of the UAV industry, most research exists in the form of technical journal articles, web articles, discussion boards, and manufacturer's guides and bulletins. Though the technology has existed in rudimentary forms for over a century, most of the development and use of UAV technology has occurred in the past ten years, especially in the commercial context. This section will focus on UAV development as it pertains to non-military uses, and specifically, uses in the geospatial sciences. Uses outside the military are becoming more commonplace, interest in the technology is increasing, and even the government is monitoring the use of UAVs in the commercial airspace.

Technical Challenges

There are many technical challenges facing the UAV industry due to the complexity of the related topics. These include the dependability of the components, the reliability of the communications equipment, and the complexity of the flight dynamics. This can be extended to include mechanical and aerodynamic design, propulsion systems, and sensors. The technology is new, the standards are evolving, and developers working in the open source side of the UAV industry are still few in number. These challenges will be addressed as interest in UAVs increase.

Complexities in UAV development include the design of platforms, propulsion systems, subsystems, and components. The greatest challenge is integration, as there are still multiple standards from various manufacturers for each of the components, whether they are the power, communications, video, or autopilot systems. All components must work together as a unified platform. For example, one of the first tasks of installing the components into a UAV is to cut off the various electrical connectors and standardize on one type. Besides human error, getting all the components working properly represents the greatest risk to the safe operation of the aircraft (Logan and Vranas 2005).

Professor Todd Humphreys of the University of Texas at Austin has demonstrated other risks by hacking the incoming GPS signals received by a UAV in order to change its navigation. This is exactly what Iran claimed when they captured an American drone that disappeared over the country in 2011. Humphreys stated that his research team wanted to demonstrate the potential risks, so that the FAA would consider this when drafting rules for commercial UAVs in 2015. Humphreys' efforts have led to greater financial support from the university, which will allow his research team to pursue more "risky types of research" (Cochran School of Engineering 2012).

In examining the future directions of the technology, Graham Purves informs us that there are two game changers in the UAV industry. First, the movement of GNSS (Global Navigation Satellite Systems) into a safety critical role, where someday we will live in a world where autonomous vehicles are the norm, and the idea of having a human behind the wheel is both complex and unsafe. Second, UAV technology is becoming a platform of innovation, enabling killer applications we have yet to conceive. The impact of airspace regulation on certification requirements, however, may possibly prevent the use of some effective technical solutions due to the software complexity. Most challenges are not technical, but regulatory (GPS World Staff 2014).

One of the major technical challenges of this project is the difficulty in matching UAV payloads (sensors) to the different weight classes defined by the FAA for small UAV maximum takeoff weight (Johnston 2013). The first weight class is UAVs weighing less than 4.4 pounds, a very small weight for most operations, only allowing a payload of approximately one-half pound. This would generally only allow a small CCD camera and video communications equipment. It was for this reason a large RC trainer-style aircraft was chosen for this project, with lift being a large criterion, and a size sufficient to fit all of the required components.

Another major technical consideration involves the state of communications technology. Scientists are addressing one of the specific and critical areas of UAV operations, that being communications. The following can be attributed to James Griner, Project Engineer at NASA:

> First, you have to start with allocating radio frequencies, and that takes the agreement of an international body of regulators. These are global frequencies requiring many countries to come together for a vote. The negotiations take years, but in February, the World Radio Communication Conference sanctioned two bands for UAV use. (Dunbar 2012)

These frequencies will be important, as most communications equipment use the 2.4 GHz band, common to cordless phones and other consumer electronic equipment, and the 5.8 GHz band, popular with wireless computer networks. Using these bands subjects the radio frequency signals to interference by consumer equipment, which can result in loss of communication to the UAV. Most RC communications equipment utilize frequency hopping, but this is not a viable long-term solution.

Human Challenges

The human challenges of remotely piloted and fully autonomous aircraft are outlined in a thesis presented by Tobias Nisser and Carl Westin of the Lund University School of Aviation in their work entitled *Human Factors Challenges in Unmanned Aerial Vehicles (UAVs): A Literature Review* (2006). In their thesis, Nisser and Westin illustrate the strong interest in UAV technology, the road to maturity for the infant technology, the need for regulatory constraints to ensure safe operation, and the importance of integration of UAVs into the civil airspace. Human factors to be considered when evaluating the safety of UAV integration include workload and vigilance, situational awareness, teamwork, decision-making, performance monitoring, reversion to manual control, improperly calibrated trust in automation, and environmental/ergonomic aspects. These factors were integrated into the design parameters of this UAV project.

For safety, NASA operates full-size aircraft with an autopilot guiding the navigation, but with a human pilot in the aircraft for safety, until the removal of technical barriers allow for unpiloted aircraft. Engineers can control the UAV from the ground during testing, but there is a pilot on board for safety purposes. Explains James Griner of NASA:

> We are basically creating a whole new industry. Once the technical barriers are figured out, UAVs will be used mainly for long endurance, high altitude missions that are not feasible or practical with piloted aircraft. (Dunbar 2012)

<u>Regulatory Challenges</u>

According to Steve Sliwa at NASA's Langley Research Center, UAV technology will improve as business and technology work together, and applications will become more numerous when the FAA determines how to mix unmanned and manned aircraft. Steve Sliwa states:

> UAVs now are like in the 1940's, when there were hundreds of airplane companies and it was like the Wild Wild West, just waiting to take off when the FAA gets a handle on their proper integration. (Lineberry 2012)

Perhaps the FAA will support the fledgling industry in such a way that supports legitimate and safe (within reason) UAV operation, and not just saddle another over-regulated industry with too many rules.

It appears that the FAA is not the only one taking notice of the increase in UAV usage for non-military operations. Catherine Ho reports on two law firms starting drone practice groups to address the increasingly mainstream commercial and private UAV use. The FAA estimates that there will be as many as 7,500 small commercial drones in use in the United States by the year 2018, and there are most likely more drones privately operated in recreational use in the United States already. The UAV manufacturers are having a hard time expanding their business, but as we see these new rules come out in the next year or two, you will see an explosion of manufacturers and end users (Ho 2014). This is one reason that UAV research is so important – to mature the industry before the sky fills with thousands of unmanned aircraft.

Even PBS is chiming in on the UAV controversy with an article entitled "How Will Thousands of Drones Impact Already Crowded Skies" (Argrow 2013), where the organization interviews Rick Carr of the University of Colorado's Research and Engineering Center for Unmanned Vehicles. In the article, Carr prefers that people, including the public and reporters, not call them drones. Carr also points out the numerous commercial benefits, including the efficient pinpointing and treatment of agricultural diseases, which would lead to fewer chemicals making it to the dinner table. However, Carr agrees that the FAA is making it impossible for the private sector to operate UAVs, and predicts that the industry would grow exponentially if the FAA were to make it easier to get permits.

CBS news, referring to a 60 Minutes interview, reports that "Amazon Octocopters Will Be Flying Packages Directly to Your Doorstep in Less Than 30 Minutes." Most have shrugged this off as a publicity stunt, but there appears to be some substance to their announcement. If this is true, and the FAA clears this operation, this could dramatically revolutionize the UAV industry, and pave the way for commercial use to expand dramatically. However, for now, the FAA has grounded Amazon's drones, stating that the online shopping powerhouse may not utilize UAVs to deliver packages anytime in the near future (Rose 2014).

The FAA reiterated in a December 2013 memo that all uses must fall within the requirements set forth for recreational and hobby use (FAA 14 CFR Part 91), which is an interpretation of the special rule for model aircraft within the FAA Modernization and Reform Act of 2012. Even the AMA (Academy for Model Aeronautics), which represents model aircraft (RC) owners and operators, has filed a response to the Part 91 interpretation, indicating the overreach of the FAA in regulating the modeling industry (in an email to AMA members dated September 23, 2014). Thus, Amazon has been relegated to testing drones in the Australian Outback, where regulations have progressed much more swiftly.

Craig Whitlock of the Washington Post has put fear in the minds of the American public regarding the safety of UAV technology (Whitlock 2013), including the management in my workplace at the City of Huntington Beach, California. According to Whitlock, there have been forty-nine military drone crashes in the U.S. since 2001. The military has stated that they consistently provide extensive training to pilots, and drones will be no different. Considering that the military owns over 10,000 drones, and that not a single death has resulted from a drone accident, the record of the military domestically is solid. This article illustrates the overblown concern regarding the safe operation of commercial UAVs. Small commercial UAVs generally weigh less than ten pounds, compared to military drones with wingspans of sixty-six feet (General Atomics MQ-9 Reaper) weighing over ten thousand pounds.

Industry Benefits

The aerospace industry recognizes the important uses of UAV technology beyond military applications, while recognizing the challenges. These include, but are not limited to, the communication frequency limitations, legal status, regulatory compliance, and public perception of drones.

> Unmanned aircraft systems have been used in a variety of civilian applications, from aerial surveys in support of Vanderbilt University's efforts at the Mawchu Llacta archeological site in Peru, to conservation of zebra populations in South Africa. 80 percent approve of UAS use in search and rescue missions, 67 percent supported their use to track down criminals at large, and 64 percent said they should be used to patrol the U.S. border. (Aerospace Industries Association 2013)

Due to the popularity of personal UAVs, their number has exceeded that of military drones. Chris Anderson, founder of Wired magazine, the DIY Drones web site, and 3D Robotics Corporation (which manufactures many of the parts used in the UAV developed for this project), attributes the popularity of personal drones to the smartphone industry, which has miniaturized and economized the sensors (GPS, gyroscopes, accelerometers, etc.) used in today's autopilots (Anderson 2012). These autopilots also incorporate the same processors found in smartphones – in essence, a drone is a flying smartphone.

In an article from the Motherboard blog, “Even Anti-Drone Groups See the Benefit of UAVs,” the author comments on those most critical of drone activities, especially activities conducted by the military and the CIA, and reveals the fact that even these groups do not support an outright ban on drones.

> There are certainly lots of legitimate potential commercial, humanitarian, and law enforcement uses of drones. They are already being used at national borders to stop drugs and illegal crossings, Code Pink co-founder Medea Benjamin told me. Humanitarian groups will use them more and more for tracking wildlife, stopping illegal logging or whaling, surveilling war zones. Farmers seem very keen to use them, as do weathermen and real estate agents, and delivery services. (Benson 2014)

The main concern is privacy, which the FAA will define with the legal definition of private airspace.

The key to realizing the many potential benefits of UAVs involves changing the public perception and conversation. The use of the term “drone”, with its negative connotation, should be dropped from our vernacular when addressing this topic. Those in the practice of the geosciences need to promote the technology, and serve as evangelists to inform the public of the benefits provided by the thoughtful use of this technology. The benefits are too great to leave the future of UAVs to chance. We also need to carefully monitor the safe and respectful operation of UAVs, or else risk losing the right to operate these beneficial machines.

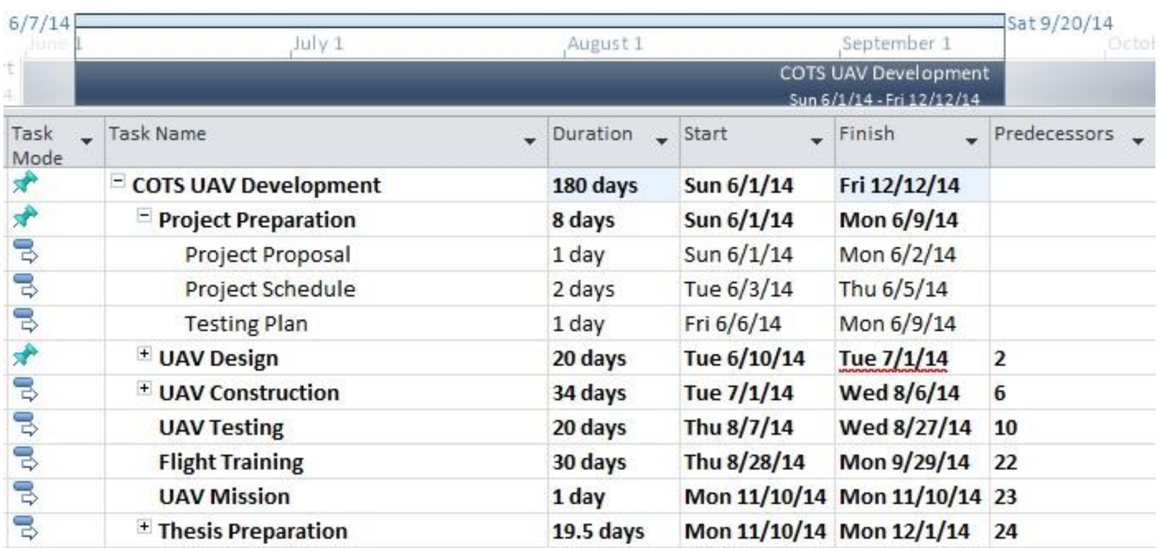
Because this technology has been predominantly industry driven, much of the literature related to this subject matter is derived from poplar (rather than scholarly sources). This project, and resultant thesis, hopes to contribute to the literature by providing a source of information for those interested in embarking on a UAV project. The most important portion of the project is the documentation – to provide a repeatable process to streamline the development of an open source UAV platform that can be adapted to many uses. This will assist in mitigating the steepness of the learning curve, and facilitate entry into this exciting area. It is anticipated that the legal issues that are currently inhibiting the expansion of this technology will soon be overcome, and the results of this project will further the accessibility of this technology.

One may ask, with all of the current legal controversy, why anyone would want to build a UAV in this environment, considering the limitations and controversy surrounding this technology. Taking on challenges, even in unsupportive and uncharted areas where the stress is greater, can make success in this environment more appreciated. As the industry overcomes these obstacles, UAVs will move off the shelf and into the airspace where they belong, supporting geographic research. The FAA has released some encouraging new rules (Federal Aviation Administration 2015), which may allow the commercial industry to realize the potential of UAV technology, and be rewarded for their efforts.

CHAPTER 3

MATERIALS AND METHODS

This chapter describes the planning, design, materials, and construction of the UAV platform. As in any project, identifying the tasks, components, deliverables, and associated timeline is essential to successful project completion. This was achieved by outlining the various deliverables and milestones in Microsoft Project (Figure 3), and identifying the primary and subordinate tasks. Many estimates were created, and flexibility was incorporated into the delivery dates due to the experimental nature of the project. In addition, some tasks were not under direct scheduling control. It is important to document the progress and make adjustments as needed to keep tasks moving forward.



Task Mode	Task Name	Duration	Start	Finish	Predecessors
	COTS UAV Development	**180 days**	**Sun 6/1/14**	**Fri 12/12/14**	
	Project Preparation	**8 days**	**Sun 6/1/14**	**Mon 6/9/14**	
	Project Proposal	1 day	Sun 6/1/14	Mon 6/2/14	
	Project Schedule	2 days	Tue 6/3/14	Thu 6/5/14	
	Testing Plan	1 day	Fri 6/6/14	Mon 6/9/14	
	UAV Design	**20 days**	**Tue 6/10/14**	**Tue 7/1/14**	**2**
	UAV Construction	**34 days**	**Tue 7/1/14**	**Wed 8/6/14**	**6**
	UAV Testing	**20 days**	**Thu 8/7/14**	**Wed 8/27/14**	**10**
	Flight Training	**30 days**	**Thu 8/28/14**	**Mon 9/29/14**	**22**
	UAV Mission	**1 day**	**Mon 11/10/14**	**Mon 11/10/14**	**23**
	Thesis Preparation	**19.5 days**	**Mon 11/10/14**	**Mon 12/1/14**	**24**

FIGURE 3. Project management tasks and timeline.

Planning and Design

The first issue to be addressed was the configuration of the UAV, which was determined by the goals of the project. The design considered many factors, which included cost versus function, where and how to test the platform, the limitations of the technology, and the time required to develop the platform. Because time for development was a significant consideration, RTF (ready-to-fly) components were preferred, provided the costs remain within the limits of the project. Skills included basic woodworking with balsa and hobby plywood for modifications to the airframe, and soldering for electronic components. Knowledge of basic electrical circuitry also proved to be beneficial.

Flight Dynamics

Because flight times are constrained by flight dynamics, criteria included selecting a UAV having wings with a flat bottom, semi-symmetrical airfoil that provide maximum lift rather than dynamics (Kroo 2003). The goal was to obtain flight times sufficient to take the maximum number of photos that the camera will allow. This required something between a trainer and an advanced aerobatic platform (Figure 4), with gentle flight characteristics that make the vehicle easier to fly manually and land in a smaller space. It must also be maneuverable, as unresponsive aircraft can be difficult to fly, and difficult to turn with an adequate radius for effective flight control. The goal was to achieve the balance between these two factors, such that mapping is supported, aerodynamics are optimized, and the UAV can be flown without requiring years of operator experience. The UAV was equipped with air brakes to allow flying at slow speeds, and forward wing extensions to prevent tip stall.

The UAV needed to be of adequate size, and have adequate lift capacity to handle a high-resolution compact camera with a battery. The autopilot controls the camera through a USB interface, so wires need accommodation. In addition, the camera requires isolation from the airframe to reduce vibration from the motor. Camera battery life is often a limiting factor to the number of photos possible on one flight, so the camera was configured to reduce battery consumption by turning off Wi-Fi and all unnecessary functions, including autofocus (set to infinity). Extra batteries are essential for multiple flights.

As this was an RC fixed-wing airplane platform, user control of the UAV was imperative in the event of flight controller failure. The UAV required landing gear of adequate size to handle the weight of the vehicle, and a large and relatively smooth landing zone. The camera was placed toward the bottom of the UAV, so belly landings were not an alternative without further modifications to the underside of the airframe. Since the size of the airframe did not support hand launching, the UAV required some room for takeoff as well.

Enhancing Safety

Safety is of utmost priority when operating an autonomous vehicle. First, the UAV flies close to the stall speed of 17 miles per hour, to minimize damage in the event of an incident, and to allow more pictures to be taken. The UAV was equipped with the lightest components possible, enhancing the flight characteristics, as well as safety. An FPV (first person view) camera was mounted near the nose of the vehicle, providing real-time flight video from a cockpit perspective for ease of flying manually, and for tracking the position and attitude of the vehicle in flight. The UAV was also fitted with sensors, tracking flight information (telemetry) and deviations from the intended flight plan. A recovery and mitigation plan should be drafted before testing has started. In addition, flight control software supports the use of a "geofence", to limit the geographic area in which the software permits the UAV to operate.

Transportation

The typical fixed-wing UAV needs to be broken down into components, because they are larger than a common sedan will accommodate. For this reason, an aircraft with a removable wing was selected, which will allow for transportation in almost any vehicle. In addition, there are many other flight components required for operation of the UAV, including battery chargers, a monitor for FPV, laptop for flight planning and monitoring, voltage alarms and sensors, various antennas, recording equipment, and numerous cables and connectors. Most of the components, along with the tools needed in the field (wrenches to tighten loose propeller nuts), will fit into an RC equipment bag. To keep things simple for the scope of this project, all equipment was powered with Lithium Polymer (LiPo) batteries, so that an AC generator or 12-volt battery was not necessary.

The most challenging aspects of the project have not involved designing or constructing the UAV, but performing the extensive research on a variety of subjects where documentation is scare or does not exist. This has led to progress by trial and error, and has extended the time required to put the UAV in the air. Every time a component is installed or configured, another necessary part is discovered. Before deciding to construct a UAV, one's capacity for research and tolerance level for trial and error should be considered.

FIGURE 4. The Hobbico Nexstar Select EP before modification and conversion.

Equipment and Materials

In order to select the best components and minimize the costs, diligent research is necessary to gather relevant information. This information is readily available on the Internet, though instruction on some of the new and less well-known topics may require diligence to find. The primary criteria is obtaining high quality photography through proper equipment selection, while minimizing the cost by using common items and open source components wherever possible. This also requires weighing the contribution of each component to the overall probability of success of the mission, and prioritizing the larger expenditures on these items, generally the autopilot and airframe.

One of the goals of this project included implementing a technology geographers can replicate by obtaining materials from widely available commercial sources (Tower Hobbies 2015), and information gathered by searching the web. Most of the information required to research, obtain, install, and configure the equipment came from manufacturer's web sites and RC/UAV related discussion groups (RC Groups, RC Universe, Flite Test 2015). No one source supplies all of the diverse components that go into the development of a UAV, and it is better to use sources that specialize in a particular area so that proper materials are obtained. Some equipment (batteries) were obtained from Chinese sources to reduce cost. Since this technology is still developing, installation and setup required extra time to order unanticipated equipment needed to finish the installation (connectors, diodes, converters, etc.).

RC Model Airplane

The Hobbico NexStar Select EP was chosen, as it was a ready-to-fly, advanced trainer complete with transmitter, receiver, motor, and speed control. This is an electric powered RC model, and accounted for about 28 percent of the total project cost. Being a mandatory criterion, the fuselage needed to be of adequate size to fit a consumer grade camera and other flight components. Constructed of hobby plywood and balsa, the airframe was easy to modify, only requiring an X-Acto knife and razor saw.

The NexStar comes equipped with a Futaba six channel 6EXA Transmitter and R168DF eight channel receiver. These components were replaced with a FrSky (pronounced "free sky") Taranis open source transmitter/receiver (FrSky Corporation 2014). The Futaba transmitter did not meet the minimum specifications for the autopilot to support more than two flight modes (Futaba 2003). The Taranis is a far more robust

RC transmitter, capable of supporting 16 channels, and can be fully customized at the firmware or interface level. Of the eight channels on the FrSky receiver, four will be used for the primary fight controls (elevator, ailerons, throttle, and rudder), one for the autopilot to trigger the camera shutter, one to control the flight modes, and one for the future use of flaps.

The NexStar also includes an Electrifly Rimfire .32-size motor connected to a 60-amp speed controller. This motor is an out-runner type, containing a fixed armature, and outer rotating magnets, providing greater torque than an equivalent in-runner type (Great Planes Model Manufacturing 2013). The electronic speed controller (ESC) is a Hobbico branded unit, capable of supplying the maximum required amperage to the motor without generating excessive heat. The speed controller does not contain a battery elimination circuit (BEC), because a separate battery supplies the power to the servo rail, as well as backup power to the autopilot.

Since this airframe was considerably heavier than stock, different prop sizes and pitches were used to determine what combination produced maximum thrust. This information can be calculated by using a great web tool found through a Google search (Adam One 2014). This web site can be used by entering the battery, electronic speed control, motor type, and desired prop size, and it calculates the motor and prop efficiency with the entered parameters (Figure 5). This tool saves on buying numerous propellers to model different sizes and pitches. Based on the component specifications, the best propeller to drive the UAV is a 10x5 inch model.

FIGURE 5. Motor and propeller calculations.

Autopilot/GPS

The autopilot chosen for the project is the latest generation of the Arduino based APM Plane autopilot called the Pixhawk. This is manufactured by 3D Robotics of San Diego, California, and is a product of an open source project (Pixhawk Project 2014). The Pixhawk works with the uBlox LEA-6H GPS/Compass module, providing accurate positioning (2.5 meter), with on-board battery and storage (uBlox 2015). A digital airspeed sensor was acquired to provide additional measurements to compliment the calculations performed by the GPS module. The Pixhawk also comes equipped with an LED for determining autopilot status, including GPS lock, and an audible alarm for communicating other functional information (3D Robotics Corporation 2014). To alleviate voltage surges on the servo rail common with digital servos, a Zener diode was obtained.

Communications

To provide telemetry information (air speed, ground speed, altitude, pitch, yaw, etc.), a 915 megahertz telemetry radio has been selected. This radio, provided by 3D Robotics, integrates directly into the Pixhawk autopilot. Based on FCC requirements for radio communications in the unlicensed spectrum, 915 megahertz was chosen as the frequency of choice for compliance reasons (United States Department of Commerce 2014). The 915 ISM band (industrial, science, and medical) is the center point of the 902 to 928 MHz spectrum (Shandle 2011), and is appropriate for short-range audio and video transmissions. The transmitter outputs at 100 mW (milliwatts), adequate for a range of approximately one kilometer, which will accommodate operation within line-of-sight. The radio also incorporates frequency-hopping spread spectrum (FHSS) technology, where the radio will select the best frequency within the frequency range to provide the strongest signal.

For FPV, the UAV is equipped with a Sony Super HAD (hole accumulation diode) 520 CCD (charge coupled device) camera supporting a 768 x 492 pixel resolution. This is connected to a MinimOSD on-screen display board, which interfaces with the Pixhawk autopilot to provide flight data for the video feed. The OSD board connects to a 5.8 gigahertz 200 mW transmitter paired with a diversity (dual antenna input) receiver outputting video to a Black Pearl 7-inch FPV monitor. The monitor is connected to a mini DVR, and supports HD video capture and playback with a handy LCD screen for viewing content in the field (ReadyMadeRC 2015). This can also be helpful in finding a runaway UAV.

This combination should have an effective range of approximately two kilometers. Being a higher band than the telemetry transmitter, the video feed is more susceptible to obstruction by objects within line-of-sight. To increase the range of the video feed, the stock dipole antennas were replaced with cloverleaf antennas on both the transmitter and the receiver (Greve 2011). An additional 4-turn helical antenna was constructed from 10-gauge wire from Home Depot to provide directional signal tracking and extend the effective range of the diversity receiver.

Camera

The digital camera chosen for this project is a Canon S110 digital point-and-shoot model capable of 12 megapixel images (Figure 6). The 4000 by 3000 pixel format is large enough to capture high-resolution imagery at elevations below 400 feet. The ability to accept SDXC high-speed, high-capacity memory cards allows quick picture cycling and storage. The camera also incorporates a high-resolution, color touch-screen monitor, perfect for checking picture quality in the field.

The camera is equipped with a 24-millimeter wide-angle F2.0 lens, which captures generous amounts of light, even in dim settings. The 24-millimeter lens is the equivalent of a 38-millimeter lens on a full frame camera (Digital Single-Lens Reflex, or DSLR), giving this camera a wide field of view, without adding unwanted barrel distortion (fish-eye) common with wide-angle lenses. The camera also weighs in at under 196 grams, which is an important factor in selecting components that will not overload the payload capacity of the UAV (Canon America 2015).

This particular model supports the CHDK (Canon hack developer kit) autopilot hack, which allows the Pixhawk autopilot to control the shutter of the camera. Scripts are readily available on the Internet, and support basic intervalometer routines needed for shutter control. Connecting the camera required obtaining a specific USB (universal serial bus) cable, obtained from Gentiles Ltd. of the United Kingdom. Unfortunately, after reading some posts, it was determined that the Pixhawk only outputs 3.3 volts to the camera, insufficient to trigger the shutter. Soldering a 5-volt step-up converter between the power leads of the USB cable was necessary to resolve the voltage deficiency.

FIGURE 6. The Canon S110 “professional point and shoot” camera.

Ground Control Station

The ground control station (GCS) provides a platform for running the Mission Planner software, which will update and configure hardware components, as well as provide flight planning and mission control (Figure 7). The GCS connects to the telemetry receiver through a USB port to provide flight information and control of the Pixhawk autopilot. After having trouble reading the screen in bright daylight with standard laptops, a Panasonic Toughbook CF-19 MK1 running Windows 7 was chosen as the GCS. This laptop has a bright, trans-reflective screen, and is fully rugged, perfect for field use with a small footprint (10-inch screen) and convenient handle.

FIGURE 7. Ground control station.

Miscellaneous

A balancing LiPo battery charger (Turnigy dlux AC/DC130W 10A 6S Balance Charger/Discharger) was acquired for charging all battery types, including LiPo, NiCd (Nickel Cadmium), and NiMH (Nickel Metal Hydride). An additional, 12-volt only, Turnigy battery charger was also obtained to assist charging the numerous batteries in the field. Connectors were also constructed for charging batteries with JST type connectors (video battery), and servo lead connectors (receiver battery). Completing the build required a 100-watt soldering gun, scroll saw, combination belt/disc sander, X-ACTO knife, razor saw, propane torch, heat gun and sealing iron, hand drill and bits, and various wrenches and screwdrivers.

Other materials required to complete the UAV included silicon 12 AWG wire and XT60 battery connectors for power connections. One two cell (7.4 volt 2S) 2700 mAh (milliamp hour) and one three cell (11.1-volt 3S) 2700 mAh battery are connected in a series, and power the motor and autopilot. Another three cell (11.1-volt 3S) 900 mAh battery powers the video transmitter. Since the video batteries have JST connectors, an XT60 to JST adapter was constructed. The receiver battery powers the servos (4.8-volt 4S NiCd 700 mAh), and serves as backup power for the autopilot. In all, the battery collection includes four sets of flight batteries, three sets of video transmitter batteries, three RC receiver batteries, and extra batteries for the RC transmitter.

In order to retrieve the UAV in the event of a flyaway, a UHF tracker was constructed from a Baofeng Radio attached to a standard Yagi UHF antenna (Figure 8). This unit receives radio signals from a UHF beacon obtained from FMKit located in Israel (FMKit US 2014), and has a range of about 10 miles. The beacon comes with a 3-

cell (3.7 volt 300 mAh) LiPo battery that can be charged via the USB port on the beacon. An 8-inch RG58 N male plug to an SMA female jack cable was acquired from eBay to connect the UHF antenna to the Baofeng radio. The UHV tracker works by pointing the antenna toward the beacon, and observing the strength of the tones, with the tones becoming stronger as the antenna is pointed toward the beacon. For short ranges (under 300 feet), a “KeyRinger”, which emits a loud tone when activated by a paired KeyRinger, was placed in the UAV.

FIGURE 8. UHF based lost plane locator.

To accommodate optimal placement of the autopilot, GPS receiver, and communications equipment, extra DF13 cables of various lengths were ordered from 3D Robotics. To complete the installation, protective foam, Velcro straps, and various glues were obtained. For making the electrical connections, electrical solder with a rosin core was used in combination with flux paste to ensure solid and reliable connectivity. Below are some of the various materials collected for the project (Figure 9).

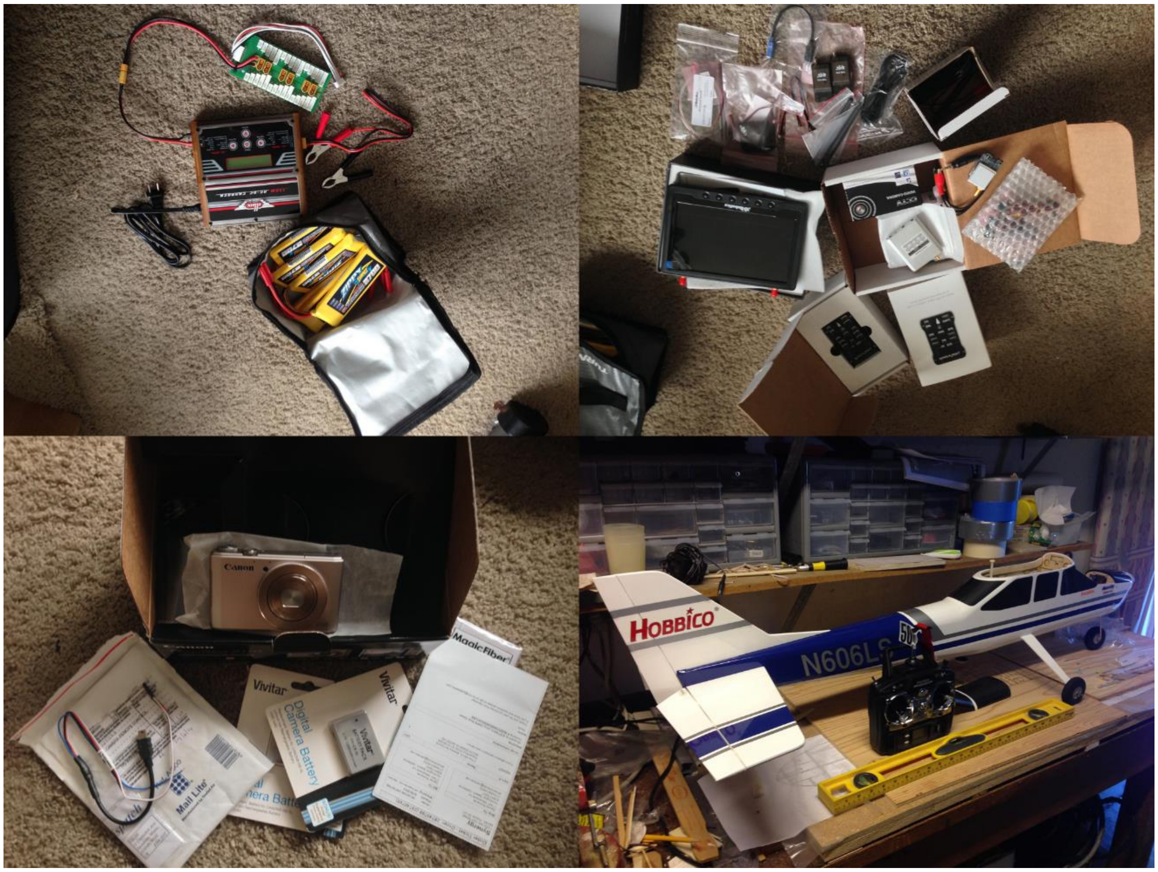


FIGURE 9. Various materials collected for the UAV build.

<u>Hardware Installation</u>

The hardware installation preceded the software installation, with the exception of firmware upgrades, as the software installation required working connections between the various hardware components. Before installing any hardware, a detailed hardware connection diagram was created to organize the various connections and relationships between components (Figure 23, page 82). Familiarity with all of the components is necessary to keep track of what cables belong with each component, and which component groups belong together.

Camera Installation

The first, and most difficult component to install, was the Canon camera. The camera was mounted on the underside of the vehicle in the nadir position (downward facing), just forward of the rear landing gear (Figure 10). Being the heaviest component, the camera was located near the center of gravity to maintain aircraft balance. The area already contained an opening for venting the inside of the vehicle, which was enlarged, so that the camera would slide neatly into the opening. This required removing a non-structural partial bulkhead, and slightly shaving a couple of parallel structural stringers, resulting in no loss of structural integrity to the airframe.

Next, the cable connecting the camera to the autopilot required modification to install the step-up converter (Sparkfun Electronics 2014). This required cutting the power leads on the cable, and soldering the power wires to the converter to act as a switch on the positive leads. The step up converter was spliced into the cable with a servo connector for easy replacement (Figure 11). It is important to shrink-wrap the exposed wires and converter to avoid shorting the connection. The forward bulkhead also contains a hole sufficient for pass-through of the cable.

The compartment was then lined with foam to insulate the camera from vibrations, and Velcro straps were installed to secure the camera in place. While mounting the camera, the tires were changed to a larger diameter (3.5 inches), to allow the UAV to take-off and land on rough surfaces, and to create a greater clearance between the camera lens and the ground.

FIGURE 10. Camera installation in the nadir position.

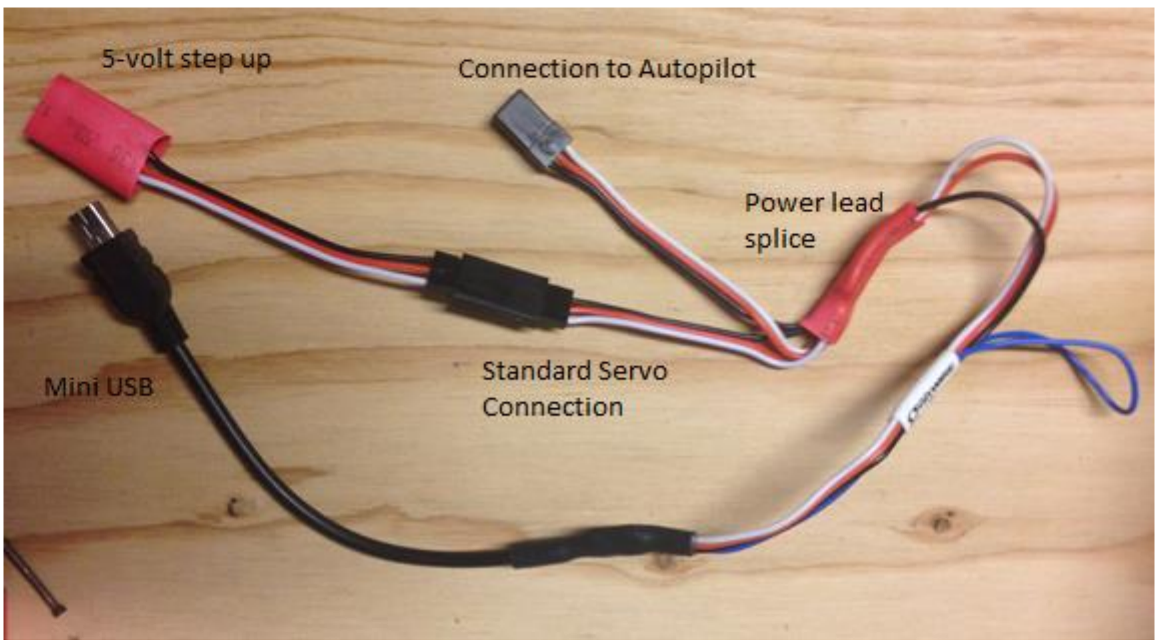


FIGURE 11. Camera USB cable with step-up converter.

Power Connections

Next, standardizing the power connections was achieved by removing the HXT connectors (4 mm bullet from the flight batteries) and the Deans connectors (T style on the ESC), and soldering XT60 connectors in their place. It is important to shrink-wrap all solder connections to avoid receiving a shock, or shorting the batteries. The flight batteries are connected in a series with an adapter constructed from 12 AWG silicon power wire and XT60 connectors. Connecting batteries in a series adds to the voltage numbers, which spins the prop faster (more power), while connecting batteries in parallel increases the capacity measured in milliamp hours (mAh), increasing the flight times. A single two-cell (7.4-volt 2S) 2700 mAh and a single three-cell (11.1-volt 3S) 2700 mAh battery were connected to supply 18.5 volts to the motor (Figure 12).

The next task included locating the battery for the video transmitter (11.1-volt 3S 900 mAh). The transmitter needs to be located as far from the GPS unit and motor as possible to minimize electromagnetic interference. This battery has a JST connector, which was not changed, so an XT60 adapter was created for charging. The receiver battery (4.8-volt 4S NiCd 700 mAh) is already located in a forward compartment near the nose gear, which was disconnected from the receiver, and connected to the servo rail. This battery also supplies backup power to the autopilot, as well as power to the receiver and servos. A switch was also installed between the receiver battery and the servo rail to facilitate disconnecting power to the servo rail. All batteries were held in place with Velcro for easy removal and charging. The receiver battery could have been eliminated with a BEC (battery elimination circuit), but this would have left the autopilot without a backup battery.

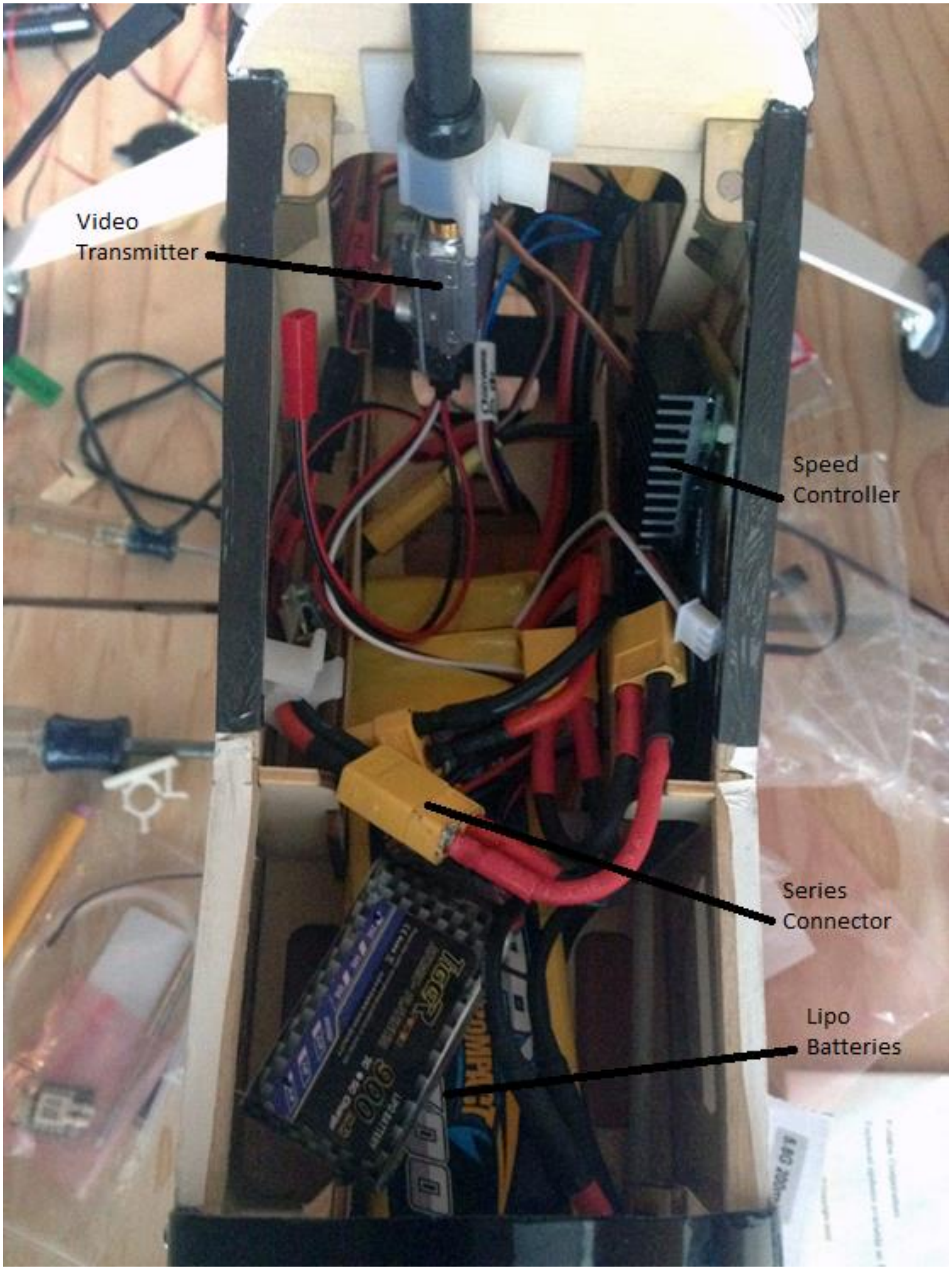


FIGURE 12. Battery compartment.

Autopilot Installation

The Pixhawk must be mounted with anti-vibration foam to isolate the sensitive components from motor vibration in a manner similar to the RC receiver and camera. The Pixhawk is light, and will have a negligible impact on the center of gravity, so it can be mounted anywhere, as long as it can connect to the various sensors (GPS and airspeed), as well as the ESC and battery circuit (Figure 13). In addition, the servo circuits from the RC receiver connection are routed through the autopilot, which requires access to all control surfaces. The MinimOSD and the telemetry radios also connect to the Pixhawk, with most components in the UAV connecting in some way to the autopilot. It is important that the autopilot is firmly mounted, maintaining its orientation relative to the airframe, with the arrow pointing in the forward direction.

Installing the airspeed sensor required opening the wing, and installing the sensor tube on a platform made from scrap hobby plywood. The platform was mounted on the underside of the wing at a location outside of the prop wash, parallel to the direction of the airflow under the wing. The DF13 cable connecting the autopilot to the airspeed sensor required splitting, so a JST connector was spliced to allow easy disconnect when removing the wing. DF13 connectors can be very difficult to uncouple (and can be damaged in the process), and should be considered semi-permanent connections (Figure 14). After the JST cable was routed through the wing, the airspeed sensor module was shrink-wrapped, and mounted with two-way tape to a cross member installed between two ribs. The JST cable was then secured to the innermost rib to alleviate any stress on the DF13 connector.

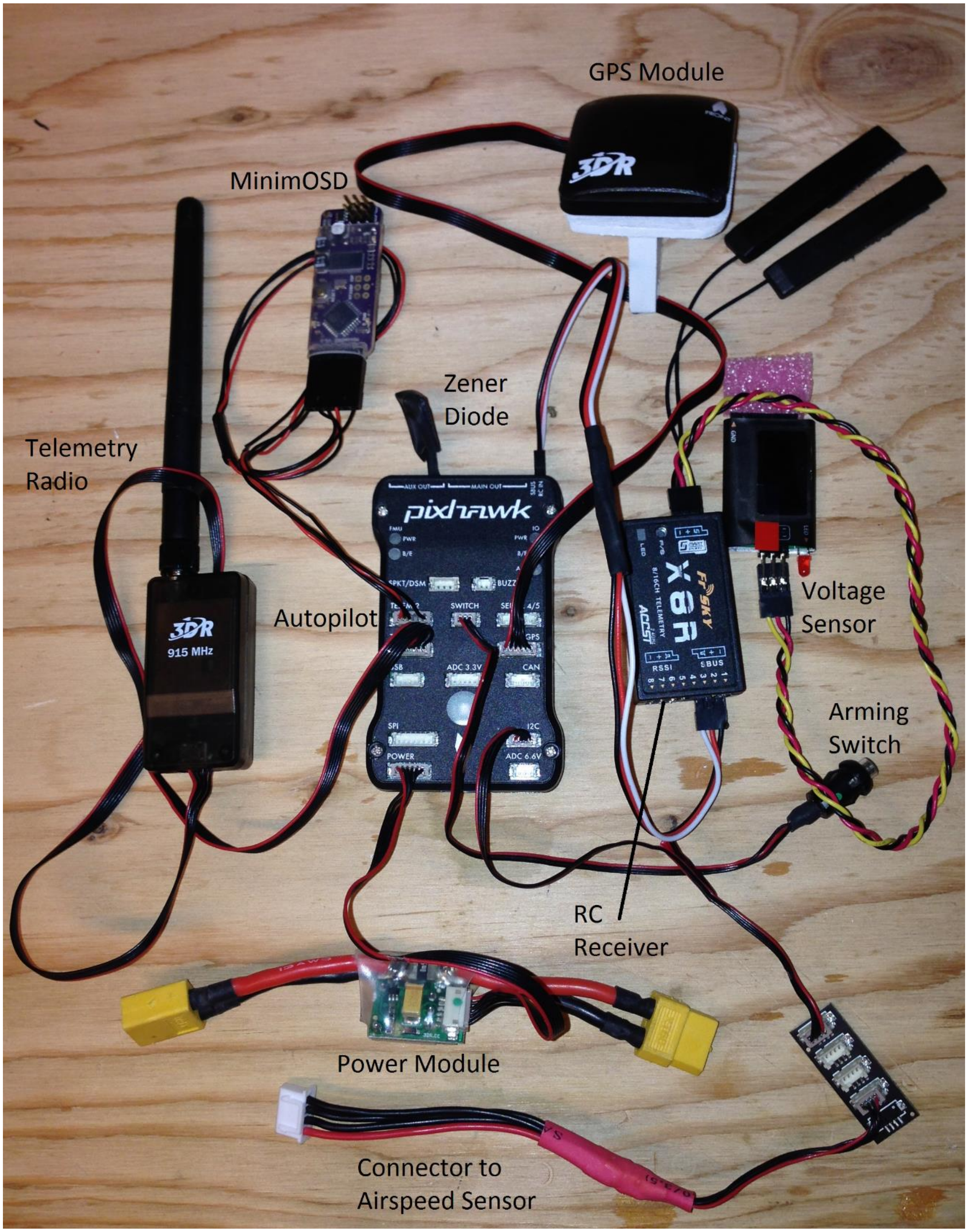


FIGURE 13. Autopilot and attached sensors.

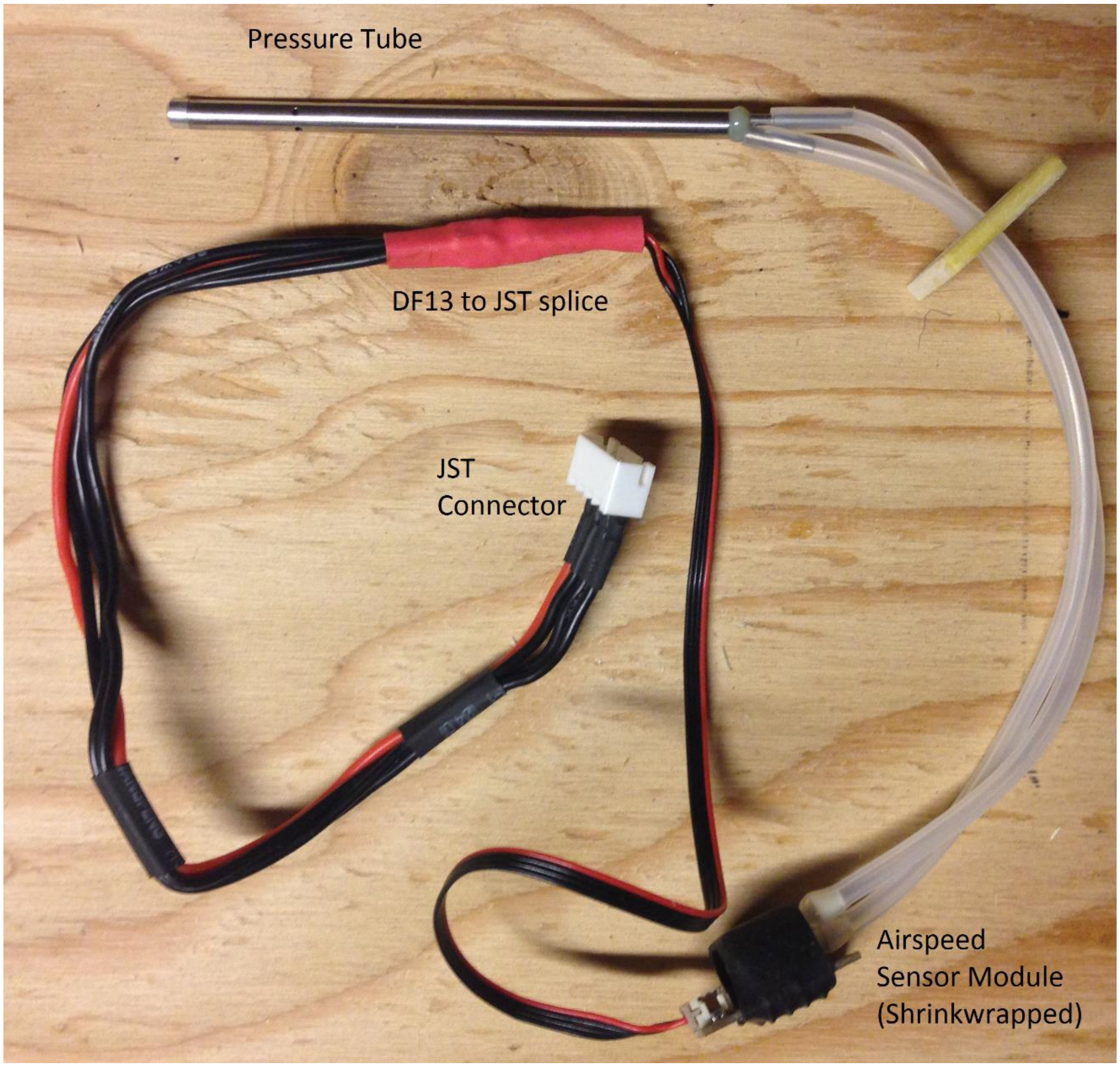


FIGURE 14. Airspeed sensor components and connections.

Communications Equipment

The main challenge when installing the communications equipment involved placing the antennas in areas with the least electromagnetic interference. The other antennas were placed strategically to maximize distance from themselves and sources of interference. The importance of placement should not be overlooked, because the GCS must remain in communication with the UAV.

Mounting the GPS unit required the most care and thought, due to the sensitive nature of the device, and its importance in navigation. Since the GPS antenna requires an unobstructed view of the horizon, it was mounted on the upper side of the fuselage, just aft of the wing trailing edge, far from the batteries, speed controller, and motor. Mounting at this location necessitated constructing a platform made from some scrap, lightweight plywood fastened to the exposed balsa skin of the airframe. Thin cyanoacrylate glue was used to add strength to the balsa sheeting at this location. In addition, since this unit has a compass, it was elevated above the level of the fuselage to reduce magnetic interference.

The telemetry transmitter was connected to, and powered by, the Pixhawk unit. Making this connection was simple, but required obtaining a longer lead from 3D Robotics to reach the autopilot. This unit requires line-of-sight with the telemetry receiver, because the frequency is in the UHF (ultra-high frequency) band. Since this is the most important RF (radio frequency) connection to the aircraft, the transmitter antenna was mounted on the underside of the aircraft in the former location of the AFS (active flight stabilization) antenna. Placing the antenna at this location provides the best possible line-of-sight with the telemetry receiver. The transmitter connection to the autopilot is an extended 45-millimeter DF13 cable, while the receiver connection to the laptop is a standard USB connection. The autopilot interfaces through a logical COM port on the laptop at a data exchange rate of 57600 baud. This is a full-duplex, two-way communication between the transmitter and receiver that relays real-time information between the autopilot and the ground control station, and allows the GCS to change parameters and mission details on the autopilot.

Frequencies in the higher portion of the UHF electromagnetic spectrum have longer wavelengths with less ability to penetrate solid objects (National Aeronautics and Space Administration 2014). Where the 915 MHz link may be strong, the 5.8 GHz link may be weak, even though it is outputting more power. The 5.8 GHz link provides telemetry data from the autopilot to the FPV monitor, though this is not a link to the GCS for flight control. All video signals and power for the video camera and transmitter route through the MinimOSD, which is also powered by the video transmitter battery (Figure 15).

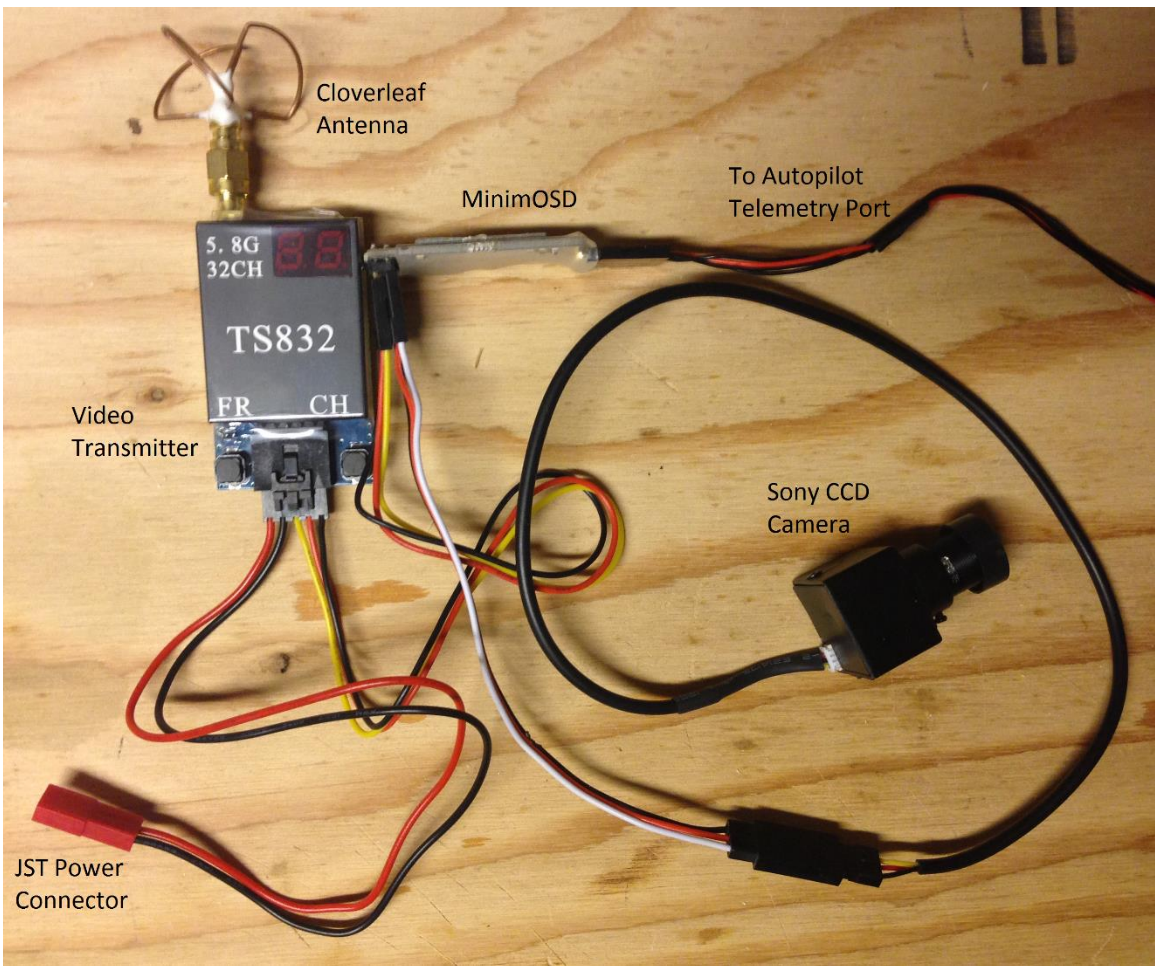


FIGURE 15. Video components and connections.

The new FrSky receiver (X8R Telemetry) was placed against the right side of the fuselage, with the new antenna leads mounted at a 90-degree angle. The receiver is a sensitive component, so it is isolated by foam from the structure of the aircraft. The RC receiver antenna is a diversity antenna, incorporating two antennas from which the receiver can choose the strongest signal. The FrSky RC receiver works on the newer 2.4 GHz band, and provides frequency hopping to help alleviate interference problems.

A voltage regulator was connected to the "Smart" port on the receiver to monitor flight battery voltage on the UAV. This information can be programmed as audio announcements on the transmitter to monitor voltage levels while flying waypoints in an automated mission. In addition, a Zener diode was soldered to a servo connector, and placed on the servo rail to minimize voltage spikes, which could reboot the autopilot in flight, causing a crash or flyaway (Oskay 2012). It is important to get the polarity correct on this diode, or system components will burn up quickly. After shrink-wrapping the diode, it can be placed on any open receiver channel connection on the autopilot.

The servo wires were removed from the RC receiver, and routed through the autopilot (Figure 16). Servo extension leads are available if needed, and in our case, we used only one for the aileron servo, because the wing is removable. The RC receiver has only one connection, which works from the receiver Sbus port, and transmits all receiver channels to the autopilot through the RC port. In addition, it is very important to ensure that all connections are tight, secure, and pushed completely into their receptacles, so that the vibrations that occur during flight do not cause components to become disconnected. This is especially true of servo connections, and these should be checked before every flight.

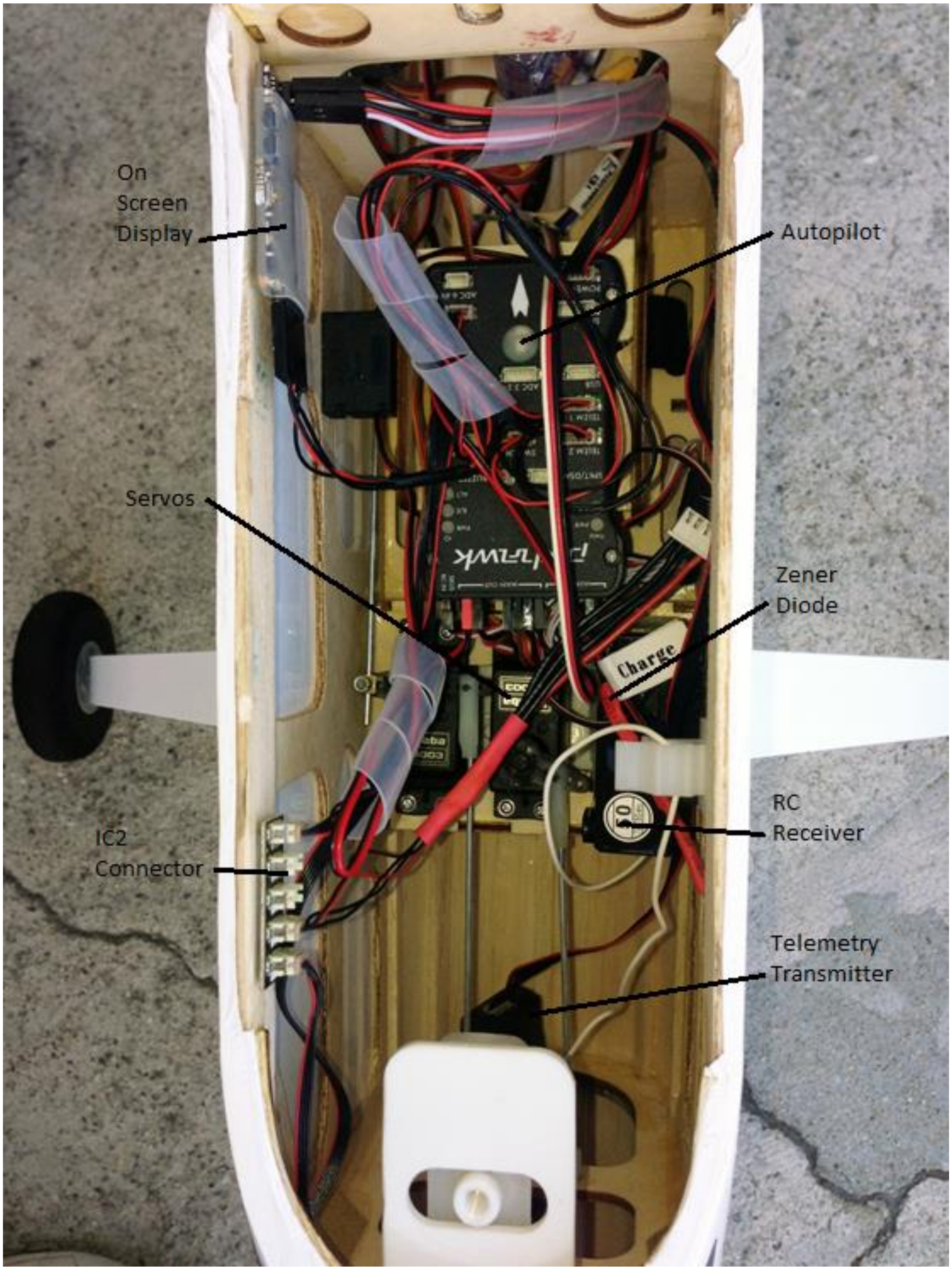


FIGURE 16. Equipment compartment.

Software Installation

First, Mission Planner, an open source flight planning and GCS software, was downloaded from the APM Plane web site (http://plane.ardupilot.com), and installed on the GCS laptop. Mission Planner updates the firmware on the Pixhawk, and tests and configures all hardware components (3D Robotics Corporation 2015). Then, the firmware of the Canon S110 camera was updated using the CHDK script (CHDK Team 2014), written to an SD card, and loaded onto the camera, allowing the autopilot to control the shutter of the camera (Figure 17). To test shutter control, the Gentles cable was attached to the autopilot, with the USB end plugged into a specially constructed adapter (a mini USB female plug soldered to an XT60 connector). When activating a switch on the RC transmitter, a 5-volt pulse from the autopilot was confirmed with a voltage tester.

FIGURE 17. Canon S110 camera running CHDK hack.

Hardware and Software Configuration

The FrSky Taranis is an open source transmitter based on the openTX platform, consistent with the goals of this project. The FrSky Taranis is highly advanced, exhibits superb build quality, and is fully customizable. Changing the radio required removing three Futaba standard S3003 servos and the Futaba receiver, and installing three upgraded Hitec servos and the FrSky receiver (X8R). Though this improved transmitter supported advanced configuration options, it required reading extensive documentation to setup the UAV.

Next, all of the control surfaces for the UAV were adjusted for proper alignment and deflection. This ensures straight and level flight when all control gimbals (control sticks on the transmitter) are set to their home, minimum, and maximum positions. While checking the deflection, hinges were inspected to ensure safe and successful flights, as control linkage failure is a common reason for fixed wing UAV crashes. In addition, the controls required further adjustments due to the tendency of the UAV to nose up and bank left on the maiden flight.

The default settings for the openTX firmware loaded onto the Taranis placed the primary controls on non-standard channels. The mixer function is used on the model setup menu to change the channels, placing the ailerons on channel 1, the elevator on channel 2, the throttle on channel 3, and the rudder on channel 4 (Figure 19). This allows Mission Planner to calibrate the controls on their proper channels. In addition, using the mixer, channels to be used for flight mode and other functions executed by Mission Planner can be configured. It is a good idea to set the flight mode on channel 8, and other functions on channels 5 through 7. At this time, the audio prompts for each flight mode can be chosen so that memorization or labeling is not required.

Mission Planner software connects to the autopilot via the telemetry radio MAVLink (Micro Air Vehicle Link) protocol. Upon plugging in the telemetry radio (USB), the laptop did not recognize the device. After some research, it was determined that the USB adapter contains an FTDI (Future Technology Devices International) chip. This is required for interfacing RS-232 (Serial) device transmissions to USB signals that modern operating systems can recognize (Future Technology Devices International 2015). Installing the FTDI driver for serial emulation installs a COM port (Figure 18).

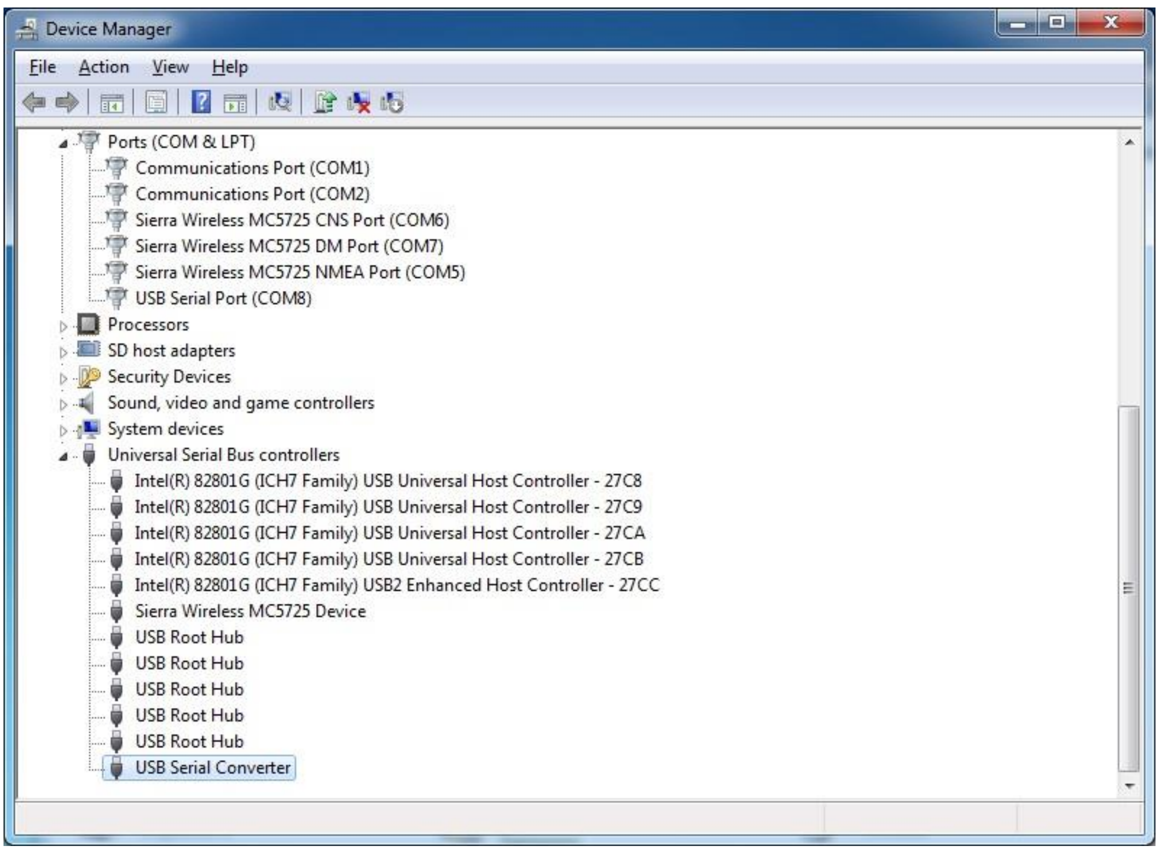


FIGURE 18. Windows Device Manager with USB Serial Converter and COM ports.

First, the compass, gyroscope, and accelerometers are tested by holding the UAV, changing its attitude (pitch and yaw), and watching the horizon in Mission Planner reflect the correct attitude of the aircraft. Next, the gimbal channels are calibrated, recording the throws of all of the gimbals, and reversing the directions, if the output is reversed. The RC Transmitter outputs PWM (Pulse Width Modulation) signals, which are interpreted as numbers representing the proportional stick location. Then the flight modes are configured on a series of switches (one 2-position and one 3-position) to include Manual, Stabilize (simple stabilization), Fly-by-wire (pitch hold), Auto (follows a mission set of waypoints), Loiter (plane will circle and maintain altitude), and Circle (failsafe is triggered). The RTL (Return to Launch) function was placed on a different two-position switch. After configuring the flight modes, the hardware (sensors including gyroscope, accelerometer, compass, and airspeed) was calibrated, and the UAV was ready for testing.

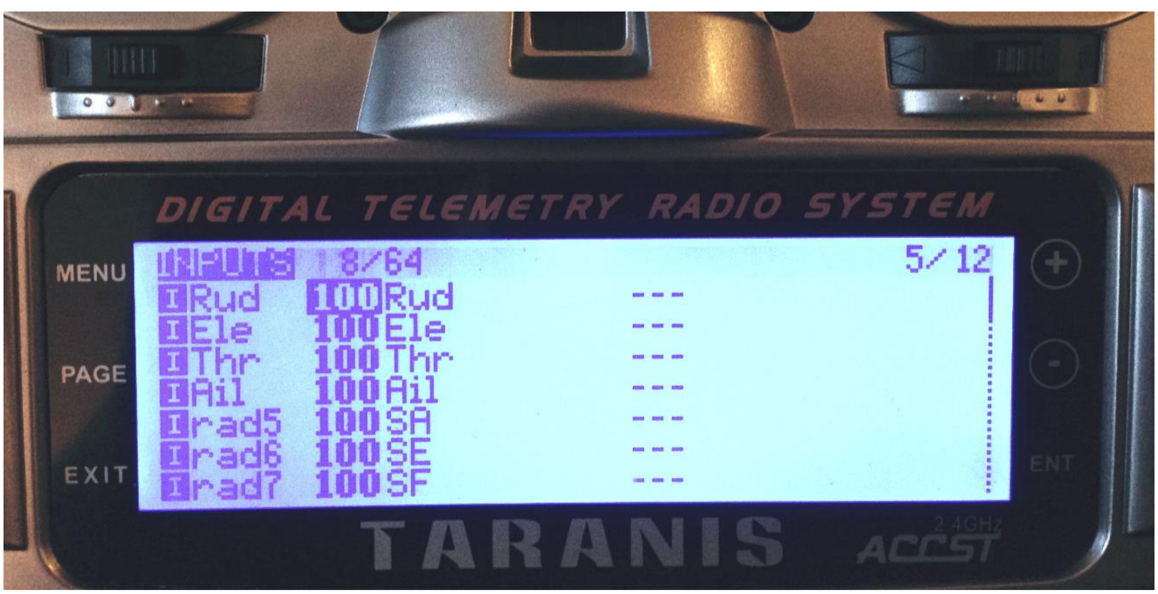


FIGURE 19. FrSky transmitter interface.

Testing the Equipment

Once installed, the equipment can be ground tested before attempting a flight with the UAV. Testing the equipment involves setting up all the components to make sure everything is in working order, performing as would be expected during flight conditions. After the batteries, camera, and antennas are installed, the connection between the UAV and the ground station is established via the telemetry modem. Each flight mode can be tested by changing the switches on the transmitter, noting the change in the Mission Planner flight screen, and then checking the behavior of the flight surfaces.

RC Transmitter Setup and Range Checking

In manual mode, the flight surfaces should only respond to transmitter stick input. This is a good time to make sure that all of the flight surfaces are configured properly before attempting to fly the UAV. When moving the right stick down, the elevator should move up, and vise-versa. When moving the right stick left, the left aileron should move up, and the right aileron move down, and the opposite when moving the right stick in the right direction. The left stick controls the throttle and rudder, and when moved up, the throttle should beep once to indicate full throttle position, and then beep twice to enter the armed state with the throttle in the minimum position. This is a safety feature of ESCs. When moving the left stick to the left or right, the rudder should move the same direction.

Once manual mode is tested, stabilize mode can be tested to determine if the flight controller is properly managing the flight surfaces. When entering stabilize mode, the flight surfaces should move in an attempt to level the UAV when the airframe is placed in a positon that deviates from level. When pitching the nose up, the elevator should move down. This would have the effect of pitching the nose down in flight. The opposite should occur when pitching the nose down. When banking the airframe to the left (roll), the left aileron should move down while the right aileron moves up, and vise-versa for a right bank. These are the only controls needed to stabilize the UAV in flight (pitch and roll).

Next, the RC transmitter/receiver should be range tested to ensure proper communication between the transmitter and the UAV. The RC transmitter is the sole source of manual control over the UAV, and a flight should not be attempted until the transmitter/receiver range is checked. The range of these components should be approximately 2 kilometers (1.22 miles), and most transmitters have a function that will range check the connection without needing to separate the transmitter and receiver over a large distance.

Testing the Power Components

Next component to test is the motor, which should spin in a counter-clockwise direction, and provide generous force when in the maximum throttle position. Test this by placing the UAV on the ground and placing your feet on either side of the fuselage in front of the rear stabilizer. Then move the throttle to the maximum position, and observe the direction and intensity of the UAV movement. If the UAV does not want to move forward, the motor will need to be reversed. Switching any two of the three wires that connect the motor to the speed controller will change the direction of the motor. It is important to keep hands and other objects out of the way of the propeller as these can spin at speeds over 10,000 revolutions per minute.

After this, the center of gravity of the aircraft must be adjusted. With all of the components installed, the airframe can be balanced by using a CG apparatus, or by using a small level and two fingers. When placing your fingers approximately one-third the length of the wind chord from the leading edge of the wing, and balancing the aircraft on the tips of your fingers, the airframe should be level. Leveling can be carried out by placing a very small leveler on the stabilizer. If the airframe is nose-heavy, then the flight batteries should be moved towards the rear, and the opposite if tail heavy. It is more desirable to have an airframe nose-heavy than tail-heavy, as nose-heavy airframes will make it difficult to achieve level flight, but tail-heavy airframes fly only once. In addition, it is important to balance the propeller, tightly fasten the propeller nut, check the control linkages, and inspect the batteries and wires.

Video and Telemetry Range Checking

The video equipment can be tested by installing the antennas and checking the picture in the video monitor. Make sure to set the focus on the camera, or a clear picture will not be possible (twist the lens on a CCD camera). More importantly, the telemetry radio needs to be range checked, because losing communication with the GCS will invoke a failsafe condition. This can only be tested by separating the UAV and GCS, and observing the signal strength indicator in the Flight Data screen in Mission Planner. Perform this before operating in any flight mode, including manual mode.

Ground and Flight Testing

Once the UAV is considered air-worthy, ground-handling practice is in order. This is best performed in an open area where the UAV will not run into obstructions, and break the propeller, or suffer other types of damage. The UAV should be driven slowly at first, with small stick inputs of the throttle and rudder. When taking off, the rudder will be used to keep the UAV moving in a straight line so that safe lift-off can be achieved. Ground handling is performed with the left stick only, and flight handling is primarily handled with the right stick. In addition, the UAV has no brakes, so keep this in mind when using the throttle.

Once the UAV pilot is comfortable with ground maneuvering, it is time to test the UAV in the air. Operating remote fixed-wing aircraft is challenging, and requires significant practice to master the basic skills. First, practice should be done on RC simulation software, including RealFlight (Great Planes Model Manufacturing 2015), or Phoenix R/C (RunTime Games 2015). These programs present a realistic remote flight experience, and will allow one to master stick input and flight orientation without the risk of crashing a real aircraft. Second, the first flights should be performed alongside an experienced instructor, who can take over the control of your UAV in the event of trouble, and trim the UAV on its maiden flight. Qualified instructors can be found at a local RC airfield, and they are a very helpful group of people. It is a good idea to spend some time in flight training before performing a mission.

Planning the Mission

Now that the UAV is flight ready, and the pilot has acquired some flight skills, it is time to create a mission in the Mission Planner software (Figure 20). Mission Planner uses Google Earth as its map engine, so data is available for any location. When choosing a location, it is important to consider the accessibility of the site, proximity to critical infrastructure and airports, availability of takeoff and landing areas, and terrain characteristics. At this point, until the FAA allows urban mapping, flights will need to be conducted in remote areas where the flight activity will not raise the scrutiny of local public officials. Choose an area outside of a five-mile radius of any airfield and outside of a national park, as operating in these zones will raise the attention and potential fines from the FAA.

<u>Objects on the Landscape</u>

The most significant consideration in mapping natural areas is the density of land cover and general slope characteristics of the terrain. When flying at lower elevations, objects that are closer to the camera will be more distorted, so the flight altitude will need to be adjusted according to the overall relief. In addition, tall landforms can disrupt radio frequency communications, as most communication protocols operate in the UHF band, which requires line of sight between the GCS antennas and the UAV. This can all be reflected in Mission Planner.

FIGURE 20. Mission Planner Flight Planner screen.

The first task includes zooming to an area of interest and constructing waypoints. These are points that the UAV traverse in auto mode in the sequence of the waypoint numbers. Each waypoint has a horizontal and vertical location, which can be set as the distance above the surface, or absolute elevation above sea level. Waypoints can be entered manually, or the software can automatically draw waypoints by defining a study area polygon (Figure 21). This is the quickest and most efficient way to construct a mission optimized for aerial photography. After constructing the flight lines in automatic mode, the size of the polygon defining the study area can be changed, which will cause a redraw of the flight lines. More area can be added based on the estimated mission time and flight battery duration at the specified airspeed. The flight line angles can also be adjusted so that they are perpendicular to the wind direction, insuring that the UAV will be able to maintain constant airspeed, and thus, photography coverage.

FIGURE 21. Mission Planner flight plan using Grid function.

Once the mission has been constructed in the Flight Plan screen, the waypoints can be written to the autopilot using the “Write WPs” button, which will send the data to the autopilot via the MAVLink connection. Once the waypoints are written, placing the autopilot in auto mode will cause the UAV to fly the waypoints in order, then loiter or circle until the return to launch function is executed, or manual control is established. The autopilot is capable of autonomous takeoff and landing, but with the nature of GPS accuracy, especially in the vertical dimension, it is best to land the aircraft manually.

The mission can be constructed in the field, or prior to the field trip. In either case, make sure to right click on the screen, choose “Map Tool”, and “Prefetch” to download all of the Google Earth map tiles prior to heading to the field. In the field, there will not likely be access to a high-speed internet connection, and the tiles can be numerous and large. The screen area can be downloaded, or just the waypoints path. This is important to view the flight path on the map, or construct the mission in the field.

After calibrating the airframe, testing the components, performing the safety check, constructing the mission, and charging the batteries, the UAV can be transported to the mission location. Having access to a van or truck is preferable, as the components can require significant space. The components should be organized in a flight bag, including tools (wrenches, hex drivers, utility knife, CA glue, screw drivers, etc.), video and communications equipment, batteries, charger, antennas, and other miscellaneous equipment. It is also good to have an “Easyup” canopy, table, and chairs to provide shade for the equipment, as the ground station and video screens will be difficult to view in direct sunlight.

CHAPTER 4

RESULTS

Building an open source UAV was far more challenging than originally anticipated. The process consisted of taking two steps forward, and one step back. Many tasks required to assemble the UAV spawned new tasks, as small details were buried in documentation (or not documented at all). Even small details cannot be overlooked, as they can contribute substantially to the ability of the UAV to perform a mission. Obtaining aerial photography from an unmanned aerial vehicle has two distinct aspects requiring very different skill sets. Working with the UAV requires technical skills and an attention to detail, whereas working with the aerial photography requires spatial analytical skills and attention to processes.

The first task in constructing an open source UAV was the research. The amount of information required to select and construct a UAV is vast, covering topics including RC construction and flight, electrical systems and wiring, communications systems and the electromagnetic spectrum, autopilot hardware and software, cameras and sensors, and various related subjects. When taking on highly technical challenges requiring expenditures on equipment, diligent research will minimize unnecessary expenses and wasted time. Many of the web sites that provided valuable information are listed in the references. Considering the topic is of a recent nature, not much traditional literature is available on the subject.

UAV Development Assessment

First, the primary components were acquired (airframe, camera, autopilot, and communications), and the manufacturer's documentation reviewed. This was necessary to determine what additional parts would need to be acquired to connect the components together. Many of the additional parts were acquired incrementally as primary components were assembled and configured. It was also a challenge to keep room in the fuselage when placing the components. The component installation process was repeated through numerous iterations. Then, all components were prepped for final installation, and documentation was created (Figure 22).

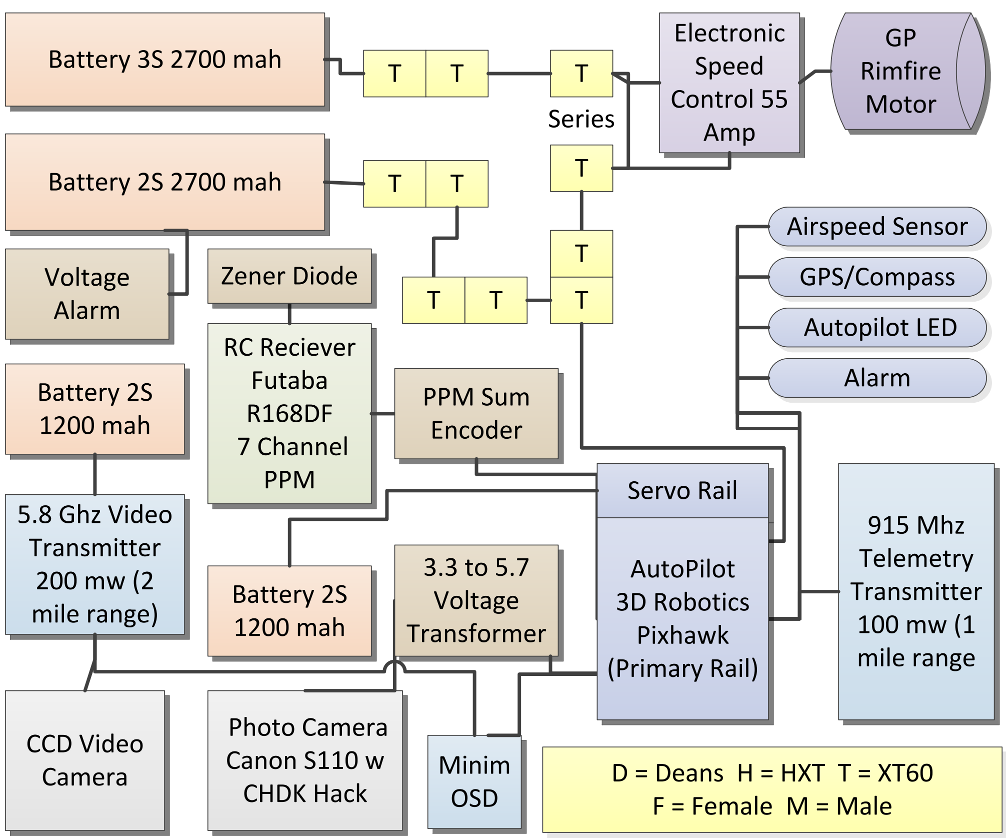


FIGURE 22. Component relationship diagram.

Connecting the components proved to be challenging as well. Soldering was perhaps one of the most important skills required, as nothing will cause an airplane to crash faster than a poorly soldered electrical connection. The next challenge involved placing the components, which must be expertly positioned in the small spaces of the narrow airframe. The components also need to be placed in locations that will contribute to the balance of the airframe. When all was finished, the entire workflow was documented (Figure 23).

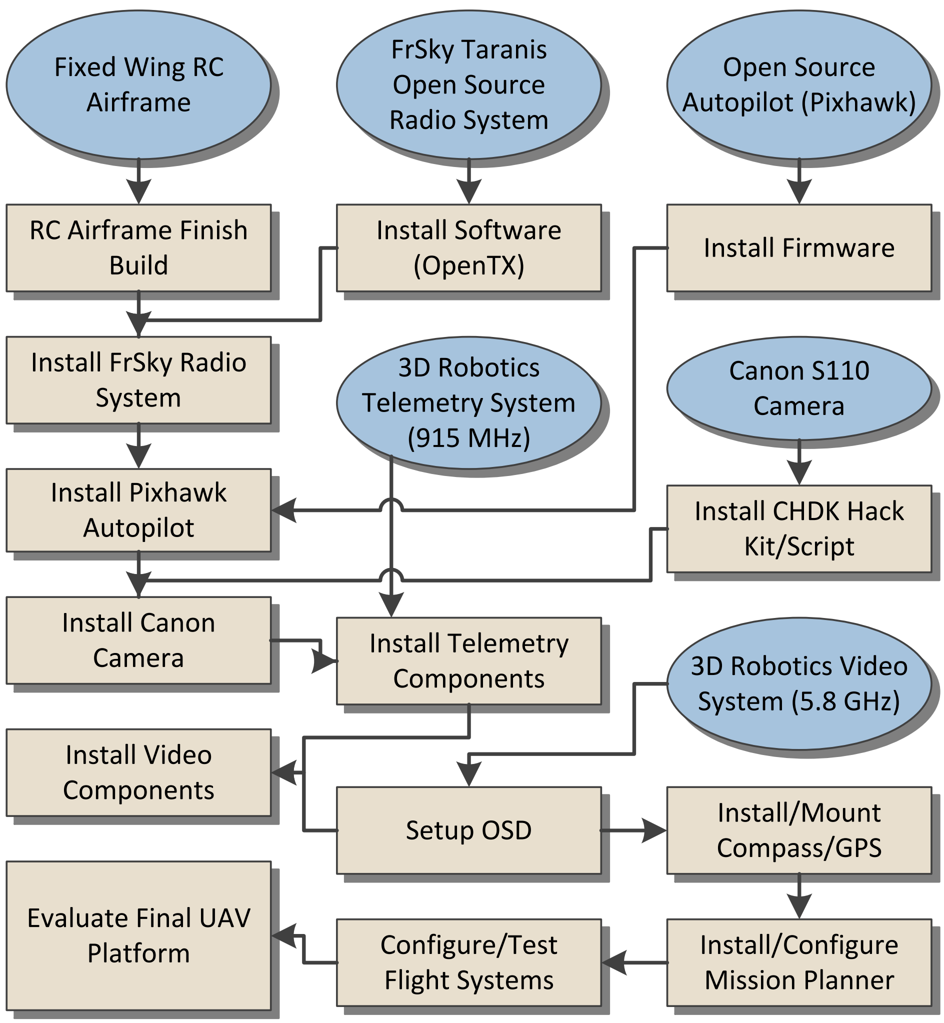


FIGURE 23. UAV development workflow.

After many months of building, modification, and component installation, the UAV was solid, balanced, and capable of taking clear photography. The UAV was inspected and tested, and was now ready for a mission (Figure 24, 25).

FIGURE 24. Finished UAV front view.

FIGURE 25. Finished UAV side view.

The Mission

Silver Lake dry lake bed, approximately six miles north of Baker, California, in a remote part of the Mojave Desert, was selected as the mission location (Figure 27). A day for the mission was chosen where the weather would not be a factor. Flying at times when the sun is at its highest point, before the afternoon winds increase, is preferred.

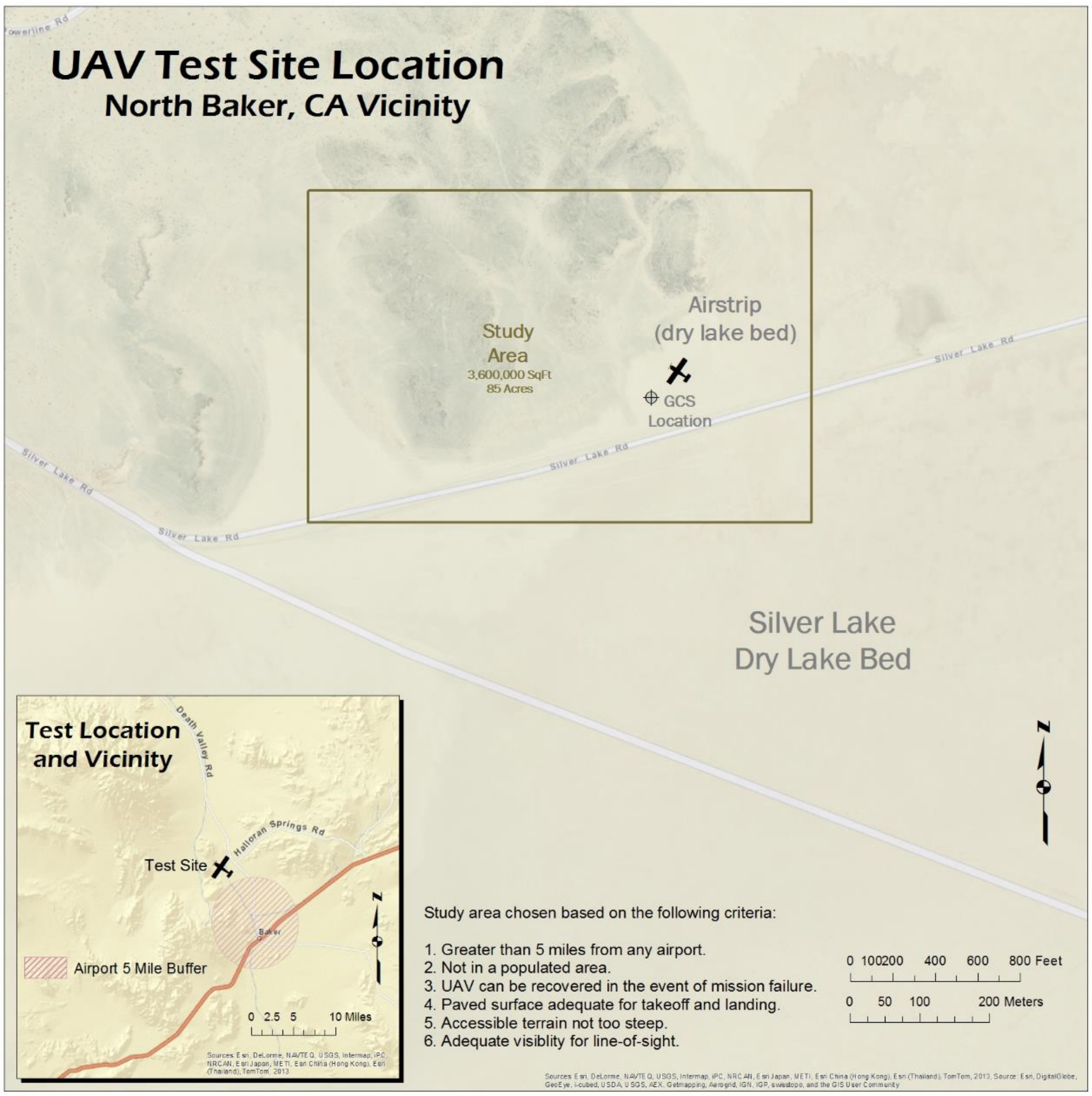


FIGURE 26. Map of study area.

The map tiles were prefetched the day before, so the tiles were viewable quickly. A very conservative flight plan was constructed in the field, consisting of 14 waypoints with a total estimated flight duration of three minutes. The goal was to test the technology, not map a large portion of the Mojave Desert. Since there are so many components to consider, a checklist was created, and the components were stored in areas where they would not be forgotten. Careful handling of the airframe is also important, because damaging the UAV can compromise the mission.

Heading out to the field

Upon arriving at the mission location, the first task completed involved setting up the equipment. Setup started at the site on November 8, 2014, at about 10:00 a.m. This was completed patiently, as haste could lead to mistakes. When determining a ground station location, obstructions between the ground station and the vehicle flight paths were avoided. First, the table and Easyup were unfolded, and then the video equipment, with the monitor on a tripod, was set up with the antennas pointing at the flight location. Time was taken to make all of the proper connections, and place the components where they would be viewable and accessible. Then the RC transmitter was checked, and the airframe was assembled. This involved connecting the airspeed sensor and wing servo wires, and bolting the wing to the fuselage.

Next, the GCS was booted, and the Mission Planner software loaded, but no attempt was made to connect to the autopilot at this time. The RC transmitter was powered, and the flight batteries were connected to the UAV. The autopilot will boot, but not enter the armed state. The autopilot was connected using the Mission Planner software, and the UAV was placed at the spot defined as the home location. While placed at the home location, the autopilot was armed by pressing the arming button, which changed from blinking red to solid red, indicating the ready state. Once armed, the Flight Data screen in Mission Planner (Figure 26) changed from "Disarmed" to "Armed", indicating that the UAV was ready for flight. The flight mode switch on the RC transmitter was also in the desired manual flight mode position, which was indicated on the Flight Data screen.

FIGURE 27. Mission Planner Flight Data screen.

Once the UAV was armed and in manual flight mode, the flight surfaces were tested for proper movement. Then the main flight camera was powered up, the intervalometer script was started, the camera was fastened to the airframe, and the DVR was powered on for video flight recording. Then UAV was pointed into the wind, and the area was surveyed to make sure that conditions were safe for flight.

Performing the Mission

With four sets of batteries fully charged, the UAV was ready to perform the mission. The target area consisted of a ridge with about 100 feet of vertical relief suitable for low level, high-resolution mapping. The next decision was to select a takeoff and landing location. The evaporite surface, though cracked, was smooth enough for the oversized wheels that were installed on the UAV. When all flight modes were verified to be working, the intervalometer script was started, the pre-flight checks were performed, and the UAV was headed into the wind for takeoff.

Liftoff was labored, as the UAV weighed in at over seven pounds, and the stock motor was exhibiting difficulty in gaining altitude. The UAV could only climb at a modest rate, and notations were taken of the insufficiency of the power train. Once the UAV gained altitude, the flight characteristics were adequate for maneuverability and sustaining altitude. After climbing the UAV to a safe altitude of about 400 feet, it was time to test the functioning of the autopilot.

First, the UAV was set to stabilize mode, which performed perfectly. After activating the camera, the UAV was switched to auto mode, and the vehicle immediately flipped over on its back and began flying upside down at a descending trajectory. After switching the UAV back to manual mode, the vehicle recovered from its undesirable flight attitude about 50 feet above the ridge. This was not the desired scenario, but experiencing a malfunction in auto mode was a definite possibility, considering the complex nature of the flight controller. The mission continued in manual mode, approximating the mission flight lines while continuing to take pictures at an elevation of approximately150 feet above the surface.

After a few minutes of taking pictures, the low voltage alarm started beeping, and the plane was prepared for landing. Only one extra pass was required to gauge the landing distance, and the UAV touched down for its first semi-successful mission. This UAV can only hold 2700 mAh batteries due to weight considerations, so the flight times were limited. While on the ground, the pictures were examined and considered well focused and exposed, so the batteries were changed for the second flight. Since the flight controller seemed to be having an issue determining up and down, the UAV was put through the entire calibration routine to adjust the accelerometer and gyroscope, hoping to eliminate the tendency of the UAV to flip over on its back when engaging auto mode.

After the calibration was complete, the UAV was armed and ready for the second attempt at completing a mission in auto mode. The UAV took off into the wind, but again struggled to gain altitude, and barely cleared the ridge directly in the flight path. After obtaining proper altitude for flight mode testing, auto mode was engaged again. The UAV exhibited the same behavior, so manual mode was immediately selected. The rest of the mission was performed in manual mode, and the flight lines were flown at various altitudes in an attempt to capture adequate photography for complete coverage.

After the second flight, the goal was to get in one more flight before the afternoon winds picked up over the desert. Approximately one minute into the flight, control of the UAV was lost as it flipped upside down and crashed into a hill approximately 500 feet in the distance (Figure 28). The UAV did not respond to commands from the transmitter sticks, and would not respond to changes in the flight mode. This resulted in a trek up the hill to recover the downed UAV, while contemplating the reason for the malfunction.

Upon reaching the UAV, the damage was obvious. The first concern was for the camera, as the photographs were needed to complete the project. Keeping the schedule was important to completing this project, and this crash was going to set back the ability to take additional photography for at least a couple of months. Ironically, the camera was still taking pictures when it was lifted off the rocks, and the damage to the camera appeared to be minimal. Later examination would reveal that the USB port was damaged, most likely due to a voltage surge from the batteries upon impact, but this was inconsequential, as the SD card could be read from a card reader.

FIGURE 28. The crash site.

As it is apparent in the photo, the damage to the airframe was extensive. The entire front half of the fuselage was reduced to a pile of plywood, balsa, and MonoKote (vinyl covering material). Fortunately, the airframe absorbed most of the impact. After carting the remains down the hill and examining them, it was discovered that only a few items suffered irreparable damage. The damaged items included the airframe ($200), the voltage sensor ($15), and CCD video camera lens ($20). Considering the extent of the damage, it is amazing that most of the components, including the most expensive component, the autopilot, survived without even a scratch. This shows the importance of solid installation techniques with padding and support sufficient to survive the inevitable crash.

Wrapping up the Mission

After inspection, the components were bagged, and the equipment was broken down for transport. An inventory of the UAV components was conducted to determine if anything might have been lost in the crash, but everything appeared to be present. This is an unfortunate aspect of remote flight that every pilot should be aware. There will be days when things come back in one piece, and days when one needs to bring the bag. I cannot even count how many crashes I have witnessed at the RC flying field. One field even has an “RC airplane graveyard” that illustrates the risks involved with RC technology.

Post Mission Processing

With the mission wrapped up, it was now time to determine what was taken away from the field. The primary unknown was the geographic coverage of the photos, considering that automated flight lines were approximated in manual mode. If the coverage were inadequate, this would result in holes in the point cloud developed from the photography. The only method to examine the coverage was to clean up the photos and import them into an image processing software package.

Photography Evaluation

The good news is that the photography was intact and available for processing (Figure 29). After downloading the photos, and examining them with imaging software (Digital Photo Professional from Canon, Inc.), the photos were selected for proper angle and relevance to the study area. After the selection process, 253 photos out of the original 497 photos were considered usable for the model, which is a high percentage. The photos that were taken while the UAV was turning were not chosen, and those too close to the ground were eliminated.

FIGURE 29. Sample raw photography of the desert mission.

The image quality was very good, with optimal exposure and clarity. The camera was set at 1/1000 shutter speed, with an aperture setting of 5.6, giving a good depth of field for sharp imaging. The high level of illumination reflecting off the light desert surfaces allowed for high shutter speeds, compensating for the movement of the UAV, resulting in sharp pictures, capturing generous amounts of light, even with the narrow aperture setting. The auto focus was turned off and set to infinity, which was probably a contributing factor to the camera being able to take substantially more pictures than its rating. Even though the camera battery life was considered the limiting factor to the number of pictures possible with each flight, the camera was able to take continuous pictures for the entire duration of the life of the flight batteries.

Camera Performance Evaluation

The Canon S110 (successor to the S100 used by some aerial photographers) proved to be a suitable camera for aerial photography. The Canon can connect directly to the autopilot through the USB port, which provides a clean and reliable solution for shutter triggering. In addition, the camera, with its 24-millimeter, F2.0 lens, created crisp pictures with minimal barrel distortion at 12 megapixels each. This is far superior to pictures captured with a GoPro, or other "action camera" with an ultra-wide angle, fish-eye lens. Photos taken from one of these cameras must be pre-processed to remove the barrel distortion, which results in a reduction in quality, and crops portions of the photo. The CHDK scripts were installed easily, and they controlled the shutter perfectly.

Processing the Photography

After the pictures were selected and corrected for tone, they were loaded into AgiSoft Photoscan for processing (AgiSoft 2012). The 253 photos were imported, the photos were aligned, and the dense point cloud was built (Figure 30). This process would reveal whether the manual flight would provide adequate coverage without any holes in the imagery. After the photos were aligned and the point cloud built, the results were examined and found to provide coverage for the entire study area. The various camera locations were widely distributed, and the photos taken from the nadir position were a large percentage of the total. Most of the photos were taken between 100 and 150 feet in altitude, and some were taken at altitudes over 200 feet. This was done to ensure adequate coverage in case the lower altitude photos provided insufficient coverage. The camera positions and original calculations can be seen in the following screen capture:

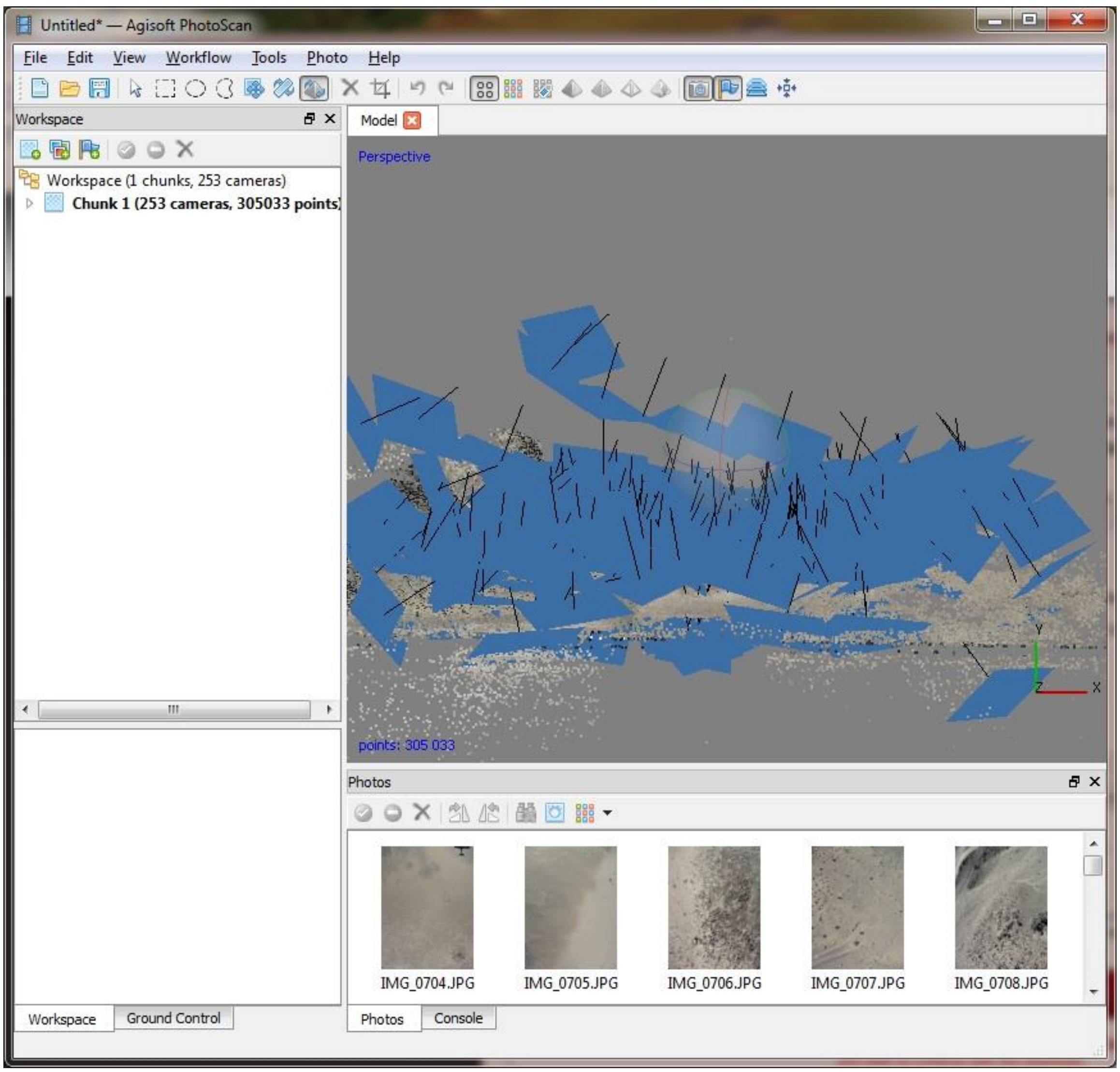


FIGURE 30. Photo locations and point cloud.

The dense point cloud consisted of 21,999,981 points, resulting in approximately two-centimeter ground resolution, the actual target of the original flight plan and waypoints (Figure 31). This was achieved through ample amounts of flight time with the RC practice aircraft, and being able to judge altitude from a third person ground perspective. The goal was to photograph the area at fifty meters above the surface, which resulted in a resolution just greater than the two-centimeter target. Then the mesh was built, and the surface started to take shape, revealing the high-level quality of the photogrammetric process. The surface is visualized in figure 31 below:

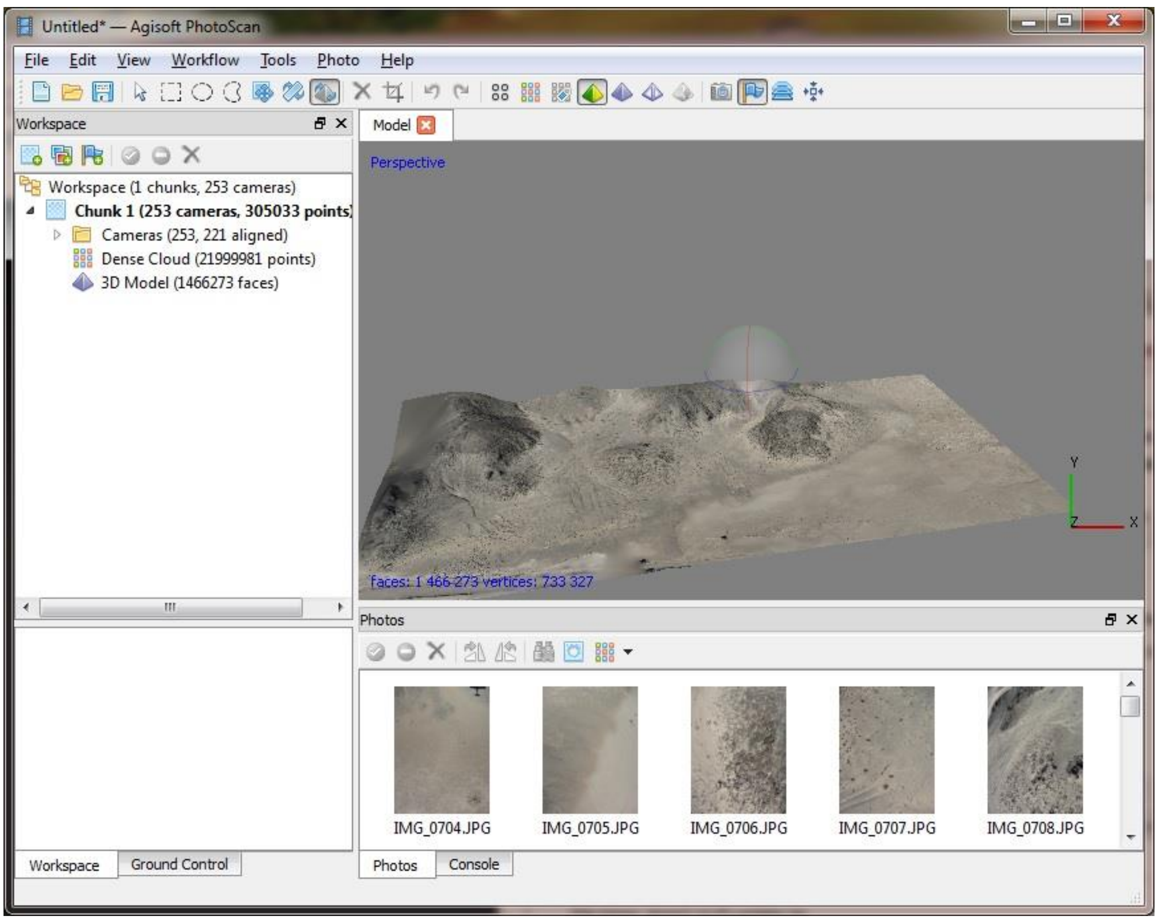


FIGURE 31. Dense point cloud.

Then the orthophoto was exported, and the image was examined against Google Earth for a comparison of the quality and resolution. The orthophoto was not georeferenced, as the control points were not made available, but this was not a major consideration for the photography. The results of the photography can be visualized in software applications that are capable of image display (Figure 32).

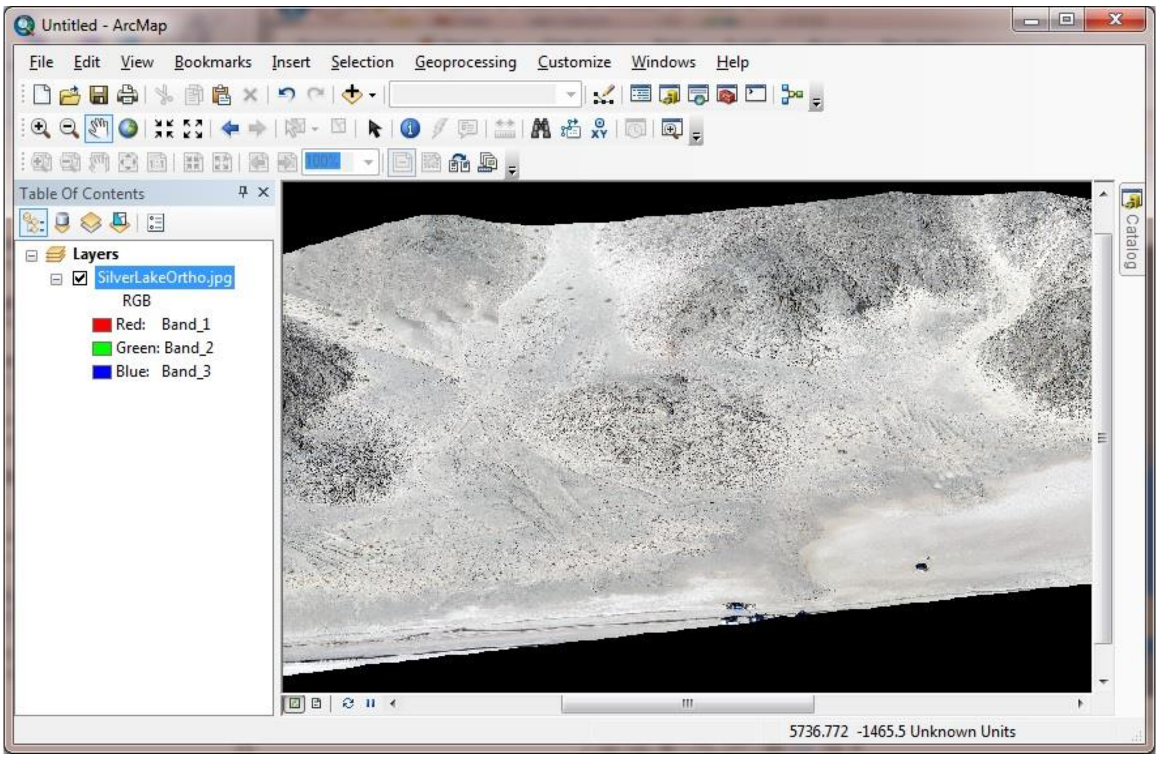


FIGURE 32. Photography generated from dense point cloud.

The figure on the next page displays the detail in the photography, where small rocks appear large, demonstrating the high resolution possible with low-level photography. In addition, photography taken at a lower altitude exhibits less distortion, and the atmospheric conditions have a lesser effect on the results. The detail in the exported orthophoto can be examined when zooming in to a large scale (Figure 33).

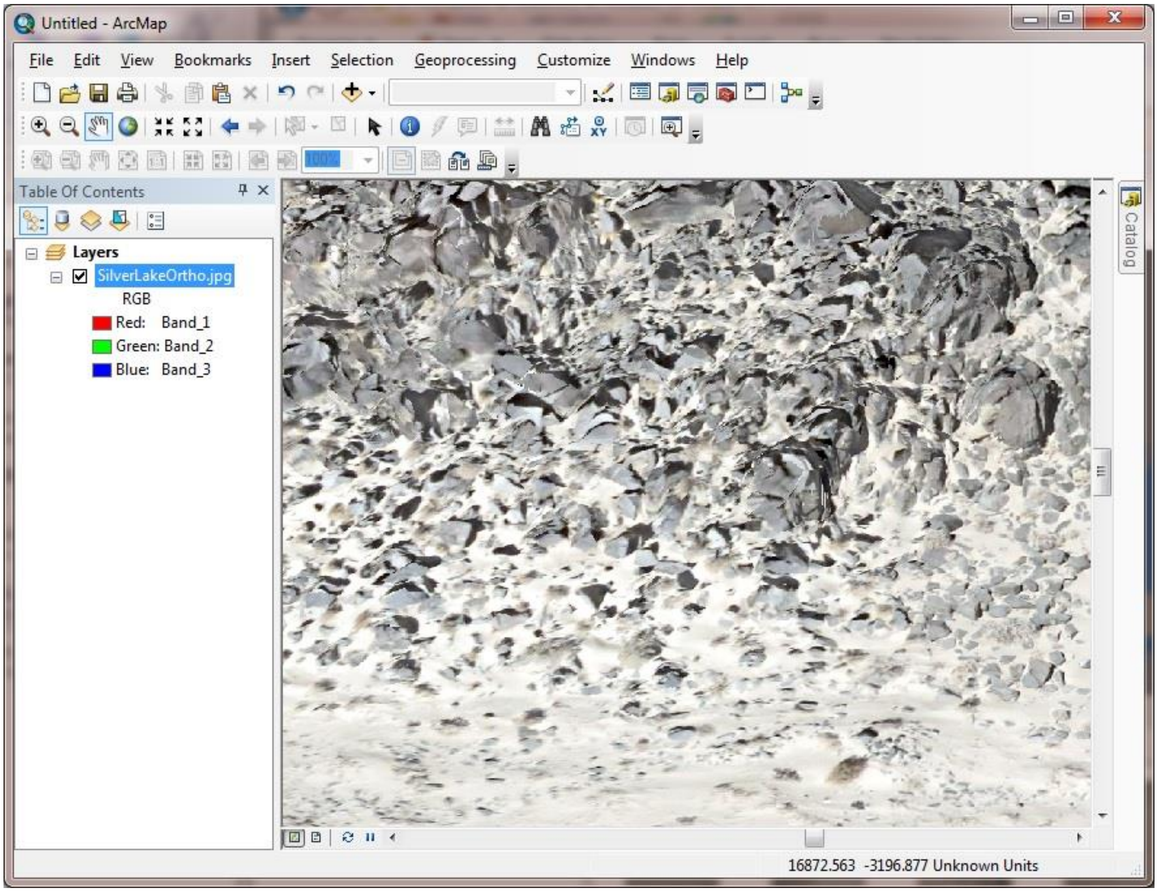


FIGURE 33. Zoomed-in view of generated photograph.

As one can see, the resolution is quite impressive. I was skeptical of the results due to the manual nature of the mission, but the final product speaks for itself. The actual photo resolution was close to the estimated resolution based on the flight and camera parameters, and far surpassed the resolution of any commercially available product for this or any other area. Overall, the photography demonstrated the capability of UAVs to produce professional results at a reasonable cost.

Mission Evaluation

The mission revealed a few deficiencies that will need to be overcome in the next generation of the UAV (already in the planning phase). The airframe was underpowered, which resulted in long takeoff distances and marginal climb rates. This almost proved fatal on the second flight, as the UAV was barely able to fight the breeze coming down the mountain and execute the initial turn. This could also provide challenges to the autopilot when attempting to maintain ground speed when flying into the wind. Options will need to be explored to either reduce the weight of the UAV, or increase the thrust of the drive train.

Since the auto flight mode on the autopilot was not working, the autonomous nature of the UAV was not a factor in capturing the photos. It would have been interesting to compare coverage by manual means versus autonomous coverage to determine the importance, or difference, in autonomous capture and its value to coverage. Considering the speed of the camera, the overlap goals would not have been obtained in one flight in autonomous or manual mode. The ability of the UAV to function in autonomous mode would be more important for novice pilots who would have a difficult time approximating flight lines and elevations.

Then there is the ultimate fate of the UAV, the crash, which needed to be examined to determine the ultimate cause. The autopilot would perform a 180-degree roll when initiating auto mode. Re-calibrating the autopilot did not fix this behavior, which was most likely being controlled by one of the hundreds of parameters that control the flight characteristics of the autopilot. This is not something that can be corrected in the field, and required some research to discover the reason for the roll tendency.

First, the flight logs on the GCS were examined, and the three flights reviewed to determine what was going on between the autopilot and the GCS. The first two successful flights recorded numerous amounts of data, whereas the third flight recorded the initial parameters, but no actual flight data. Since no information could be ascertained from the GCS flight logs, the SD card was pulled from the autopilot to download the onboard logs (Figure 34). The third flight never received a “heartbeat” from the GCS, which means that the autopilot was not connected to the GCS during the entire flight. When the heartbeat was not established within the one-minute time out period, the autopilot entered a “failsafe” condition, and executed an RTL (Return to Launch) function. Unfortunately, auto flight mode was not working properly. For future flights, all “failsafe” parameters will be disabled until the UAV can successfully fly in auto mode.

2014-11-10 21-26-59 37.log - Notepad

File Edit Format View Help

```
STRT, 7, 13
CMD, 13679, 13, 0, 16, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000
CMD, 13679, 13, 1, 22, 20.00000, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000, 30.00000
CMD, 13679, 13, 2, 206, 47.50000, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000
CMD, 13679, 13, 3, 16, 0.000000, 0.000000, 0.000000, 0.000000, 35.36546, -116.1400, 65.00000
CMD, 13679, 13, 4, 16, 0.000000, 0.000000, 0.000000, 0.000000, 35.36544, -116.1419, 65.00000
CMD, 13679, 13, 5, 16, 0.000000, 0.000000, 0.000000, 0.000000, 35.36570, -116.1419, 65.00000
CMD, 13679, 13, 6, 16, 0.000000, 0.000000, 0.000000, 0.000000, 35.36572, -116.1400, 65.00000
CMD, 13679, 13, 7, 16, 0.000000, 0.000000, 0.000000, 0.000000, 35.36597, -116.1400, 65.00000
CMD, 13680, 13, 8, 16, 0.000000, 0.000000, 0.000000, 0.000000, 35.36596, -116.1419, 65.00000
CMD, 13680, 13, 9, 16, 0.000000, 0.000000, 0.000000, 0.000000, 35.36621, -116.1419, 65.00000
CMD, 13680, 13, 10, 16, 0.000000, 0.000000, 0.000000, 0.000000, 35.36623, -116.1400, 65.00000
CMD, 13680, 13, 11, 206, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000, 0.000000
CMD, 13680, 13, 12, 21, 0.000000, 0.000000, 0.000000, 0.000000, 35.36538, -116.1406, 0.000000
MODE, 13680, Manual, 0
MSG, Failsafe - Short event on,
MODE, 13680, Circle, 1
MSG, flight mode = 1
MSG, Failsafe - Long event on,
MSG, No GCS heartbeat.
MSG, flight mode = 11
```

FIGURE 34. Flight log showing failsafe and RTL activated.

CHAPTER 5

DISCUSSION

This project was a great learning experience, but its completion came at a great cost in terms of both time and effort. Translating that time into dollars would add significant cost to the development of an open source UAV. Depending on the value of your labor, the cost can quickly equal the cost of proprietary solutions, though there are other advantages of open source other than cost. These benefits include, but are not limited to the following:

1. Flexibility of the open architecture—nonproprietary solutions provide the opportunity to choose which components will be used, and how they will be implemented.

2. Customization options—especially for those that can program, the open source platform provides unlimited customization opportunities only constrained by time and resources.

3. Community support—open source technology, especially autonomous flight software and hardware, enjoy enormous support from the worldwide technology community.

4. Ease of acquisition—open source software is readily available for instant download from numerous web sources, and hardware is produced by numerous manufacturers dedicated to the open source approach.

5. Opportunity to give back—users can make customizations and upload them to the global user community to benefit other open source activities. Any updates resulting from this project will be uploaded for use by other UAV developers.

Considering these benefits, cost should not be the only driving factor when choosing open source, but a careful consideration of the goals of the endeavor should be evaluated to determine if open source is the right approach for a UAV development project. Before choosing an open source approach, it is important to answer the following questions:

1. Do I have the time to invest in the research?
2. Do I have the interest level to sustain focus on the project?
3. Do I have a high tolerance level for overcoming obstacles?
4. Do I have the aptitude for the complex subject matter involved?

If you can answer "yes" to these questions, then the open source approach might be right for you. Otherwise, you may be setting yourself up for disappointment. Many people choose open source because it is fashionable or perceived as noble, but there is nothing wrong with choosing a proprietary solution. The needs of the application should drive the nature of the solution. A good example of this is choosing Esri GIS software over their open source competitors. Esri has been very successful in creating a productive and healthy ecosystem, despite being a proprietary solution. In some cases, proprietary technology is the best option for geospatial projects. However, this does not mean that open source software will not eventually compete effectively with the dominance of the Esri solutions. In the area of UAVs, especially in the United States, open source solutions have strong support and popularity among enthusiasts.

Lessons Learned

The platform was based on an established airframe, and performed properly in the air, though not without limitations. Considering the extensive modifications, there could have been issues with the flight dynamics, but these did not materialize, as sound aerodynamic principles were followed when modifying the airframe. In addition, the autopilot was not tested with the stock propulsion system, was never installed in this airframe (to my knowledge), and was required to interact with numerous components all at once. The analysis of the topology was sound, and the UAV performed well with only a few exceptions. Many things could have been done differently, but considering the complexity of this project, the results demonstrate the capabilities of open source UAV technology.

The first element to change would be the RTF package purchased. Since the transmitter and receiver were not used, the RTF package was rendered to the equivalent of a lower cost ARF package (almost ready-to-fly). This presented an opportunity to acquire an open source radio, consistent with the overall open source theme of the project. This transmitter is far superior to the stock transmitter, allowing for greater flight capabilities. It is also the recommended transmitter to be used with the autopilot, and increased the chances for mission success. Finally, this transmitter will improve over time, with new firmware being released consistently by the open source community.

In addition, a duplicate aircraft was constructed for flight practice, to minimize the chance of pilot error, as RC aircraft can be difficult to fly. This time, just the airframe components were ordered, a better option than the RTF package. Initially, the plan was to take the UAV directly to the field to perform the mission, but this plan was altered based on the risk of limited flight practice. There was no desire to practice on the UAV, which proved to be a wise decision when the autopilot behaved erratically. The second, non-autonomous plane was flown at the local flying field until skills were adequately refreshed. Then the actual mission was planned and executed.

As mentioned before, the autopilot never achieved auto mode to fly a mission autonomously. Though the photos produced manually were sufficient, it would have been informative to fly an autonomous mission. Before re-installing the autopilot into another airframe, the autopilot was tested on the XPlane software purchased for flight simulation (Laminar Research 2014). In order for the autopilot to interface with XPlane, a different GCS software was downloaded, QGroundControl, which was specifically developed for the Pixhawk autopilot by the developers of the Pixhawk platform (Meier 2014). To make QGroundControl work with the autopilot, the firmware needed to be upgraded. Performing this process presented problems, most likely due to firmware corruption, which was possibly the issue with the autopilot's inability to attain auto mode.

Once the firmware was successfully upgraded, the XPlane software was setup to interface with QGroundControl and the RC transmitter. Orange County Airport (John Wayne) was set as the home location, and waypoints were created in Costa Mesa, California to test auto mode. After writing the waypoints to the autopilot, the virtual airplane was taken off in manual mode. The RC transmitter worked well in manual mode, and the airplane responded properly. The real test was determining if the 180-degree roll problem would still manifest itself, or if the autopilot would be able to fly the virtual airplane properly. The autopilot was placed in auto mode, and the virtual airplane successfully flew all of the waypoints smoothly, and then loitered around the airport until it was landed perfectly. The autopilot is now ready to be tested in the field again.

In addition, the final weight of the UAV exceeded seven pounds, with over a pound of equipment installed into the stock airframe. This included the weight of the camera, the video equipment, autopilot, attached sensors, and additional batteries required to power all of the equipment. The test airplane was adequately powered, but the UAV was over a pound heavier (500 grams). The added weight made the UAV sluggish on takeoff, and limited the climb angle, requiring more time and battery power to achieve the target altitude. Once in the air, the UAV flew well, but flight time was limited. Smaller batteries were used to compensate for the weight, but this further reduced the flight times.

Considering this airframe did not have an adequate thrust to weight ratio, the first theory was to increase the size of the motor. This would also require increasing the capacity of the speed controller, and would require a move up to six cell batteries producing 22.2 volts, as opposed to the two and three cell combination (five cell equivalent) producing 18.5 volts. This option was scrapped when reviewing the specs for voltage limitations on the autopilot, which has a maximum input of 18 volts. This system, when fully charged, was already exceeding the specifications of the autopilot, and adding another cell would have overloaded the autopilot.

Instead of this airframe, a switch has been made to an RC plane also used for initial flight practice, the Apprentice S from E-Flite. This is an EPO (Expanded PolyOlefin) foam based airplane, which exhibits dynamic flight characteristics and a generous thrust to weight ratio. The stock airframe weighs just over three pounds, and the wingspan is only seven inches shorter than the Hobbico NexStar's wingspan. After strapping on a 500-gram weight (the weight of the camera, autopilot, and video equipment), the airframe exhibited superb flight dynamics. Even with the added weight, the Apprentice still flew superior to the stock NexStar, and the airframe can be upgraded to a more powerful motor without exceeding the voltage capacity of the autopilot.

The Canon S110 camera performed beautifully, and captured sharp, well-exposed pictures producing a final image with a two-centimeter resolution at an altitude of approximately 150 feet. The CHDK script worked perfectly, and the battery life was far more than advertised. Even after taking over 700 photos on one battery, the battery indicator was still reading a 75 percent charge. This was anticipated to be the limiting factor for the mission extent, but the flight battery life ended up being the only factor that limited the number of photos that could be taken in one mission. The only limitation of the camera was the picture cycle speed of the camera, with the camera only being able to take pictures every 1.2 seconds. With the lighter airframe and slower stall speeds, the next UAV will be better equipped to overcome this limitation.

In addition, the video feed signal was not strong through the duration of the flights. This could have been a limitation of the antennas, or the low power output of the video transmitter at 200 milliwatts. A new 600-milliwatt video transmitter will be tested on the next UAV, and the video antenna will be located under the fuselage near the location of the telemetry antenna, which worked well throughout the duration of the flight. Another point to consider is the type of GCS used, as not all displays are created equal. The first GCS used was a Lenovo Helix convertible laptop, but was switched to a Panasonic CF19 Toughbook with a much brighter trans-reflective screen that performed well under daylight conditions. This screen was lower resolution than the Helix, but was much more usable when constructing the mission at the site. Some Android based laptops or tablets may also suffice for GCS hardware.

Suggestions for Future Work

In the future, perhaps as a dissertational project, I would like to explore the development of a fully custom airframe, designed around a high-end consumer camera like the Sony A7R (36-megapixel, full-frame camera). I have already developed the plans, and have a shell partially constructed, and would like to eventually complete this task. This would have the advantage of acquiring higher resolution pictures, performing flights of longer durations, and operating at greater distances. Constructing the airframe would require approximately six months to a year, with all of the unplanned adjustments and modifications required of a prototype. To provide an additional element of flexibility and safety, an emergency parachute can be added, for bailing out of failed missions, or accommodating landing in rough terrain. Since the new transmitter is capable of sixteen channels with only six being used, this is now a possibility. This would be an optimal platform for performing urban aerial photography, if the FAA allows these uses in the future.

This project also included a COTS approach to reduce the cost and complexity of the components. Choosing the Canon S110 camera proved a wise choice, but this was not without its compromises, considering the S110 can only take a picture every 1.2 seconds, as mentioned previously. This is in manual mode, with autofocus turned off, using a Class 10 UHS-1 SD card, so the speed cannot be increased. This becomes a factor when desiring large side (60 percent) and front (80 percent) overlaps optimal for developing 3D models. When flying at higher altitudes, this is not a concern, but for low level, high-resolution photos, multiple passes and varying flight lines will need to be made. The slower the stall speed of the UAV, the greater the overlap that can be achieved on one flight line. However, considering the excellent quality of the photos, this camera is hard to beat for lighter airframes.

In the professional compact camera space, the Canon S110 has very few competitors. The only comparable cameras currently on the market are the Panasonic Lumix DMC-LF1 and the Sony RX100 cameras. The Panasonic has the same resolution, comparable weight and size, but has a longer lens (28mm) with a narrower field of view, and a price tag about $100 higher (Panasonic Corporation 2014). The Sony would have been a great choice, as it has a larger sensor supporting 20 megapixel images and a 24mm lens, but it is much heavier (290 grams) with an $800 price tag (Sony Corporation 2014). Camera gimbals will also be evaluated as a mechanism to maintain nadir position of the camera, provided they do not greatly increase the weight of the UAV.

A future expansion of this project would be applying this technology to mapping urban landscapes. In the future, I would like to explore mapping an area on the former El Toro Marine Base that is currently an abandoned housing area nestled in a valley perfect for simulating urban aerial photo capture. The keys to accomplishing this goal are determining the current property owner, gaining permission, and having new laws in place to govern the use of UAVs in urban areas. Mapping in urban areas presents a unique challenge, because of the nature of populated areas and issues of safety. Many other ideas will be generated by other deployments of the UAV, and will be documented and possibly implemented as time allows.

Project Management

The proposed timeline for this highly complex project was aggressive at the start. There have been numerous learning experiences and obstacles that required addressing before progress could be established. Time was spent waiting for parts to arrive from other countries, which delayed portions of the construction process. Certain vendors were used solely to keep costs down, even though they required longer shipping times. An unlimited budget would have accelerated the pace of completion, but would have ultimately caused the failure of a primary project goal regarding cost.

After scaling down the scope to realistic deliverables, creating a project schedule became straightforward. This did not mean that the schedule was followed perfectly, as some tasks were constrained by availability of resources. The schedule required adjustments, and every effort was made to minimize the impact on project completion. Considering the trial and error nature, the tasks proceeded smoothly, and the clearly defined project management goals and objectives helped keep the progress moving forward.

The knowledge gained from this project will be applied to the future construction of alternate airframes, evaluating which types are best suited for certain goals or environments. This will again include the development and flight, as well as the evaluation of photography tasks. The main goal was to keep this project on schedule, though certain factors moved the mission date forward, including obtaining permits to fly at certain RC fields, and arranging times to meet with a flight instructor. Since I was not able to coordinate flight training, time was spent on a simulator. Then a foam-based airplane was purchased for initial flights, complete with safety features that worked well for training.

Overall, the project selection was timely and relevant, and the learning experience was extremely valuable and rewarding. This project addresses a strategic issue that the industry is watching carefully as regulations and technology unfolds. The project proposal was grand, but the scope was quickly adjusted, honoring the goals of the project without compromising the methodology. The objectives, though streamlined through the filtering process, remained intact, and the results reflect the success of accomplishing the objectives.

Ethics

Due to the controversial nature of the project, ethical considerations have been involved from the design phase to the mission planning. The industry is currently under the watchful eye of the FAA, and clarifications on the various circulars covering the use of UAVs have been issued. Most concerns regard safety, but there are also privacy aspects related to the proper use of UAV technology. Like any new technology, there is potential for abuse as well as benefit, and until the FAA rules on UAV airspace integration, those who operate these vehicles need to consider the consequences of unethical behavior.

First, are there true ethical problems with the use of UAV technology? Considering the privacy issue, should the use of UAVs be subjected to more scrutiny than any other technology, or is this technology being unfairly singled out? Should this technology be regulated any more than general surveillance cameras that can be readily purchased at any electronics store? There are technologies that spy on computers, cell phones, and other devices, as well as physical premises. Even the government is engaged in spying on its citizens (Associated Press 2014). With this spying, has a single person been held to account, or even lost a job over eavesdropping?

Then there is the issue of safety. No one would diminish the importance of public safety, but are the current guidelines put forth by the FAA reasonable? Has anyone died due to UAV use? In addition, have any reputable studies been conducted on the impact of UAV use on air safety? I have not found any in my extensive research. What is a reasonable level of safety? Many people are harmed in automobiles and with the use of other technologies, but we do not hear of any calls for limiting their use. Furthermore, how will safe use be defined, or even monitored? We have airport police, but this would not be feasible if applied to the widespread use of UAV technology.

To answer these questions, we need to evaluate the facts. First, though UAVs may be used for clandestine purposes, this should not preclude their use, any more than we should limit the use of cameras, which are used in the surveillance process. In this case, we should not transfer the blame to the tool, but to the user of the tool, as the user is the only one capable of forming unethical intent. UAVs are just a new method of doing what has been done for centuries. Just because there is potential for abuse is no reason to ground these machines, as there are too many highly valuable uses of UAV technology. We would only limit their effectiveness in helping to solve some of the world's greatest problems.

In addition, we need to examine the safety record of UAV use in context. We have heard of recent reports citing the numerous crashes of UAVs and the property damage that has occurred because of these incidents (Whitlock 2014). What is not mentioned is that most of these crashes are highly complex military UAVs, some prototypes, and most have been lost in military service over Iraq and Afghanistan. In reality, even though UAVs are presently prone to malfunction, UAVs have not taken a single life unintentionally, and have only harmed those who have been targeted in military operations. In addition, most accidents are a result of user error, which will be addressed as the technology improves, and operator's knowledge and care increases. However, we should be fair to UAV technology, and apply the same standards of safety that we apply to automobile and aircraft use in general.

So, considering these ethical issues, how should we proceed in implementing this technology in a secure and safe manner? According to the GISCI Code of Ethics, GIS professionals should always strive to do what is right, not simply what is legal (GISCI 2014), and this pertains to the operating of UAVs in a respectful and safe manner. GIS professionals should also be our own regulators, observing the unprofessional conduct of others, and striving to correct unethical behavior when it occurs. This is prudent for the continued practice of our profession, whether in this, or any other context. We are also responsible for mitigating risks, and ensuring the safety of the public when practicing our profession. The GISCI Code of Ethics also states that professionals in the geospatial profession are responsible to respect the privacy of individuals, especially when collecting data that can reveal sensitive information.

There are risks with the unregulated use of UAV technology, if we are relying on the standards of ethical professional conduct. I do not think that the geospatial industry and profession would be resistant to regulation, just over-regulation that can come with some bureaucratic agencies that are more interested in control than promoting safe use.

As long as the regulations promote safe use, within reasonable limits, the GIS profession could embrace this approach, and still derive the benefits of the proper use of UAV technology. It is not in the best interest of the public to have UAVs flown casually, being operated by untrained people who do not consider their ability to cause harm.

Therefore, with proper ethical use by trained geospatial professionals, and reasonable regulation by the FAA, UAVs can be allowed to achieve their potential and make a difference in the world. We need to be diligent in policing our own area, or risk losing the myriad of benefits that this technology presents. We need to get involved in education, and distance the use of UAVs from the military context of drones, so that the public will have a different perception of the technology, and not have preconceived fears regarding the privacy or safe use of this technology. If we can utilize UAV technology with common sense and respect, we stand to enjoy the many potential benefits of its use.

CHAPTER 6

CONCLUSION

In this paper, I examined whether a UAV could be built using open source and COTS components for less than $2000. This endeavor was successful, but not without considerations for the cost of complexity and time. All of the components used were obtained from open source providers, or were purchased directly from hobby stores or through eBay, the Internet auction site. All of the components are readily available today, and some were even purchased in used "like new" condition. This approach is very flexible and cost effective, but does require some time to find and assemble the components. Buying a ready-made solution is quick, but it is not an educational process.

Goals and Achievements

This project not only succeeded in demonstrating the value of low cost small UAV based aerial photography, but also demonstrated the practicality of UAV use in the mapping sciences. With a simple airframe and some off-the-shelf components, aerial photography rivaling the products produced by high-end cameras on full-scale platforms was acquired. This photography was captured at a greatly reduced cost, with the added benefit of flexibility and quick turnaround. This may not challenge the photography captured by satellites, but for detailed, large-scale applications, it is hard to beat the practicality of a small scale UAV. I am amazed at the results accomplished with a $200 camera and an RC airplane.

Project Relevance and Value

Perhaps the greatest benefit of this approach is the hands on knowledge obtained though researching and building your own UAV. Nothing can replace the valuable practical knowledge gained by the "do-it-yourself" experience. Countless evenings were spent after work researching multiple subjects, covering areas involving aeronautics, RC materials and construction, RC transmitters and receivers, electrical circuits and wiring, communications technology and radio frequencies, autopilot and GPS technologies, and open source programming and software. This was just a fraction of the subject knowledge required to implement the numerous functions of a fully autonomous UAV.

However, this benefit can also be a weakness for those not predisposed to learning large amounts of complex material. Many evenings were filled with frustration due to the inability to find pertinent information, or just having a difficult time absorbing a complex subject in a short amount of time. Persistence is the key, but does not come without a cost. Many complex questions kept appearing, all of which required a solution. Many solutions were buried in pages on the web, and some solutions required original thinking. This type of project is well suited to those who enjoy technical challenges without much direction.

When working with UAV technology, the subjects span many disciplines, so a tendency towards being a "jack of all trades" is highly beneficial. Topics deal with aeronautics, technology, photography, electronics, physics, and geospatial analysis all in one application, which can test the knowledge base of the average geospatial professional. Even though geospatial professionals tend to have varied knowledge and skills, this is an extreme case, and perhaps the most challenging project undertaken in my twenty-five year career in the geospatial profession.

Project Considerations and Realities

Though open source technology has many benefits, and is a promising approach to technology, geospatial practitioners should be aware of some pitfalls. First, open source is very technical, and many people enter the field of geography to escape technology, though in a modern context, this may no longer be possible. In my 25 years of experience, I have found that geographers tend to be right-brained individuals on the creative side, but dealing with open source technology requires left-brain skills. This is more of an innate skill that I find difficult to teach – one generally has an aptitude, or not. This will be a source of frustration for some, because open source is not just a set of applications that one may get with a software suite like Esri's ArcGIS. It is a set of programs and APIs (application programming interfaces) developers use to create custom applications. There are some polished applications in the open source community, but they are the exception, not the rule. When dealing with the open source community, one is dealing with a highly technical community.

In addition, since open source solutions are provided by programmers that generally tend to develop applications for their own use, the documentation can be lacking. Open source developers generally write the code, test the code, and then release the code to a repository. Documentation comes later, if ever (Dean 2014). This is the main weakness of the open source approach, where one must rely on forums and wikis for information on how to use, or implement the applications. With 3D Robotics and APM solutions, documentation is sparse, but much better than other efforts on the web.

Then there is the technology in general. This is a highly technical subject matter, requiring technical skills. Background in computers is mandatory, and programming experience is helpful. It is a good idea that all geospatial professionals have well developed technical skills, and some basic understanding of programming, through Python or another popular programming language that teaches the basics of logic and design. Working with computer scripting is beneficial, as the Canon camera required hacking to automate the shutter function. In addition, most of the components can be customized through programming, and having these skills will allow one to move further with the technology and realize more of the potential benefits. Continuing to learn to program the RC transmitter and autopilot will enable implementing new functions that will assist the mapping process.

Developing an open source UAV also requires the development of some practical skills. Fortunately, unlike programming, almost anyone can develop these skills with some practice. The first challenging skill involves the soldering of electrical contacts, something that most people have never performed. With some patience, creating solid electrical connections is possible for non-electricians, and can reduce the potential for a flight mishap. In addition, attention to detail must be given to the numerous mechanical linkages found in the typical RC airframe, as these are the most common point of failure and reason for lost RC aircraft.

Next, there are the RC piloting skills. This is easy to take for granted, as RC planes are much more difficult to fly than traditional aircraft. While the traditional pilot enjoys a view from the cockpit, the RC pilot has a third person view from a fixed point on the ground, and must learn to judge the attitude and speed of the aircraft. Developing this skill requires practice, and learning must be done alongside an experienced RC pilot to avoid needlessly losing aircraft. Before the actual UAV was transported to the desert for testing, numerous hours were spent on a simulator and at the practice field to establish a comfort level with flying the UAV.

With all of these necessary skills and abilities, it is not surprising to find a lack of geospatial professionals taking this approach to UAV mapping. It is far easier to just buy a preassembled, off-the-shelf UAV, attach a camera, and start taking some photos. This reduces the up-front cost of entry in terms of effort, but entails more effort on the backside. This is due to the challenge in maintaining adequate coverage and photo overlap. The investment in time and effort, considering that this is a reusable vehicle, is well worth the results that can be obtained from a fully autonomous solution that controls every aspect of the mapping process, leaving nothing to chance.

The effort required to implement an open source solution should diminish over time as the industry matures, and more professionals adopt this approach. The open source community is driven by participation, and this industry is just starting to gain momentum. As more people get involved, more standards will evolve, and the obstacles to using this approach will disappear, bringing more people into the fold. Whether or not the FAA gets in front of this wave, it is coming, and it will be impossible to stop the use of UAVs as they become more important as a tool in mapping our world.

This project, and ones like it, will help pave the way for innovation, as they help to overcome some of the more rudimentary challenges. As the issues are tackled, time and energy will be applied to creative uses and alternative platforms to extend the usefulness of these vehicles. I am hoping to extend my use of UAV technology to urban mapping, and work has already started on a new airframe (Figure 35) that will be optimized for the unique challenges of mapping populated environments.

In summary, it has been demonstrated that a common RC airplane can be modified to become an autonomous mapping machine, fully capable of producing aerial photography with common equipment and materials. Eventually, I would like to see this lead a revolution in aerial photography, where someday GIS professionals will not need to pay an expensive aerial mapping firm to perform a custom flight. We will just need to power up the UAV, and let if perform the work, while minimizing cost and turn around, producing a product that meets or exceeds professional standards.

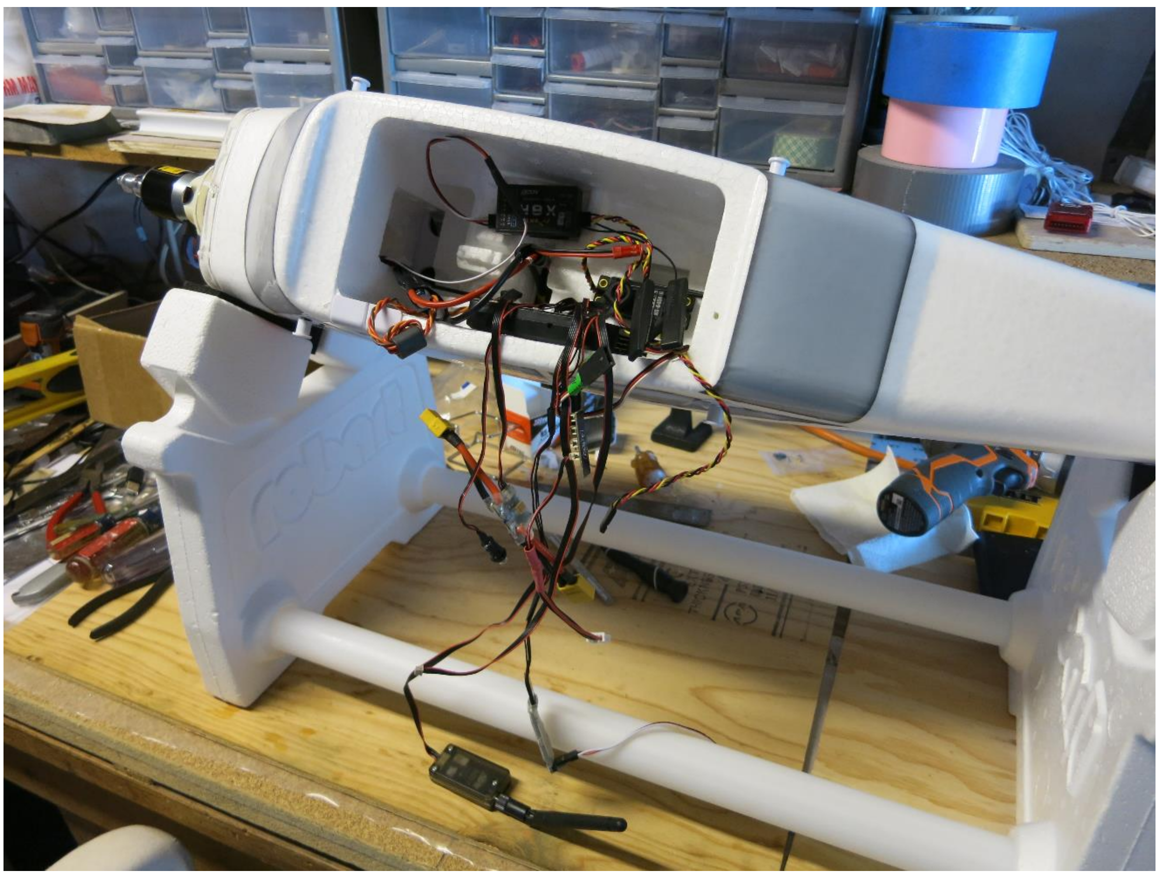


FIGURE 35. UAV 2.0 already under construction.

APPENDIX

LIST OF MATERIALS

TABLE 1. Equipment and Materials

Part/Material	Obtained From	Cost
Hobbico NexStar Select EP	Hobby Zone	$500
Pixhawk autopilot/GPS	3D Robotics	$280
915MHz telemetry radio	3D Robotics	$100
Digital airspeed sensor	3D Robotics	$55
External LED and USB module	3D Robotics	$20
PPM encoder	3D Robotics	$25
u-blox GPS with compass	3D Robotics	$80
5.8 GHz video/OSD system kit	3D Robotics	$190
FPV (first person view) monitor	3D Robotics	$200
2S-3S batteries/charger	Hobby King	$180
Canon S-110 digital camera	eBay	$175
Autopilot camera trigger cable	Gentiles, Inc.	$30
5 volt DC-DC step-up converter	Sparkfun	$20
5 – 6 volt Zener diode	eBay	$5
XT60 connectors (10 pair)	eBay	$10
Silicon 12 AWG power cable	Local Retailer	$10
Total		$1880

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