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DEVELOPMENT OF AN UNMANNED AERIAL VEHICLE FOR LOW-COST REMOTE SENSING AND AERIAL PHOTOGRAPHY

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ABSTRACT OF THESIS

DEVELOPMENT OF AN UNMANNED AERIAL VEHICLE FOR LOW-COST REMOTE SENSING AND AERIAL PHOTOGRAPHY.

The paper describes major features of an unmanned aerial vehicle, designed under safety and performance requirements for missions of aerial photography and remote sensing in precision agriculture. Unmanned aerial vehicles have vast potential as observation and data gathering platforms for a wide variety of applications. The goal of the project was to develop a small, low cost, electrically powered, unmanned aerial vehicle designed in conjunction with a payload of imaging equipment to obtain remote sensing images of agricultural fields. The results indicate that this concept was feasible in obtaining high quality aerial images.

KEYWORDS: Unmanned Aerial Vehicle, UAV, Remote Sensing, R/C Plane, Precision Agriculture

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THESIS

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DEVELOPMENT OF AN UNMANNED AERIAL VEHICLE FOR LOW-COST REMOTE SENSING AND AERIAL PHOTOGRAPHY.

THESIS

A thesis submitted in partial fulfillment of the requirements

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CONTENTS

List of Tables

List of Figures

List of Files

CHAPTER 1: INTRODUCTION

1.1 Introduction

Effective management of agricultural crops is critical. Optimization of inputs, yield, and quality is becoming of greater importance to all farmers. Agrios (1988) estimated that losses due to insects, diseases, weeds, fertility, water problems, and other factors account for as much as 20 billion dollars annually in the United States. To reduce these losses, farmers are relying increasingly on diagnostics and subsequent recommendations from crop scouts or by diagnosing problems within the fields themselves. Crop scouting is a service offered to farmers whereby trained personnel diagnose agricultural problems and suggest localized solutions to farmers. Crop scouting is slow, laborious, expensive, and often inaccurate due to small sample size and limited training of personnel. Scouting inaccuracies often result in unnecessary application of resources over large areas, improper timing, misplaced applications, or unnecessary replications (Obermeyer, 2001).

Precision agriculture (PA) is the careful tailoring of soil and crop management to fit the different conditions found in the field, and relies on precise diagnosis and mapping of problems in conjunction with precisely applied solutions (Johannsen, 1995). This is a new concept in farming that incorporates remote sensing, Geographic Information Systems (GIS), and Global Positioning Systems (GPS). The concept is based on the ability to locate a position repeatedly within a field. Increasingly, precise diagnostics are performed via remotely sensed data. One specific tool, Remote Sensing (RS), has shown promise to enhance crop scouting efforts. RS consists of the interpretation of measurements of electromagnetic energy reflected from or emitted by a target from a vantage-point that is distant from the target (Eastman, 1996; Mather, 1999). Earth observation is the interpretation and understanding of measurements of electromagnetic energy that is reflected from, or emitted by the Earth's surface or atmosphere (Mather, 1999). RS has become a widely used tool for various earth observation needs. It is particularly useful for monitoring natural resources (Verbyla, 1995).

Currently, RS images are primarily obtained using piloted aircraft or satellites (Cochran, 2000). RS imaging platforms can contain multi-sensor payloads including daylight and low-light cameras, infrared sensors, long focal length lenses, and laser rangefinders and designators. The systems provide image stability through gyro-stabilization:

Both these imaging platforms are capable of

- single and multi-spectral payloads
- short-range, mid-range and long-range lenses
- daylight, low-light and thermal sensor cameras.

There are several limitations to these collection techniques. The quality and resolution of the data can be inadequate for accurate diagnostics (Cochran, 2000). Weather conditions such as cloud cover or a hazy atmosphere affect image quality and availability. Moreover, satellites are only in position to collect images every few days, and data is often not available until weeks after data collection, so timing is an additional problem. These timeliness issues can prevent RS from being used for time-critical management opportunities as required in agriculture. Additionally, price is often prohibitive. For RS to be an effective diagnostics tool for PA, image quality, timeliness and cost must be improved.

Unmanned Aerial Vehicles (UAVs) are one possible alternative to current remote sensing methods. UAVs can reduce the expense and time involved in crop diagnostics and mapping. UAVs can be designed to carry payloads sufficient to hold specialized equipment for RS, and fly at low altitudes, increasing image resolution, enhancing image quality and eliminating some cloud interference problems experienced by satellites and aircraft. Higher resolution images facilitate more precise diagnostics of agricultural lands. Additionally, UAVs do not require scheduling, which means that images can be obtained whenever a management opportunity exists. If properly designed, they can be rapidly deployed for small area imaging and are relatively simple to operate. Since no human pilot is on board, authorization for UAV flights is typically simplified (Albers et al., 1996). The use of digital imaging equipment in the UAV will mean immediate availability of imagery.

The development of UAVs will eventually allow the airborne acquisition of information in such a manner as to give users the ability to choose the spatial and time resolution of the data to be acquired, define the appropriate geographical coverage, and select the sensor system of relevance for a specific data-gathering mission, while doing so at a more readily affordable cost (Elfes et al., 2000). This will lead to the expansion of scientific and civilian uses of aerial data and to significant social and economic benefits deriving from this expansion (Elfes et al., 2000).

1.1.1 Applications

Advances in telecommunications and microelectronics and micro sensors give UAVs an enormous potential in a wide variety of scenarios (Martínez-Val and Hernández 1999; Dovis et al., 2001). UAVs have been proposed for a variety of applications including:

1. Military applications such as reconnaissance and conflict resolution (Ashley, 1996).

2. Civilian applications such as traffic monitoring, urban planning and inspections of large-scale man-made structures (Elfes et al., 2000).

3. Environmental monitoring such as agricultural and livestock studies, crop and yield prediction (Yang, 2001; GopalaPillai, 1999), land use surveys, and planning of harvest (Elfes et al., 2000; Dovis et al., 2001).

4. Missions of surveillance including boarder and coastline patrol, fire detection, and search and rescue (Martínez-Val and Hernández 1999).

5. Scientific data collection missions in areas such as mineral and archaeological prospecting, satellite mimicry for ground truth/remote sensor calibration, environmental biodiversity, and climate research and monitoring (Elfes et al., 2000).

UAVs are capable of flying at a range of speeds and altitudes, which makes them desirable for scientific and commercial use (Schoenung and Wegener, 1999). This technology will be of great importance to farmers as PA becomes more widely used and starts relying more on precise diagnostics. Although the potential has been realized and appreciated for some time (Stephens et al., 2000), demonstration of the advantages of these platforms over manned aircraft under actual operating conditions is lacking.

According to Nyquist (1996), UAVs can be used to take inexpensive, high quality aerial photographs, which is one of many applications that are now possible with UAVs. Several researchers have developed completely autonomous drones (UAVs) operated by on board computers (Ashley, 1996; Tirpak, 1997). The United States Department Of Energy (DOE) developed a UAV system to aid in the characterization and monitoring of waste (Albers et al., 1996) and environmental sites (Nyquist, 1994). A variety of payloads can be carried by these aircraft (Schoenung and Wegener, 1999); the most common are *in situ* atmospheric or imaging sensors.

Two possible agricultural scenarios for the UAV system exist: characterization and monitoring of small sites typically within the pilot's line of site (<50 acres), and surveillance and monitoring of large tracts (50 to 1000 acres) (Albers et al., 1996). The UAV has the potential to emerge as a viable alternative to manned aircraft and satellites for industrial use.

UAV systems have tremendous innovative and attractive potential for use in precision agriculture. They can be rapidly deployed for small area imaging and are relatively simple to operate. Since no human pilot is on board, authorization for UAV flights is typically simplified (Albers et al., 1996). UAVs therefore have the potential to compliment and extend the observations of satellites and piloted aircraft, providing a unique vantage point. These UAVs are capable of flying at a range of speeds and altitudes that make them desirable for scientific and commercial use (Schoenung and Wegener, 1999).

The potential applications for UAVs fall into the following categories defined by Schoenung and Wegener (1999):

1. Very high altitude, which is useful primarily for *in situ* atmospheric sampling. (Ozone depletion or climate change research).

2. Mid-to-high altitude with relatively long endurance, which is ideal for many types of remote sensing.

3. Low altitude, medium endurance, which has been the province of the military and other specialized agencies

4. Low altitude, short endurance, which fill a niche for localized measurement, such as in precision agriculture or utility monitoring.

When UAVs are used for remote sensing, the mission classifications could include (Schoenung and Wegener, 1999):

- Meteorology, especially remote sensing and dropsonde measurement,
- Natural hazard and disaster detection, monitoring, and management,
- Loitering or frequent revisit, as in traffic monitoring or other surveillance,
- Mapping, where high altitudes give adequate field of view, or where long duration is needed,
- Remote science (activities needing long range such as measurement of polar, tropic, or ocean features),
- Diurnal science (>24 hour data showing changes or cyclic nature or man made processes),
- Environmental monitoring,
- Agriculture and forestry management, especially where real time or near real time data are needed for daily activities,

In all afore mentioned missions, performance, safety, cost-effectiveness, data quality, and ease of use are the primary concerns to the UAV developer.

1.1.2 UAV Performance Concerns

Nominal performance goals for the design of any UAV-based imaging system include real-time imaging, navigation, and communication capabilities. Other performance concerns include safety, cost effectiveness, data quality, and ease of use (Albers et al., 1996, and Nyquist, 1994). Additionally, the aerodynamic and propulsive efficiencies cannot be neglected as a performance parameter, as well as the flight envelope and should be contemplated in any UAV design. UAV platforms need to address these concerns if they wish to be utilized in today's busy airspace.

1.1.2.1 Safety

Worker and public safety are perhaps the most important concerns in the system operation. The UAV system must be proven safe for operation over populated areas. This is particularly true for heavier UAVs (> 50lb), which pose a substantial risk to people in the event of an accident (Albers et al., 1996). Small UAVs (< 50lb) pose a modest safety risk in crash situations (Albers et al., 1996).

On the other hand, no human crew is placed at risk for low level flights or flight in unfriendly environments with the use of UAVs (Schoenung and Wegener, 1999). Flights can be made extremely close to objects without placing the pilots at risk (Daida et al., 1993) as pilots can control the UAV from ground sites.

1.1.2.2 Cost effectiveness

The use of innovative technologies has possibly held the greatest potential for the reduction of costs associated with remote sensing. UAV systems not only eliminate the need for a pilot and a large sized aircraft, they also eliminate the risk and expense involved in flying and mapping large areas of cropland on a routine basis. UAVs must prove to be less costly than comparable manned systems to be acceptable and used in the community (Albers et al., 1996). Nyquist, (1994) has demonstrated that the low cost of using UAVs for aerial photography makes it economical to fly repeated missions over the same site. McCown, (1996) suggests that based on initial cost analysis, UAVs appear to be less than half as expensive as manned systems. This is due in part to the fact that no human crew is placed at risk and thus reduces the operational costs compared to traditional manned aircraft (Schoenung and Wegener, 1999). Reducing the cost of the airborne part of the UAV system minimizes financial liability for the portion of the system most prone to catastrophic failure (Daida., 1993).

1.1.2.3 Data Quality

Data quality from the UAV system must satisfy user requirements and be of suitable quality. UAV systems could improve the quality of data collected from existing sensors by flying lower and slower than is possible with current manned vehicles, thereby increasing the data's spatial resolution (Albers et al., 1996). Nyquist (1994) suggested a solenoid switch in the plane, activated by radio from the ground to trigger the camera. He also suggested that the camera be capable of shutter speeds of greater than 1/1000th of a second. The fast shutter speed is seen to be essential in reducing "blur" created by the movement of the plane. Aircraft platforms in turbulent atmospheric conditions present unique challenges and can lead to severe image distortions in the raw data (Lee and Bethel; 2001). At a speed of 24km/h the plane travels 6.6_10^{-3}m in 1/1000th of a second (Nyquist, 1994). There is a trade-off between flight speed of the aircraft and payload; to carry more weight, the UAV needs to fly faster (approximately 5mph for each additional pound), which reduces time over the target (Nyquist, 1994) and increases the likelihood of image blur.

1.1.2.4 Ease of Use

New and innovative technologies need to be relatively easy to use and understand as these are more readily accepted by the users. Complex "black box" technologies, which are not well documented, are not readily accepted (Albers et al., 1996).

1.2 Project Objectives

The goal of this project was to explore the use of UAV technology as a tool for cost effectively capturing scientific quality remote sensed imagery for precision agriculture. The project focused primarily on remote sensing applications for agriculture; however, many other applications could benefit from low cost UAV technologies. The project included the design, construction, and testing of a simple, inexpensive UAV system, in conjunction with the selection and design of RS equipment to be placed onboard. The two tasks directly influence one another. The system had to be flexible in its flying characteristics (altitude, speed, direction), and provide a stable platform free of vibration, allowing the capture of high quality RS imagery. It was also desirable for the system to be quickly and easily assembled and prepared for flight on location.

The project was completed through implementation of the following sub-objectives:

1. Design of the UAV platform and control system to provide stable and reliable flight.

2. Selection of cameras, computers, software for the UAV platform.

3. Evaluation of the system effectiveness through real-time evaluation of sensor data and constraints on the airborne system to its surroundings.

The successful completion of this project will provide many advances in the field of precision agriculture and remote sensing including the ability to image large areas in a short time, the capacity to image routinely on a convenient schedule, and to alter imaging times and dates depending on the on-site conditions. Other unique advantages will be the ability to view and analyze images shortly after flight completion even in remote locations via portable computing technology. This will provide near real time crop diagnostic information to farmers, crop scouts, and other interested parties.

CHAPTER 2: DESIGN OF LOW COST UAV

2.1 Introduction to UAV Design.

New and innovative technologies are needed to reduce the costs involved in the characterization of small remote sites (Albers et al., 1996; Dovis et al., 2001). Small and medium sized areas provide a problem for the collection of remotely sensed data, as imagery is not always available from satellites and manned aircraft in a timely and detailed manner (Ashley, 1998; Dovis et al., 2001). It is a known shortcoming of optical satellite systems that their regular re-visit time of a few days, which is often protracted by bad weather, does not allow sufficiently suitable earth monitoring for those applications where promptness of action is most critical. Additionally, cost may prohibit the justification of imaging small sites in this manner.

UAVs provide an innovative alternative to satellite or manned aircrafts. Interest in UAV platforms has been stimulated by the availability of military equipment and expertise and by the rapidly growing technologies that provide more reliable operation of these aircraft through improved communication, navigation, and data telemetry systems (Stephens et al., 2000). Expansion of the payload carrying capabilities of the UAVs added to the overall desirability of the system as observing platforms for remote sensing research (Stephens et al., 2000). Dovis et al. (2001) expressed the major advantages as being less expensive, more flexible, movable on demand, and suitable for a large class of applications. It is also interesting to note that the current United States administration is pushing to increase the use of UAVs in United States airspace (http://www.fas.org).

UAVs are defined as a powered aerial vehicle that does not carry an operator. Additionally they use aerodynamic forces to provide vehicle lift, can fly autonomously or are piloted remotely, can be expandable or recoverable, and can carry lethal or non-lethal payloads. Generally, they differ from simple remote controlled (R/C) aircraft with respect to their size and uses. UAVs are designed and constructed to carry payloads and perform tasks. The tasks for which they will be used guide the design, layout, and size of the overall system. UAVs vary in size from wingspans of 2m in small UAVs, to much larger vehicles such as the 14.8-m Predator and 35.3-m Global Hawk, both US Air Force UAVs. The cost of current UAVs is vastly higher due to their specialized development, military applications, construction and uses. The Predator has a price tag of $40 million. R/C planes on the other hand are designed for recreational use, often being smaller versions of popular full-scale aircraft. R/C planes generally range in size from 1 to 5 meters in wingspan. Recreational R/C planes can be as inexpensive as $1000 or less.

It is becoming increasingly difficult to distinguish between UAVs and R/C aircraft. The size of operational UAVs is dropping as new missions and tasks are becoming apparent. Additionally, equipment is getting smaller reducing the need for larger platforms. R/C plane developers are now developing aircraft with imaging and other capabilities aimed at recreational enthusiasts.

The use of large UAVs has rapidly advanced in the last few years, primarily in the military arena (Tirpak, 1997), but also in agriculture. UAVs can be designed to carry payloads sufficient to hold specialized equipment for RS. The ability of UAVs to fly at altitudes ranging from ground level up increases image resolution, enhances image quality, and eliminates some cloud interference problems experienced by satellites and aircraft. Higher resolution images facilitate more precise diagnostics of agricultural lands. Additionally, UAVs do not require scheduling, which means that images can be obtained whenever a management opportunity exists. The use of digital imaging equipment in the UAV will mean immediate availability of imagery.

Although the potential has been realized and appreciated for some time (Stephens et al., 2000), demonstration of the advantages of these platforms over manned aircraft under actual operating conditions is lacking. Schoenung and Wegener (1999) developed very sophisticated autonomous aircraft that offer a range of altitude, duration, and payload carrying capabilities. They expressed the advantages of these autonomous aircraft as:

- Long range capability - can fly to remote places or cover large areas
- Long endurance capability - can fly longer than manned aircraft and revisit frequently
- High altitude capability - can fly above weather, traffic or danger
- Slow speed flight - can loiter at or near one location
- Pilot exposure is eliminated - allows for long duration or dangerous flights.

The disadvantage of these systems was cost. Reducing the cost would make the UAV more appealing to a broader range of consumers. Their capabilities are far higher than what is needed for agricultural remote sensing. A small, simple, low-cost alternative to these large UAVs would be most beneficial in demonstrating and applying this technology in the field. Merging the lines between traditional UAVs and R/C planes could provide a cost effective, simple solution.

The major components of any UAV system are the same: aircraft platform, communications and control system, sensor system, and data acquisition system (Schoenung and Wegener, 1999). The aircraft platform should be designed sufficiently rugged to allow reuse following simple recoveries (Foch, 1996). A suitable, UAV platform for remote monitoring must also have adequate payload, stability in flight, and have reasonable flight time between refueling (Pendergast and Hofstetter, 1996).

Advances that have occurred over the last decade in areas of sensors, sensor analysis, and control and navigation systems have supported the increasing use of unmanned semi-autonomous land and sea vehicles (Elfes et al., 2000). However, relatively little progress has been made in the advancement and deployment of autonomous robotic aerial vehicles (Elfes et al., 2000). As mentioned earlier, UAVs play an important role in military reconnaissance and surveillance missions. Additionally agencies such as NASA are developing airborne systems as platforms for environmentally and climatologically focused research (Morring 2001; Daida et al., 1993. Many of these vehicles are flown using a combination of remote control and onboard navigation (Elfes et al., 2000).

2.2 Objectives

The goal of this portion of the project was to create a UAV specifically designed to carry airborne image capture systems over agricultural fields in remote locations. This goal was accomplished through completion of the following objectives.

1. Obtain a clear understanding of missions and performance requirements for the UAV system.
2. Evaluate alternatives of a unique design or modification of commercially available equipment.
3. Design and analyze UAV
    a. Aerodynamic analysis.
    b. Design and selection of hardware to meet the aerodynamic and performance goals.
    c. Sizing, design and arrangement of the fuselage to house all equipment.
4. Design launching mechanism.
5. Evaluate UAV system against performance and design constraints.

2.3 UAV Design

2.3.1 Initial Design Progression

2.3.1.1 Mission and Performance Requirements of the UAV system.

Given the objectives of the project, several design parameters were identified for the UAV system. Features important to the missions that were to be performed were considered high priority and were established as goals. The platform would have to meet the following criteria for all missions:

- **Functionality:** The system had to be able to acquire aerial images with a field of view of at least 12 ha and minimum spatial resolution of 1 m/pixel.

- **Portability:** The platform had to be easily transportable to and from target areas. The entire hardware platform had to fit easily in a full-sized pickup truck or similar vehicle. Modularization of the system would facilitate on-site assembly and disassembly, which had to be accomplishable by one operator in no more than 10-15 minutes using only basic tools.

- **Simplicity:** The system had to be very simple to operate and maintain. Operators should be able to launch and fly the vehicle with minimal training and experience. This means that the UAV should have a high degree of inherent stability. The airframe should be constructed of materials and components that can be easily repaired or replaced in the event of minor damage or failure.

- **Robustness:** The UAV had to be deployable multiple times from terrain conditions typically found around farm fields. The launch and recovery areas could be rather small and surrounded by obstacles such as standing crop, trees, or power lines; therefore, the system had to have ample climb rate to avoid these obstacles. Generally, no prepared runway areas are available near farm fields. The system had to be rugged enough to withstand landings in locations with long grass or standing crop as well as on bare hard earth. The sensing equipment is usually the most delicate and expensive items onboard the platform. The platform design had to provide ample protection for this equipment during crashes caused either by operator error or component failure.

- **Cost:** The total capital cost of the system was to be less than $1000, and operating costs were to be minimized.

2.3.1.2 Initial Design Specifications

Given the system design parameters, the platform needed to meet the following performance specifications to successfully complete the image capturing missions.

Endurance: In remote sensing and aerial photography applications, the operation needed to be maintained for periods long enough to obtain images. Typically, a flight time of approximately seven to ten minutes was sufficient to capture adequate images of a 12ha area.

Mission Range: The mission range is the maximum allowable distance between the UAV and the operator. This parameter is critical to the design of the control and data transmission equipment. A mission range of 450m was deemed adequate for the proposed system functionality.

Maximum Altitude: The maximum altitude is a compromise between operator limitations and maximum area captured per image. As UAV operating altitude increases, it becomes more difficult for the operator to distinguish which direction the plane is heading, or if it is gaining or losing altitude. However, the higher the altitude, the greater the field of view of the camera and the greater the area captured per image. The operational goal was an altitude of 300m.

Payload: The UAV had to be capable of carrying a sensor payload with a volume of approximately $100cm^3$ and a mass of 0.5kg.

Flight Speed: The UAV was to have a minimized stall and cruise speed with small turn radius. The slow stall and cruise speed were required to obtain crisp images, to enable the UAV to loiter over the desired target long enough to capture images, and to make landings easier. The limited flight endurance of 10 minutes also necessitated a relatively high maximum speed and climb rate to allow the UAV to gain altitude and arrive at the target quickly. The desired cruise speed was approximately 40km/h, and the desired climb-rate was 3m/s.

Safety and integrity of operation: Worker and public safety were perhaps the most important concerns in the system operation. The UAV system had to be proven safe for operation near populated areas.

Operating conditions: Wind is the primary limiting weather condition for UAV operation. The platform was expected to be operable in average wind speeds of up to 16km/h. The platform was also to be operable under cloud cover, in light mist or fog, and shortly after rainfall events.

Launch and recovery: The system was required to operate from a hand or mechanically assisted launch, over unprepared terrain. The system was also expected to be sufficiently durable to make belly landings on unprepared surfaces or in vegetation.

2.3.2 Platform Design Alternatives

The design of small UAVs provides some significant engineering challenges. The platforms must be lightweight, yet have high power and high energy density propulsion and power sources. They must also have adequate lift generation and stable flight control for aerodynamic environments with low Reynolds numbers. These restrictions mean that UAVs must have low-power onboard electronic processing and communications with sufficient bandwidth for real time image processing, small onboard guidance systems, advanced lightweight structure, and advanced sensing technologies (Ashley, 1998; Smith et al., 2000). It is important to note that the design of the UAV system can not be separated from design of the RS system. The payload size and weight influences the size and layout of the UAV system.

A review of the current procedures for remote sensing and the possible alternatives to the current methods was completed. Four remote controlled (R/C) vehicle types were compared on characteristics important to a remote sensing application (Table 2.1).

Following the evaluation, fixed-wing aircraft emerged as the most plausible solution for the UAV platform and of a monoplane configuration. Foch (1996) and Martinez-Val and Hernandez (1999) recommended that the monoplane configuration achieves good aerodynamic performance with the minimum number of drag-producing junctures between the aero surface and the fuselage.

After reviewing the current R/C technology, it was determined that an electrical powered UAV could carry a payload of remote sensing equipment over agricultural lands. Electric power was selected over glow-fueled engines for several reasons:

- All equipment within the R/C plane could be powered from the electric flight cells (or battery pack) thereby reducing the over all weight.
- The batteries could be prepared before field operation.
- Rechargeable batteries are clean and quick to change.
- An electrical propulsion system requires less maintenance and support equipment than internal combustion powered aircraft.
- The motor could be shut off in flight to reduce vibration while collecting images, then restarted reliably.
- There would be no image interference from exhaust smoke.

The disadvantage of electric power is limited flight duration. Battery powered flight offers high reliability and simple system integration according to Smith et al. (2000).

Two approaches for development of the RS platform were evaluated. The first approach was to design and build a custom-made UAV for this particular application. The second approach was to modify a commercially available R/C aircraft to make it suitable for carrying the RS equipment. A custom-made UAV held many advantages because it could have been optimally designed for RS operation to meet all design and performance specifications. The design could have featured an advanced composite structure, and high energy density propulsion batteries. The UAV would also have the ability and capacity to accept a digital microprocessor autopilot and GPS navigator for autonomous flight after future development. This design would produce a vehicle ideally suited for remote sensing applications. However, it would have been very expensive, and could not have been quickly and easily produced. Thus, the decision was made to explore inexpensive commercially available kits that could be modified to meet design and performance criteria.

Table 2.1: Comparison of four UAV platform types with respect to the requirements deemed critical for remote sensing in agricultural environments. High compliance is indicated by four marks (____), one mark (_) indicates low or no compliance.

Requirement	Fixed-Wing (Electric)	Fixed-Wing (Internal Combustion)	Helicopter	Airship
Low speed , Low altitude flight	__	__	____	____
Hovering capability	_	_	____	____
Endurance	_	__	__	___
Vertical take-off/Landing	_	_	____	____
Good maneuverability	__	__	____	___
Payload to weight Ratio	__	__	_	____
Safe operation	__	__	_	____
Low Noise	___	_	_	____
Operable Turbulence level	__	__	_	_
Low vibration	___	_	_	___
Low operational Cost	____	_	_	____
Simplicity of operation	___	__	_	____
Size	____	____	____	_
Deployment time	____	__	__	_
Time to target	____	____	___	_
Operation in adverse conditions	____	____	__	_
Manpower required	___	____	____	_
Stability	___	___	_	____
Controllability (propulsion)	____	___	___	__
Controllability (aerodynamic)	____	____	_	__
Simplicity of repair	___	___	__	_

The plane kit that was used in this study was a Lanier SloComet (Lanier RC, Oakwood, GA), which was actually a sailplane (Fig. 2.1). This product was selected for its wide fuselage, stable flight characteristics, high potential payload carrying capacity, ease of construction, and commercial availability. The aircraft's flight characteristics were very stable due in part to the dihedral design of the wings, which allowed the aircraft to self correct to a straight and steady flight path. The airframe had only two control surfaces (rudder and elevator), simplifying operation and complexity and allowing pilots with minimal flight experience to operate the aircraft.

The dihedral wing provided sufficiently strong yaw-roll coupling to eliminate the need for ailerons; therefore, the rudder commanded yaw included the roll required for smooth turns. The large wingspan allowed for the potential of a large payload, but was still short enough to fit into a "pick-up" sized vehicle. The UAV could be hand launched and landed safely on the fuselage with no landing gear. The airframe components were sufficiently rugged to allow for reuse and repair in the event of crash. The fuselage was made from ABS plastic laid over plywood structural reinforcement. The wings were made of Styrofoam covered with plastic film and reinforced with a 23mm _ 3mm plywood spar. The kit could be optimized to achieve the mission and performance specifications.

Cursory tests of the first generation UAV (Fig. 2.1) showed that the concept was feasible. The aircraft was built and flight tested with a payload of small board cameras and microwave video transmitters. This equipment enabled the transmission of a real time video feed from the aircraft to the ground. The pilot on the ground viewed the video feed on a TV screen while the aircraft was in the air, and video was recorded on VHS cassettes. Single frame images were then captured from the VHS tapes once this tape was converted into digital format.

Although the flights were successful, wind conditions severely limited operation. The propulsion system originally selected was inadequate for the application. The propulsion system was unable to overcome breezy conditions, and the aircraft was buffeted by the wind turbulence. The flight characteristics were sluggish and additional power was required for a reasonable climb rate. The motor and propeller combination also lacked the power/thrust required for additional payload, which would later be required.

Figure 2.1: First generation UAV with board camera transmission.

The second-generation aircraft, also a Lanier Hawk, was equipped with a larger more powerful motor powered by a bigger battery pack. The aircraft had better flight characteristics, was less influenced by small gusts of wind, and allowed for an increase in the payload carrying capacity. This motor provided additional power needed to meet the payload carrying capacity requirement of the UAV.

The R/C platforms being used were designed for recreational flight and not to carry increased payloads. It became apparent that this unmodified commercial R/C planes may not provide sufficient durability or payload carrying capabilities. The frame of the aircraft was not rugged enough to avoid complete failure as a result of minor landing anomalies. Additionally, there was little protection for the payload equipment in the event of a crash landing. The durability of the aircraft came into particular question following two initial crashes. The crashes were due in some part to the inexperience of the pilot but also to the airspeed of the aircraft. Due to the increase in payload, the minimum air speed or stall speed increased in order to generate sufficient lift over the airfoil. As discussed earlier, this increased speed made landings more difficult.

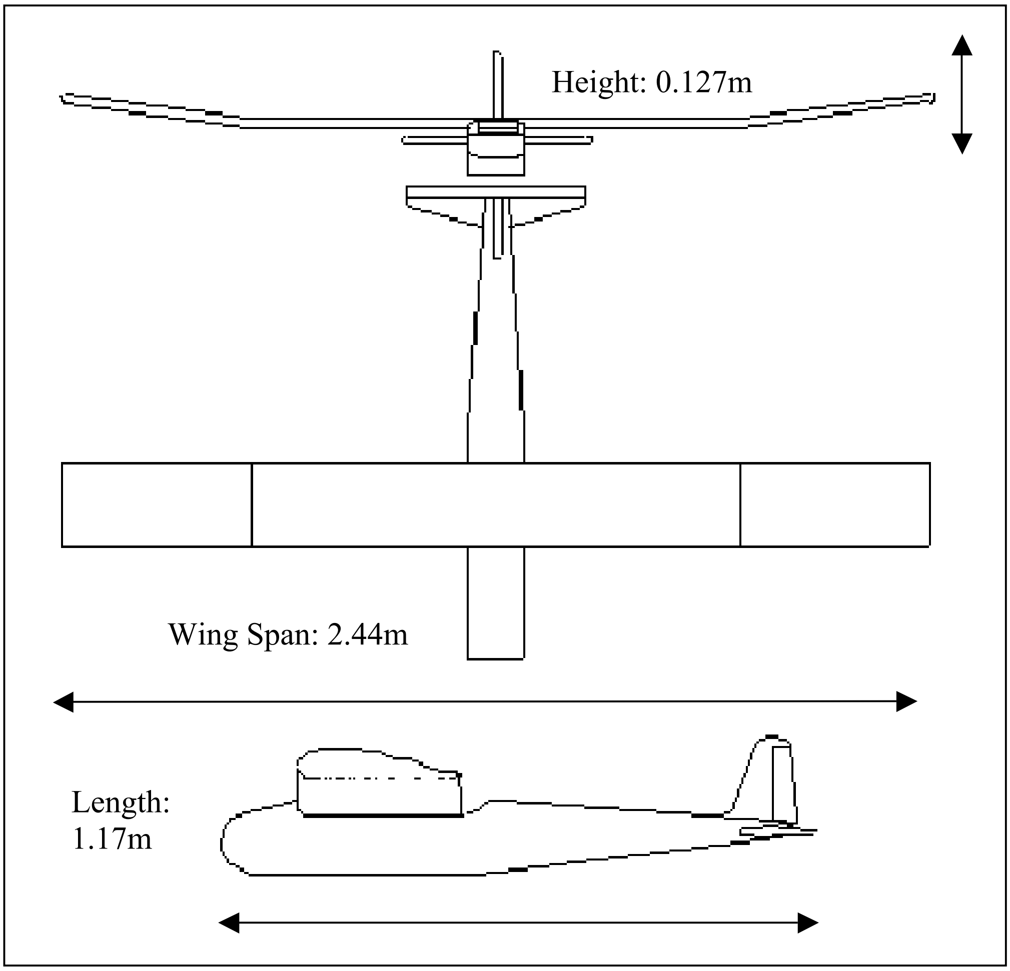


Figure 2.2: Front, top and side view of the SloComet platform (not to scale).

To overcome the limitations of the first platform, the researcher chose to use a Lanier SloComet model airframe (Fig. 2.2 and Fig. 2.3), a slightly larger kit with a bigger fuselage. The model had the same wing design as the first generation UAV; thus, a review of the aerodynamic characteristics was performed in order to determine if the aircraft could be redesigned to reduce speed and be acceptable for the project.

Figure 2.3: SloComet Platform and transport vehicle.

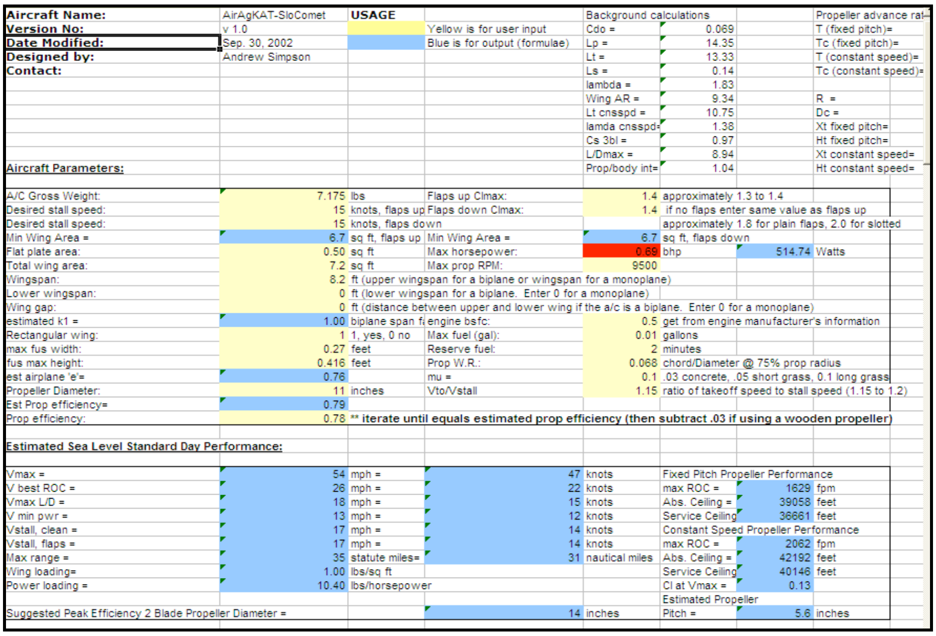
2.3.3 UAV Design and Analysis

The ultimate goal of this analysis was to develop a useable platform from which instrumentation can be used to obtain images. The analysis revolved around the desire to take a commercially available remote control plane, make modifications to the structure, enabling the kit to carry a payload of imaging equipment at the correct height and speed over the target. Further goals were to do this with the least amount of major modifications from the original kit, thereby reducing cost and time in producing the system. Finally, the system complexity could not be increased to the point that it became difficult to operate the platform.

2.3.3.1 Aerodynamic Analysis of UAV Platform

The unacceptably high stall speed of the UAV platform prompted an aerodynamic study of the wing and wing-body design. A programmed spreadsheet developed by Daniel Raymer (Conceptual Research Corporation, Playa del Rey, CA), which included all the aircraft's specifications, was used to examine the dynamics of the aircraft (Fig. 2.4). The effects of different platform characteristics were evaluated in an attempt to identify the simplest modification that would increase performance. The airfoil of the original kit was then modified to increase payload capacity and decrease stall speed. The analysis showed that increasing the airfoil span 33% by adding a second horizontal wing section from a second wing kit would sufficiently increase performance. The longer wing was reinforced with carbon fiber tape along the cords of the wings and plastic covers on the leading and trailing edges of the inner parts of the wings. The increased wingspan accommodated the larger payloads, but was still short enough to meet portability constraints. Other options, which were briefly entertained, included the addition of flaps to the wing, the addition of a parachute, and an air brake. The addition of flaps and the air brake were abandoned due to the complexity these modifications would have brought to the design and construction. Furthermore, the benefits were not significantly greater than increasing the wingspan. A parachute system was not incorporated due to the bulkiness and reliability of the system. The parachute added considerable weight and volume to the airframe, and there were questions regarding the functional effectiveness.

Smith et al. (2000) suggested that small RC planes have potential problems with high drag due to laminar separation and relatively low maximum lift values resulting from low flight Reynolds numbers; therefore, a study of the airfoil was performed to determine if it was suitable for the application. The manufacturer selected a “Clark Y” airfoil (Fig. 2.5), developed in the 1920’s and popularized due to the flat bottom characteristic and relative thickness of the airfoil. The flat bottom characteristic simplifies fabrication and is thus a favorite amongst hobbyists. The airfoil provided favorable stalling characteristics (Fig. 2.6).



Aircraft Name:	AirAgKAT-SloComet	**USAGE**		Background calculations			Propeller advance rat
Version No:	v 1.0		Yellow is for user input	Cdo =	0.069		T (fixed pitch)=
Date Modified:	Sep. 30, 2002		Blue is for output (formulae)	Lp =	14.35		Tc (fixed pitch)=
Designed by:	Andrew Simpson			Lt =	13.33		T (constant speed)=
Contact:				Ls =	0.14		Tc (constant speed)=
				lambda =	1.83		
				Wing AR =	9.34		R =
				Lt cnsspd =	10.75		Dc =
				lamda cnsspd=	1.38		Xt fixed pitch=
				Cs 3bl =	0.97		Ht fixed pitch=
				L/Dmax =	8.94		Xt constant speed=
Aircraft Parameters:				Prop/body int=	1.04		Ht constant speed=
A/C Gross Weight:	7.175	lbs	Flaps up Clmax:	1.4	approximately 1.3 to 1.4		
Desired stall speed:	15	knots, flaps up	Flaps down Clmax:	1.4	if no flaps enter same value as flaps up		
Desired stall speed:	15	knots, flaps down			approximately 1.8 for plain flaps, 2.0 for slotted		
Min Wing Area =	6.7	sq ft, flaps up	Min Wing Area =	6.7	sq ft, flaps down		
Flat plate area:	0.50	sq ft	Max horsepower:	0.69	bhp	514.74	Watts
Total wing area:	7.2	sq ft	Max prop RPM:	9500			
Wingspan:	8.2	ft (upper wingspan for a biplane or wingspan for a monoplane)					
Lower wingspan:	0	ft (lower wingspan for a biplane. Enter 0 for a monoplane)					
Wing gap:	0	ft (distance between upper and lower wing if the a/c is a biplane. Enter 0 for a monoplane)					
estimated k1 =	1.00	biplane span f	engine bsfc:	0.5	get from engine manufacturer's information		
Rectangular wing:	1	1, yes, 0 no	Max fuel (gal):	0.01	gallons		
max fus width:	0.27	feet	Reserve fuel:	2	minutes		
fus max height:	0.416	feet	Prop W.R.:	0.068	chord/Diameter @ 75% prop radius		
est airplane 'e'=	0.76		mu =	0.1	.03 concrete, .05 short grass, 0.1 long grass		
Propeller Diameter:	11	inches	Vto/Vstall	1.15	ratio of takeoff speed to stall speed (1.15 to 1.2)		
Est Prop efficiency=	0.79						
Prop efficiency:	0.78	** iterate until equals estimated prop efficiency (then subtract .03 if using a wooden propeller)					
Estimated Sea Level Standard Day Performance:							
Vmax =	54	mph =	47	knots	Fixed Pitch Propeller Performance		
V best ROC =	26	mph =	22	knots	max ROC =	1629	fpm
Vmax L/D =	18	mph =	15	knots	Abs. Ceiling =	39058	feet
V min pwr =	13	mph =	12	knots	Service Ceiling	36661	feet
Vstall, clean =	17	mph =	14	knots	Constant Speed Propeller Performance		
Vstall, flaps =	17	mph =	14	knots	max ROC =	2062	fpm
Max range =	35	statute miles=	31	nautical miles	Abs. Ceiling =	42192	feet
Wing loading=	1.00	lbs/sq ft			Service Ceiling	40146	feet
Power loading =	10.40	lbs/horsepower			Cl at Vmax =	0.13	
					Estimated Propeller		
Suggested Peak Efficiency 2 Blade Propeller Diameter =			14	inches	Pitch =	5.6	inches

Figure 2.4: Spreadsheet model to predict aerodynamic and performance parameters (www.aircraftdesign.com).

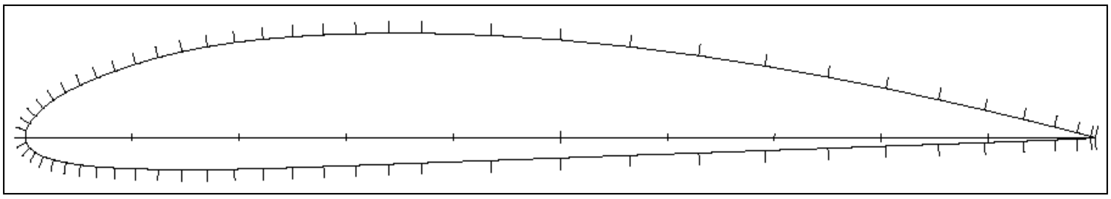


Figure 2.5: Clark Y airfoil profile.

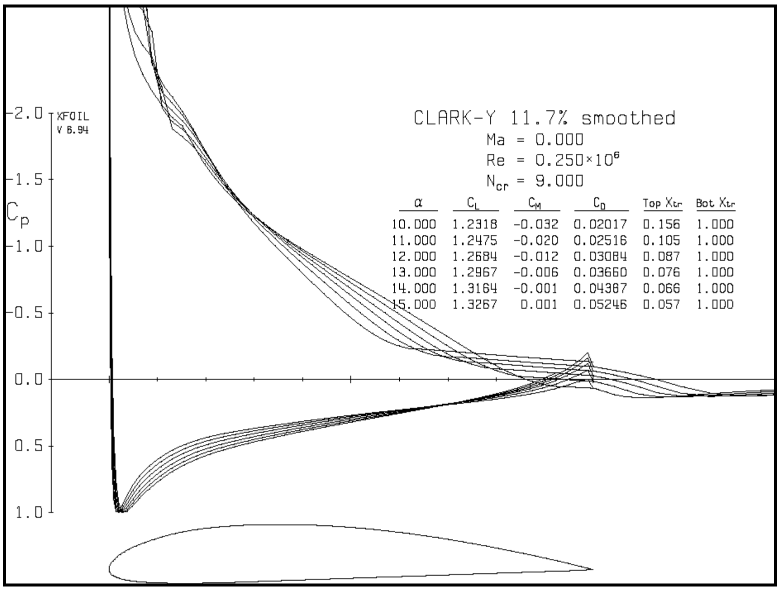


Figure 2.6: Output from X-foil, airfoil analysis software for Clark Y airfoil.

The airfoil lift coefficients fell between 0.4437 – 1.399 range at Reynolds numbers in the order of 0.25_10^6 and angles of attack of 0 - 12º, determined from use of the X-

Foil (Drela, 1989) computer program (Fig. 2.6). The airfoil stalls at an angle of attack of approximately 12º (Fig 2.7).

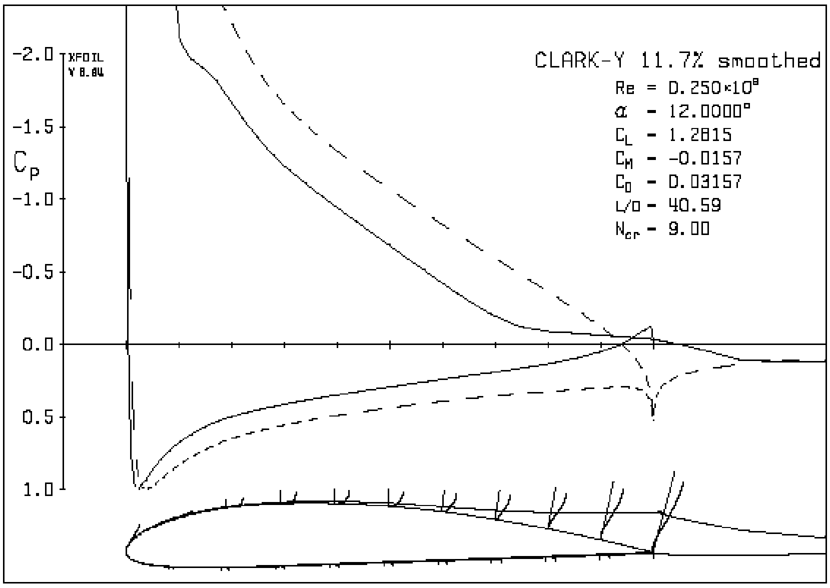


Figure 2.7: Onset of separation at an angle of attack of 12º.

The coefficient of lift vs. drag of the Clark Y airfoil is shown in Figure 2.8, and the coefficient of lift vs. angle of attack (alpha - _) is shown in Figure 2.9.

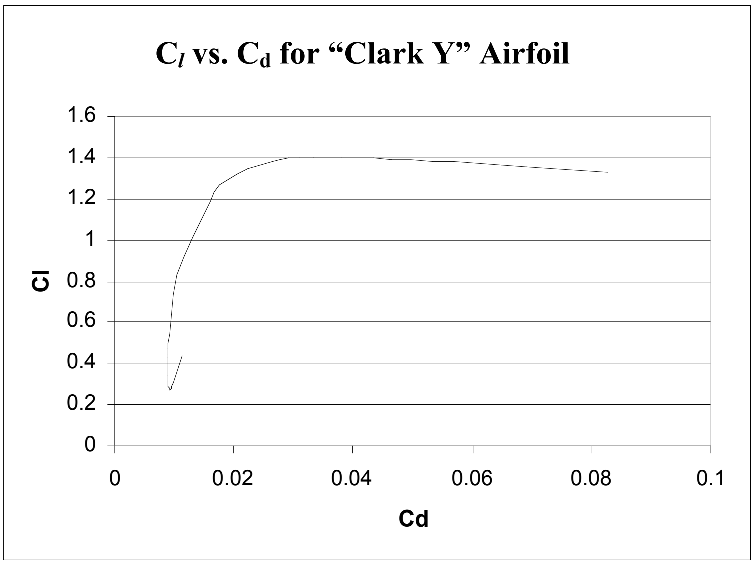


Figure 2.8: Coefficient of lift (C_l) vs. Coefficient of drag (C_d) for the Clark Y airfoil at Re of 250000.

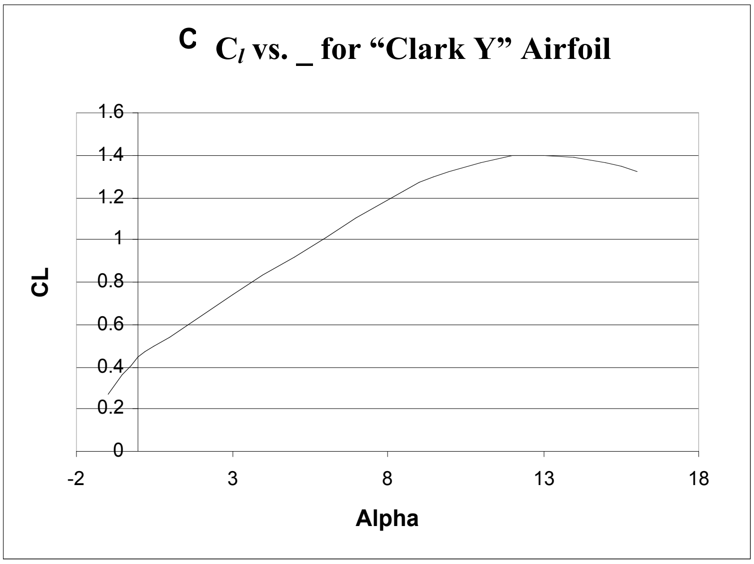


Figure 2.9: Coefficient of lift (C_l) vs. Angle of Attack (_) of the Clark Y airfoil.

At Reynolds numbers (Re) on the order of 100,000, the flow is laminar. The laminar flow over the suction surface of the wing cannot withstand an adverse pressure gradient and will tend to separate at even low angles of attack. At moderate values of Re, the separated flow region may cause the flow to transition to turbulence, which results in reattachment. In this case, the separated region is referred to as a separation bubble. In this case, the lift is reduced and the drag is increased. At low values of Re, however, the flow may not transition to turbulence at all and the wing effectively stalls, causing a dramatic drop in lift to drag ratio. Great care is needed in the design of airfoils in the low Reynolds numbers range to ensure that the flow over the wing will not separate.

A dihedral wing arrangement of 6º, inflecting at the mid-span of each wing, was used to provide natural inherent stability. In addition, the dihedral can provided a sufficiently strong yaw-roll coupling to help eliminate the need for ailerons. Therefore, the rudder commanded yaw included the roll required for smooth turns. The dimension and performance estimates for the aircraft are provided in Table 2.2.

Table 2.2: Main Features of the UAV platform.

Name of Variable	**Value**
Maximum Height	0.127m
Maximum Length	1.17m
Wing Span	2.44m
Maximum Take-off Weight	3.75kg
Operating Empty Weight	3.29kg
Maximum power at take-off	0.4kW
Power /Weight Ratio	106.67W/kg
Wing Gross Area	0.6m^2
Wing Loading	6.2Kg/m^2
Mean aerodynamic cord	.005m
Wing aspect ratio	1
Payload Capacity	0.01355m^2 (±1_), 0.454kg
Endurance	0.167Hrs
Climb Rate	3.5m/s
Cruise Air Speed	35kph
Landing Speed	30kph

All payload components including antennas from the video transmitter and the R/C receiver were placed inside the fuselage to further reduce the drag and increase efficiency. The GPS antenna, which needed an unobstructed vertical view, was attached to the top of the fuselage behind the wing. This location coupled with the low profile of the antenna did not obstruct the airflow over the wing or past the control surfaces of the platform and did not appreciably increase drag. Landing gear added weight and increased drag to the aircraft, which resulted in reducing the payload capacity and thus was removed, enforcing hand launching and belly landings.

Upon initial testing, the extended airfoil was found to be susceptible to cracking and failure at the restraint points to the fuselage at both the leading and trailing edges. Cracks developed on the skin of the airfoil during a relatively gentle landing. These cracks were caused by momentum change as the aircraft came to a rapid stop. The outer shell of the airfoil split at the leading and trailing edges. These cracks lowered the strength of the airfoil and were difficult to repair.

To gain a better understanding of the stresses and strains placed on the airfoil in this region, an finite-element analysis was performed on the airfoil. A three-dimensional representation of the airfoil was created with the SolidWorks (Concord, Massachusetts) modeling package, and a finite element analysis of the airfoil was conducted using the CosmosWorks addition to the SolidWorks package. The simulation fixed the airfoil to the fuselage at the center of the airfoil. The restraint did not allow displacement or rotation between the airfoil and the fuselage. Forces applied to the unrestrained portions of the airfoil simulated forces of an object impacting the airfoil. The resulting visualization can be seen in Figure 2.10.

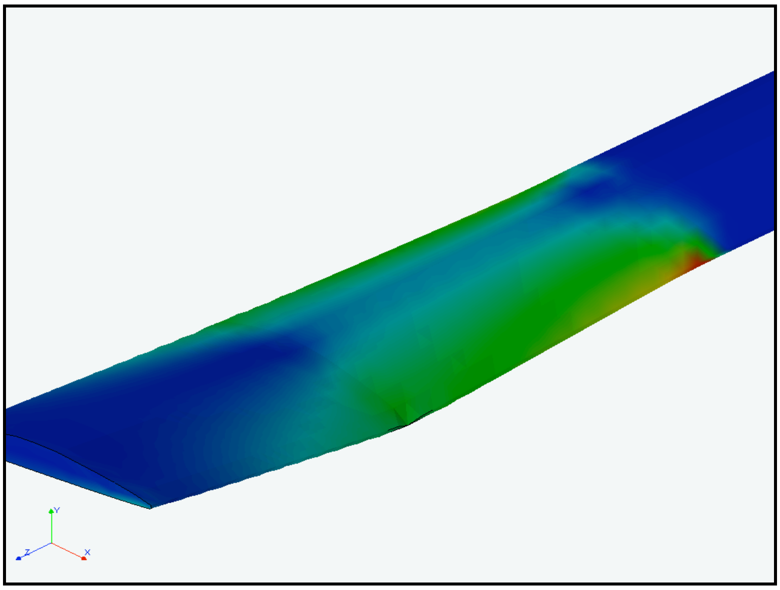


Figure 2.10: High airfoil stress concentrations during simulated landings.

Severe stress concentration areas were noted in the regions where the airfoil attached to the fuselage. Further simulation involved applying a uniformly distributed load along the trailing edge of the airfoil. This simulated the stresses placed on the airfoil under abrupt deceleration. The results showed concentrated stresses at the restraint junction between the trailing edge and the fuselage. Additionally, simulated flight loads were placed on the bottom surface of the airfoil. These loads simulated the forces experienced by the airfoil during flight. The result of the analysis demonstrated high stress concentrations (Fig. 2.10) in the region were the fuselage joined the airfoil. Furthermore, the airfoil's geometry compounded the stresses placed on it during flight. Large bending loads were placed on the airfoil during flight and especially during landings and turns. These forces were strongest in the middle of the airfoil were the airfoil was attached to the fuselage.

A solution was required to strengthen the airfoil from both the normal operating stresses and the addition forces placed on the airfoil during landings. The solution was tri-fold. First, the leading and trailing edges of the airfoil were strengthened by extending plastic supports along the two edges (Fig. 2.11). These supports were manufactured from plastic sheeting, molded and bonded to the leading and trailing edges of the airfoil.

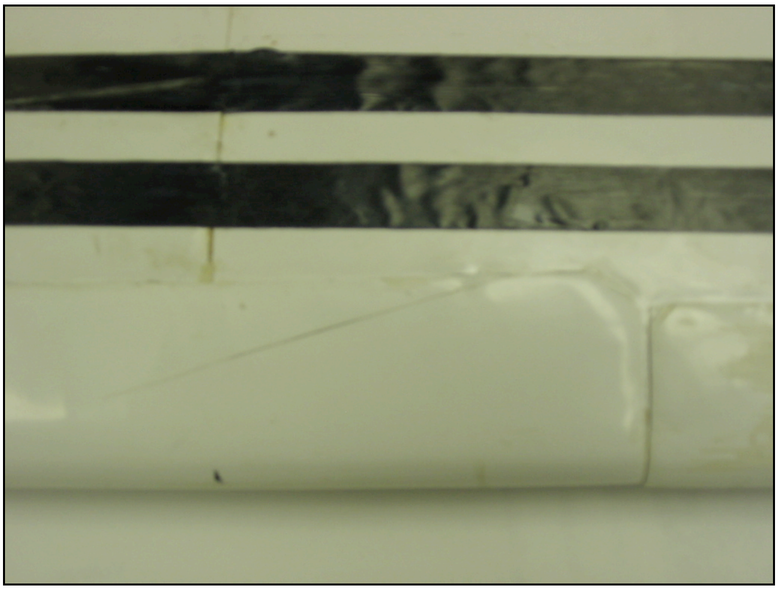


Figure 2.11: Additional molded support placed on leading and trailing edges.

Second, thin carbon fiber strips were affixed to both surfaces of the airfoil. These strips provided the necessary tension to counteract the bending during turns. The carbon fiber strips were placed along the main cord of the airfoil (Fig. 2.12). Finally, the lengths of the spars in the center of the airfoil were increased. Each section of wing contained one main spar running down its length. Additional spars were used the join wing sections together and the lengths of the additional center spars were increased to adequately distribute the loads (Fig. 2.13).

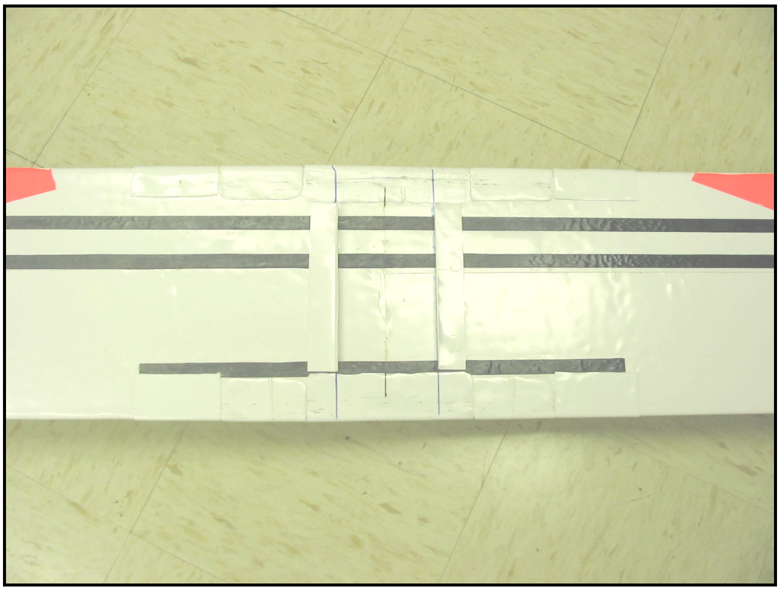


Figure 2.12: Additional Carbon fiber support for extended airfoil.

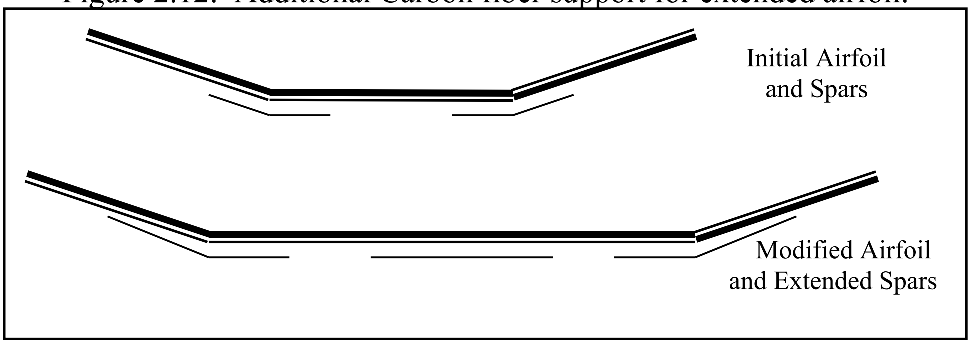


Figure 2.13: Comparison of original and modified airfoil spans with additional spars.

2.3.3.2 Selection of Propulsion Components.

As mentioned earlier, the primary challenge in designing an electric propulsion system was to maximize thrust and endurance while minimizing airborne weight. A computer program called ElecrtiCalc (SLK Electronics, Greensboro, NC), was used as a tool to size and select components. This program predicted aircraft performance from pertinent technical data related to system components (Fig. 2.14). The user inputs information concerning battery pack, motor, airframe, and flight parameters.

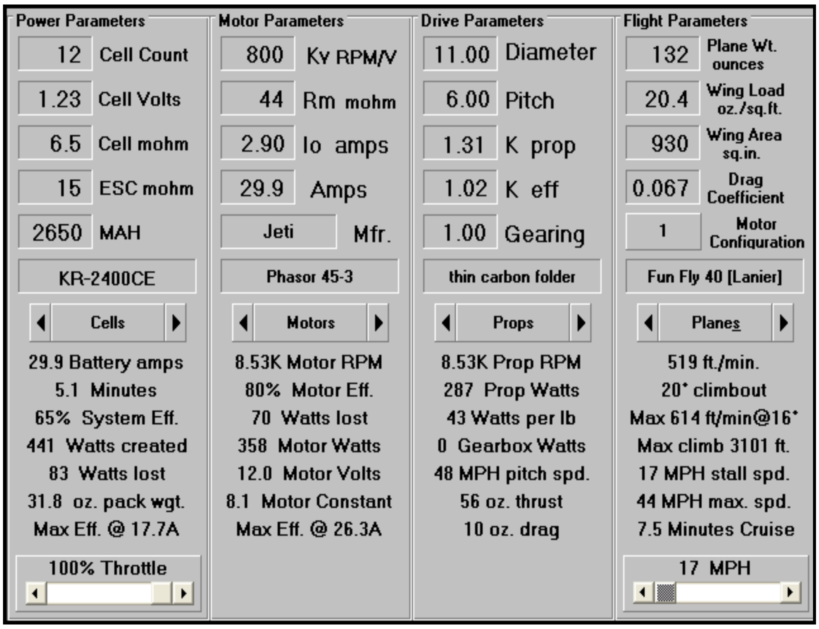


Figure 2.14: Screen shot of input parameters and results obtained from ElecrtiCalc.

Initially, the size, weight and dimensions of the platform were introduced into the ElecrtiCalc program. The SloComet airframe was available in a database of current platforms available in the software. However, the parameters were adjusted to account for additional payload and increased wingspan of the platform. The program data were further manipulated to include existing equipment in the platform. The goal was to use as much of the existing equipment as possible while still obtaining an effective platform. Battery pack information was inputted into the program. This information included number of cells, volts per cell, and capacity in mA-hr.

The majority of manipulation involved the motor and propeller sizing. Electric flight enthusiasts use a general rule of 50 to 100 Watts per pound of aircraft (or 50 to 100 Watts per 0.45kg). Table 2.3 gave a good starting point for the estimations. The motor, gearbox and propeller sizes are largely dependant on the size of the aircraft and the required performance of the system. Motor data were selected from a database of commercially available motors. The program then calculated the best combinations of propeller size and gear reductions for the given platform size, battery pack and motor combinations. This was determined through a series of graphical outputs (Fig. 2.15), where the main driving condition was the current drawn for the propeller and diameter/pitch combination. ElecrtiCalc was most beneficial at the outset of the project, to determine values of the components. This process was iterative and better estimations of component size were obtained through repeated use and trial and error. The motor selection was based on availability from dealers, performance and cost. The output parameters for the final UAV design can be seen in Figure 2.14, where the total system efficiency was estimated to be 65% at full throttle. This gives an estimated flight time of 5.1 minutes and a climb rate of 519ft/min. However, once airborne the throttle can be reduced, significantly increasing estimated flight time of the platform.

Table 2.3: Approximate guide to the motor size.

Wing Area	**Glow-Fueled Engine(in^3)**	**Electric Motor**
200-300 in^2 (0.13-0.2m^2)	0.049	Speed 400
300-500 in^2 (0.20-0.32m^2)	0.100-0.150	05-15
500-600 in^2 (0.32-0.39m^2)	0.250-0.400	25
600-750 in^2 (0.39-0.48m^2)	0.600	40

ElecrtiCalc also generated a series of graphical outputs, which streamlined the selection of the motor, propeller and gear combinations. The first graph provided a graphical estimation of the propeller dimensions (diameter and pitch), vs. the current draw from the motor/propeller combination (Fig. 2.15). This information was used in the selection of propeller and battery packs sizes. The larger the diameter and pitch, the greater the current draw from the batteries.

The lower graph in figure 2.15 shows a few of the projected flight characteristics. Following the drag line, the “best” operational speed is at the point of lowest drag, 27km/h. Far left of this point we are in the unstable flight régime. The maximum speed is at the intersection of the drag and thrust lines.

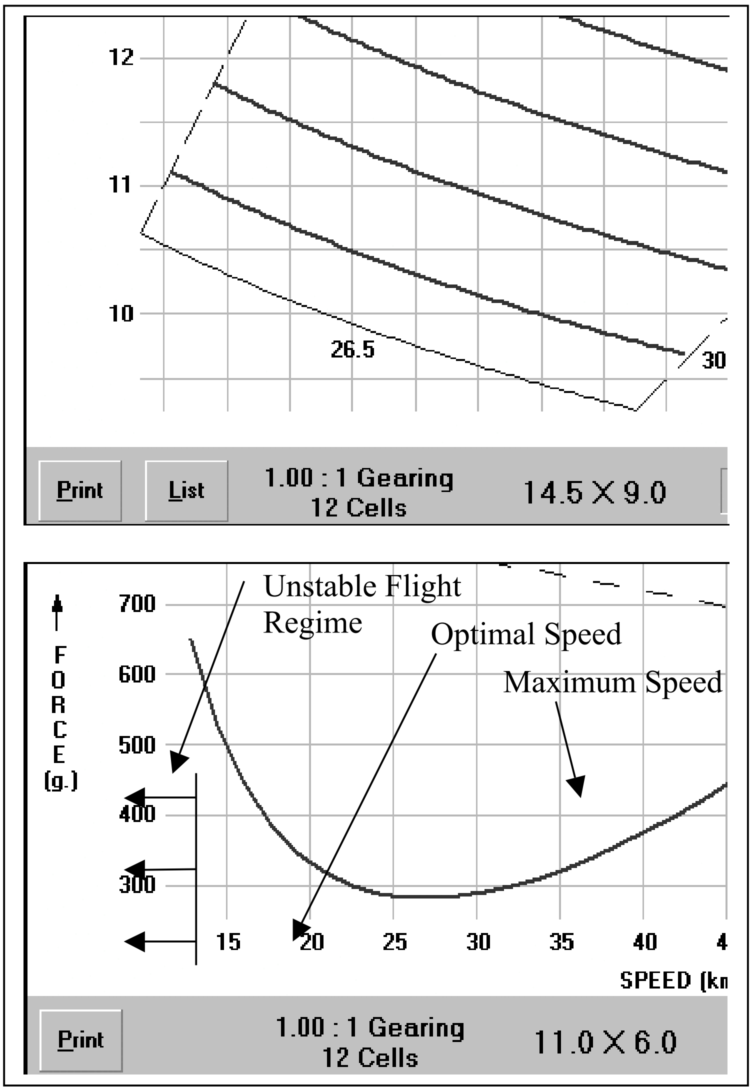


Figure 2.15: Graphical outputs generated by ElectriCalc.

This gave an estimation of the motor run time given a certain battery pack capacity, with different propeller sizes. The second graph gave an estimation of thrust and drag relative to the flight speed. The best motor for the UAV was found to be a Jeti Phasor 45/3 motor and 40-3P Opto speed controller (Jeti, Koprivnice, Czechoslovakian Republic), for the 12-cell, 2400 mAH battery pack. This was suitable for use in model aircraft up to 2500g (5.51lbs) in weight and is 83% efficient according to the manufacturer (80% according to EletriCalc). This motor was brushless, and developed as a direct drive motor (i.e. not requiring gearing between the motor and propeller). The motor was also sensorless, meaning that it requires a motor controller to control the motor over the full range of power. The best propeller option was a Graupner CAM folding high performance propeller specially designed for electric sailplanes. The propeller had the ability to fold back when the motor stopped to reduce drag and allow the UAV to land without landing gear. Centrifugal motion caused the propeller to resume its original position once the motor was restarted.

2.3.3.3 Mounting Propulsion and Payload Components

The mission and goal of the project imposed rigorous size and weight constraints on the UAV platform. Effort was expended on identifying reliable, inexpensive components for the required flight and science payload. The necessary systems included flight control and GPS, data handling and transmission, and the cameras used for scientific imaging. The term "payload" refers to all systems and equipment not directly linked to the airframe and propulsion system.

The fuselage had to accommodate both the propulsion components and payload components. The payload components included imaging equipment, and transmitters. These components are discussed in more detail in Chapter 3. The propulsion and other operational components included motor, motor controller, receiver, battery pack and servos. The key considerations in the arrangement of these components within the airframe were balance, protection, reduction of EMI (electro magnetic interference) between components, and ease of removal and exchange. This particular airframe performed best when balanced at 10º nose down when supported at the aerodynamic center of lift of the wing. This specification was provided by the manufacturer and required the majority of the equipment to be placed ahead of the center of lift of the platform. Figure 2.16 shows the internal arrangement of the components in relation to the center of lift within the fuselage.

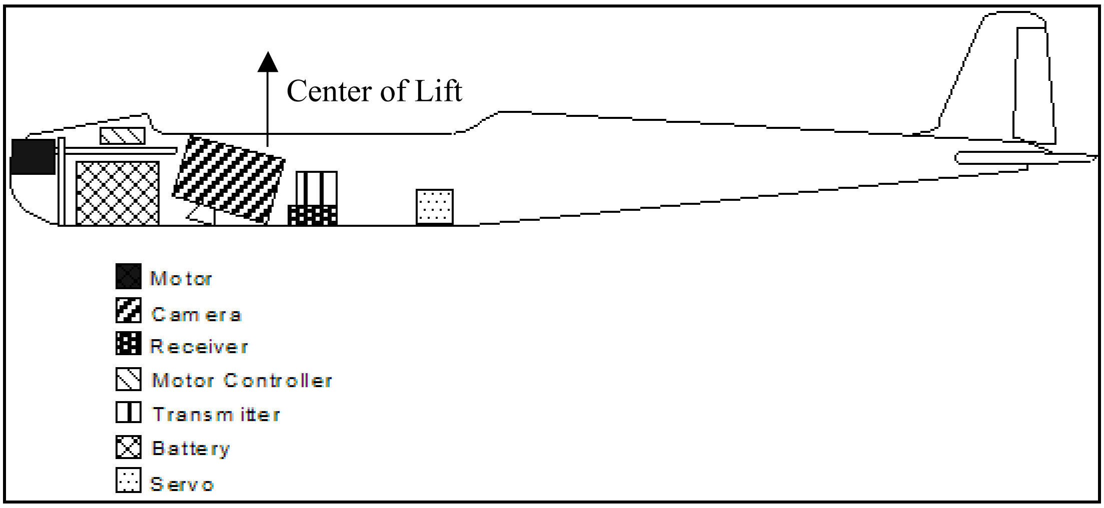


Figure 2.16: Component layout within the fuselage.

The motor was mounted to the plywood structural components in the front of the airframe with thin brass strips (Fig. 2.17). In addition to holding the motor in position during flight, the limited strength of the brass mounts also enable the motor to break free from the fuselage in the event of a frontal impact to minimize damage to the motor.

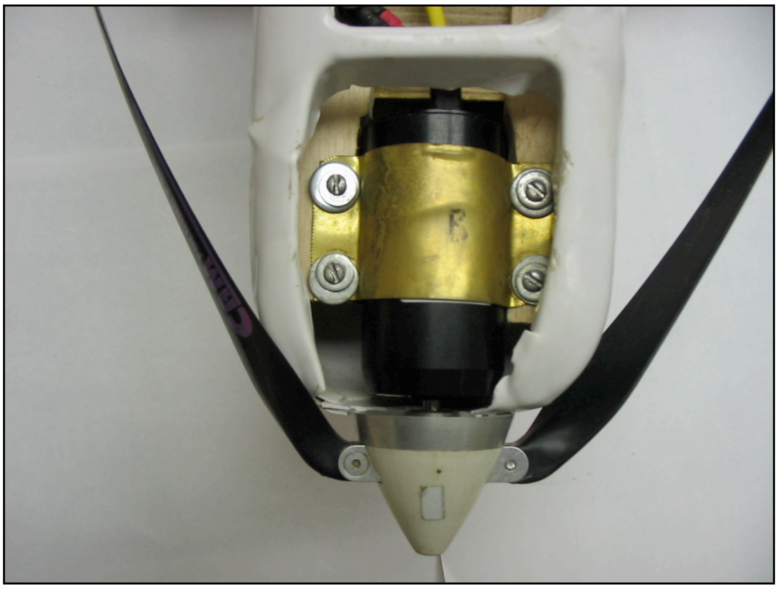


Figure 2.17: Motor, mounted in front of fuselage and held in place with thin brass straps.

The battery pack was positioned just behind the motor mounting frame, the forward most practical position. The wooden structure of the fuselage in this area provided extra protection for the battery, which was held in position with Velcro on the floor of the fuselage. The motor controller and other small electronic devices were stowed above the battery and ahead of the center of lift of the aircraft.

The camera was placed just forward of the center of lift of the wing. This meant that changes in camera configurations, positions, and attachments would not adversely affect airframe balance. This also provided maximum separation from electrically noisy motor and motor controller. The camera was positioned in the cargo bay so that there was ample space to attach different lenses and optical filters to the camera if required by the mission. The camera was held in position by protective high density foam mold inserted into a LEXAN® protective box (Fig. 2.18). This box cushioned the camera and protected it during hazardous periods. This protective foam has proven to be dependable in protecting the camera. The camera lens does not protrude through the airframe, making it less likely to be damaged if the components shift position.

Figure 2.18: Digital Camera and Protective LEXAN® case

The telemetry system, which receives flight control data and transmits imagery data to the ground station, was placed behind the camera. The telemetry components are small enough to be placed behind the center of lift without drastically affecting the

UAV balance. This location also achieved maximum separation from the electrically noisy motor and controller.

The UAV was equipped with standard R/C servos as the actuators, and a standard receiver. The servos are controlled directly with an RC transmitter at the ground station. Every surface had its own control channel, which allowed the pilot to mix the controls as needed to improve the flight handling of the aircraft.

The wing was attached to the fuselage by means of four rubber bands (Fig. 2.19). This attachment technique is common to R/C plane construction, and allows the wing to release or move during hard landings.

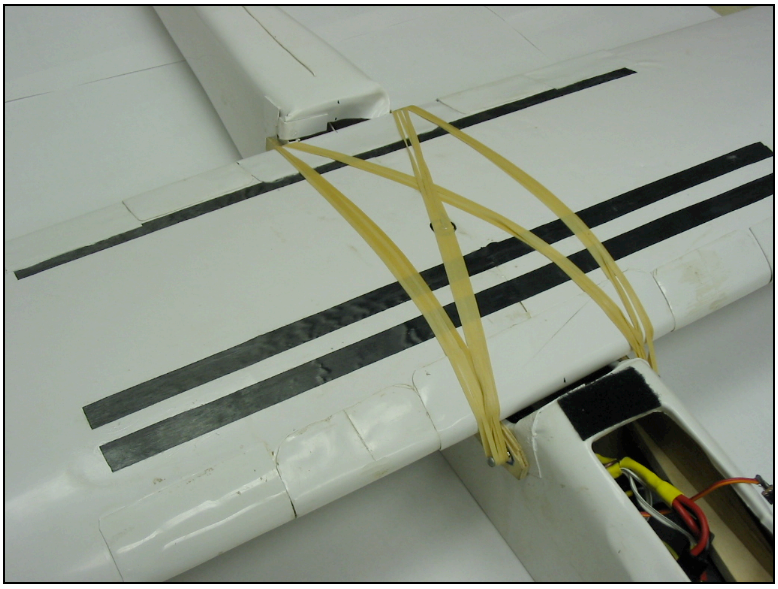


Figure 2.19: Rubber bands attaching the airfoil to the fuselage.

2.3.4 UAV Performance.

Ground-based activities were timed to provide data for evaluation of system deployment and operation. An onboard GPS receiver was used to record flight data for analysis of flight characteristics. The GPS equipment is further described in section 3.3.4.

The system had a set-up time of approximately 7 - 10 minutes. The bulk of that time was spent installing the onboard hardware and checking operation of the system. The speed at take off was found to be approximately 9km/h, allowing undemanding hand launch of the system. The platform had an operational speed of approximately 30km/h, ensuring adequate time over target and little image blur due to relative ground speed. The system had a climb rate of approximately 3.5m/s, allowing the platform to reaches an operational height of 250m in approximately 180s (time to operational height is affected by operational skill). The landing speed of the aircraft was approximately 17km/h allowing pilots with minimal experience to land the system. The operational height of the system was in the region of 250m depending on the skill of the operator. As pilot skill improves the operational height can be increased. To date the system has achieved altitudes of 300m.

Operation of the platform was best performed from a vantage point away from the target area. This is an operational choice and may vary between pilots. Generally, the system is difficult to control directly overhead, and is thus easier to operate from a slight distance. Once again the maximum operational rage of the aircraft is governed by the pilot’s ability to see the aircraft and not by the transmitter or receiver distance (1.45miles). A range of approximately 400m is the maximum for the pilot to remain in control of the aircraft. The platform’s handling was sluggish as predicted, but this ensured a stable platform. The aircraft’s flight was steady and straight while the motor was off. The altitude loss during un-powered flight was sufficiently small to allow the pilot to glide considerable distances. The electric motor was very dependable and allowed almost instantaneous throttling to full power. The ability to glide and then resume powered flight and gain altitude increased the flight time of each mission. The maximum duration of flights, from battery pack connection to disconnection, was approximately 15 minutes. Of this time, the maximum time spent aloft was approximately 10 minutes. Most flights had a shorter duration, but still enabled the operator to make numerous passes over the selected locality. The time taken between two successive flights depended on the quantity of battery packs available. Operating with two packs, ensured almost continuous operation, with approximately 10 minutes taken between flights to download images and install new batteries while recharging the old.

Damage during a mission (typically during landings) was generally minor and often repairable within the field. In the event of serious but recoverable damage, the maintenance time was usually under a day and typically, less than the time taken to build a new aircraft (15-25 hours). Damage was normally limited to the fuselage and wings, allowing reuse of all hardware components. The UAV platform achieved most operational goals set for the project, fulfilling the criteria for most missions:

- The modular construction allowed the system to be transported in a pick-up truck or similarly-sized vehicle. The modular platform facilitated easy packing and unpacking of the system from the transport vehicle and quick assembly at the site.

- The platform was easy to assemble, maintain and operate. Initial assembly was accomplished with rudimentary tools. Initial construction time was typically 15 – 25 hours. Assembly time at the mission site was generally short and in the region of 10 minutes.

- Operational damage was typically minor, with most damage reparable in the field. Operation was simplified through the utilization of two control surfaces, facilitating users with minimal experience to utilize the system, after instruction.

- System costs were low, reducing the cost to obtain remote sensing imagery to farmers, crop scouts, educators, and researchers (Table 2.4).

Table 2.4: Components weight and cost for the UAV system.

Component	**Weight**	**Price**
Plane (Kit)	1950g (4.29lb)	$70.00
Motor and Prop (Kit)	267.4g (0.589lb)	$140.00
Motor Controller	51.5g (0.114lb)	$97.00
Battery	737.4g (1.626lb)	$100.00
Radio (Including: Servos and Receiver)	58g (0.128lb)	$125.00
Camera	268.6g (0.636lb)	$175.00 – 399.00
Video Transmitter	66.9g (0.147lb)	$100.00 – 500.00
Total	3399.8g (7.5lb)	$532.00(+last two)

- The system achieved durability requirements allowing the platform to be operated repeatedly in remote locations. Repeated testing in ill-equipped and unprepared locations demonstrated the platform's durability and ability to operate in these locations.

- Equipment protection was achieved through placing the delicate equipment within the protective fuselage structure, allowing the components to detach in break-away zones, and housing the equipment in custom-made protective structures.

- Launch of the platform was achieved by hand, allowing one team member to hand launch the platform while another guided the system.

- Equipment was recoverable and reusable in the event of a major crash. Damage during successful flights was typically inconsequential.

2.4 Conclusions

The UAV-based RS platform developed in this project was used and operated successfully. The system had the desired performance and flight characteristics to make it a feasible platform for collection of RS imagery (Table 2.5). Most of the initial design specifications were met in the design of the system:

- Functionality: The system acquired images with a field of view of approximately 10 ha. This was below the desired field of view of approximately 12 ha. Field of view could be increased with greater operator skill and with the use of wide angle lenses.

- The storage volume encompassed 1.2m_1.5m_0.3m of space for the fuselage, and 2.5m long area for the wing section. This was sufficient to allow easy portability, and transport in a van or pick-up.

- Simplicity: the system was reasonably simple to operate and maintain.

- Robustness: operation of the system over unprepared terrain showed the system to be reasonably robust.

- Cost: total system cost was below the $1000.

- Flight times of 7 minutes were achieved through taking advantage of the good gliding characteristics of the platform, and the sparing use of battery pack power.

- Data transmissions at distances of 300m were verified with minimal interference.

- Altitudes of 250m were achieved, with higher altitudes possible with greater operator skill.

- The payload capacity of the system was $100cm^3$ (or 1*l*) and 0.45kg (or 1*lb*.) This was 0.227kg (or 0.5 lb) under the initial payload goal.

- Operational flight speeds of 27.35km/h (or 17mph) were achieved by the platform, well less than the desired 48.3km/h (or 30mph).

- Safety and integrity of the system was acceptable in the hands of an experienced pilot.

Table 2.5: Performance Characteristics of the UAV Platform.

Characteristic	**Desired Result**	Result
Set-up Time	Short duration	10 minutes
Payload: Mass and (Volume)	1.5 lbs ($100cm^3$)	1 lbs or 0.5kg ($100cm^3$)
System storage volume	Pick-up Vehicle	Pick-up vehicle
Endurance	10 minutes	10 minutes (max)
Mission Range	500ft (152m)	400m
Flight Speed	20mph (32km/h)	30km/h
Cruise Altitude	**600ft (182m)**	300m

CHAPTER 3: REMOTE SENSING IN PRECISION AGRICULTURE

3.1 Introduction to Remote Sensing

Remote sensing (RS) can be defined as any process of gathering information about an object, area or phenomenon without being in contact with it (Mather, 1999). Human eyes are examples of this; they are able to gather information about surroundings by gauging the amount and nature of reflected visible light energy from an external source (Eastman, 1996). The science of remote sensing (RS) consists of the interpretation of measurements of electromagnetic energy reflected from or emitted by an object from a vantage-point that is distant from the object (Eastman, 1996; Mather, 1999). RS as defined in this thesis as the observation, interpretation, and understanding of measurements of electromagnetic energy. This is energy reflected from or emitted by the Earth's surface or atmosphere (Mather, 1999). This thesis refers to RS as the process of gathering information devices, from a vantage point above the earth's surface (Eastman, 1996).

RS and image diagnostics are not new to agriculture, but their use is still limited. This is due to the cost of imaging (using satellites, piloted aircraft and land-based sensors), data analysis, time to receive the data, lack of accurate ground truthing, and environmental conditions. RS techniques have been available for fifty years, but only recently is their full potential being realized in agriculture (Johannsen et al., 2000). Piloted aircraft, satellites or land-based sensors can currently be used to obtain remote-sensing images (Cochran, 2000). The vast majority of RS research has utilized satellite-based systems, but the techniques and principals involved in RS are the same irrespective of RS platform. RS has become a widely used tool for various earth observation needs and has become increasingly useful in agriculture, particularly in the monitoring of natural resources (Verbyla, 1995). However, it is often difficult to differentiate between formations, that are floristically similar but extremely heterogeneous with regard to the degree of land cover density and biomass amount (Marchetti et al., 1995).

3.1.1 Background

Most objects including plants emit or reflect electromagnetic radiation. The electromagnetic spectrum (Fig. 3.1) range varies from very short wavelengths of less than ten trillionths of a meter known as gamma rays, to radio wave lengths of several hundred meters. Due to lens and atmospheric absorption, the first significant window of reflectance is that of the visible wavelengths (Verbyla, 1995). The green, red and near-infrared (NIR) wavelengths all provide good ability to gauge earth surface interactions without significant atmospheric interference (Eastman, 1996).

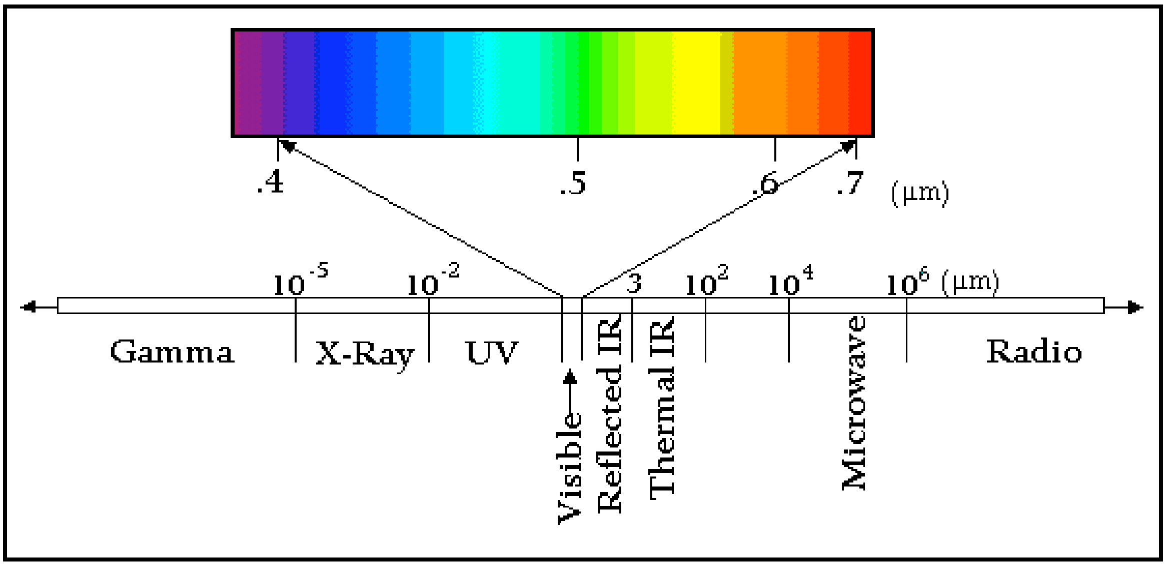


Figure 3.1: Electromagnetic Spectrum

The source of the electromagnetic spectrum is the sun's radiant energy. The sun's radiant energy strikes objects on the ground. That energy can be absorbed, scattered, or reflected back to the remote sensor. The spectral response of an object is the amount of energy reflected by the object and detected by the sensor.

3.1.2 Spectral Response of Vegetation due to Radiation

Spectral response patterns are also referred to as signatures (Verbyla, 1995). A simple example of a spectral response pattern or signature is a human's concept of color. The eye is able to sense spectral response patterns because it is truly a multi-spectral sensor. In the early days of RS, it was hoped that each earth surface material would have a distinctive spectral response pattern that would allow it to be accurately detected by visual or digital means (Eastman, 1996). However, in reality, this is not often the case. For example, two different trees might have quite a different coloration at one time of the year and quite a similar one at another. This may be because chlorophyll primarily absorbs red and blue to violet wavelengths for use in photosynthesis, which may vary in amount according to season. Green light is not readily absorbed and thus is reflected, giving vegetation a green appearance. In addition, NIR wavelengths are reflected due to scattering caused by the high air/cell interface area in the leaf tissue called mesophyll (Gates, 1970; Verbyla, 1995). Chlorophyll is transparent to NIR light. The sharp increase in the reflected energy just beyond the red region of visible light into the NIR region is not static and changes over the life of the leaf. This sharp increase is located around a wavelength of 0.7_m (Fig. 3.2).

Environmental stress factors such as drought, disease, weed pressure, and insect damage, cause physiological changes in the plant tissue. These changes cause the plants to have a different spectral response than healthy plants at the same growth stage. Thus, RS can become a useful tool for the identification of plant stress. Finding spectral response patterns is the key to most procedures for computer-assisted interpretation of remotely sensed imagery. An idealized spectral reflectance curve of vigorous vegetation (Fig. 3.2) illustrates relatively low values in the red and blue regions of the visible spectrum, with a minor peak in the green spectral band.

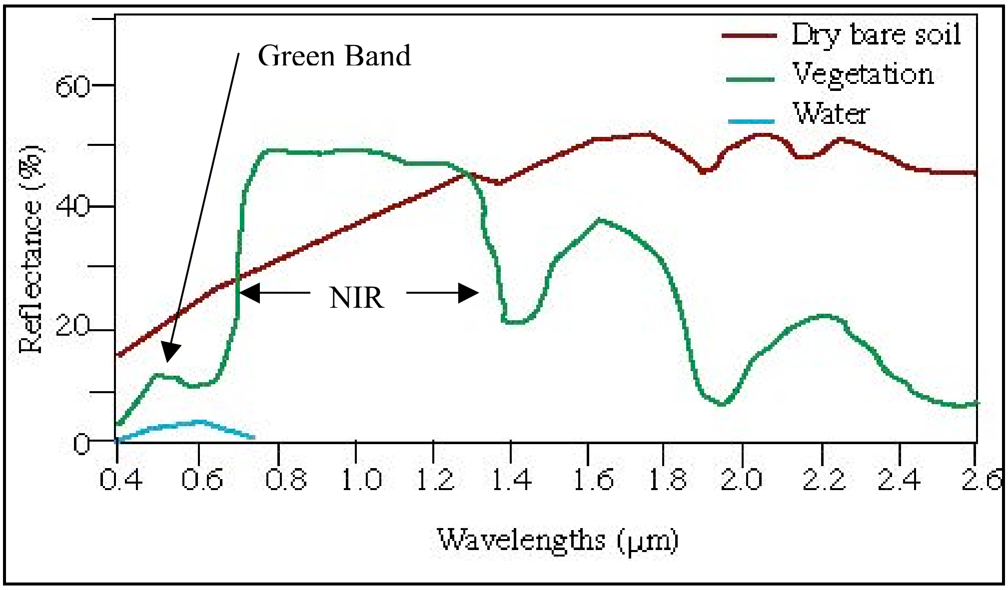


Figure 3.2: Idealized spectral reflectance curves for vigorous vegetation, soil and water (www.ucalgary.ca/.../SS/GEOG/ Virtual/remoteintro.html)

These peaks and troughs are caused by absorption of blue and red light by chlorophyll and other pigments. Typically, 70-90% of both the blue and the red light are absorbed to provide energy for photosynthesis (Mather, 1999). The slight reflectance peak between 0.5 and 0.6 μm is the reason that actively growing vegetation appears green. Reflectivity rises sharply at about 0.75 μm, and remains high in the near-infrared region between 0.75 and 1.35μm because of internal leaf structure and the air/cell interface area in the leaf tissue. Between 1.35 and 2.5μm, the reflectance is controlled by leaf-tissue water content. As the plant ages, the level of reflectance in the NIR region declines, while the reflectance in the visible part of the spectrum is not significantly affected. The reflectance curves of soils are generally characterized by a rise in reflectivity as wavelength increases. This is the opposite of the spectral reflectance curve of clear water (Mather, 1999).

The middle-infrared region (MIR), 1.55 – 1.75 μm, is an area where significant differences can arise between mature species. As a result, applications looking for optimal differentiation between species will typically involve both NIR and MIR regions (Eastman, 1996).

Water reflection varies greatly according to the extent of turbidity of the water. Clear water, for instance, reflects very little in most spectral regions, while very turbid water reflects significant amounts of radiation, especially in the red and NIR spectral regions (Verbyla, 1995). In short, the electromagnetic spectrum is broad and not all wavelengths are equally effective for RS purposes.

3.1.3 Sensor types

RS imaging sensors fall into two categories: active and passive sensors. Passive sensors measure only naturally occurring reflected solar energy. These sensors make up the majority of the sensors used for RS. Active sensors provide their own controlled source of electromagnetic energy, which is transmitted to the object and the reflectance measured.

3.1.4 Resolution

An imaging/remote sensing instrument platform operating in the visible and infrared spectral region is described in terms of its spectral, spatial, and temporal resolution (Mather, 1999; Verbyla, 1995).

3.1.4.1 Spectral Resolution

Spectral resolution is the ability of a sensor to respond to a specific frequency range. A discrete frequency range that a sensor is able to detect is called a Band. Spectral resolution refers to the width of these bands across the total electromagnetic spectrum span of the sensor. A wide-band instrument would simply average out differences in reflectance of various spectral regions (Mather, 1999).

Figure 3.3, is a representative plot of the reflection from healthy (dotted line) and unhealthy (solid line) vegetation versus wavelength (Mather, 1999). Most of the difference occurs in the near-infrared region. If the spectral resolution of the sensor is relatively low (Fig. 3.4), information from the near-infrared region might be lumped with the red information. In this case, the differences in the vegetation would not be apparent (Mather, 1999). Landsat TM, a satellite based RS platform collects seven bands: blue (0.45-0.52μm), green (0.52-0.60μm), red (0.63-0.69μm), near infrared (0.76-0.90μm), mid-infrared (1.55-1.75μm) and far-infrared (2.08-2.35μm), and thermal infrared (10.4-12.5μm) (Eastman, 1996). To provide more reliable identification of particular targets on a RS image, the spectral resolution of the sensor must match as closely as possible the spectral reflectance curve of the intended target (Mather, 1999).

3.1.4.2 Spatial Resolution

The term spatial resolution refers to the fineness of detail visible in an image and generally corresponds to ground pixel size, or the amount of area covered on the ground per pixel of resolution. It is the ability of the sensor to identify the smallest size detail (or pixel) of a pattern on an image. However, this does not mean that an object smaller than the pixel size will not be detected. Each pixel is a representation of the weighted average of reflectance in that area.

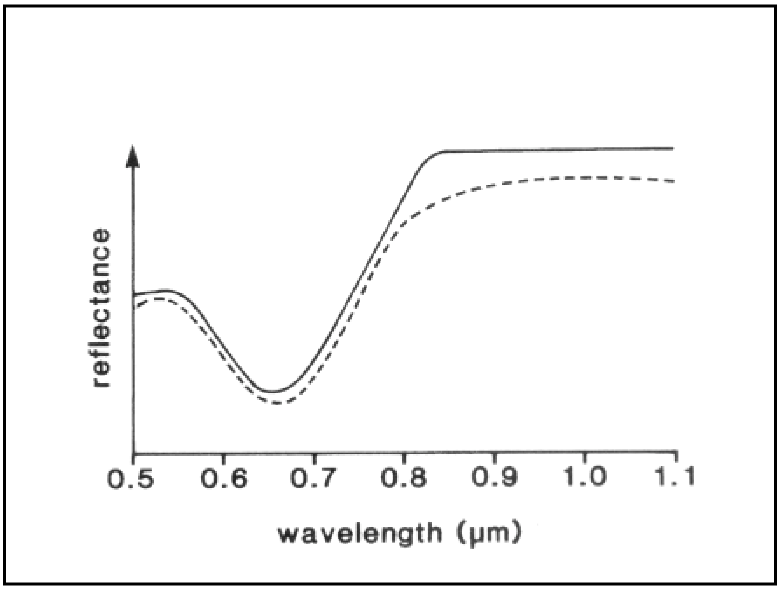


Figure 3.3: Spectral reflectance curve for healthy (dotted line) and senescing (solid line) vegetation (Mather, 1999).

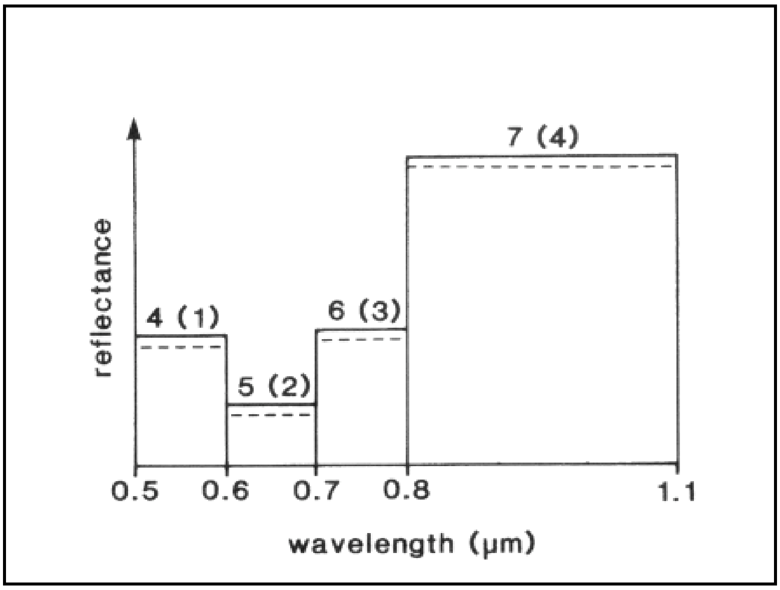


Figure 3.4: Spectral reflectance curve recorded by an instrument with four spectral bands of resolution (Mather, 1999).

The spatial resolution for Landsat TM images is 30 m and for NOAA-AVHRR systems is 1.1 km, which are also Satellite based platforms (Eastman, 1996; Mather, 1999).

3.1.4.3 Radiometric Resolution

Radiometric resolution or contrast, describes the ability of the sensor to measure the signal strength or brightness of objects. Radiometric resolution is often given in terms of the number of bits of digital information. An 8-bit sensor, for example, will report one of 2^8 or 256 discreet intensity values for each band of spectral resolution. Obviously, as spectral, spatial, and radiometric resolutions increase, data file sizes can become quite large.

3.1.4.4 Temporal Resolution

Temporal resolution is the imaging revisit interval (Eastman, 1996); it is the time elapsed between images taken of the same object at the same location. The greater the frequency the sensor can revisit the same location, the finer the temporal resolution. The temporal resolution of Landsat is 16 days, which is smaller than some other sensors such as SPOT, which has an orbital cycle of 26 days. NOAA-AVHRR on the other hand, can show wide areas on a daily basis (Eastman, 1996). Temporal resolution of satellite imagery also generally improves at higher latitudes due to the significant side lap between consecutive satellite passes. Side lap is the area that is digitized twice in two adjacent satellite passes; thus, the same area falls into two images. The percentage side lap for Landsat scenes ranges from 15% at the equator to 85% at extreme latitudes (Verbyla, 1995).

3.1.5 Image Processing

Digital image processing involves the manipulation and interpretation of digital images with the aid of a computer. This is the process whereby raw RS digital data is processed into usable data. This process aims to correct data distortions. It refers to four basic operations: image restoration, enhancement, classification and transformation (Eastman, 1996), and can be viewed in two major operations: preprocessing and post processing.

3.1.5.1 Pre-processing

Preprocessing of RS data includes the correction of radiometric and geometric distortions, which is referred to as image restoration. Image restoration aims to correct distorted or degraded image data to create a more faithful representation of the original scene. This typically involves the initial processing of raw image data to correct geometric distortions, calibrating the data radiometrically and eliminating noise present in the data (Lillesand & Kiefer, 1987). Radiometric corrections are made to raw data to correct for brightness of objects on the ground, which have been distorted. The distortion occurs because of scattering of reflected light due to atmospheric conditions. Geometric corrections are made to the raw data to correct the inaccuracy between the location coordinates of the picture elements in the image data, and the actual location of the feature on the ground. Geometric corrections could include a georeferencing operation where pixels are first assigned to a spatial coordinate.

3.1.5.2 Post-processing

Image enhancement is the modification of images to make them more suited to assessment by human vision (Eastman, 1996). This process involves techniques for increasing the visual distinction between features in a scene. The object is to create “new” images from original image data that increase the amount of information that can be visually or digitally interpreted from the data.

3.1.5.3 Enhancements

Image enhancement techniques include contrast stretching, spatial filtering and ratioing. Contrast stretching changes the distribution and range of the digital numbers assigned to each pixel in an image. This is done to allow the user to visually discern and interpret data. Spatial filtering involves the use of mathematical algorithms to either emphasize or de-emphasize brightness. Ratios are computed by taking the digital numbers for a given frequency band and dividing them by the values of another band. Manipulation of the ratios can highlight certain image qualities.

3.1.6 Remote Sensing and Vegetation Indices

Vegetation indices (VI) are one image enhancement technique designed to provide valuable information about the density and greenness of vegetation and simultaneously minimize the effects of soil background brightness and atmospheric noise. The index one uses depends on one's image processing needs. The choice requires an understanding of the problem at hand and depends on whether the user wants to retain the effect of background soil or remove it (Eastman, 1996; Mather, 1999).

The most commonly used vegetation index is the normalized difference vegetation index (NDVI). NDVI is calculated from the reflectance of red and NIR radiation (Yoder and Waring, 1994).

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \qquad \ldots\ldots \quad (1)$$

The NDVI works as a vegetation index on the following principles: As discussed earlier, chlorophyll absorbs red and blue wavelengths for use in photosynthesis. NIR wavelengths are reflected by the leaves at an amount relative to the air/cell interface area in the leaf tissue. Thus, the amount of chlorophyll in the leaves determines the levels of red light reflection and the water level in the plant tissue determines the amount of NIR wavelength reflection. If the plant is healthy and contains high quantities of chlorophyll, the red light reflectance will be low and the NIR reflection will be at a normal level. Thus, the difference between the two reflections will be quite high. On the other hand, if the plant is unhealthy, it will have low levels of chlorophyll, hence high red light reflectance, and low moisture content, consequently higher NIR wavelength reflection (Carter, 1993). However, the NIR reflectance increase will not be as substantial as the red light reflectance and thus the difference between their reflectances will be low and often negative.

NDVI has been related to the amount of green leaf biomass by Tucker (1979) as evidence of its general relation to vegetation biomass variations. Spanner *et al.* (1990) also related it to leaf area index (LAI). The NDVI has been used to study global vegetation using bands one and two of the NOAA AVHRR. For example, Justice *et al.,* (1985) used the NDVI in a study of vegetation patterns on a continental scale.

Another group of vegetation indices is distance-based VIs, which are essentially based on the perpendicular vegetation index (PVI) suggested by Richardson and Wiegand (1977). The main objective of these VIs is to cancel the effect of soil brightness to generate an image that only highlights the vegetation signal. This effect is particularly important in arid and semi-arid lands where vegetation is sparse. The procedure is based on the soil line concept. The soil line is obtained through linear regression of the NIR band against the red band for a sample of bare soil pixels. In analysis of the image data, pixels falling near to the soil line are assumed soils while those far away are assumed to be vegetation (Eastman, 1996; Verbyla, 1995). It is important to remember that in order to do any significant computations with VIs, both visible and NIR bands need to be obtained.

3.1.6.1 Principal Components Analysis

Adjacent bands in a multispectral image are generally correlated. Multi band visible/NIR images of vegetated areas will show negative correlation between the NIR and visible red bands and positive correlation among the visible bands because the spectral characteristics of vegetation. The presence of these correlations among the bands of a multispectral image implies that there is a redundancy in the data (Mather, 1999). Principle component analysis is a technique to identify this redundancy.

In order to describe the process of a principal components analysis (PCA), consider the following simplification. If two variables are perfectly correlated, then measurements on x and y will plot as a straight line sloping upwards to the right (Fig. 3.5). Since the positions of the points shown along line AB occupy only one dimension, they could be represented equally well by using the line AB as a single axis. Even if x and y are not perfectly correlated there may be a dominant direction of scatter or variability, such as that shown in Figure 3.6. If this dominant direction of variability (AB) is chosen as the major axis then a second minor axis, (CD) could be drawn at right angles to it (Fig. 3.6) (Mather, 1999).

A plot using the axes AB and CD rather than the conventional axes x and y might in some cases, prove more revealing of the structures that are present within the data. This example shows that we must draw a close distinction between the number of spectral bands (variables) in the image data set and the intrinsic dimensionality of that data set.

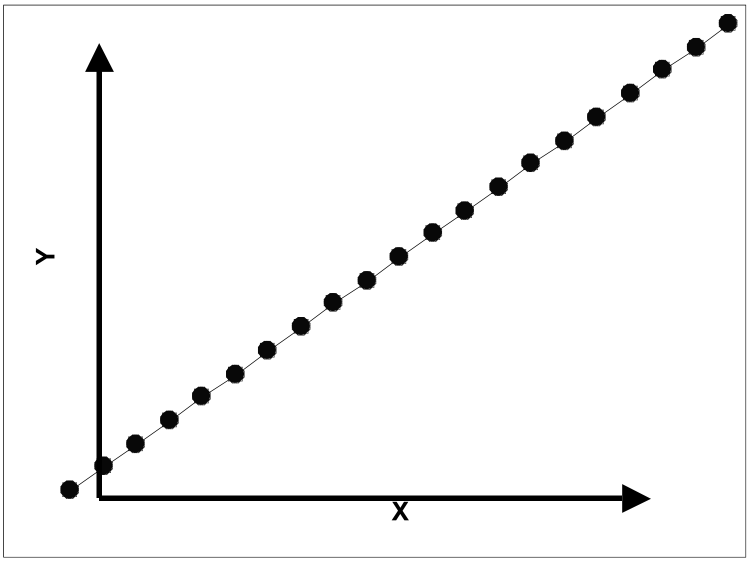


Figure 3.5: Plot of two variables x and y which are perfectly correlated (adapted from Mather, 1999).

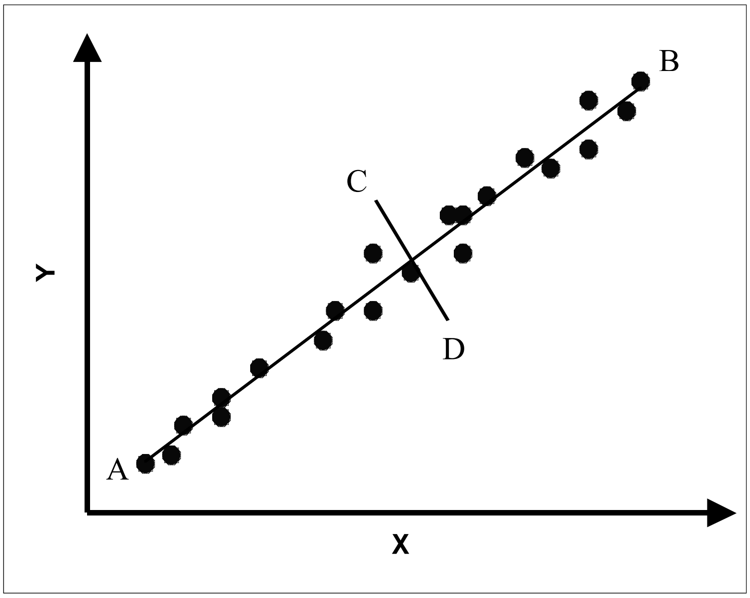


Figure 3.6: The two variables x and y show a high positive correlation (adapted from Mather, 1999).

In both of the above examples, the use of the single axis AB rather than the axes x and y accomplishes two aims:

1. a reduction in the size of the data set, and

2. the information conveyed by the coordinates on AB is greater than the information conveyed by the measurements on either the x or y axes individually (Mather, 1999).

Multispectral image data sets generally have dimensionality that is less than the number of spectral bands. The purpose of PCA is to define the number of dimensions that are present in the data set and to fix the coefficients that specify the positions of the set of axes that point in the directions of greatest variability in the data (such as the AB and CD axes in Figure 3.6). A principal components transform of a multispectral image might therefore be expected to perform the following operations:

- define the dimensionality of the data set, and
- identify the principal axes of variability within the data (Mather, 1999).

These properties allow for relationships between different groups of pixels, representing different land cover types, to become clearer if they are viewed in the principal axis reference system rather than in terms of the original spectral bands (Mather, 1999).

3.1.7 Image Classification

Image classification is a process in which all the pixels in an image that have similar spectral signatures are identified (Lillesand and Kiefer, 1994). Specifically, it is the process of grouping pixels that have similar spectral values. Each group of similar pixels is called a spectral class, which is assumed to correspond to a cover type class such as wetland or production crop types. The purpose of classification operations is to replace visual analysis of the image data with quantitative techniques for automating the identification of features within a scene (Eastman, 1996).

The magnitude of the reflected or emitted energy measured in each waveband for a single pixel is considered to be related to the characteristics of the material forming the surface cover over the ground area corresponding to that pixel (Mather, 1990). The overall objective of image classification is to automatically categorize all the pixels in an image into land cover classes or themes (Lillesand & Kiefer, 1987). However, in reality there are always complicating factors, which occur due to:

- the effects of interactions between electromagnetic energy and the components of the atmosphere,
- the effects of the geometry of the imaging system, particularly when compared with topography and
- the assumptions underlying the statistical techniques employed in the classification process (Mather, 1990).

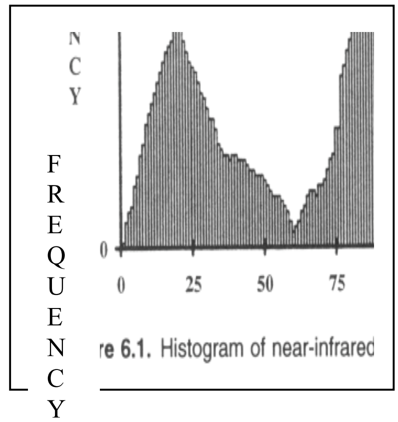
The detection of spectral signatures of land cover classes is the basis for the majority of image classification. The success of classification depends on two factors:

1. the presence of distinctive signatures for the land cover classes of interest in the band set being used, and
2. the ability to reliably distinguish these signatures from other spectral response patterns that may be present (Eastman, 1996).

There are two general approaches to image classification: supervised and unsupervised. They differ in how the classification is performed. For instance, supervised classification involves detecting already known specific types of land cover, while unsupervised classification is where the analyst attempts to define all categories existing in the image (Eastman, 1996). The type of classification used depends on whether spectral response pattern data is available to the analyst.

3.1.7.1 Unsupervised Classification

The first step in a histogram-based procedure is to generate a histogram showing the number of pixels within each digital number class (Verbyla, 1995). Figure 3.7, shows an example of a hypothetical NIR histogram from a region with water, broad-leafed shrubs, coniferous trees and rock outcrops.



Hypothetical near-infrared numbers

Figure 3.7: Histogram from near-infrared digital numbers from a hypothetical image. (Verbyla, 1995)

The histogram from pixels of a uniform cover type is often bell shaped. Histogram-based unsupervised classification relies on this bell-shaped assumption and follows a series of rules to delineate spectral classes (Verbyla, 1995). The procedure first determines peaks within the histogram throughout the range of image digital values, where, each peak in the histogram corresponds to a spectral class. For example, the histogram in Figure 3.7, has four distinct peaks (at approximately 20, 95, 150, and

175), thus four spectral classes will be delineated. The next step is to determine the boundaries of each class.

One simple way of doing this is to assume that the boundaries between spectral classes will be half the distance between class peaks (Verbyla, 1995). The boundaries for Figure 3.7, will be, 60, 125 and 162.5 (Table 3.1).

Table 3.1: Classification thresholds based on histogram peaks (modified from Verbyla, 1995)

Spectral Class	**Range of Digital Images**	**Assigned Color**
1	Less than 60	Blue
2	61 through 125	Dark green
3	126 through 162	Yellow green
4	Greater than 162	Brown

The final step is to classify the original image based on these classification rules. Each pixel would be assigned to a class according to which range it falls into. For example, if a pixel has a value of 140, it would be assigned to class three and assigned the color 'yellow green.' Histogram-based unsupervised classification can be applied to multispectral images. For example, with a two-band image, the peaks in the histogram would be similar to the peaks of hills (two-dimension peaks). With seven spectral bands, there would be peaks in seven dimensions, where the spectral distance could be calculated mathematically (Verbyla, 1995).

3.1.7.2 Supervised Classification

The basic strategy in supervised classification is to sample areas of known cover types to determine representative spectral values of each cover type. The sample areas used are referred to as training areas and their representative values are called spectral signatures (Verbyla, 1995). This method of classification is regarded as being more accurate than unsupervised methods.

To explain this process, consider five bands of data from a Landsat image. Figure 3.8; shows the location of a single line of the data collected over a landscape of several land types. Typical digital numbers (DNs) over six land cover types are shown. The vertical bars indicate the relative intensities in each spectral band; therefore, the histograms represent a coarse description of the spectral response patterns of the various terrain features along the scan line. If these spectral patterns are sufficiently distinct for each feature type, they may form the basis for image classification (Lillesand & Kiefer, 1987; Mather, 1999).

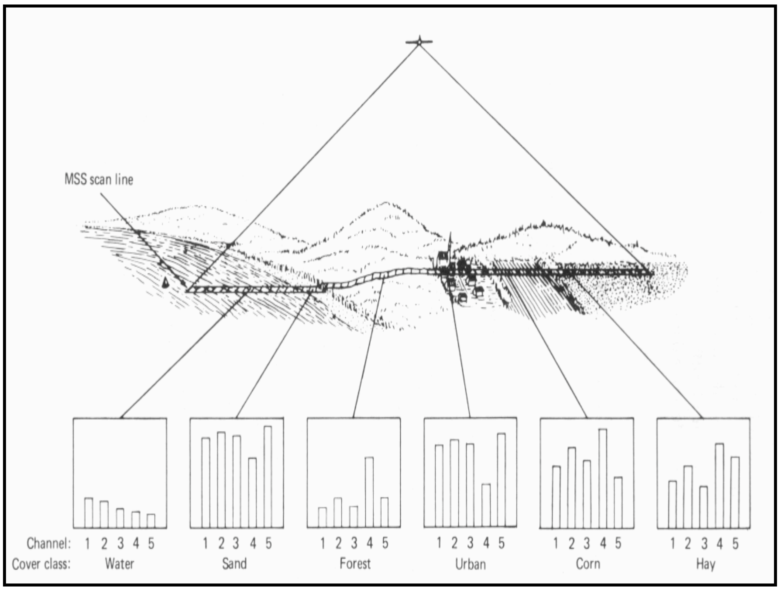


Figure 3.8: Selected Landsat measurements made along one scan line (Lillesand & Kiefer, 1987).

There are three basic steps involved in a typical supervised classification procedure (Fig. 3.9). In the training stage (1), the analyst identifies representative training areas and develops a numerical description of the spectral attributes of each land cover type of interest in the scene.

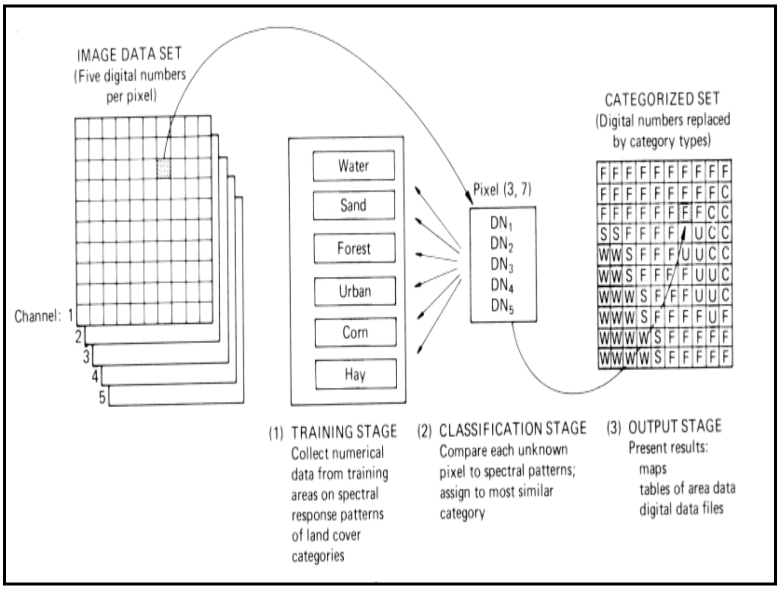


Figure 3.9: Basic steps in supervised classification (Lillesand & Kiefer, 1987).

The classification stage (2) consists of categorizing each pixel in the image data set, into the land cover class it most closely resembles. If the pixel is insufficiently similar to any training data set, it is usually labeled as 'unknown.' The category label of each pixel is then recorded in the corresponding cell of an interpreted data set. The final step (3) is the output stage where the results are presented. This is done in various ways such as thematic maps, tables of statistics and digitally for the inclusion into GIS (Lillesand & Kiefer, 1987).

3.1.8 Acquiring Remote Sensing Data

3.1.8.1 Sensors

Remote sensors are grouped according to the number of bands and the frequency range of those bands. Categories of RS sensors include panchromatic, multispectral, and hyperspectral.

Panchromatic sensors cover a single wide band of wavelengths in the visible and/or infrared spectrum. An example of a sensor of this type is a black and white camera. Multispectral sensors are capable of covering two or more spectral bands simultaneously. Hyperspectral sensors cover bands narrower than multispectral sensors; often several hundred bands are collected at the same time. Hyperspectral sensors offer a much greater spectral resolution than sensors covering wider bands; however, image size and subsequent data storage requirements can be large.

With recent developments in digital photography, high-resolution cameras can provide a true alternative to researchers (Ries et al., 2003). High-resolution cameras can now be obtained in ever-smaller packages, reducing the overall volume and weight of the cameras and increasing the practicalility of their applications in UAVs. Additionally, as popularity, sales and technology mature, the cost of these technologies will drop fueling their use in unconventional applications. Blimps, balloons, kites, model airplanes, and helicopters have been used before by scientists as unmanned platforms for photographic and video cameras (Burkert et al., 1996; Palacio-Prieto and López-Blanco, 1994; Walker and De Vore, 1995; Ries et al., 2003).

3.1.8.2 RS Platforms

3.1.8.2.1 Aircraft

From the advent of powered flight, airplanes have served as RS platform, carrying the first camera into the air. Aircraft have the advantage as a platforms for RS of being able to fly at relatively low altitudes (<1524m or 5000ft) allowing sub-meter sensor spatial resolution. Additionally, aircraft can change their schedule to avoid weather problems such as clouds, which may block a passive sensor's view of the ground. Timing changes to adjust for illumination from the sun, the location of the area to be visited, and additional revisits to the location can be made. Sensor maintenance, repair and configuration changes to the aircraft platforms can be made on the ground.

However, the low altitude flown by aircraft narrows the field of view of the sensor requiring many passes to cover a large area. Time to deliver data to the user is delayed due to the necessity of returning the aircraft to the airport before transferring the raw image data to the data provider's facility for preprocessing. Furthermore, costs of hiring pilot and aircraft can be high.

3.1.8.2.2 Satellite

Several satellite systems are currently in operations that collect imagery, which is subsequently distributed to the general public. Each type of satellite data offers specific characteristics that make them more or less appropriate for a particular application. Satellite platforms provide wide fields of view for the sensor and offer regular and systematic re-visit. However, resolution is limited due to the satellite's fixed altitude and orbital flight path. Satellites do not have operational boundaries, which give them global coverage, but they require expensive ground support facilities. Data from the following satellite-based RS platforms are available to the general public.

- Landsat Thematic Mapper (TM),
- SPOT (*Syste'me Pour L'Oservation de la Terre*) which is a system operated and developed by the French Centre National d'Etudes Spatiales (CNES),
- NOAA-AVHRR (*Advanced Very High Resolution Radiometer*), operated by the U.S. National Geographic Oceanic and Atmospheric Administration (NOAA) (Lillesand & Kiefer, 1987; Eastwood *et al.,* 1998)

There are several limitations to satellite collection techniques. The quality and resolution of the images can be inadequate for accurate diagnostics (Cochran, 2000).

Image quality of all satellite platforms is affected by adverse weather conditions such as cloud cover or a hazy atmosphere. Moreover, although re-visit is systematic, satellites are only in position to collect images every few days, so timing is an additional problem. Many commercial satellite systems such as LandSat and SPOT provide insufficient resolution and the revisit time is too long for many agricultural applications.

3.1.8.2.3 Terrestrial

Terrestrial RS systems are ground-based sensor systems. Research has been done using remote sensors attached to booms, hoisted above the crop canopy from the ground. Images collected from such a close distance have resolutions that are much greater than images from aircraft or satellites; however it is more difficult to produce images of larger areas.

3.1.9 Remote Sensing in Precision Agriculture

RS is one potential component of a larger integrated technology known as Precision Agriculture. Before RS becomes a widely used tool for everyday farmers, the economic benefits of RS need to be demonstrated. One way of achieving this goal is to reduce the costs involved in the collection of RS imagery. Currently, RS is an expensive endeavor. Satellite companies will deliver NDVI maps for approximately $0.47 per acre, while commercial aerial images tend to be more expensive at approximately $0.75¢ per acre (http://www.amesremote.com). However, images cover vast areas, dramatically increasing costs. In addition, it is not guaranteed that the area of interest will be located entirely on one image. Due these concerns, few farmers obtain RS images. Development of inexpensive platforms and image capturing systems will help drive the use of RS in agriculture. Unmanned Aerial

Vehicle (UAV) platforms are one option that could help drive adoption of RS imagery.

In the last decades, Dovis et al. (2001), reported that governmental and private organizations increased their demand of earth observation data defining a new research and commercial trend. This was highlighted at the 2001 Fifth Framework Program of the European Union (http://europa.eu.int), which addressed the need for enhancement of RS systems, as well as the development of new ones.

3.2 Objectives

The goal of this part of the project was to create a cost effective camera imaging system to capture RS imagery that would be valuable to a wide range of users and suitable for use in a UAV platform. This project was accomplished through the implementation of the following objectives:

1. Identification imaging hardware alternatives.
2. Evaluation of the alternatives through testing.
3. Selection of the best alternative.
4. Demonstration of the quality of image obtainable.
5. Testing of additional Equipment for UAV platform.

The design of the remote sensing equipment was closely linked to the design of the UAV (Chapter 2), as sizes and weights of the imaging equipment affected UAV design. The ultimate imaging capturing system would provide high resolution, georeferenced, hyperspectral images from a small light weight package. In addition, it would be available at a low cost. Unfortunately, systems of this nature are not available and thus compromises between cost, size and image quality were evaluated.

3.3 Methods and Equipment

Three different imaging equipment options were explored in the pursuit of the desired imaging system: specialized multispectral cameras, single board cameras with wireless video transmitters, and digital still cameras. All of these systems were explored in the context of the project's goals and constraints.

3.3.1 Multispectral Sensors.

At the outset, multispectral camera were explored as imaging devices (Fig. 3.10). These image capturing systems are designed specifically for agricultural remote sensing.

Figure 3.10: Multispectral camera initially explored for integration into the platform.

Unfortunately, the commercially available multispectral cameras are relatively heavy and expensive. The goal to develop an inexpensive platform, in addition to the weight restrictions of the imaging sensors, made the use of these cameras impractical. Thus, multispectral cameras were discarded as a viable alternative in a low cost system.

3.3.2 Single Board Camera System.

A small single board camera and wireless video transmitter system were tested in the UAV (Fig. 3.11). This system consisted of a board camera from Edmond Optics® (Barrington, NJ) and a wireless video transmitter from Wireless Video Cameras L.L.C. (Rancho Santa Margarita, California).

3.3.2.1 Board Camera

The board camera (Table 3.2) was extremely small and light allowing easy incorporation into the imaging platform.

Table 3.2: Board Camera specifications.

Signal Format	NTSC, YC	Min. Sensitivity (without lens)	3 lux
Interline Transfer CCD	1/4" format	S/N Ratio	>48 dB
Pixels (H x V)	768 x 494	Electronic Shutter Speed	1/60 - 1/10,000 sec.
Pixel Size (H x V)	4.75 x 5.55µm	Gamma	0.6 / 1.0 selectable
Horizontal Resolution	480 TV Lines	Auto Gain Control	On 20 dB / Off Select
Sensing Area (H x V)	3.6 x 2.7mm	Operating Temperature	-10°C to 60°C
Video Output	Via 10" wire leads	Power Requirement	12V DC, 130 mA
Lens Mount	CS-Mount or M13 x 1mm	Dimensions (W x H x L)	42 x 42 x 30mm
Back Flange Distance	12.5mm (CS-Mount)	Weight	42g

Power was supplied to the camera by regulating power from the main flight battery pack. Due to the camera's small size (42 x 42 x 30mm), placement within the fuselage was easy. During operation, the camera was wrapped within a protective foam covering to prevent damage. The board camera output was an NTSC signal, with 480 TV lines of resolution.

3.3.2.2 Microwave Transmitter

The transmitter was originally marketed for use in RC airplanes; its transmission range of 2.4km or 1.5miles exceeded the normal operational range of radio control transmitters. For system integration, the transmitter was removed from its protective casing to reduce the weight and size of original transmitter package. Velcro was adhered to the underside of the transmitter and to the floor of the platform to enable the position of the transmitter to be altered as needed and to restrain the transmitter during flight.

Specifications of this transmitter can be seen in Table 3.3, and further detail is given in section (3.3.4.3). The transmitter was powered by regulating power from the main flight battery pack of the platform. The camera was connected to the transmitter through RCA jacks.

Table 3.3: Specifications for the microwave video transmitter.

Range:	1.45 Mile
Power Output:	100mW
Modulation:	FM
Frequency:	2 channels, 2.434GHz & 2.411GHz
Transmitter Antenna:	21" end feed dipole, omni directional
Receiver Antenna:	Built-in patch
Transmitter Dimensions:	2.5" (d) x 3.0" (w) x 1.0" (h)
Video Bandwidth:	6MHz
Video Format:	NTSC or PAL
TV Lines Max:	525
Connectors:	RCA jacks - yellow video, red right audio, white left audio
Mounting:	Aircraft grade Velcro
Power Required - Transmitter:	12vdc @ 240mA (without camera)
Power Required - Receiver:	12vdc @ 360mA

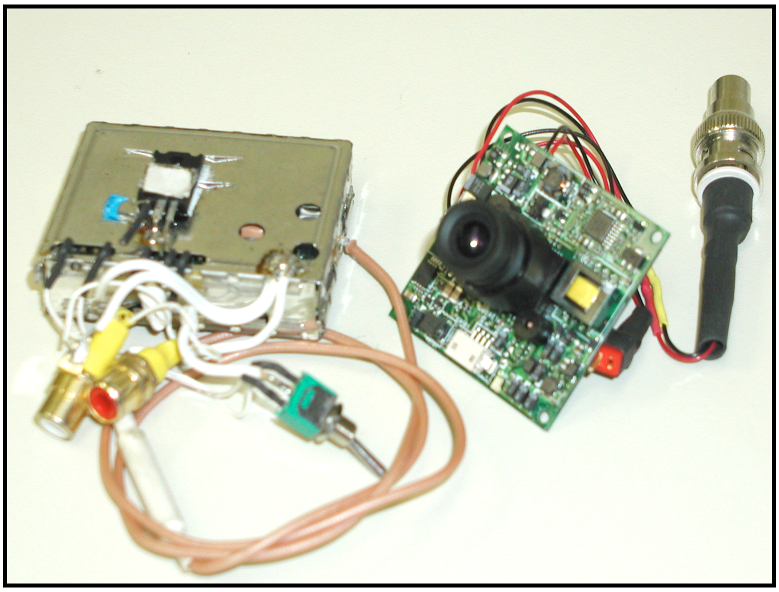


Figure 3.11: Board camera and wireless video transmitter, tested in the UAV platform

3.3.2.3 Board Camera System Operation

The board camera system was tested in the UAV on several missions. Live video streams were transmitted from the platform to the ground station via the on-board video transmitter discussed above (Fig. 3.12).

Figure 3.12: Ground Station, receiving live video stream transmitted from UAV.

At the ground station, the live video feed was received through a receiver supplied with the video transmitter and recorded onto VHS video cassettes. Thus, the system was capable of displaying a real time video feed to the operators. Following the mission, the analog VHS video was digitized through a digital camcorder. Once in digital form, still images were extracted from the digital video.

3.3.3 Digital Still Cameras

Next, digital still camera systems were tested. Integration of this option was more complicated than the board camera system. The cameras were physically bigger and heavier than the board cameras placing increased space and payload demands on the platform. Additionally, the digital still cameras required a method of triggering the shutter to capture images at the correct time. The system transmitted live images back to the ground station in the same manner as the board cameras. However, the system was able to capture high resolution still images onboard the platform at high shutter speeds.

3.3.3.1 Camera Descriptions

A search was conducted of current cameras fulfilling cost, weight, and resolution requirements. Two digital cameras were evaluated for possible integration into the platform: a Nikon Coolpix 800 (Fig. 3.14) and a Canon PowerShot A60 (Fig. 3.15). Both cameras had the capability to include additional filters, and had manual control of the image capturing process.

Figure 3.13: Nikon Coolpix 800 digital camera with additional filters.

Figure 3.14: Canon PowerShot A60 Digital Camera with additional filters.

The digital still cameras offered NTSC video output of the LCD screen image. This output was passed through the wireless video transmitter system as described in section 3.3.2.2. Both cameras stored captured images within the camera on compact flash cards at a resolution of 2.1 mega-pixels (1600 _ 1200 pixels maximum image size). Camera operation in both cases was controlled via an additional onboard servo that pressed the image capture button.

The cameras were encased within protective boxes made from Lexan®. The servos used to trigger the camera were mounted to these protective cases. Additionally, both cameras had the capacity to be supplied power from the onboard battery pack. Table 3.4 gives some additional specifications of the two cameras evaluated, including weight and dimensions of the units.

Table 3.4. Specifications of the Nikon and Canon Digital Cameras.

	Nikon Coolpix 800 Specifications	**Canon PowerShot A60 Specifications**
CCD	_ in CCD	1/2.7 in. CCD
Camera effective pixels	2.11 million pixels	2.1 million pixels
Shutter	Mechanical and charge coupled electronic shutter	Mechanical and electronic
Exposure Control	Programmed auto exposure (AE), Manual exposure compensation	Program AE, Shutter-priority AE, Aperture-priority AE or Manual exposure
Sensitivity	ISO 100 Auto-ISO or ISO 100, 200 or 400 settings	AUTO/ISO 50/100/200/400 equivalent
Image Recording	File Format TIFF RGB (uncompressed) or JPEG (Exif 2.1); 24-bit RGB	Still images : JPEG (Exif 2.2)
Storage	CompactFlash Type I card	CompactFlash Type I card
Video Output	NTSC standard for output to TV	NTSC standard for output to TV
Power Source	4 x alkaline, 1.2v NiCd or NiMH or 1.5V FR-6 lithium AA batteries, AC adapter (optional)	Four AA alkaline batteries (included) Four AA rechargeable NiMH batteries (optional) AC Adapter Kit ACK600 (optional)
Dimensions	(W x H x D) 4.7 x 2.7 x 2.4 inches	101.0 x 64.0 x 31.5 mm (4.0 x 2.5 x 1.2 in.) excluding protrusions
Weight	Approx 9.5 oz. without batteries	Approx. 7.6 oz. without batteries

3.3.3.2 Digital Still Camera System Operation.

Both cameras offered a video output port allowing the transmission of the LCD screen of the camera to the ground. This transmitted live video feed enabled the operator to frame and select the correct shot and monitor the camera operation while in flight.

This framing was done by displaying the real-time video feed on a monitor at the ground station. This allowed the operator and ground crew to trigger the camera at the appropriate time in order to capture the desired image. The cameras were triggered using a servo and a spare channel on the RC radio. This channel controlled the additional servo placed onboard the platform, and was situated to depress the image capture button of the camera.

Images were stored on compact flash cards inserted into the cameras. These cards could then be downloaded directly to a computer upon retrieval of the platform. In addition, all transmissions to the ground station were recorded, allowing for the capacity to extract images in the same manner as that of board cameras.

3.3.4 Additional Equipment for UAV platform.

Several other pieces of hardware were necessary for platform operation and data collection: GPS receiver, On Screen Display (OSD), ground station equipment and R/C controller.

3.3.4.1 Global Positioning System and On Screen Display.

A Swift B2 ™ GPS receiver with WAAS differential correction capabilities (Axiom Navigation Inc., Anaheim, CA) was installed on the UAV to track platform position for performance evaluation. Communication with the GPS receiver is through an RS232 interface. An external antenna mounted on the upper side of the airframe using Velcro give an unobstructed receiving path for the GPS signal. The maximum solution up-date rate of the GPS receiver was 1Hz, and the published accuracy was 7m horizontal with WAAS correction. The system had a power usage of 150mA at 3.3V.

Data from the GPS receiver were passed through an OSD (On Screen Display), which overlaid GPS position information onto the transmitted image (Fig. 3.15). The combined data is then sent via the video transmitter to the ground station.

Figure 3.15: GPS data superimposed on images sent to ground station.

3.3.4.2 Ground Station

The ground station was housed in the rear of a van. The vehicle provided ample equipment storage and transportation space, and was equipped with a power outlet. The ground equipment was composed of wireless video receivers, TV/VCR, imaging equipment, maintenance equipment, spare equipment and computers (Fig. 3.16).

Figure 3.16: Ground Station with power supplies, TV, receiver, and other equipment.

3.3.4.3 Telemetry System

Communication between the aircraft and the ground station was done via radio links and transmitters. These operate in analog mode to transmit video imagery from the platform to the ground station, and control information from the ground station to the platform. Live image data were communicated from the aircraft to the ground station via the wireless video link for framing purposes. Flight control communications from the ground station to the platform were sent via a Futaba ® (Schaumburg, IL) radio controller. Separate channels were used to control electronic servos for flight control and to trigger the camera shutter.

3.4 Results

3.4.1 Single Board Camera

The single board camera system explored was a very attractive option for several reasons. The cameras were light, inexpensive and relatively rugged. In addition, they allowed for simple integration into the platform. However, the images exposed several limiting drawbacks to the system. First, the resolution of the board camera was too low to obtain the desired quality images. The highest resolution of a readily available single board camera is 480 TV lines, which is insufficient to achieve the desired spatial resolution and field of view. Second, the camera optics caused severe image distortion and intensity graduation from the center to outside of image (Fig. 3.17).

Figure 3.17: Image captured from board camera system (approximate area of 2.5 ac).

Third, the motion of the UAV coupled with the relatively slow shutter speed of the camera caused the image to be fuzzy. Finally, the wireless video link was susceptible to electromagnetic interference causing further image quality degradation. This was of concern due to the user relying on these transmitted images to obtain still images.

The single board camera systems were therefore ruled out as a viable alternative for UAV RS equipment.

3.4.2 Digital Still Camera

Digital still cameras provided good performance within the platform. Images collected with this RS platform (Fig. 3.18) showed that the system was capable of obtaining clear, high resolution aerial images of agricultural fields. This image shows areas within a field that has been partially harvested; the image quality is good and free from distortion.

Figure 3.18: Image captured with Canon PowerShot A60 digital camera.

The digital cameras were capable of imaging areas of approximately 10 acres (4.04 ha), which was achieved at a platform height of between 200 and 300m. Table 3.5 gives area information vs. flight height for the Nikon and Canon cameras.

Table 3.5: Flight heights to achieve required image area.

Flying Height above the ground (m)	Scale	Area(ac)
25	1:715	0.1
50	1:1428	0.4
100	1:2857	1.7
200	1:5714	6.9
300	1:8620	15.7

A significant advantage of the digital cameras was the amount of flexibility allowed to the user. These cameras allowed the user to manually control many camera settings such as aperture opening, shutter speed, and exposure control. Adjustments to these parameters could be made for the ambient light conditions. This gave greater flexibility in the type of image captured.

The on-board data storage eliminated data quality degradation caused by the wireless video link. Therefore, the wireless video link was utilized only to help the ground crew position the platform above the target and frame the photograph. The video link sent to the ground could be recorded as back-up data.

Initially, power consumption was a problem due to the automatic focusing of the cameras. This problem was eliminated by turning off the automatic focusing features of the cameras and setting the focal distance to infinity. Setting the shutter speed to 1/60s or faster insured that images were not blurred due to movement of the UAV.

The cameras provided ample pixel resolution to achieve desired image spatial resolution; however, the desired field of view was not achieved. As seen from the above table, altitudes of greater than 200m are required to obtain images of greater then 7ac (2.8 ha). The desired field of view could be achieved by using a wide-angle converter lens on the cameras and by flying the imaging platform higher as operator skill increases. Figure 3.19 illustrates an image captured with a wide angle converter lens. The image distortion increases towards the perimeter of the image. This is due to the "fisheye distortion" of wide angle lenses.

Figure 3.19: Digital still camera image with wide angle conversion lens.

Though digital cameras are heavier than board cameras, they are relatively inexpensive. Additionally this sector of technology is rapidly developing, and new lightweight cameras with exceptional image resolution are becoming more cost effective.

Some digital still cameras can also be used to obtain NIR images. The CCD (charge-coupled device) sensing elements used by most camera manufacturers are sensitive to NIR light. Some higher-quality cameras utilize filters to prevent NIR wavelengths from entering the camera. Other cameras rely on software compensation or increased sensitivity to red, green, and blue information to eliminate NIR input. On these cameras, it is possible to obtain NIR images by placing optical filters that block visible light in front of the lens. Unfortunately, this capability could not be verified with the test cameras and it was suspected that NIR filters were present within the cameras.

3.5 Discussion and Conclusion

The hardware most suitable for the remote sensing missions was the consumer digital camera. This was shown through testing each alternative in the platform. High-end multispectral cameras proved to be heavy, bulky and expensive. These cameras did not suit the low cost goals of the project. Board cameras were a good low cost alternative. Their size and cost made these cameras desirable for use in the RS platform; however, the image quality was not at the desired level.

Consumer digital cameras, proved to be the best alternative through testing. The cameras fell within the payload carrying capacity of the platform. Additionally the cameras provided good image quality at an affordable price. The only point of concern was the ability to obtain the desired field of view from the system. This aspect needs to be improved in order to make this technology more appealing.

The image capturing system developed in this project achieved its imaging and cost goals. The system was developed at low cost while still offering good resolution and picture quality. Unfortunately, the capacity of the imaging systems to detect NIR wavelengths was not verified.

Although technologically advanced RS systems are not yet economically viable, there is still a need for low cost aerial imagery for farmers. Low cost digital cameras can provide useful visible images to farmers and with the addition of NIR filters, may be able to provide information about vegetation health. Although the causes of plant stress cannot be determined through these low cost alternatives, the existence of crop stress can be predicted. The causes of this stress can be later diagnosed through direct crop scouting. In addition to plant stress, farmers, through the unique vantage point offered by the platform system, can examine management practices. Areas of low plant density, skipped planting, missed fertilizer application, and under irrigation can be easily determined.

CHAPTER 4: OPERATIONAL TESTING OF UAV PLATFORM

4.1 Introduction

Aerial crop scouting is one of many possible applications of UAVs in agriculture. UAVs carrying RS equipment can provide a unique vantage point to farmers. If images were available from these alternate vantage points, the farmer could gain a better understanding of farming practices, possible problem areas, or size of harvest expected. The opportunities for farmers to obtain aerial images is limited, but not due to a lack of demand.

Additionally, low cost aerial imagery on demand has broad appeal. Construction sites, development planning, law enforcement, and naturalists (to name a few) all require aerial images from time to time. Images of construction sites can reveal information about construction progress, layout, impact the construction will have on its surroundings, and progress of construction. The development of a low cost aerial photography method would attract many interested parties.

4.2 Objectives

The goal of this part of the project was to demonstrate and evaluate the operation of a UAV-based image capturing system to be used by crop scouts, farmers, researchers, or other interested parties. This goal was met through the establishment and completion of the following specific objectives:

1. Establish the set-up and operational procedures for the system before and after flight. This includes the selection of base site, preparation of equipment, and retrieval of platform and data.

2. Apply the imaging system to a range of aerial photography applications and evaluate its ability of the system to transmit imaging information and capture the desired target image.

3. Examine the system's image capturing ability and quality through imaging of targets such as construction sites, research plots, livestock fields, and agricultural fields.

4. Examine additional uses of the platform such as use in conjunction with GIS packages, and use with NIR filters.

The fulfillment of these objectives would give a clear understanding of the system's capabilities as a low cost and convenient platform for aerial imaging.

4.3 Methods and Procedures

4.3.1 Pre-flight Operational Procedures

Operational procedures were established during initial flight tests to aid in the selection of base sites, the set-up of equipment, the operation of the equipment, and the retrieval of both the platform and the images.

4.3.1.1 Base Station Site Selection

Assuming the target has been selected, the first step upon arrival at the site is to select the base station site. The base station site refers to the ground operational area of the system, and combines the base station (transport vehicle and accompanying equipment) and the take-off and landing areas of the UAV. The base station site should be thoughtfully selected with numerous factors determining the site's position and orientation with relation to the target area. These factors include position of the target or area of interest, hazardous obstacles in the target vicinity, surface conditions in the area, wind direction, sun orientation, surrounding gradient and the availability of an open clearing. Selecting the base station site upon arrival at a new site takes a few minutes and selection is based upon the amalgamation of factors.

- Position relative to target: Effective platform operation required that the base station be at a distance away from the target area (60-100m). This location allowed the pilot to operate the aircraft while keeping the target area in peripheral vision. Positioning the base site too close to the target forced the pilot to look directly upward. This body position is uncomfortable and difficult to sustain. In addition, it hinders the ability to position the aircraft over the target, and limits the ability of the pilot to detect changes in orientation and direction of the platform relative to the target position.

In addition, the layout of the target can determine the position of the base site relative to the target. If the target is significantly longer in one direction relative to another, positioning the base site in-line with the length of the target area can be helpful. This allows the pilot to operate the platform longitudinally over the length of the target. The pilot can thus make straight passes over the length of the target while capturing images and reducing the number of maneuvers required.

- Hazardous obstacles: The base site was to be positioned away from obstacles that may obstruct or threaten operation, interfere with the radio control or transmission, or obstruct the pilot's view of the aircraft. Trees and other obstacles threaten operation primarily during takeoff and landing. At take-off speed (9km/hr), the platform can achieve a climb rate of approximately 2.5m/s. Higher climb rates can be achieved once airspeed increases. This suggests that the platform could clear a 20m obstacle if launched from 25m away. However, this distance should be doubled for additional safety. Obstacles (such as trees) are far more threatening during landing as airspeeds are much higher (17km/hr). A distance of at least 50m from the base of a 20m obstacle is required for landing. Take-off and landing directions should be established upon arrival at the site, thus the base station should be positioned away from these areas. The position of the target should not affect the take-off and landing directions; these are more significantly influenced by surrounding obstacles and the following factors.

- Surface conditions: The surface conditions of the base site should be amiable for belly landings of the aircraft. Grassy areas were most suitable for belly landing, and hard, wet, and rough areas should be avoided if possible.

- Wind direction: It is easier to fly the aircraft directly into the wind and precisely over the target than to attempt to fly the aircraft over the target in a crosswind. Although operation in heavy winds (>16km/hr) is not foreseen or advised, moderate winds can still hamper operation. Additionally, to maximize lift during take-off, the launch should be directly into the wind. Moreover, if possible the landing direction should also be into the wind allowing for a slower approach.

- Sun orientation: An important factor in determining the base site is the position of the sun. The sun position should be at the pilots back with reference to the desired target. Flight between the pilot's position and the sun can cause the pilot to loose visual contact with the aircraft and hence place the platform at risk. Additionally, the base station contains monitors, which become difficult to view under direct sunlight. Consideration to the position of the sun should be given when selecting the orientation and position of the vehicle around the base site.

- Slope: During take-off and landing, the slope of the site can make operation challenging. A flat area is most desirable but not very common. Take-off is assisted by a slope as the aircraft can be launched from a high point. However, landings can be come hazardous (but not impossible) when attempted on a site with a slope.

- Open clearings: As suggested above, the most desirable base site is a flat open area slightly removed from the target. An open clearing of about 150_300ft is ideal; however, this size can be reduced as operator skill increases.

4.3.1.2 Equipment Set-up

Once the base station site was selected, the next step was to prepare the equipment for the mission (Fig. 4.1). It is important to note that a few tasks were completed prior to arrival at the site. These tasks primarily consisted of charging the battery packs and radio controllers, but may include many other tasks depending on changes, alterations or repairs that were made to the system.

- The aircraft fuselage and wing were retrieved from the van and placed clear of the transport vehicle. Toolboxes, imaging, and sensing equipment were also retrieved from the vehicle.

- Base station equipment were retrieved from the vehicle and prepared. This included TV monitors and video receivers. The TV monitor was setup in the rear of the vehicle and connected to a video receiver placed on the roof of the vehicle. Both the TV and video receiver were powered through supplies housed in the rear of the transport vehicles.

- Essential flight equipment were then unpacked from the vehicle and toolboxes. These include pre-charged battery packs, camera, radio transmitter, and operational wiring.

- The equipment was then installed into the platform. First, the battery pack was installed, followed by the camera, and then the transmitting equipment. The wiring was placed into the platform but was not connected.

- The power supply and battery charger were set-up in anticipation of re-charging the battery pack after flight.

- Power was supplied to the TV and video receiver, and the wiring inside the platform was connected. Reception of a clear transmitted signal to the base station from the aircraft was verified, and the camera was tested to verify operation.

- The wing was then attached to the airframe. Radio communication between the platform and the receiver was re-verified, and the control surfaces and motor operation confirmed.

Figure 4.1: Preparation of UAV for mission at the base station.

4.3.2 Launch and Recovery Procedures.

A typical flight lasted about 7-14 minutes and consisted of hand launching the airplane, flying to an altitude of about 200m, making several passes over the target area while performing the desired mission, landing the platform and extracting the data.

The platform was hand launched into the wind by the helper, and then piloted away from obstacles and over the target area. The platform was held aloft and the helper simply takes a few running steps and throws the platform into the air. The platform is thrown at a slight upward angle. The launch angle is approximately the angle made by the length of ones hand, above the horizon at an arm's length away (Fig. 4.2). Full power is applied to the motor prior to the launch.

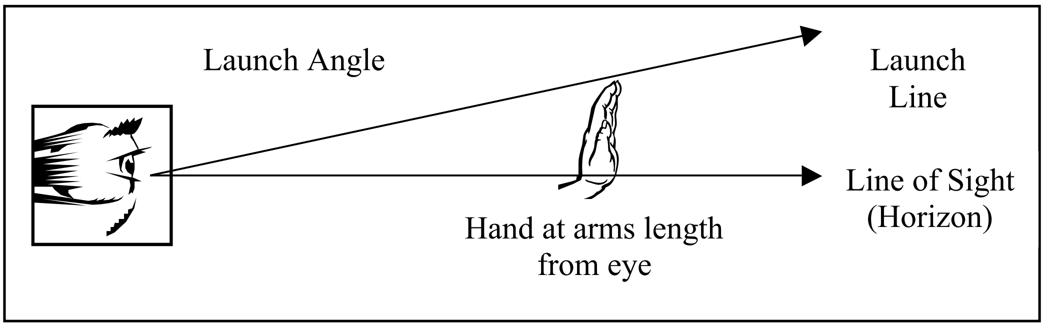


Figure 4.2: Launch trajectory angle

Upon retrieval of the platform, the camera was exhumed from the fuselage. Images from the memory storage card were then downloaded onto a portable computer. The battery was then removed from the fuselage and connected to a battery charger. A spare battery could then be used to repeat the set-up and launch procedures.

4.3.3 Operational testing

The platform was put through a series of operational tests, with every test increasing in operational and technical complexity.

4.3.3.1 Initial System testing

Initial testing was conducted at one of the University of Kentucky's research farms. The goal was to set up the ground station, launch the platform, capture aerial images of a target, and retrieve the platform and the images.

The platform operation and image capture was successful. However, once specific targets were desired for image capture, problems with the platform operation were discovered. Difficulty was experienced in capturing the target within the image. This difficulty was due to the manner in which the image capturing was performed.

Initially, the system configuration was such that the pilot was responsible for the control of the platform and the triggering of the imaging device. The helper launched the platform and signaled the pilot to capture the image at the correct time by watching the live video feedback from the platform. This method, while successful in obtaining images, had a few fundamental flaws. Delays between the helper viewing the target in the viewfinder, signaling the pilot to trigger the camera, and then the pilot physically triggering the camera were too great. The delay in triggering the camera, along with the normal movement of the platform, caused the target to move out of the center of the image and thus the desired coverage was not obtained. Most of the images obtained contained 70-90% of the desired target as seen in an image of a construction area (Fig. 4.3).

Figure 4.3: Missed target due to lag time in image capturing.

This method did not facilitate timely imaging of the target area. Numerous missions were performed to obtain the desired image of the target area.

The solution to the image capture delay problem was to modify the controller by adding an external button. This button was operated by the helper watching the live video feed from the platform. The helper could then capture images as seen in real time through the data link. Thus the responsibilities of the platform crew altered. The pilot maneuvered and positioned the platform over the target area, while the helper triggered the camera. This had numerous advantages, including:

- Eliminating the delay in capturing the image,
- Enabling operation at lower altitudes, while capturing required target,
- Improving picture quality and resolution.

The helper's responsibilities were thus to launch the aircraft, trigger the camera at the appropriate time, and aid in the positioning the platform over the target area. This method expedited the process and enabled much quicker imaging of the site. Typically, using the old method, two or more flights over the target were needed to ensure the target was sufficiently captured. Now numerous images could be obtained in one flight.

4.3.3.2 Aerial Photography Applications

Aerial photography is a low cost form of remote sensing, as it usually implies visible light images and little or no post processing. The UAV system was utilized for numerous applications at the University of Kentucky to collect visible aerial images. In one example, researchers requested aerial images of test plot area, to verify that the layout and construction were correct. Plots constructed for the experiment were not on existing aerial images of the area. The site proved an ideal subject for testing of the system and in establishing a procedure for future aerial surveys. The desired result was to capture high quality aerial images of the construction site using the aerial platform. Numerous passes would be made over the target area while capturing images. This would ensure numerous good quality images of the target.

Aerial images of a rainfall simulation facility were also collected in a similar application. The method used was the same; however, in this application, the goal was to arrive at the site and make one launch over the desired target in order to capture the required image. Numerous passes were made over the target area within the single launch. This demonstration hoped to show that many images could be obtained with ample resolution and image quality, which required a stable platform.

It should be noted that in both of these examples, the image area was small enough to be captured in a single frame of the RS system. Thus, the ability of the system to capture a specific target was under scrutiny and not the ability to image a large area.

4.3.3.3 Site Categorization and Mapping of a Large Area with GIS

Through creation of ample control points, mosaics of large target areas become possible. One role of UAVs may be in updating conventional aerial photography over sites which may have changed. Raw aerial images are helpful, but aerial images can become especially useful once the images have been rectified and placed within a geographic information system (GIS). Once the new image of the site has been obtained they can be superimposed onto the existing maps to give a more up-to-date coverage of the area.

An aerial survey was performed on a cattle pasture at the University of Kentucky's Woodford county farm. Researchers required current aerial photography shots of the pasture to be added to an existing Geographic Information System (GIS) database of the site. In order to complete image georeferencing, ground control points needed to be established in advance. Control points were established along field boundaries, tree lines, lone trees, water troughs, and river crossings. The idea was to create many evenly spaced control points throughout the area at locations which would be easily identifiable. These control points were then mapped using a GPS, and imported into the GIS software (Fig. 4.4). The uniform squares indicate experimental fertilizer and herbicide applications; the "round" shapes are the positions of the trees; the long thin shape in the middle of the pasture is a stream. Once within the GIS software, the images can be used to analyze roads, streams, field boundaries, buildings, management practices, and land use classifications. The images can also be used as a base to superimpose and layout further plans and projects.

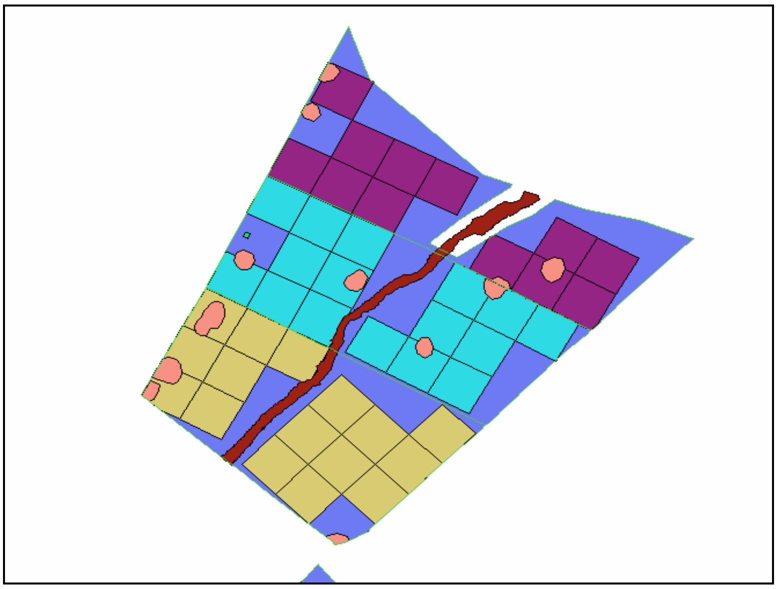


Figure 4.4: Control Point information collected at the site.

4.3.3.4 Agricultural Monitoring of Nitrogen with use of GIS

In a second case, images of a research plot concerning studies of subsurface drip irrigation and variable rate nitrogen application were collected. In the study, varying rates of nitrogen and subsurface drip irrigation were applied to corn, tobacco and alfalfa in the different plots. The goal for the UAV imaging system was first to distinguish between the crop types, and then to analyze the ability to discriminate nitrogen application rates within the field through visible aerial images of the fields. GIS databases of the actual applied nitrogen, and crop types were available.

The total area of the nitrogen plots was greater than could be captured with a single image from the RS system. On sites too large to obtain one image covering the entire site, it was possible to combine numerous smaller images into a composite mosaic image of the site by georeferencing each image. Each digital image was rectified within the GIS package using the procedure outlined in the previous section. As each image requires reference points, high concentrations of reference points are needed throughout the target area. A minimum of three points were required at the extremities of each image in order to georeference it; however, more control points increased georeferencing accuracy.

4.4 Results

4.4.1 Pre-Flight procedures

The platform was relatively easy to set-up, operate, and retrieve. This facilitated timely operation. Table 4.1 gives a detailed estimation of the time taken to complete the required pre-flight tasks. The maximum time taken in setting up the ground station, setting up the equipment, operating the platform and retrieving the data is less than one hour. This enables the platform to be rapidly deployed over unprepared terrain to obtain aerial imagery.

Table 4.1: Approximates times to complete mission tasks.

Task	Time (minutes)
Site selection	2-10
Set up	
Base Station	3-5
Aircraft	7-10
Testing	
Signal quality	1-2
Flight controls	1
Final preparation	1
Flight	
Launchand accent	1-3
Mission	5-9
Landing	1-2
Retrieval	
Aircraft	1-5
Data from aircraft	1-5
TOTAL	<60

Table 4.2 gives a detailed explanation of the tasks performed on the platform during the flight. Different tasks are performed throughout the various stages of the flight profile.

Table 4.2: Operational tasks during distinct mission functions.

Tasks	Takeoff	Ascent	Cruise	Mission	Cruise	Decent	**Landing**
Monitoring	_	_	_	_	_	_	_
Positioning for liftoff	_						
Avoidance of Objects	_	_				_	_
Ground Turbulence	_	_				_	_
Ascent to Target		_	_				
Attaining Altitude		_	_		_		
Information Gathering	_	_	_	_	_	_	_
Active Sensing	_	_	_	_	_	_	_
Adaptive flight re-planning		_	_	_	_	_	
Identify landing site					_	_	
Positioning for landing					_	_	
Retrieval							_

4.4.2 Operational Testing

4.4.2.1 Aerial Photography Applications

Aerial photography tests with the platform resulted in good quality images of the target area. The platform was able to make numerous passes over the target area in each flight capturing images. Additional flights could be made to recapture images of the target if the first flight was unsuccessful. As can be seen, the platform was capable of capturing high quality and distortion free images (Fig.4.5).

Figure 4.5: Subsurface sediment plots at the University of Kentucky.

In the subsequent test, the platform was used to capture images of the rainfall simulation plots (Fig 4.6). Numerous images were obtained of the research area during one flight.

Figure 4.6: Rainfall simulation plots.

4.4.2.2 Site mapping with GIS

High quality coverage cannot always be achieved by mosaicing multiple images. Failure to obtain complete image coverage of the target leaves blank areas in the mosaic (Fig. 4.7). In addition, the image quality is affected by non-uniformity of irradiance and camera settings. In figure 4.7, the camera settings were not uniform; hence, the mosaic image quality was poor. In addition, the images were collected on different days and at different times. Thus, the sun's illumination of the target area was different and its position was not the identical.

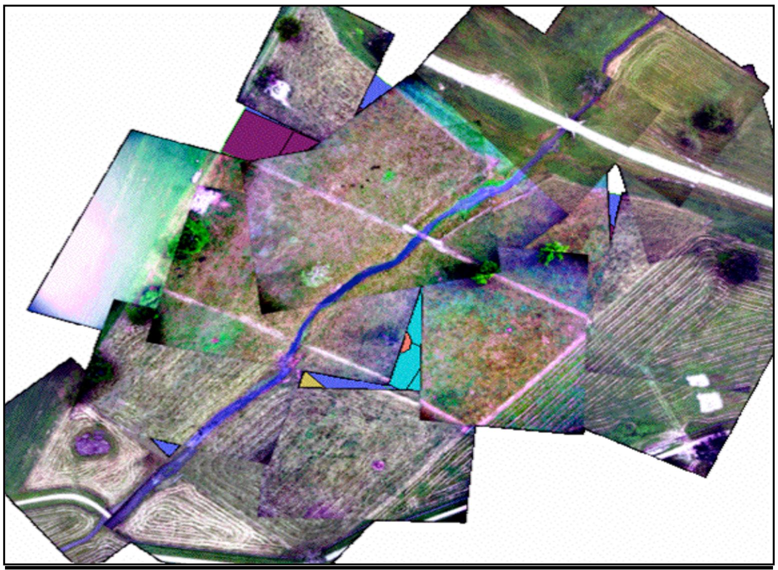


Figure 4.7: Mosaic of cow pasture created in a GIS software package.

The purpose of the images obtained by this platform is not to equal the quality of a geo-referenced satellite or aerial images; however, as discussed earlier, there is tremendous management value in these aerial images. An aerial view of a field can reveal problems and patterns that cannot be easily seen from the ground. From these aerial images, informed management decisions can be made.

4.4.2.3 Agricultural Monitoring of Nitrogen with GIS

At the nitrogen/irrigation site, full coverage was obtained of the target area, enabling the generation of a complete mosaic of the target area (Fig. 4.9). From the mosaic and individual images (Fig. 4.8), researchers were able to clearly distinguish the different nitrogen application rates in conjunction with different irrigation treatments. In addition, crop type was easily identifiable.

Figure 4.8: Nitrogen Application Plots.

The differing nitrogen application was especially prevalent at low application rates, leading to the possibility of the system's usefulness at diagnosing inadequate nitrogen application. The nitrogen application rates of 0, 40, and 80*lb*/acre were clearly visible (Fig. 4.9), however application rates of 105*lb*/acre and above showed little variation.

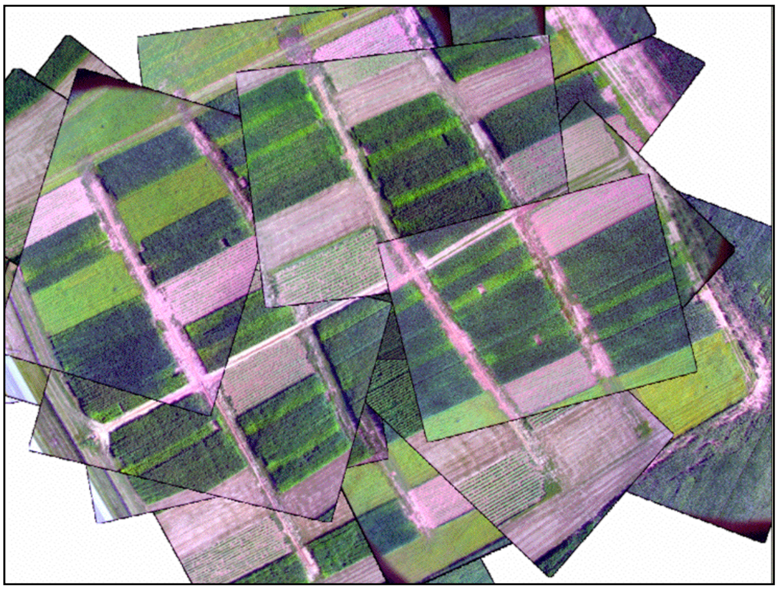


Figure 4.9: Mosaic image of Nitrogen Application plots.

This may give an early season indication of where the nitrogen response curve begins to flatten out based on observation of biomass color. The original GIS data were then superimposed onto the mosaic image (Fig. 4.10), lining up near perfectly and verifying what was seen visually.

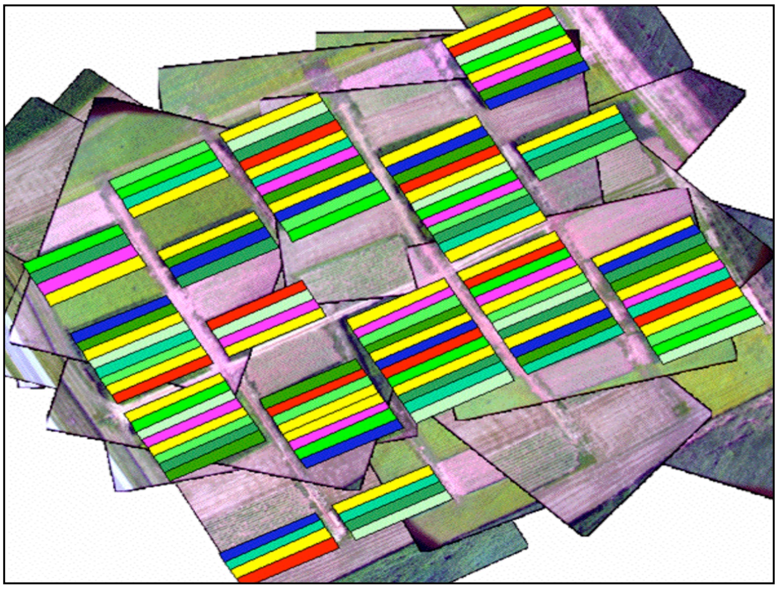


Figure 4.10: Mosaic of nitrogen application plots with GIS data superimposed.

CHAPTER 5: CONCLUSIONS

The UAV-based RS system developed in this project was used to successfully collect visible aerial images. The design produced a UAV capable of stable and reliable flight. The platform displayed inherently stable flight due to the dihedral wings, and was not hampered by vibration. Operation of the platform was simplified due to utilizing only two control surfaces, and through the reduction of stall speed to 17km/h (or 10.5mph). The electric motor provided sufficient thrust to carry a 1lb (or 0.45kg) payload, and was reliably stopped and started in flight.

The platform was capable of climb rates of 3.5 m/s (or 11.4ft/s), offering good potential obstacle avoidance, and allowing operation in relatively confined locations. The platform was suitably robust, allowing landings on unprepared terrain (such as in cornfields), while maintaining the integrity of the airframe. In the event of serious accident, expensive equipment was generally undamaged and reusable. The platform structure absorbed the majority of the impact, and offered protection to the internal equipment.

Modularization of the platform allowed it to be disassembled, transported and stored, and then reassembled from the rear of a conventional full-sized pickup truck or similar vehicle. Construction was kept simple, with only basic tools needed. Materials and components were common and readily available at hobby shops. Preparation time after arrival at the site was approximately 10 minutes, allowing for quick deployment of the system.

The system was capable of imaging an area of ±12ac (or 48562.47m^2) in a 7-minute flight, capturing approximately 50 images during the flight. The maximum operational range from the pilot was approximately 300m, limited by the pilot not the platform. The operational altitude was approximately 220m, offering an image area of 7ac.

The weight of each component of the UAV system is summarized in Table 5.1. The total weight of the platform was 3.4kg (or 7.5lbs) with the fuselage and battery being the majority of the weight. The imaging and video transmitting equipment comprised the largest proportion of the systems cost. A typical flight lasted 7-14 minutes, and consisted of launching the airplane, ascending to the desired altitude, making several passes over the target while collecting data, landing, and extracting the data. If the data were not satisfactory, the system was re-prepared and the process repeated. With the current system, two people were required to operate the system - one to fly the aircraft and another to launch the plane and trigger the camera shutter via remote switch through the flight radio.

The UAV has proven to be very rugged. Damage caused by operator error during landing (the most perilous point in the mission) was usually minor and repairable in less than 30 minutes. Even during major crashes, the camera, servos, radio receiver, and motors rarely were damaged. Extensive damage from a bad crash was repairable overnight or during the following day, but presumably, less than the 15-25 hours required to build a new plane.

Table 5.1: UAV, RS system component weight and cost.

Component	**Weight**	Price
Plane (Kit)	**1950g (4.29lb)**	$70.00
Motor and Prop (Kit)	**267.4g (0.589lb)**	$140.00
Motor Controller	**51.5g (0.114lb)**	$97.00
Battery	**737.4g (1.626lb)**	$100.00
Radio (Including: Servos and Receiver)	**58g (0.128lb)**	$125.00
Camera	**268.6g (0.636lb)**	$175.00
Video Transmitter	**66.9g (0.147lb)**	$249.00
Total	3399.8g (7.5lb)	$956.00

The system easily met cost constraints imposed by the project with a total platform cost of $956. The images collected with the system met resolution constraints, and showed that the system was capable of obtaining useful images for farm management purposes. The images were available within minutes of the platform landing through a portable computer. Further refinement will be necessary to achieve a greater field of view.

Further plans to improve the system's effectiveness are to place a microcontroller into the triggering system to cause continuous, periodic image acquisition during flight. With the current system, 20 – 30 images are obtainable per flight. A 256MB compact flash card can hold on the order of 200 - 215 images in highest resolution mode. Thus, the storage capacity of the camera is underutilized. As the images can be viewed, downloaded, and discarded if unwanted, full utilization of the storage capacity should be a priority. The camera has the capacity to capture an image every ±2 seconds, a faster rate than is possible with the helper triggering the camera. The camera can be triggered continuously while over the target and the unwanted images discarded. The pilot could initiate the continuous acquisition function from the R/C radio once the UAV is over the target area.

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