ABSTRACT

Title of Document:	THE DESIGN, FABRICATION, AND FLIGHT TESTING OF AN ACADEMIC RESEARCH PLATFORM FOR HIGH RESOLUTION TERRAIN IMAGING.
	David Daniel Billingsley, Masters of Science, 2011
Directed By:	Langley Distinguished Professor, Dr. James E. Hubbard Jr., Department of Aerospace Engineering

This thesis addresses the design, construction, and flight testing of an Unmanned Aircraft System (UAS) created to serve as a testbed for Intelligence, Surveillance, and Reconnaissance (ISR) research topics that require the rapid acquisition and processing of high resolution aerial imagery and are to be performed by academic research institutions. An analysis of the requirements of various ISR research applications and the practical limitations of academic research yields a consolidated set of requirements by which the UAS is designed. An iterative design process is used to transition from these requirements to cycles of component selection, systems integration, flight tests, diagnostics, and subsystem redesign. The resulting UAS is designed as an academic research platform to support a variety of ISR research applications ranging from human-machine interaction with UAS technology to orthorectified mosaic imaging. The lessons learned are provided to enable future researchers to create similar systems..

The Design, Fabrication, and Flight Testing of an Academic Research Platform for High Resolution Terrain Imaging.

by

David Daniel Billingsley

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of the requirements for the degree of
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Dedication

To my darling wife, Stephanie. Thank you for your patience, love, and support.

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This research was carried out on the premises of my gracious hosts: the University of Maryland, the National Institute of Aerospace, NASA Langley Research Center, the US Army Research Lab: Vehicle Technology Directorate: Autonomous Vehicle Lab, and the US Army Research Lab: Fort Indiantown Gap facility.

I am grateful for the assistance and support of my research group, the University of Maryland: Morpheus Lab, housed at NIA. Thanks to its members: Dr. Hubbard for being my advisor and mentor; Robyn Harmon, Ben Nickless, Dr. Sandra Ugrina, Aimy Wissa, for helping to shape my research goals; Jared Grauer for his generous sharing of electronics knowledge; Alex Brown for his enthusiasm, assistance coordinating hardware delivery, and presence on the flying field; Geoff Slipher for his advice, general mechanical know-how, close support, and construction assistance; and to Nelson Guerreiro for his flight wisdom and constant consultation to get the aircraft ready to fly.

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My primary contact, aide and educator of construction, chief consultant, and expert pilot was Brian Porter of ARL. He contributed his thoughts and talent to nearly every aspect of the design and construction process of the MARP Mark II UAV. On many occasions, Brian volunteered his time to fly the UAVs for my research. Thanks, Brian, big time.

Thanks to those that attended my flight at Fort Indiantown Gap site: my friend, Khashayar Parsay; my mom; and Brian Porter, Harris Edge, Ainsmar Brown, and Jason Collins from ARL. A huge thank you to my brother (Steve) and my wife (Stephanie) for rushing to the scene to provide much-needed help in last minute preparations before the flight. Thank you, Chris Jones, Stephanie Billingsley, and especially Dan Billingsley (a.k.a. Dad) for proof-reading sections of this heavy document.

Thanks be to God who gave me the mind and motivation to carry out this research.

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Nomenclature

AMA	Academy of Model Aeronautics.
ARL	Army Research Lab.
ARP	(new term) Academic Research Platform. A UAS suitable for conducting ISR research by academic research institutions.
Controp	Controp D-STAMP. The gimbaled camera of the testing apparatus, created by Controp Precision Technologies.
CPU	Central Processing Unit. Standard processor of a computer.
CRT	Cathode Ray Tube.
DARPA	Defense Advanced Research Projects Agency.
D-STAMP	Daylight Stabilized Miniature Payload. The gimbaled camera of the testing apparatus, created by Controp Precision Technologies.
FAA	Federal Aviation Administration. Government administration with authority to regulate the nation's airspace.
FHSS	Frequency Hopping Spread Spectrum. Safety mechanism in a radio signal system that coordinates the transmitter and receiver to hop to a changing frequency along a frequency spectrum to avoid prolonged transmission on an occupied frequency.
GPS	Global Positioning System. Satellite based system that sends messages to a device on the ground or in the air, allowing the device to calculate its 3D coordinates, usually as latitude, longitude, and altitude.
GPU	Graphics Processing Unit. Computer component specializing in performing large matrix calculations at high speeds.
GS	Ground Station.
IMU	Inertial Measurement Unit. A device that includes motion sensors like accelerometers and rate gyroscopes to integrate the sensed rates of change in position to provide an estimate on the relative displacement of the device.
LiPo	Lithium Polymer. Battery type.
MARP	(new term) Maryland Academic Research Platform. UAS created to serve as a testbed for ISR research topics at the University of Maryland that require the rapid acquisition and processing of high resolution aerial imagery.
NiCd	Nickel Cadmium. Battery type.
NTSC	National Television System Committee. United States organization establishing standards for analog video broadcast.
Real time processing	Data calculation fast enough to keep up with an outside process [1].
UAS	Unmanned Aircraft System. System consisting of a Unmanned Aerial Vehicle and a Ground Station.
UAV	Unmanned Aerial Vehicle.
VCR	Video Cassette Recorder.

Chapter 1. Introduction and Background

Within the academic community, there is a continuing drive to perform research in Unmanned Aircraft System technology in the field of Intelligence, Surveillance, and Reconnaissance (ISR). (An Unmanned Aircraft System (UAS) is composed of an Unmanned Aerial Vehicle (UAV) and a GS (GS) as well as communications equipment to wireless link the UAV and GS.) Inevitably, this UAS research progresses to a level where the theoretical and simulated solutions to these ISR research topics require a physical testbed to demonstrate their feasibility. The military and corporate organizations employ a number of UASs, but these are uniformly unsuitable for research applications in academia due to high costs, legal restrictions, and other issues. This thesis qualifies a UAS as an "Academic Research Platform" (ARP) if it caters to the practical limitations of academic research while achieving substantial mission capability in the research areas being investigated by the academic research institution. The concept of an ARP is exemplified by the design, construction, and flight testing of a Maryland Academic Research Platform (MARP), created to serve as a testbed for ISR research topics at the University of Maryland that require the rapid acquisition and processing of high resolution aerial imagery.

This thesis is divided into six chapters. The remainder of Chapter 1 presents a summary of the requirements an UAS must meet to serve as an ARP, the potential ISR research applications that the MARP has been created to fulfill, and the contributions of this thesis research. Chapter 2 provides a technical overview of the completed MARP system, including the UAV and GS, and an operational overview for MARP test flights. In Chapter 3, a detailed review of subsystem requirements is presented, along with the selection of specific components to satisfy those requirements. Chapter 4 summarizes the issues, problems, and constraints encountered in the thesis research and their respective solutions developed in the course of the project. Chapter 5 concludes the thesis document.

1.1. Need for Academic Research Platform

The practical limitations of academic research limit the type of UAS used in the research endeavor. An ARP needs to be affordable; it needs to be legal to fly in the U.S. airspace; and it needs to be operable by a small, relatively untrained crew of civilians. Table 1.1 compares the cost and features of selected UASs (data gathered from [2; 3; 4; 5; 6]).

Table 1.1: Example features of Unmanned Aircraft Systems.

UAS	Wingspan (feet)	Cost per UAV	Control	Payload
RQ-11B Raven	4.5	$173,000	Autonomous or Remotely Piloted	High resolution, stabilized camera
Scan Eagle	10.2	$3,200,000	Autonomous or Remotely Piloted	High resolution, stabilized camera
MQ-1B Predator	55.0	$5,000,000	Autonomous or Remotely Piloted	High resolution, stabilized camera
MQ-9 Reaper	66.0	$13,375,000	Autonomous or Remotely Piloted	High resolution, stabilized camera
RQ-4A Global Hawk	116.0	$37,600,000	Autonomous or Remotely Piloted	High resolution, stabilized camera

These high costs are prohibitive for the majority of academic research institutions; furthermore, many military UASs contain components that would be unlawful for civilians to operate. As will be covered in further detail in Section 3.5.3, it is also very difficult for academic researchers to operate autonomous UAVs in U.S. airspace. This forces academic researchers to employ remotely piloted UAV solutions for UAS experimentation. And as will be covered in Section 3.1.1, the size of the UAV dictates where it can be flown and whether it can be managed by a small crew. The real world constraints of academic research reveal that no suitable, commercially available UAS exists for regular use as an ARP for ISR research. This has led many universities to create their own ARPs to conduct research [7; 8].

1.2. ISR Research Applications and MARP Requirements

This thesis documents the design, construction, and flight testing of the Maryland Academic Research Platform (MARP), a UAS for ISR research at the University of Maryland. The MARP was designed around the practical constraints described above as well as the technical requirements of UAS ISR research applications. The surveyed research applications are outlined below, followed by a summary of the consolidated requirements for the MARP.

1.2.1. Human Factors Analysis in Aerial Imagery

The majority of current military and commercial applications employ the UAS as an Aerial Imager. The UAV is set to fly above an area of interest, delivering video to the GS to provide the user with a live video feed from that aerial perspective. In this ISR application, the human is the primary processor and disseminator of information and the UAS is the tool to acquire that information. Research in this field focuses on studying and making improvements to this human-system interaction.

To perform the Human Factors Analysis in Aerial Imagery ISR application, the MARP must utilize a stable airframe that is able to sustain the weight of the entire UAV, including the sensor payload and communications equipment, by providing sufficient lift. The communications equipment must enable aircraft control from the GS and provide an adequate video stream broadcast from the UAV to the GS. The sensor payload, as a minimum, must be a camera statically mounted to the airframe of the UAV.

1.2.2. Manual Targeting

More sophisticated sensor payloads include the ability to allow a user to change the orientation of the camera from the GS, manually vectoring the camera at targets of interest. Research in this field focuses on improving the control algorithms employed to steadily vector the camera as the UAS responds to human direction while mitigating the effects of exterior factors such as planned and unplanned changes in the orientation and position of the UAV. This ISR research application requires a very stable airframe as well as gyroscopic sensors and accelerometers to measure the inertial motions of the UAV as input to stabilize the sensor payload in these control algorithms. The MARP would require an extra communications link is required to transmit these camera attitude control instructions from the GS to the UAV.

1.2.3. Orthorectified Mosaic Imaging

If the video output of the sensor payload is correctly formatted for computer processing, the individual video frames can be stretched and scaled as an overlay to two dimensional maps with computer vision techniques, providing the user real-world footage corresponding to the coordinates of the map. As many video frames are joined together in the map overlay, they form a mosaic showing, in a single image, an overview of what the UAV sensor payload has seen during its flight. Research in this field concentrates on improving the algorithms employed to correct for distortions in the mosaic and decrease calculation time. [9]

To support this research, the UAV must host equipment to measure and export inertial motion data and there must be a communications link to transmit the camera pose data (the location and orientation of the camera) to the GS. The GS must be able to record the video stream to perform batch processing on the video data.

1.2.4. Automated Target Tracking

Some UAS are able to perform Automated Target Tracking in which a user is able to lock onto a moving or static target on the ground, commanding the UAS to perform the necessary calculations to constantly vector the sensor payload toward that target. Continued research in this field may perform the processing with a combination of pixel tracking algorithms, inertial motion measurement feedback, and other procedures. In any case, real time video processing and is required to calculate faster than the camera can create video footage. (Real time processing refers to data calculation fast enough to keep up with an outside process, in this case, faster than the incoming data rate of the video stream [1].)

1.2.5. Object Recognition

With a high resolution camera, a UAS can perform Object Recognition on the incoming video feed. In this ISR application, a graphical overlay is used to highlight objects of interest by matching their appearance in the video frame to that of a reference library of images. This process can be used in a variety of scenarios ranging from search-and-rescue missions to crop surveillance in farm monitoring operations. The automated processes for Object Recognition are continuously being researched in multiple fields of study. A MARP would require real time video processing for Object Recognition, relying on computer vision techniques to output the overlay at a speed faster than the incoming video stream.

1.2.6. Real Time 3D Terrain Mapping

Real Time 3D Terrain Mapping is a computer vision application currently being developed and employed on a number of wired systems such as manned ground vehicles and manned air vehicles, but it has not yet been employed on a UAS where the camera and processor are physically separated by a large altitude; furthermore, such distances negate the advantage of two-camera stereovision techniques [10; 11]. This thesis posits that it would be possible to perform Real Time 3D Terrain Mapping with a UAS by means of an appropriate single-camera Structure from Motion algorithm [12; 13; 14]. The MARP requirements are similar to Automated Target Tracking and Object Recognition. Successful implementation of this ISR research application on a UAS would permit users to create a growing 3D map of the viewed terrain while the UAV is still capturing video.

1.2.7. Augmented Reality Graphic User Interface

Research in Augmented Reality provides a graphical overlay of waypoints, objects of interest, threats, and other Geographic Information System data in a 3D perspective view that matches a given camera pose, providing the user with an intuitive depiction of important GPS coordinates in reference to the current camera view of the UAV sensor payload. The MARP requirements are similar to Automated Target Tracking and Object Recognition.

1.2.8. Consolidated Requirements for the MARP

The requirements of the UAS ISR research applications surveyed above are summarized in Table 1.2. They are combined with the ARP requirements to form a set of consolidated requirements for the MARP in Table 1.3.

Table 1.2: Requirements of ISR research applications.

ISR Research Applications	MARP Requirements Category			
	Sensor Payload	Airframe	Processing	Communications
Human Factors with Aerial Imagery	Human viewable imagery Static or vectorable	Stable Sustain weight of UAV	Display video	Aircraft control Video stream broadcast Camera attitude control (if vectorable)
Manual Targeting	Stabilized Human viewable imagery Vectorable	Very stable Sustain weight of UAV	Display video	Camera attitude control Aircraft control Video stream broadcast
Orthorectified Mosaic Imaging	Computer processable imagery Static or vectorable Inertial motion measurement	Stable Sustain weight of UAV	Display video Record video Batch video post-processing	Camera attitude control (if vectorable) Camera pose reporting Aircraft control Video stream broadcast
Automated Target Tracking	Stabilized Computer processable imagery Vectorable	Very stable Sustain weight of UAV	Display video Real time video processing	Camera attitude control Aircraft control Video stream broadcast
Object Recognition	High resolution Computer processable imagery Static or vectorable	Stable Sustain weight of UAV	Display video Real time video processing	Camera attitude control (if vectorable) Aircraft control Video stream broadcast
Real Time 3D Terrain Mapping	Stabilized High resolution Computer processable imagery Vectorable Inertial motion measurement	Very stable Sustain weight of UAV	Display video Record video Real time video processing	Camera attitude control Camera pose reporting Aircraft control Video stream broadcast

ISR Research Applications	MARP Requirements Category			
	Sensor Payload	**Airframe**	**Processing**	**Communications**
Augmented Reality Graphic User Interface	Stabilized High resolution Computer processable imagery Static or vectorable Inertial motion measurement	Very stable Sustain weight of UAV	Display video Real time video processing	Camera attitude control (if vectorable) Camera pose reporting Aircraft control Video stream broadcast

Table 1.3: Consolidated Requirements of the MARP.

Requirement Source	MARP Requirements Category			
	Sensor Payload	**Airframe**	**Processing**	**Communications**
Requirements from ISR Applications	Stabilized High resolution Computer processable imagery Vectorable Inertial motion measurement	Very stable Sustain weight of UAV	Display video Record video Real time video processing	Camera attitude control Camera pose reporting Aircraft control Video stream broadcast
Requirements as ARP	Affordable	Affordable Legal to fly Manageable by small crew	Affordable	Affordable Remotely operated UAV Legal to fly

1.3. Research Objectives

This main objective of the thesis research is to design, construct, and flight test the Maryland Academic Research Platform to satisfy the Intelligence, Surveillance, and Reconnaissance research application requirements identified above in Table 1.3.

1.4. Contribution of Thesis

The primary contribution of the thesis is the design of the Maryland Academic Research Platform. This thesis also documents the rationales and procedures used to determine appropriate solutions to the problems encountered during the research. Some of the contributions of the thesis are broad, such as the effort to create a UAS to further ISR research at the University of Maryland. Others cater to specific problems such as the transformation required to prepare an interlaced video stream for real time video processing in Section 3.3.3.2. The lessons learned, summarized in Section 5.3, serve as a baseline in the design, construction, and flight testing of a UAS by future researchers. The explanation in Section 3.5.3.1 provides an overview of the legal implications of operating autonomous UAVs in the U.S. airspace. Section 3.3.3.1 identifies a helpful tool to characterize the lens distortion of a camera. It is the researcher's hope that use of this thesis document will expedite the UAS creation process, enabling researchers to be flying in weeks rather than months.

Chapter 2. Overview of the Maryland Academic Research Platform

A technical and operational overview of the completed MARP system is provided in this Chapter. The main components of the MARP are the Unmanned Aerial Vehicle (UAV), the GS (GS). The responsibilities of the Operational Team are presented to show how the MARP is used as a system.

2.1. MARP Unmanned Aerial Vehicle

The MARP UAV is 7 feet long and has a 9 foot wingspan. The airframe has been customized from the Sig Rascal 110 model aircraft. The primary payload is a D-STAMP gyro-stabilized, high resolution camera from Controp Technologies. The UAV is powered by a 1.6 cubic inch Evolution 26GX gas engine. Electrical power and communications equipment to support the UAV are detailed in Chapters 3 and 4. Figure 2.1 shows the MARP UAV with key components highlighted.

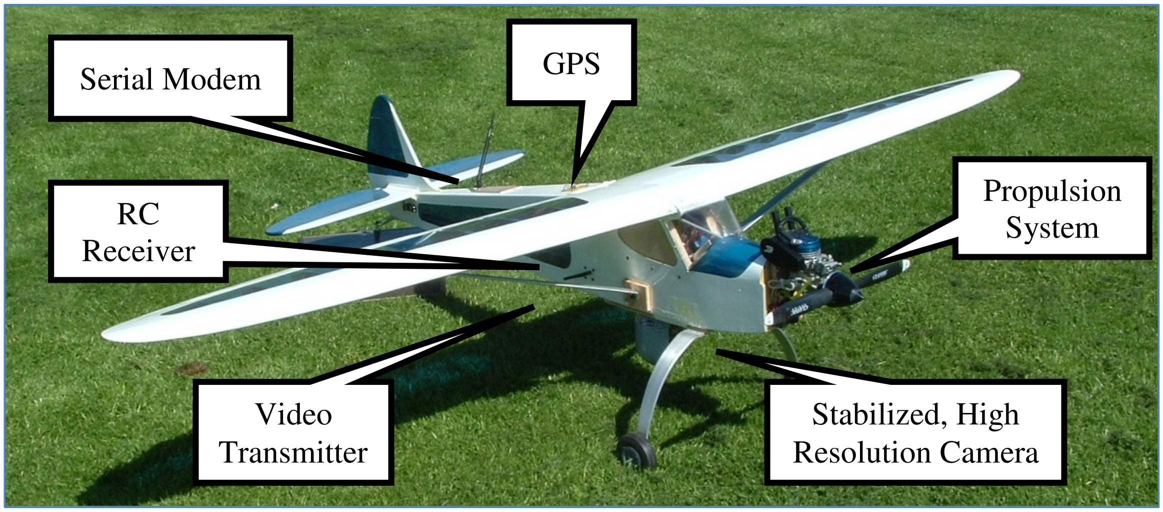


Figure 2.1: UAV with major components labeled.

2.2. MARP Ground Station

The GS is composed of a laptop personal computer, a secondary display with backup video recording, a camera attitude control joystick, three antennas to communicate with the three UAV remote devices (video broadcast, camera attitude control and camera pose reporting are combined in a serial modem, and aircraft control), a handheld flight yolk to remotely pilot the UAV, and a generator to provide power to the requisite subsystems. The GS computer serves multiple purposes as the primary display for the Camera Operator, the digital video recorder, the payload command center, and the device for computer vision algorithm implementation utilizing its dedicated Graphics Processing Unit (GPU). Additional GS equipment includes a video camcorder for documentation and an assortment of maintenance tools. Figure 2.2 shows the GS setup.

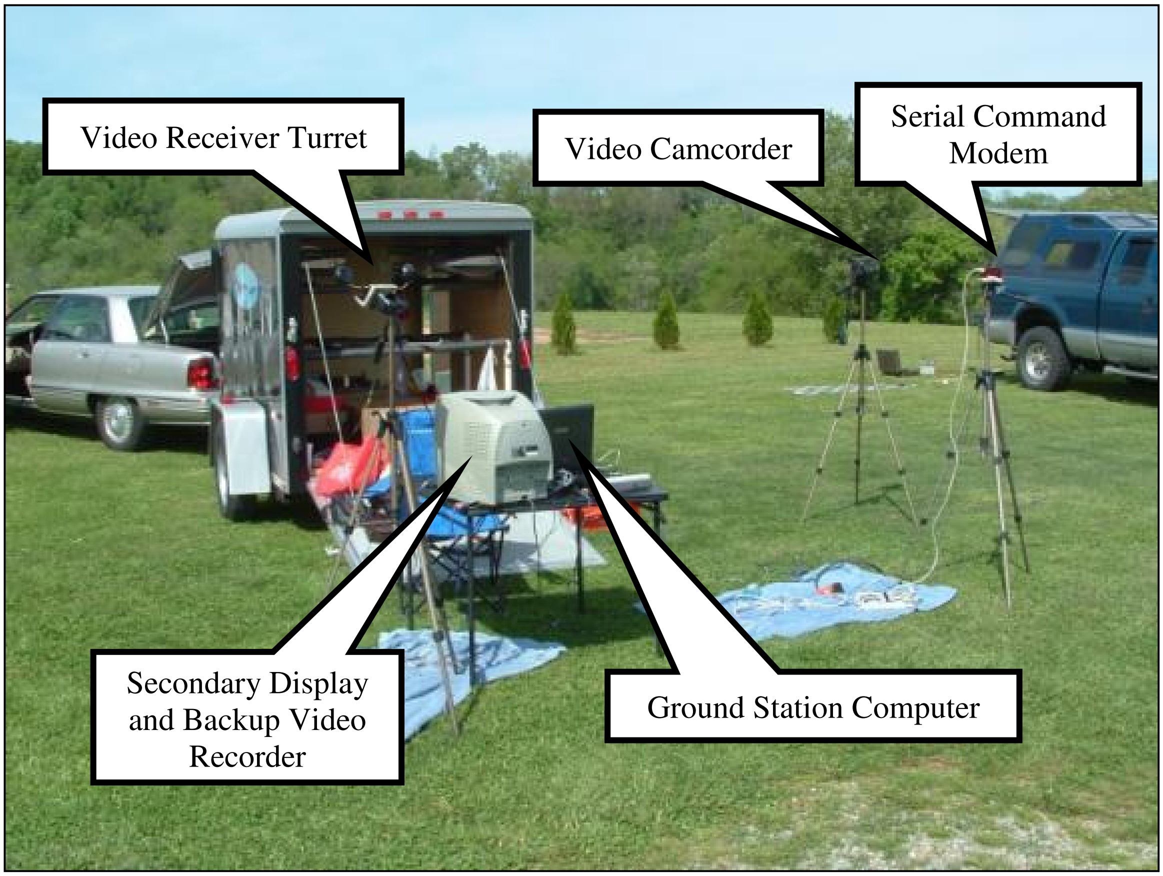


Figure 2.2: Ground Station field equipment.

2.3. Operational Overview and Preflight Responsibilities

Special preparations are required before each flight test. Flight arrangements must be made, including decisions regarding the flight location, permissions to fly at that location, weather contingency plans, and the logistics of the equipment and personnel required to fly. Transportation of the equipment is achieved using a customized trailer used for University of Maryland experiments by the Morpheus Lab, shown in Figure 2.2. The GS must be setup, the UAV must be assembled and fueled, and ground safety checks must be performed.

2.4. Flight Line Responsibilities

The MARP Operational Crew must fulfill four roles during a flight test. Ideally this is achieved with four or more people; however, as described in Chapter 4, the MARP was occasionally operated by two personnel. The four roles are Pilot, Camera Operator, Antenna Operator, and Documenter.

2.4.1. Pilot

The Pilot is responsible for the trajectory of the UAV, its safety, and the safety of others at the flight location. The Pilot must maintain line of sight with the UAV at all times and fly within the limits of the UAV's abilities, keeping the UAV within the flight boundaries established by the flight field. This is the one role where specialized experience in remote controlled (RC) model aircraft operation is a must. This position is not to be filled by a novice RC Pilot.

2.4.2. Camera Operator

The Camera Operator has a number of responsibilities focusing on the GS. Figure 2.3 shows the GS from the Camera Operator's point of view. The Camera Operator must monitor the payload status, select the operation modes of the camera payload to lock onto GPS coordinates and switch to manual command mode as needed, ensure proper video recording by the digital video recorder hardware and software as well as on the VCR backup recorder, monitor the health of the GS computer's system resources when recording video and running algorithms. Most importantly, the Camera Operator must operate the pan-tilt-zoom controls of the camera using the camera attitude control joystick, supporting the real time video processing algorithms in the provision of usable video. This individual must have a working knowledge of the algorithms to determine what camera motions are amenable to the selected research algorithms.

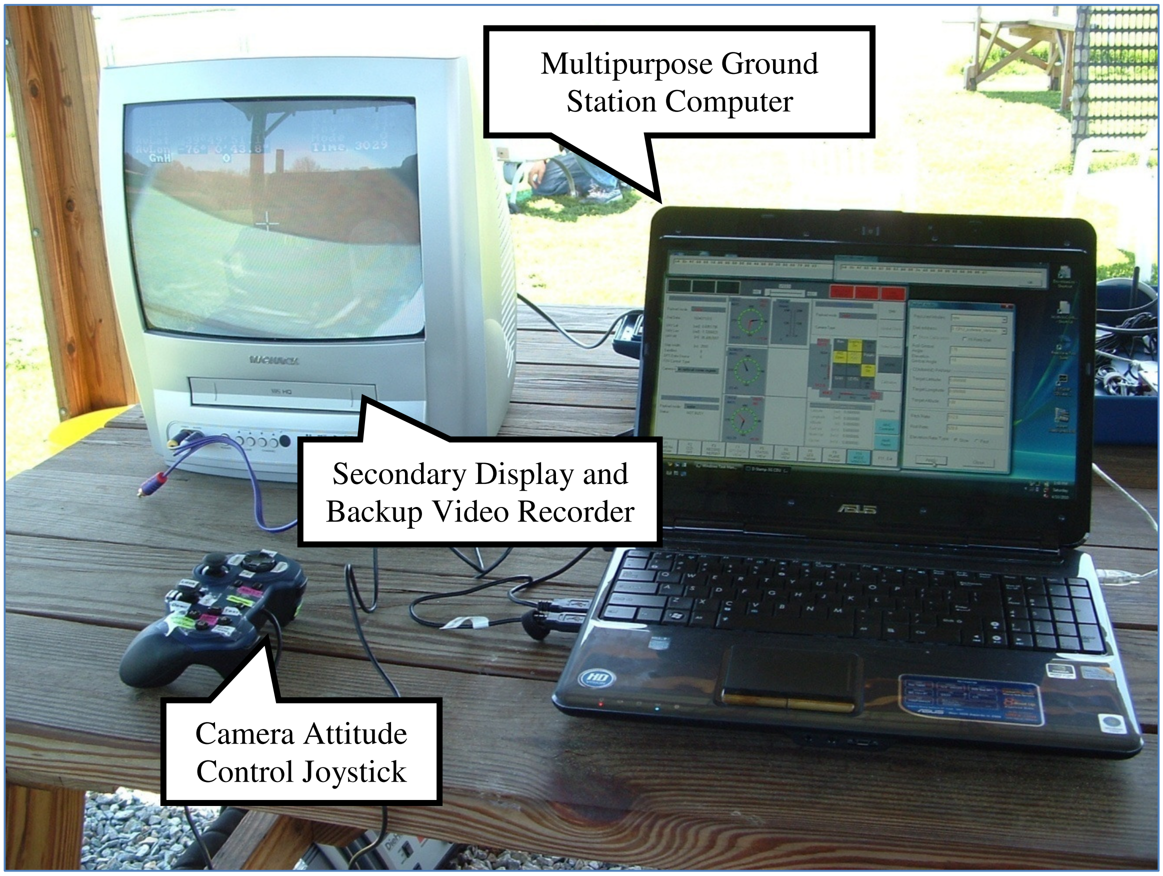


Figure 2.3: Camera Operator's view of Ground Station.

2.4.3. Antenna Operator

The Antenna Operator has far simpler job than that of the previously describe roles, but it is vital nonetheless. Due to the legal and technical limitation imposed on the broadcast and receiving power of the video stream communications link, the MARP requires the use of directional line of sight antennas. It is the Antenna Operator's responsibility to keep the Video Receiver Turret pointed at the UAV (see Figure 2.2).

2.4.4. Flight Documenter

The Flight Documenter is responsible for operating the Video Camcorder during the preflight and flight periods of a flight day to document the procedures and qualitative results of each test flight (see Figure 2.2).

Chapter 3. Subsystem Requirements and Component Selection

The design began with an allocation of the consolidated requirements for the MARP established in Table 1.3 to the subsystem level. This effort was followed by the careful selection of the MARP's critical subsystem components. These decisions were made in parallel to ensure internal system compatibility. As such, this chapter is organized by subsystem rather than by a chronological or dependency-driven order of events.

3.1. Unmanned Aerial Vehicle Airframe Requirements and Selection

In general, the selection of a particular UAV airframe is governed largely by the parameters of the ARP's intended research application. For this thesis research, the MARP ISR research applications drove the UAV airframe requirements and selection, including low cost, high stability, sufficient lift to support the additional weight of the camera payload and support equipment, as well as the ability to be operated by civilian researchers.

3.1.1. Requirements on Type and Size of Unmanned Aerial Vehicle

A vast array of UAV types and sizes could satisfy the generic requirements of an ARP. Specific criteria were determined to satisfy the consolidated MARP requirements.

3.1.1.1. Rotary-Wing versus Fixed-Wing UAV.

Rotary-wing UAVs are known for their high maneuverability, a desirable trait for use in restricted flight boundaries. But the rotary-wing propulsion method can introduce vibrations from the rotors and the engines that could disrupt the smooth trajectory demanded by applications requiring real time video processing. Additionally the skills required to pilot a rotary-wing UAV were found to be much greater than the skills necessary to pilot a fixed-wing UAV and posed a greater risk to damaging the UAV and payload [7; 15]. For these reasons, a fixed-wing UAV was chosen to be more appropriate for this thesis research.

3.1.1.2. Case for a Smaller Fixed-Wing UAV.

Many factors encouraged the use of a smaller fixed-wing UAV. For the MARP test flights, the UAV was to be flown at RC flight fields and urban environments, where the agility of a smaller UAV would enable the pilot and Camera Operator to better perform tight turns and deliberate maneuvers required to stay within the boundaries of the planned flight locations.

As for the limitations on flight altitude, the FAA limits remotely piloted vehicles to a height of 400 feet when within 3 miles of an airport. AMA appropriately enforces the FAA ruling as well. The local airfield for research is the Newport News Park RC Club Airfield of Hampton, VA. It is within 3 miles of an airport. Local club rules thus state that there is no flying above 400 feet [16]. This low altitude caters to a smaller UAV that can perform tight, coordinated turns. More detail on these regulations is provided in Section 3.5.3.

Two final factors are the cost of construction and ease of transportation. These are improved by choosing a smaller fixed-wing UAV.

3.1.1.3. Case for a Larger Fixed-Wing UAV.

There are important factors that tend to favor larger fixed-wing UAVs. The total weight of the camera, motion measurement equipment, communication link devices, propulsion system, batteries, and supporting hardware was estimated to be between 10 to

15 pounds. This payload weight, combined with the weight of the airframe, must be countered by the aerodynamic lift generated by the velocity of the aircraft and the wing area. Larger aircraft tend to have larger wing areas to support this total weight, thereby reducing wing loading, allowing them to fly at slower speeds during takeoff and steady level flight. Also, larger aircraft have smooth flight characteristics and greater turbulence rejection that is critical for effective ISR research applications requiring real time video processing. [17]

3.1.2. Selection of UAV Airframe Size

Considering the requirements for the MARP, it was decided to choose a moderately sized fixed-wing UAV. Figure 3.1 compares the size of the selected UAV airframe (Sig Rascal 110) with existing military UAVs, organized by wingspan dimension (data acquired from [18; 19; 20; 21]). Additional reasoning is provided for the selection of (1) this specific airframe, (2) an appropriate propulsion system, and (3) the batteries needed to support all onboard systems.

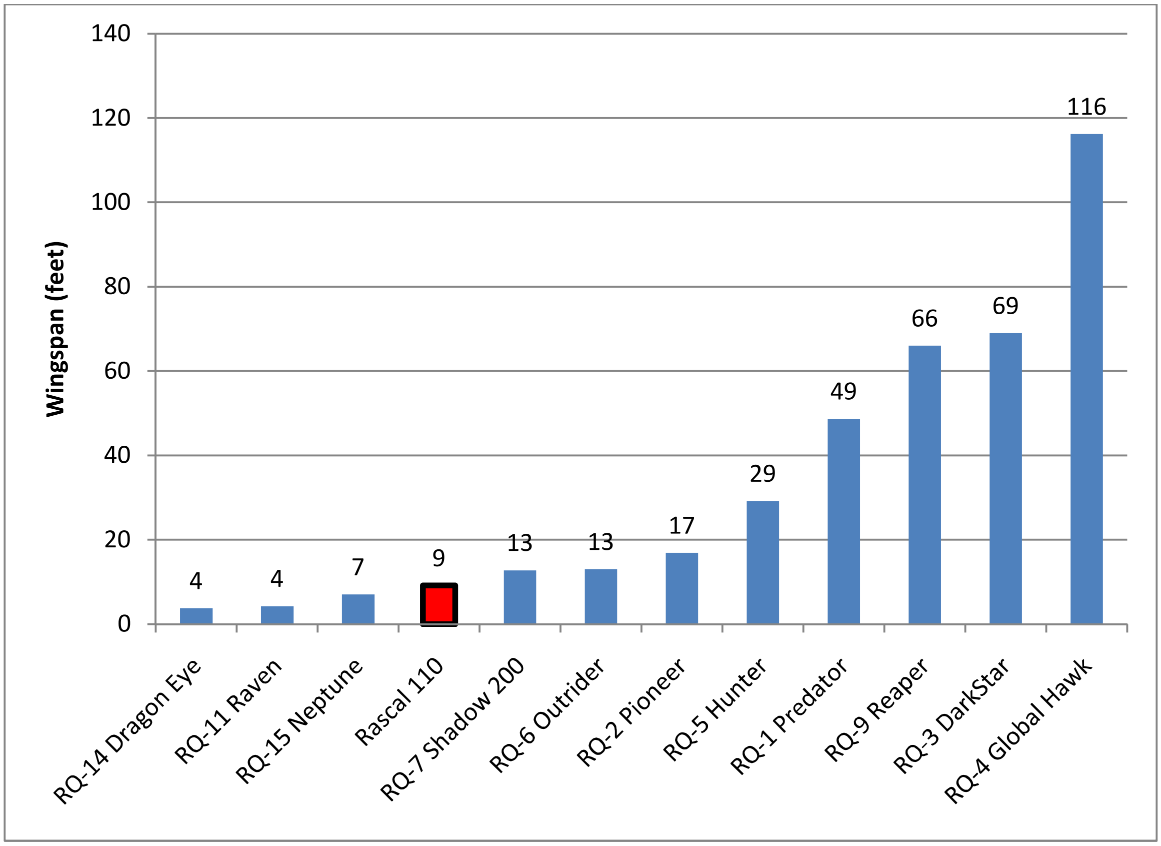


Figure 3.1: Size comparison of military fixed-wing UAVs with selected UAV highlighted, the Sig Rascal 110.

3.1.3. Trade Study for UAV Airframe

In lieu of designing and manufacturing a custom airframe to support the sensitive payload, COTS (Commercial Off The Shelf) RC model aircraft were evaluated to serve as the UAV airframe. Selection of the UAV airframe came down to two suitable candidates: the Cessna 337 Skymaster Model and the Sig Rascal 110, shown in Figure 3.2.


(a)

(b)

Figure 3.2: Candidate UAV airframes: (a) Cessna 337 Skymaster Model and (b) Sig Rascal 110.

The two candidate UAV airframes were compared with results outlined in Table 3.1, revealing two key benefits to the Sig Rascal 110 (data from[22; 23]). The first benefit is that the Rascal 110 has a smaller wing loading from its larger wingspan, assuming the two aircraft would carry similar payload weights. The second benefit is the camera protection of the Sig Rascal 110. While the Skymaster could provide an excellent unobstructed view with a nose mounted camera, it would unfortunately leave the camera unprotected on the nose of the aircraft. If the plane were to fall forward on the runway, the camera would take the full impact against the tarmac. If the plane were to have a nose-first crash into the ground or into an object, the camera would again take the full impact and with far graver results. In this respect, it is better to have a belly mounted camera on the Sig Rascal 110 and use the view-obstructing landing gear as a form of protection for the camera for tough landings. The Camera Operator is then responsible for directing the camera away from the landing gear when facing forward.

Table 3.1: Physical Comparison of Candidate Airframes.

	Cessna 337 Skymaster	**Sig Rascal 110**
Wingspan	81 inches	110 inches
Length	62 inches	75 ¾ inches
Wing Area	1085 square inches	1522 square inches
Wing Placement	High – Good Roll Stability	High – Good Roll Stability
Camera Mounting Location	Nose mounted	Belly mounted
Camera Exhaust Protection	Rear exhaust origin	Exhaust diversion
Camera View Obstruction	None – Good	Landing gear – Bad
Camera Protection	None – Bad	Landing gear – Good

Furthermore, anecdotal observations from a colleague flying a Sig Rascal 110 aircraft with 15 pounds of experimental equipment onboard confirmed the preliminary analysis of the airframe's physical shape: the Sig Rascal 110 is a rugged platform for carrying equipment in controlled flight. It was selected as the airframe.

3.2. Propulsion System Requirements and Selection

Several factors affected the determination of an appropriate UAV propulsion system for the MARP. A desirable propulsion system would have adequate power to propel the UAV, long endurance for extended flight tests and eventual ISR research flights, low exhaust to keep the camera clean, and low cost for implementation.

3.2.1. Requirements Analysis

Existing COTS RC model aircraft propulsion systems were evaluated on these parameters. A jet propulsion system would be far too expensive and complicated to maintain for this scale aircraft. Non-jet solutions included propeller-driven aircraft with three different engine types, named for the fuel they consume: (1) gasoline engines, (2) Glo fuel engines, and (3) electric engines.

Electric engines are easy to maintain and they produce no exhaust, keeping the camera very clean; yet electric engines are usually suited for use on smaller airframes. Batteries of sufficient size are commercially available to propel the Sig Rascal 110, but they are too large and too expensive for practical implementation and the process of recharging batteries is far too slow, which would require additional sets of batteries for each 30 minute flight. A popular model engine type is Glo fuel. It operates much like a diesel engine in that combustion is achieved through pressure and heat rather than a spark. They are powerful, but expel a slimy residue of unburned fuel in their exhaust – an unwelcome feature near the camera. It was decided to use a gasoline engine for its relatively clean exhaust, ability for rapid refueling, and raw power.

3.2.2. Propulsion System Selection

The specific selection of a particular gasoline engine propulsion system consisted of an engine, a propeller, and an ignition system.

Sig, the airframe manufacturer, recommends a 1.3 to 1.5 cubic inch engine when using gasoline as a fuel [22]. A 1.6 cubic inch Evolution 26GX engine was selected to increase thrust to compensate for increased drag from two main sources: (1) induced drag from the larger lift force countering payload weight and (2) parasite drag from the addition of a belly mounted camera to the airframe. This stronger engine would also give the aircraft testbed greater acceleration for faster take offs and a greater ability to climb.

Though the engine could handle a variety of propellers to interface with the drive shaft, an 18x6 propeller was selected as it is the benchmark propeller for the

Evolution 26GX. The propeller dimensions refer to an 18 inch diameter propeller with a 6 inch pitch that would allow the propeller to travel forward 6 inches if rotated a full revolution without restraint. More aggressive pitch values and larger propellers would put larger loads on the engine per revolution. A change in propeller shape exists as a small method of tuning the performance of the fully assembled aircraft. [24]

The gasoline engine requires an ignition mechanism to spark the gasoline during the engine cycle. The EVO 3314 attaches to a spark plug in the engine and is powered by a battery, timing sparks with engine revolutions as measured by a Hall Effect sensor mounted to the drive shaft.

3.3. Camera Requirements and Selection

Choosing the correct camera is essential to ensuring the effectiveness of the MARP to conduct ISR research. The camera must produce a video stream that suits the consolidated MARP requirements of Table 1.3 by being (1) gimbaled (vectorable) and (2) stabilized while (3) producing high quality, full resolution video in a format acceptable for computer processable imagery.

3.3.1. Requirements Analysis

The first requirement is the gimbaling of the camera. This is desirable to enable the camera orientation to be directed independently of the aircraft orientation, as noted in Section 1.2. It allows a single camera to view multiple sides of a target as the UAV flies overhead, giving the MARP more freedom to gain the perspectives necessary to perform the ISR research applications more effectively. The camera must be able to change orientation rapidly with a high slew rate of its gimbal servo motors. This would allow for the camera to track a target when passing at high speed or quickly change targets of interest when flying at low altitudes.

The camera must also be stabilized to mitigate the real world effects of aircraft engine vibration and wind turbulence. The ISR applications requiring real time video processing need smooth motions, but perturbations risk causing extensive camera shake that would confuse the real time video processing algorithms and provide false information regarding the motion of the camera to those ISR algorithms. The camera's internal process would require input from inertial measurement sensors to implement this stabilization.

The third requirement is that the camera must produce high quality, full resolution video in a format acceptable for computer processable imagery. If the size of a video frame is too small or if the frame rate of the video is too slow, the ISR research applications requiring real time video processing will have reduced data resolution as inputs and will be unable to perform as anticipated. This outcome is undesirable. A satisfactory camera would produce full resolution, NTSC standard video at 640 by 480 pixel image size at a full rate of 29.97 frames per second or better. Additional steps to ensure that the resulting video constitutes camera processable imagery, as specified in the MARP consolidate requirements, are detailed in Section 3.3.3.

3.3.2. Camera Selection

The Daylight Stabilized Miniature Payload (D-STAMP) from Controp Precision Technologies satisfies these three requirements and provides the additional capability of automatically aiming the camera at selected coordinates. This feature enables the Camera Operator to switch from manual direction of the camera to a "Hold Coordinate" mode once a desired target for 3D mapping is located. Table 3.2 lists additional attributes. [25; 26; 27]

Table 3.2: Controp D-STAMP Attributes.

Sensor	CCD
FOV	5.3 to 47 degrees
Continuous Zoom Optical Lens	10x Continuous Optical Zoom
Field of Regard	Pitch:+70 degrees to -40 degrees Roll: +- 175 degrees
Weight	750 grams
Dimensions	L: 160 mm D: 130 mm
Mounting	4"
Power Consumption	9 Watt

3.3.3. Ensuring Computer Processable Imagery

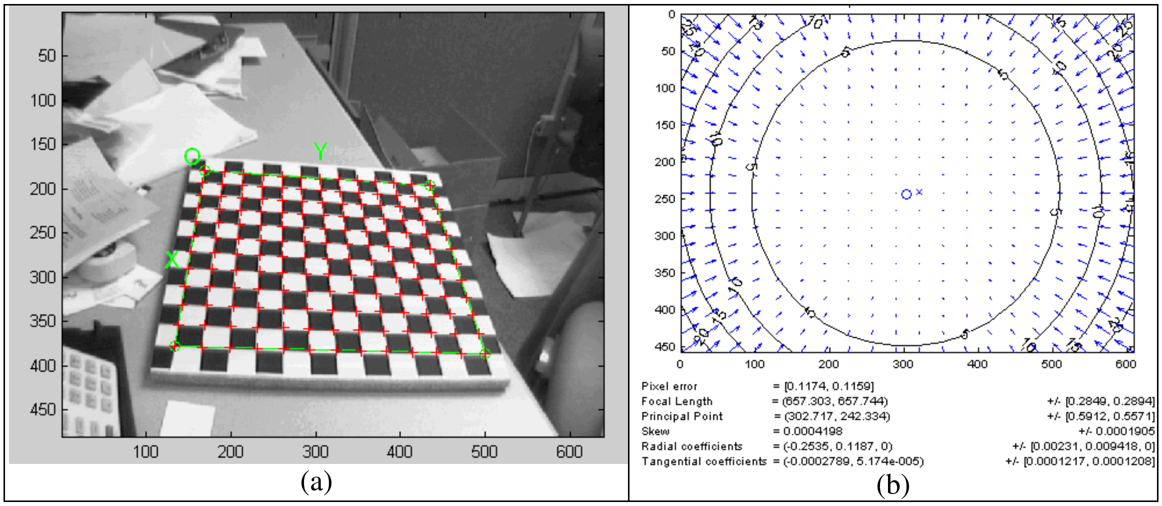
ISR research applications involving real time video processing require computer processable imagery as input. The two primary steps to meet this requirement are as follows: (1) the camera must be characterized by a process known as "Camera Calibration" and (2) the video input to the IRS research application algorithms must be in the progressive frame format.

3.3.3.1. Camera Calibration Process

For many computer vision applications, including the ISR research applications requiring real time video processing, Camera Calibration is required to define the input-output correspondence between the angle of light entering the camera and the x,y pixel location of the resultant video frame depicting that light source. Each camera has a unique lens shape that distorts light before it enters the camera; this distortion can be measured once and will remain constant for that camera. Characterization of the lens distortion enables algorithms to identify the relative azimuth and elevation angles of a particular point in 3D space represented by a 2D pixel location in the video frame. This process must be applied to the D-STAMP before its output can be used as part of the MARP. [28]

The Camera Calibration method needed to have a simple user interface, perform the characterization quickly, be flexible for use on different cameras, and be able to provide the accuracy to which the characterization was measured. For these reasons, the Camera Calibration Toolbox for Matlab by the California Institute of Technology was chosen [28; 12].

To characterize a camera, a flat checkerboard with evenly spaced corners is printed out and affixed to a rigid surface, such as a foam board this provides the Toolbox with an object of known shape. The camera to be characterized is then moved to take pictures of the checkerboard from several different perspectives (at least 30), providing the Toolbox with several unknown camera poses (a camera's pose is its position and orientation). When the pictures are given to the Toolbox, the user selects the four corners of the checkerboard. See Figure 3.3a. The Toolbox then automatically detects the positions of the internal corners of the checkerboard and solves for the unknown camera characteristics. The result is a dozen variables and measures of their accuracy defining the shape of the lens, taking into account focal length and lens distortion, to produce the correspondence of x and y pixels to relative orientation of 3D points. See Figure 3.3b. The process can be performed in 30 minutes, though more time can be spent to fine tune the error margins of the results to within tolerance of a given computer vision algorithm's requirements. [28]



```
Pixel error            = [0.1174, 0.1159]
Focal Length           = (657.303, 657.744)            +/- [0.2849, 0.2894]
Principal Point        = (302.717, 242.334)            +/- [0.5912, 0.5571]
Skew                   = 0.0004198                         +/- 0.0001905
Radial coefficients    = (-0.2535, 0.1187, 0)       +/- [0.00231, 0.009418, 0]
Tangential coefficients = (-0.0002789, 5.174e-005) +/- [0.0001217, 0.0001208]
```

(a) (b)

Figure 3.3: Camera Calibration Toolbox in Matlab examples: (a) input and (b) distortion model.

3.3.3.2. Adjusting Video Format

The second requirement is that the input video to the real time video processing algorithms must be in the progressive video format (all pixels of video frame are from the same time sample). The problem is that most video equipment sends and receives the NTSC interlaced video format instead (alternating lines of a video frame are from two different time samples). The MARP requirement for computer processable imagery requires that the video be converted from interlaced to progressive video format by the computer before continuing to the process implementing the ISR research application algorithm. Also, the MARP requirement for real time video processing requires that this conversion be done at a speed faster than the real time frame rate.

The practice of interlacing was initiated to support the technology of 1941, when Cathode Ray Tube (CRT) televisions could not update the entire video image at once. To overcome this obstacle, the NTSC standard flickers between even and odd lines of the video at double speed (59.94 Hz) to give the appearance of continuity in the displayed video. Most video cameras capture progressive video directly, but to comply with the NTSC standard, a video camera must convert from progressive video, acquired at its camera sensor, to interlaced video, ready for output. It does this by first sampling just the odd lines of a given video frame on the camera sensor, reading lines 1, 3, 5, 7, 9 … 477, 479 and storing them in a half height video image called an "odd field" with dimensions 640 by 240 pixels. After a sampling delay, the "even field" is sampled, reading lines 0, 2, 4, 6, 8 … 476, 478. After another sampling delay, the odd field is sampled again. The process continues at a rate of 59.94 times per second. The video camera must then post-process pairs of odd and even video fields, weaving them together to create a single, interlaced video frame at 29.97 Hz with frame size 640 by 480 pixels. [29]

In short, the camera output (interlaced) does not match the desired video input (progressive). To bridge this gap, the transmitted video is deinterlaced to convert it back to progressive video. This process is depicted in Table 3.3. The software utility, VirtualDub, was selected to perform the required conversion quickly [30]. Tests on sample footage confirmed that this process was fast, achieving frame rates between 60 and 67 frames per second. This is more than twice as fast as the rate required for real time processing. Thus, the testing apparatus can generate video in the format needed to satisfy the MARP consolidated requirements.

Table 3.3: Complexity of Video Format Handling as Constrained by NTSC Interlaced Video Standard. *Note: "1/60 Second" represents a single 59.94 Hz field rate time step.

<table>
<tr><th></th><th>Field 1</th><th>Field 2</th><th>Field 3</th><th>Field 4 …</th></tr>
<tr><td>Time</td><td>1/60 Second*</td><td>2/60 Second</td><td>3/60 Second</td><td>4/60 Second</td></tr>
<tr><td>Camera Sensor</td><td>Progressive Field 640 pixels on 240 lines at 59.94 Hz</td><td>Progressive Field 640 pixels on 240 lines at 59.94 Hz</td><td>Progressive Field 640 pixels on 240 lines at 59.94 Hz</td><td>Progressive Field 640 pixels on 240 lines at 59.94 Hz</td></tr>
<tr><td>Camera Post-Processing</td><td colspan="2">⇘ Interlacing Video ⇙</td><td colspan="2">⇘ Interlacing Video ⇙</td></tr>
<tr><td>Camera Output</td><td colspan="2">Interlaced Frame 640 pixels on 480 lines at 29.97 Hz</td><td colspan="2">Interlaced Frame 640 pixels on 480 lines at 29.97 Hz</td></tr>
<tr><td>Transmitter & Receiver</td><td colspan="2">Transmitting Video ⇩</td><td colspan="2">Transmitting Video ⇩</td></tr>
<tr><td>Computer Input</td><td colspan="2">Interlaced Frame 640 pixels on 480 lines at 29.97 Hz</td><td colspan="2">Interlaced Frame 640 pixels on 480 lines at 29.97 Hz</td></tr>
<tr><td>Computer Pre-Processing</td><td colspan="2">⇙ Deinterlacing Video ⇘</td><td colspan="2">⇙ Deinterlacing Video ⇘</td></tr>
<tr><td>Desired real time video processing Input</td><td>Progressive Field 640 pixels on 240 lines at 59.94 Hz</td><td>Progressive Field 640 pixels on 240 lines at 59.94 Hz</td><td>Progressive Field 640 pixels on 240 lines at 59.94 Hz</td><td>Progressive Field 640 pixels on 240 lines at 59.94 Hz</td></tr>
</table>

3.4. Motion Measurement Equipment Requirements and Selection

Motion measurement equipment is required to determine the trajectory of the camera at the particular instance of each video frame capture satisfy the consolidated MARP requirements. The chosen approach was to measure the motion of the camera base and combine this with the relative motion of the camera's gimbal deflections, integrating in time to determine the camera's pose. Four elements are necessary: (1) rate gyroscopes to measure rotational velocity, (2) linear accelerometers to determine change in position, (3) a GPS device to assist in camera pose detection, and (4) a device to coordinate these measurements with each camera time step to match the camera pose information with each video frame image.

The MicroPilot 2128g Autopilot was initially chosen to fulfill these requirements. At the time of this system design analysis, a news release from MicroPilot encouraged its use with the Controp D-STAMP camera:

“MicroPilot and CONTROP Precision Technologies Ltd are proud to announce the successful integration of MicroPilot’s line of autopilot systems with CONTROP’s STAMP Stabilized Miniature Payloads launched at AUVSI Unmanned Systems North America 2008” [31].

During implementation it was discovered that the MicroPilot hardware did not perform as advertised. This disrupted the component selection process for the motion measurement equipment, the camera attitude control communication link (Section 3.5.1), and camera pose reporting communication link (Section 3.5.2), These requirements were ultimately met by exporting the data from the inertial and GPS motion measurements calculated within the D-STAMP camera, broadcasted by a FreeWave Technologies MM2 900 MHz serial modem. This is further discussed in Section 4.1.3.

3.5. Communication Link Requirements and Selection

The nature of UAS operations physically separates the sensors onboard the UAV from the processing equipment at the GS. Communication requirements between the two locations include devices necessary to send and receive data to enable the four communication functions identified in the MARP consolidated requirements: (1) camera attitude control, (2) camera pose reporting, (3) aircraft control, and (4) video stream broadcast. The communications link devices must provide a robust connection for each function with adequate range and bandwidth. These devices must not interfere with each other and must be able to reject interference from outside sources. This final requirement is pursued by choosing different operating frequencies for each communications device.

3.5.1. Camera Attitude Control

The camera is to be remotely controlled at the GS by an individual called the "Camera Operator". The Camera Operator needs to be able to manually change the orientation of the camera with joystick commands from the GS to vector the camera towards objects of interest for 3D mapping. The Camera Operator must also be able to switch to different operating modes on the D-STAMP, such as the Hold Coordinate mode to automatically track these targets.

The communications link must support the camera attitude control function for sending these inputs. It must complete these tasks while matching the baud rate and the communications protocol of the Controp D-STAMP camera and Controp GS software. This communication link must also transmit information from the UAV to the GS to deliver an update on the camera's status. The FreeWave Technologies MM2 900 MHz serial modem was chosen over the MicroPilot 900 MHz serial modem, as described in Section 4.1.5.

3.5.2. Camera Pose Reporting

One of the communications devices must also support the function of camera pose reporting. All four motion measurement devices must report to the GS: the rate gyroscopes, the linear accelerometers, the GPS, and the device coordinating this data with the camera's time step. The FreeWave Technologies MM2 900 MHz serial modem was chosen over the MicroPilot 900 MHz serial modem, as described in Section 4.1.5.

3.5.3. Aircraft Control

Legal restrictions and technical benefits determine the requirements and nature of the aircraft control communication function. These must both be considered in the creation and testing of a MARP by civilian researchers.

3.5.3.1. Legal Restrictions on the Aircraft Control Function

Legally, two main regulatory associations have rules regarding the limits of how UAVs are to be used: the Federal Aviation Administration (FAA) is a government body that has the authority to regulate the nation's airspace and the Academy of Model Aeronautics (AMA) is a large organization that is permitted to self-regulate many matters for its recreational model flight members, determining what its members shall and shall not do when under their liability protection. Both regulatory associations set the restrictions on autonomous flight.

The rulings and practices of the FAA show that they are quite wary of UAVs, especially when they fly autonomously. In a recent report, they issued this statement, "The FAA's main concern about [UAV] operations in the National Airspace System (NAS) is safety. It is critical that these aircraft do not endanger other users of the NAS or compromise the safety of persons or property on the ground." Later they went onto say that operators of UAVs may submit a request to have the UAV inspected for a "*Special Airworthiness Certificate in the Experimental Category*", but the certificate is not valid for researchers. Another provision is made for state universities to apply for a *Certificate of Authorization*, but the conditions require coordination with the air traffic controller while fitting the UAV with a special transponder and bringing extra personnel to provide a lookout [32].

The FAA may eventually adopt a more research-friendly stance for Small UAVs, but it has yet done so. In 2008 they began studying how to regulate these aircraft. The FAA aims to make a final decision on Small Autonomous UAVs, but the ruling publication is not slated until 2011 [33].

The AMA generally does not allow autonomous flights at their airfields, but they have attempted to find away to allow student researchers the ability to have research aircraft fly autonomously. A meeting in 2005 started talks of allowing autopilots, but only for official AMA student competitions [34].

3.5.3.2. Technical Benefits to the Aircraft Control Function

As the FAA and AMA restrictions are not conducive to autonomous flights by civilian researchers, the technical benefits of remote piloting shape the requirements of the aircraft control function. The proven field of remote control (RC) model aviation technology must be utilized in the MARP if the research is to be completed by civilian researchers. An RC communications link must be established that uses the Frequency-Hopping Spread Spectrum (FHSS) method, proven to protect against accidental and some forms of deliberate interference and jamming of the aircraft control function [35]. For non-interference with other communications link functions, the aircraft RC hardware must occupy an unused portion of the radio spectrum. This communications link must also support the correct number of control surface channels (e.g. ailerons, elevators, rudder, throttle) present on the chosen UAV.

3.5.3.3. Selection for the Aircraft Control Communications Link Device

Based on these requirements, the aircraft control function was fulfilled by the selection of an XtremeLink FHSS 2.4 GHz transmitter and receiver. The manufacturer claims a range of up to 1 mile line of sight at ground level and up to 5 miles line of sight when the aircraft is airborne [36].

3.5.4. Video Stream Broadcast

The video stream broadcast function is essential for delivering the raw video signal from the UAV camera sensor to the GS processor. It is instrumental to the execution of the consolidated MARP requirements and it enables feedback to the Camera Operator, providing the current orientation of the gimbaled camera so that it may be redirected. The communications link device responsible for this function must support the full bandwidth of the video; it must have high signal strength for robust transmission; it must not interfere or be disrupted by other communications link functions; and it must have adequate range characteristics throughout the anticipated flight boundaries of the flight location.

A survey of colleagues at the NASA Langley Research Center in the field of unmanned aviation brought forth a few recommended names in video broadcast. Additional providers were discovered in literature reviews and recommendations from the online community of model aviators and civilian UAV researchers. The four most promising brands are summarized in Table 3.4 along with their respective citations.

Table 3.4: Summary of Video Broadcast Devices.

Source	Resolution	Band	Broadcast Powers
Iftron Technologies [37]	640x480	5.8 GHz	250 mW

Source	Resolution	Band	Broadcast Powers
Black Widow AV [38]	320x240	2.4 GHz	200 mW 500 mW 1000 mW
Wireless Video Cameras [39]	320x240	2.4 GHz	1000 mW
Felsweb [40]	300x220	2.4 GHz	10 mW 50 mW 500 mW

Only the Iftron Technologies video broadcast device provided full bandwidth support for 640x480 pixel resolution video and only the Iftron Technologies device utilized the 5.8 GHz band instead of the 2.4 GHz band (already reserved for the aircraft control function). The video stream broadcast equipment came with the YellowJacket Pro video receiver with RCA video outputs, the Stinger Pro 250 mW video transmitter, a small Sony testing camera, and a small power supply to power both the testing camera and the video transmitter from the same power source.

3.6. Battery Bank Requirements and Selection

The electronic devices onboard the UAV require battery power. The battery bank must provide the required voltages of each device, it must last long, and it must be light weight. The design decision was made to compose the batter bank of several batteries instead of just one. This design decision was made at the cost of increased battery weight and increased maintenance time required to charge each battery, but these penalties are accepted in place of their alternatives: the risk of crossover voltage spikes between devices and the risk of system-wide failure that could potentially result from a one-battery solution losing charge.

To fit these requirements, a suite of several Lithium Polymer (LiPo) batteries of assorted voltages was chosen over other battery types including Alkaline, Nickel

Cadmium, and Nickel Metal Hydride. A single Nickel Cadmium battery was used, however, to support the aircraft servos and the RC receiver to fit the 9.6 volt requirement. Table 3.5 outlines the batteries required for the battery bank.

Table 3.5: Voltage Requirements of System Electronics.

System	Device	Voltage Requirement
Propulsion System	Ignition for Gas Engine	12 volts
Remote Operations	Servo Board and RC Receiver	9.6 volts
Camera Subsystem	Camera, GPS, Power Supply	24-32 volts
Motion Data Measurement	MicroPilot 2128g	12 volts
Serial Command Modem	MicroHard Radio Modem	12 volts
Video Broadcast	Video Broadcast	12 volts

3.7. Ground Station Equipment Requirements and Selection

The first requirement of the GS is to support the four communications link functions of the MARP. The second requirement of the GS is include appropriate hardware components to enable the Pilot, the Camera Operator, and the various possible real time video processing software routines to interface with these four communications link functions. These components must maintain the communications bandwidth of the communications link devices and they must handle data fast enough for real time operation. The following subsections highlight the overall GS infrastructure, especially the Video Capture Device and the GS Computer.

3.7.1. Ground Station Infrastructure

GS components were selected to meet the above subsystem requirements. To meet the aircraft control function, a Futaba model aircraft RC input device was selected, equipped with the XtremeLink FHSS 2.4 GHz transmitter, to interface with the UAV pilot. To meet the video stream transmission function, the corresponding Iftron

Technologies 5.8 GHz receiver was selected with video outputs connecting to two devices: (1) a television allowing interface with the Camera Operator in the form of visual feedback and (2) an ADS Tech video capture card (later replaced by the Imaging Source DFG/USB2-lt Video-to-USB Converter in Section 4.3.3) allowing interface with the real time video processing software, calculating on a laptop computer. To meet the camera pose reporting function, the MicroPilot 900MHz serial modem and MicroPilot software (later replaced by the FreeWave Technologies MM2 900 MHz serial modem in Section 4.1.5) on the laptop was selected to interface with the real time video processing software. To meet the camera attitude control function, a Logitech Dual Action USB controller was selected to interface with the Camera Operator as the camera attitude control joystick.

3.7.2. Video Capture Device

The video capture device is the link between the video output of the Iftron Technologies video receiver and the laptop computer. Computers require this device to read the video voltage signal and convert it to the corresponding color values for each pixel of each image frame. The video capture device must make this conversion at the real time speed of the video broadcast (29.97 Hz for NTSC video) and maintain the quality of the original video without corruption.

An ADS VideoXpress was initially selected as the video capture device based on its featured ability to collect NTSC video [41] and familiarity with the thesis researcher. As will be described in Section 4.3.3, the video capture device disrupted the quality of the video transmission to the real time video processing software and was replaced by the Imaging Source DFG/USB2-lt Video-to-USB Converter.

3.7.3. Ground Station Computer

The MARP requires a dedicated GS Computer to handle multiple operations for flight tests and the eventual ISR research flights. The GS is the primary display for the Camera Operator, the digital video recorder, the payload command center, and the executor of the ISR research application algorithms.

3.7.3.1. Real Time Video Processing Requires a Dedicated GPU

One of the most demanding of the consolidated MARP requirements of Table 1.3 is the ability to perform real time video processing in the execution of the various ISR research application algorithms. Several of these ISR research application algorithms can be made to run much faster if they utilize a computer with a dedicated Graphics Processing Unit (GPU) instead of a computer that only has the standard Central Processing Unit (CPU) [42]. For ISR research applications requiring real time video processing, a GPU is a must.

As stated in Section 1.2.4, real time video processing on the MARP requires the data calculation to be faster than the incoming video data stream. The D-STAMP, along with other full resolution cameras in North America, adheres to the National Television System Committee (NTSC) standard, which outputs a 640 by 480 pixel video at a rate of 29.97 frames per second [29]. This means that the processor must be able to process each frame in a time less than about 33.4 milliseconds. As an example of the GPU's power over a standard CPU in computer vision applications, Figure 3.4 demonstrates the time required to process a video frame with the Kanade-Lucas-Tomasi Feature Tracker, a standard element that would be required by many of the ISR research applications requiring real time video processing [42]. It shows that, without a GPU, a computer would take about 240 milliseconds to complete this computation, which is far too slow [43]. The same computer with a GPU can complete the operation in under 30 milliseconds. Faster and more cost-effective GPUs continue to be developed since that study in 2006 [44; 45]. At the time of this writing, those same GPUs can now be purchased for about \$100-\$300 dollars [46]. A GPU is an affordable and necessary component for the GS Computer.

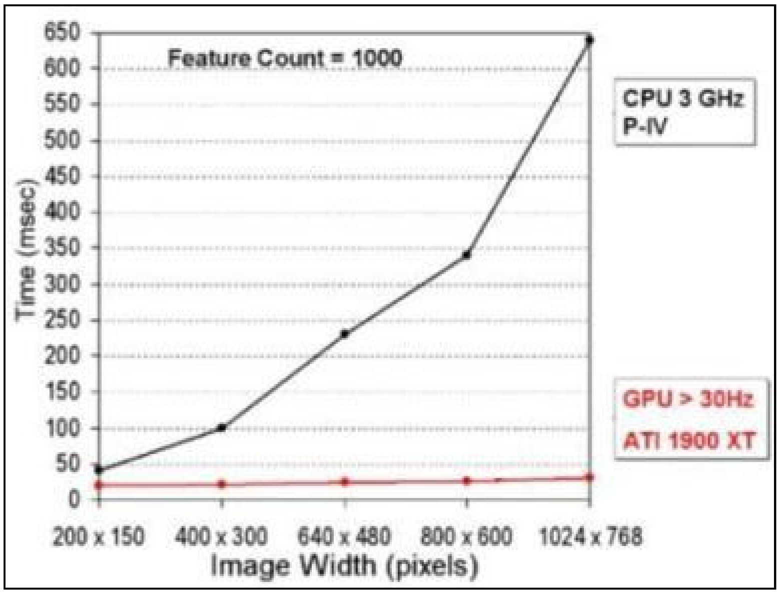


Figure 3.4: Time required to complete real time video processing iteration of video streams of different frame sizes, demonstrating a standard processor (CPU) requiring much more time than a GPU.

3.7.3.2. Ground Station Computer Selection

As discussed, the GS Computer requires a dedicated GPU. Many desktop PCs have powerful GPUs, but a laptop is better suited for field operations due to high portability and low power consumption. Previous research tested the performance of a number of computers, including a laptop with the nVidia GeForce Go 6800 Ultra graphics card in 2006 [42; 43]. A candidate GS Computer would have to have a GPU with an equal or greater processing speed compared to the tested GPU. Many factors influence a GPU's processing speed, including the GPU's clock frequency, number of pipelines, and video memory size. Standardized benchmark tests are used to evaluate the overall processing speed of the GPU for effective comparison, usually measured in floating point operations per second or by processed video frames per second. [47]

A suitable GS would also have to have enough Random Access Memory and enough CPU power to handle the many responsibilities of the MARP GS Computer (live video display, digital video recording, operating the Controp payload software, and executing the ISR research application algorithms).

It must be noted that the above requirements for an acceptable GS Computer were under consideration for several months before they could be properly prescribed and fulfilled in the purchase of a COTS laptop computer. During this time an available laptop was commissioned as an "interim computer" for testing of individual systems before full system integration. This interim laptop was used until Section 4.1.8.

A search began, using reviews and databases of laptop capabilities to find a PC that met these critical criteria. It concluded with the selection of the laptop described in Table 3.6. The processing power of the GPU of the laptop from the previous research [48] is compared with that of the chosen GS Computer at the following reference: [47]. The new GS Computer was also pictured in Figure 2.3 along with other key components of the GS equipment. With this final selection, the process of building the MARP could begin.

Table 3.6: Ground Station Computer.

Component	Description
Model	ASUS Notebook N51Vn Series
Central Processing Unit	Intel Core 2 Duo CPU T9600 @ 2.80 GHz
Graphics Processing Unit	NVidia GeForce GT 240M CUDA 1 GB
Random Access Memory	4.00 GB RAM

Chapter 4. Building the Maryland Academic Research Platform

The creation process of the MARP required several iterations of construction, diagnostics, flight testing, and upgrades before it fulfilled the consolidated MARP requirements set in Table 1.3. Design, construction, and verification were carried out in stages concentrating on individual components and their integration to bring about acceptable performance for the MARP. Flight testing served as an important step in the iterative design process to prove air worthiness and to qualify the onboard systems for use outside the laboratory.

4.1. Initial Construction

The initial construction phase of the MARP concentrated on readying the individual subsystems as they were integrated. The processes associated with creation and diagnostics ranged in complexity, requiring several different processes to be pursued in parallel. As such, the activities described below overlap chronologically.

Each subsystem posed its own problems that had to be overcome, especially the testing the camera subsystem and finding a replacement for the MicroPilot suite. The final step was to integrate all subsystems to create the first MARP.

4.1.1. Airframe Assembly and Modification

The Sig Rascal 110 airframe kit was assembled in the lab per the manufacturer's instructions. The parts were delivered with a few of the major components preassembled, including the fuselage, left and right wings, and the tail sections (as shown in Figure 4.1a). These components were installed together, the airframe was wired to interface with the Xtremelink RC receiver, and servos were installed with sufficient throw to deflect each of the control surfaces.

What followed was a series of modifications to adapt the shape of the airframe to accommodate the many components that would transform this airframe into a MARP. The modification process had to take into consideration the balance of the aircraft, structural reinforcement surrounding removed material, maintenance of the center of gravity, and a conservative limitation on added weight.

The first major modification was to create an interface sleeve for the D-STAMP. The D-STAMP needed to be transported in a protective case, separate from the rest of the UAV. The design of the airframe thus required a mechanism suited for the rapid attachment of the D-STAMP to the fuselage before flight in such a way that the D-STAMP would remain connected and secure during flight. To meet this requirement, a section of 4-inch diameter PVC pipe was filed to make a tight fit with the base of the D-STAMP, securing with five pre-set screw attachments. The other end of this "interface sleeve" had holes in its sides to allow a rod to slide through the walls of the fuselage and the interface sleeve, sandwiching the D-STAMP securely to the airframe. This interface sleeve, attached to the base of the D-STAMP, is shown in Figure 4.1b.

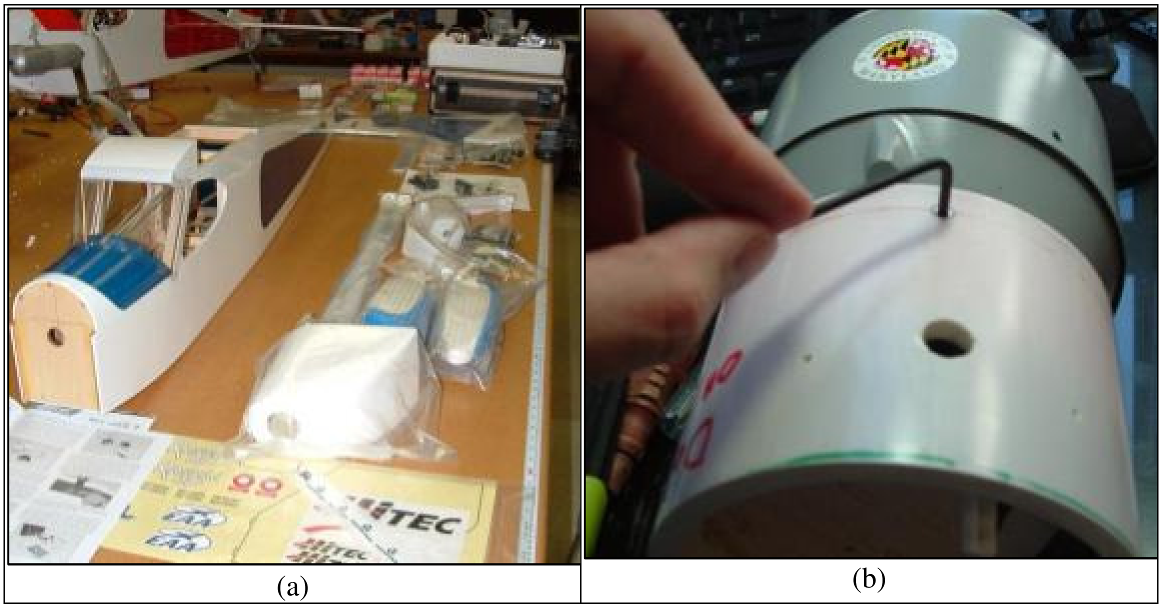

(a) (b)

Figure 4.1: (a) Airframe assembly of major components. (b) PVC neck interface affixed to D-STAMP base for rapid and secure connect/disconnect from fuselage.

The second major modification was to raise the fuselage farther off the ground. This was necessary as the original Sig landing gear did not account for a large belly-mounted camera. Custom landing gear were ordered according to a shape required for roll over stability during taxing and D-STAMP clearance off the ground in the event of the total destruction of the tail-dragger landing gear. Figure 4.6 shows the custom landing gear installed as part of the finalized MARP.

Other tasks included creating a battery bank to hold the various batteries required by the onboard equipment and building braces and portholes to secure the communications link devices to the airframe.

4.1.2. Propulsion System

The Evolution 26GX engine, the 18x6 propeller, the spark plug, the EVO 3314 ignition system, a mounting bracket, fuel lines, gas tank, and a muffler were assembled to form the propulsion system according to the instructions of the various manufacturers. The propulsion system was temporarily mounted to a workbench for outdoor testing and tuning. The throttle was adjusted to range between the idle speed of the engine and the maximum suggest rotation speed. With the engine broken in, the propulsion system was installed on the airframe. The mechanical components of the propulsion system were mounted upside down to direct the exhaust flow up and over the aircraft fuselage to keep the D-STAMP clean. Positioning of gas tank and ignition system within the fuselage took into the weight distribution of the aircraft as well as the available interior space.

4.1.3. Gimbaled Camera

The Controp D-STAMP gimbaled camera payload serves as the central component of the system design. It is also the most expensive item. The remainder of the MARP is in support of this camera to keep it flying and broadcasting video footage for processing at the GS.

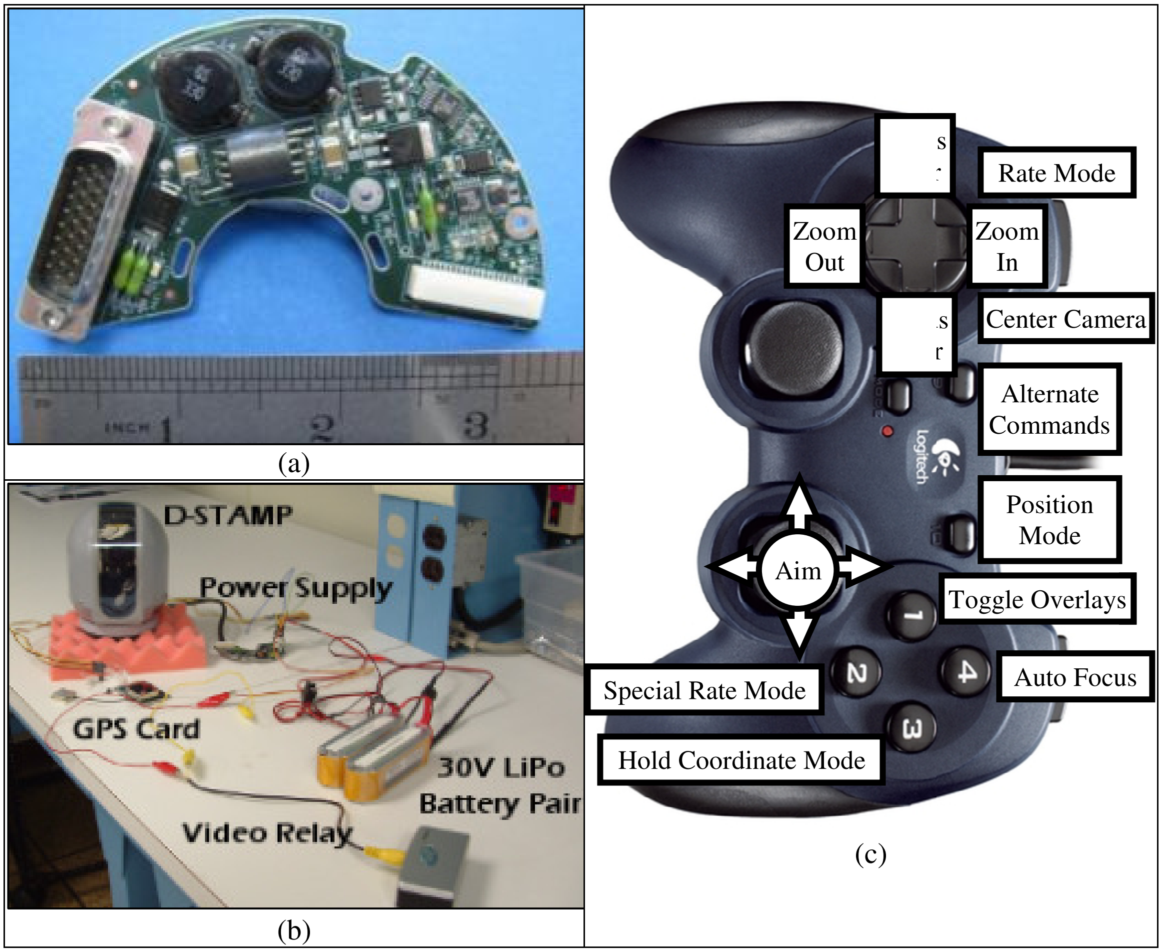
The particular unit used for this research had been in storage for a few years. Extra care, study, and planning were necessary to avoid damage to the D-STAMP. In general, any handling of the D-STAMP was done at its base, rather than its upper dome, to protect the dome from continued pressure or sharp impulses that could break the camera bearing. While working with the D-STAMP, three additional responsibilities were to be met: (1) ensuring that the correct startup sequence was observed; (2) wiring the D-STAMP to interconnect its components and interface with the communications link functions, and (3) verifying camera functionality in a series of tests as a self-contained subsystem.

First, the camera subsystem required a strict observation of its startup sequence in which the internal processor of the D-STAMP be given 12 volt power, followed by a delay, and then have the gimbal servos be given 24 volt power. This startup sequence allows the D-STAMP processor to control the servos. Uncontrolled servos run the risk of responding to static as input, violently torquing the camera past its physical limits and damaging the D-STAMP. A power supply, pictured in Figure 4.2a, was purchased from Controp to enforce this sequence and manage power from a single 30 volt source from the battery bank. [26]

Second, the D-STAMP was wired together, connecting the main camera dome, the power supply mentioned above, and a Controp GPS device. This camera subsystem was interconnected by means of a custom 26-pin tether, built in-house. The tether would also provide the connection to the devices responsible for fulfilling the camera attitude control, camera pose reporting, and video broadcast communications link functions. In the mean time, these functions would be simulated with direct wiring to a testing computer using a RS-232 serial command modem and the video capture device (See Section 3.7.2).

Finally, the D-STAMP camera subsystem was tested in three phases. In the first phase, the subsystem was powered on correctly with no camera attitude control input. The setup can be viewed in Figure 4.2b. This test verified the integrity of the camera subsystem wiring, the power supply's ability to control the initiation sequence, the D-STAMP's ability to inertially stabilize the camera when the base was moved, and the overall functionality of the camera subsystem. In the second phase of testing, the subsystem was evaluated in a laboratory setting with camera attitude control as input. To provide this input, the configuration files of Controp's software were modified to accept input from a COTS joystick with custom hotkeys, allowing the Camera Operator to change operating modes of the camera, direct the camera orientation, and adjust the zoom level of the camera. The controller is pictured in Figure 4.2c. This indoor test evaluated a subset of operating modes, those that functioned independently of a GPS signal and large motions of the D-STAMP. In the third phase of testing, the camera subsystem was evaluated outdoors to evaluate the 10x optical zoom and test those operating modes that required a GPS, but did not require large motions of the D-STAMP. The test matched the performance of the Controp GPS device against that of a handheld car navigation GPS navigation device.

By ensuring the startup sequence, wiring the D-STAMP camera subsystem, and verifying functionality indoors and outdoors, the D-STAMP camera subsystem was deemed ready for full flight evaluation to test the flight modes of the D-STAMP, such as the hold coordinate mode, and test the D-STAMP's performance with wireless data links supporting the camera attitude control, camera pose reporting, and video broadcast communications link functions.



(a)

(b)

(c)

Figure 4.2: Controp D-STAMP gimbaled camera subsystem: (a) power supply, (b) test setup, and (c) configured joystick with commands labeled.

4.1.4. Motion Measurement Equipment

A principal stumbling block in the construction phase of the MARP was the failure of MicroPilot 2128g hardware and software suite to perform as advertised, as related in Section 3.4.

4.1.4.1. Original Approach to Fix the Motion Measurement Equipment

The MicroPilot organization was contacted for technical support regarding this advertisement. They confirmed that the advertised functionality could be made available with the existing MP 2128g model (already in possession) and required the purchase of

"Extended Technical Support" before a representative would assist the process. Upon purchase of this support, MicroPilot provided only a single three-page document and a small software upgrade. All technical representatives contacted were unfamiliar with the coupling of the MicroPilot and Controp systems and the engineer responsible for the reported functionality no longer worked at the company. All these events took place within the same month as the news release advertisement.

Unassisted troubleshooting of the MP 2128g suite continued, until further testing revealed that the MicroPilot software contained a rigid restriction in its programming that prohibited the switching of operating modes for the D-STAMP, such as direct control of the camera's facing orientation in rate mode and automatic tracking of targets in the hold coordinate mode. This restriction proved to be unacceptable, even if the MicroPilot equipment was to be made ready.

4.1.4.2. Other Unsuccessful Approaches

Following the abandonment of the MicroPilot-based approach, several other approaches were considered. First, a Procerus Kestrel autopilot with a small form factor was tested to measure motion and broadcast this data to the GS. Live broadcast of the UAV's position and orientation was limited to 10 Hz (slower than the required 29.97 Hz). It was attempted to log UAV motion data at higher rates on the Kestrel for later retrieval, but this limited flight time for missions, demanded long periods of time between missions to extract the data, and went against the consolidated MARP requirements. Neither use of the Kestrel enabled coordination with the D-STAMP's video stream.

4.1.4.3. Functioning Motion Measurement Device

Internal to the D-STAMP are a set of linear accelerometers and rotational rate gyroscopes that measure the motion of the D-STAMP base as input for the real-time calculation of the internal D-STAMP control computer to inertially stabilize the camera and track GPS coordinates. This procedure is done independently of the GS and the Camera Operator. These measurements are sampled and reported through the RS-232 serial link at a rate of 10 Hz to the Controp Software at the GS, but this speed is too slow for coordination with the 29.97 Hz video signal at the GS; however, further examination of the Controp Communications ICD and a white paper by Controp revealed that this important measurement information is encoded into every frame of the D-STAMP's video output [25; 26].

The D-STAMP could serve as the motion measurement device as long as the video stream broadcast communications link function is fulfilled (see Section 4.1.5), sending the video stream to the GS for pre-processing to extract the motion measurement data, and coordinating this information with the video stream as processed by the real time video processing software. Analysis of Controp's proprietary message encoding format revealed that this data extraction would be trivial to automate at real-time speeds. A sample screenshot of a video frame with motion measurement data, encoded at the top and bottom of the image, is shown in Figure 4.3. The data includes the position, velocity, and orientation of the D-STAMP camera along with other pertinent information and it is inherently synchronized with the video stream. This process delivers accurate motion measurement data at the full frame rate required by the MARP. Additionally, it eliminates the need to independently calculate the pose of the camera from the measurement and comparison of aircraft motion and camera deflection.

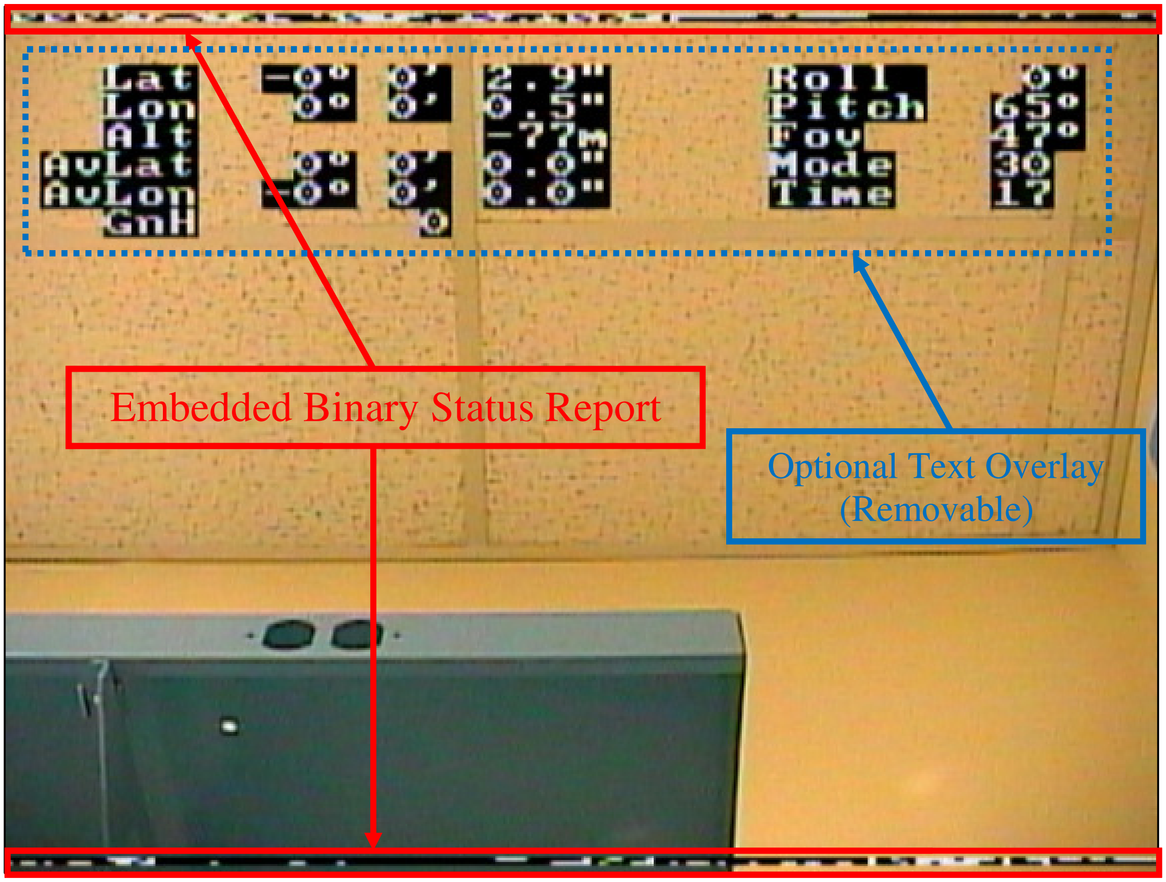


Figure 4.3: Sample of full D-STAMP motion measurement report embedded in every video frame along with optional text overlay that can be toggled on/off.

4.1.5. Communications Equipment Testing

As has been established, there are four communications link functions that must be satisfied for the MARP: camera attitude control, camera pose reporting, aircraft control, and video stream broadcast.

4.1.5.1. Camera Attitude Control Communications Link Function.

As discussed in Section 3.5.1, the initial approach relied on the advertised integration of the MicroPilot and Controp hardware. This approach was no more successful for camera control than the attempt to use the MicroPilot for motion measurement.

The alternative approach was to use a serial modem at any available frequency to communicate between the GS computer and the D-STAMP camera. Three different modem pairs were tested, using the setup diagramed in Figure 4.4, with a PicoScope 3224 digital oscilloscope to compare an original wired signal with its transmitted counterpart. The radio modems were cycled through their available settings, but the original and transmitted signals did not match.

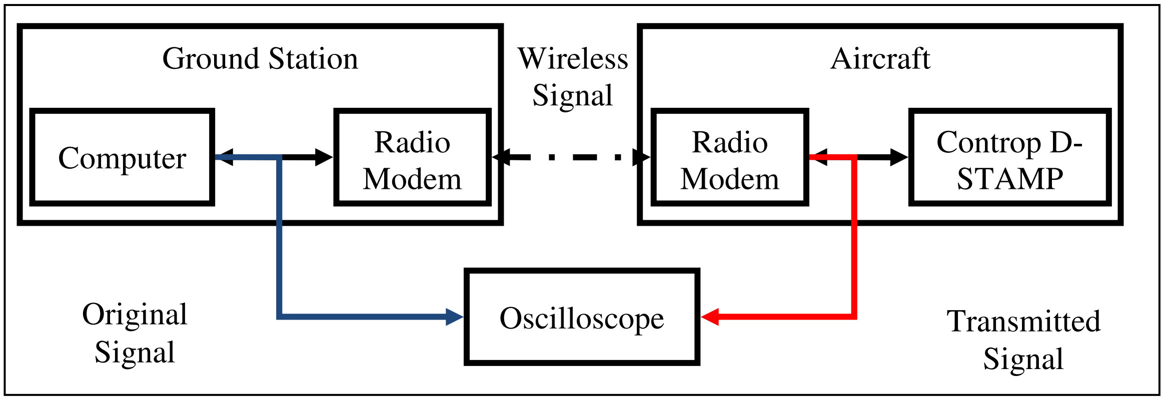


Figure 4.4: Communications diagnostic setup diagram with two channels reading the original signal (blue) and the transmitted signal (red).

Eventually, a FreeWave Technologies MM2 Developers Kit was selected that included a pair of user-reconfigurable 900 MHz radio modems and related equipment. These radio modems made a wireless RS-232 serial connection between the D-STAMP and the GS computer. Iterative testing and extensive technical support brought the FreeWave modems through about 80 different combinations of settings before discovering a configuration that would fully satisfy the D-STAMP's communication specifications. On each configuration test, the original and transmitted signals were compared to report the ratio of fragmented message transmissions to correct message transmissions. An example of such a test is shown in Figure 4.5. Reducing this ratio satisfied the requirements of the MARP.

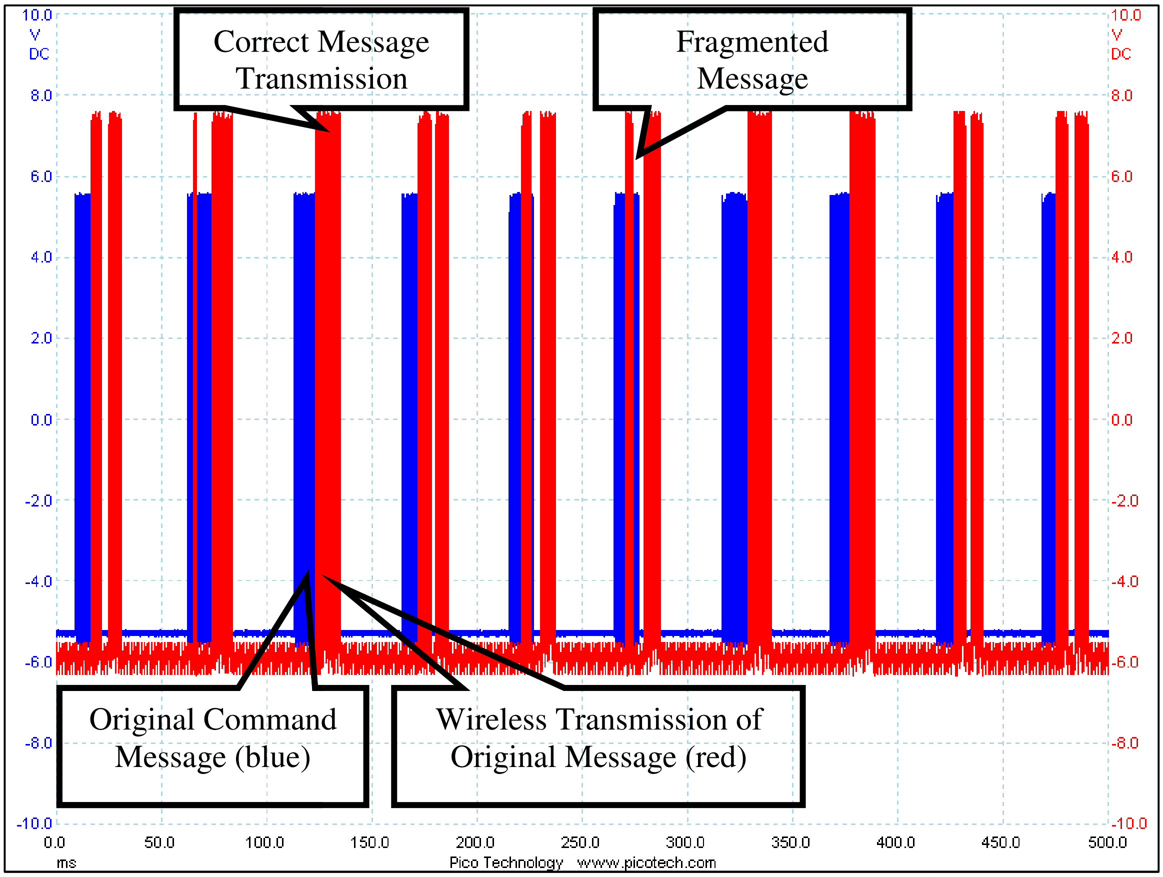


Figure 4.5: Example oscilloscope reading of original signal (blue) followed by wireless transmission of that signal (red) of a command messages between the D-STAMP and the Ground Station.

4.1.5.2. Camera Pose Reporting Communications Link Function.

The successful solution described in Section 4.1.4 for motion measurement by video broadcast and data extraction from video frames is the same method by which the communications link function for camera pose reporting would be fully satisfied. The task was thereby moved to the video stream broadcast device.

4.1.5.3. Aircraft Control Communications Link Function.

The XtremeLink FHSS 2.4 GHz transmitter and receiver worked perfectly "out of the box" to fulfill the aircraft control communications link function. This success further justified the reliance on proven RC model aircraft technology.

4.1.5.4. Video Stream Broadcast Communications Link Function.

The Iftron Technologies 5.8 GHz Stinger Pro 250 mW video transmitter and the YellowJacket Pro video receiver were successfully tested in the laboratory to transmit full-size, full-rate NTSC video signals. This equipment would also have to function outdoors, onboard a moving UAV, at larger distances, with real world strains such as vibrations and obstacles. Full field testing was needed to verify operation in this real world environment, so it was scheduled as an objective in the flight test program. Successful outdoor testing during a flight would validate the prescribed approaches for motion measurement, camera pose reporting, and video stream broadcast.

4.1.6. Ground Station

The various GS components were assembled. This included the ground-half of the communications equipment, including the FreeWave 900 MHz serial modem for camera attitude control, the Iftron Technologies 5.8 GHz YellowJacket Pro video receiver for video stream broadcasting and camera pose reporting, and the XtremeLink 2.4 GHz transmitter for aircraft control. The GS also included the camera joystick, the video capture device, the temporary laptop computer, a TV VCR for viewing video and backup recording, and assorted equipment for servicing the MARP.

4.1.7. Resulting Maryland Academic Research Platforms

The final configuration of the MARP Mark I is illustrated in Figure 4.6.

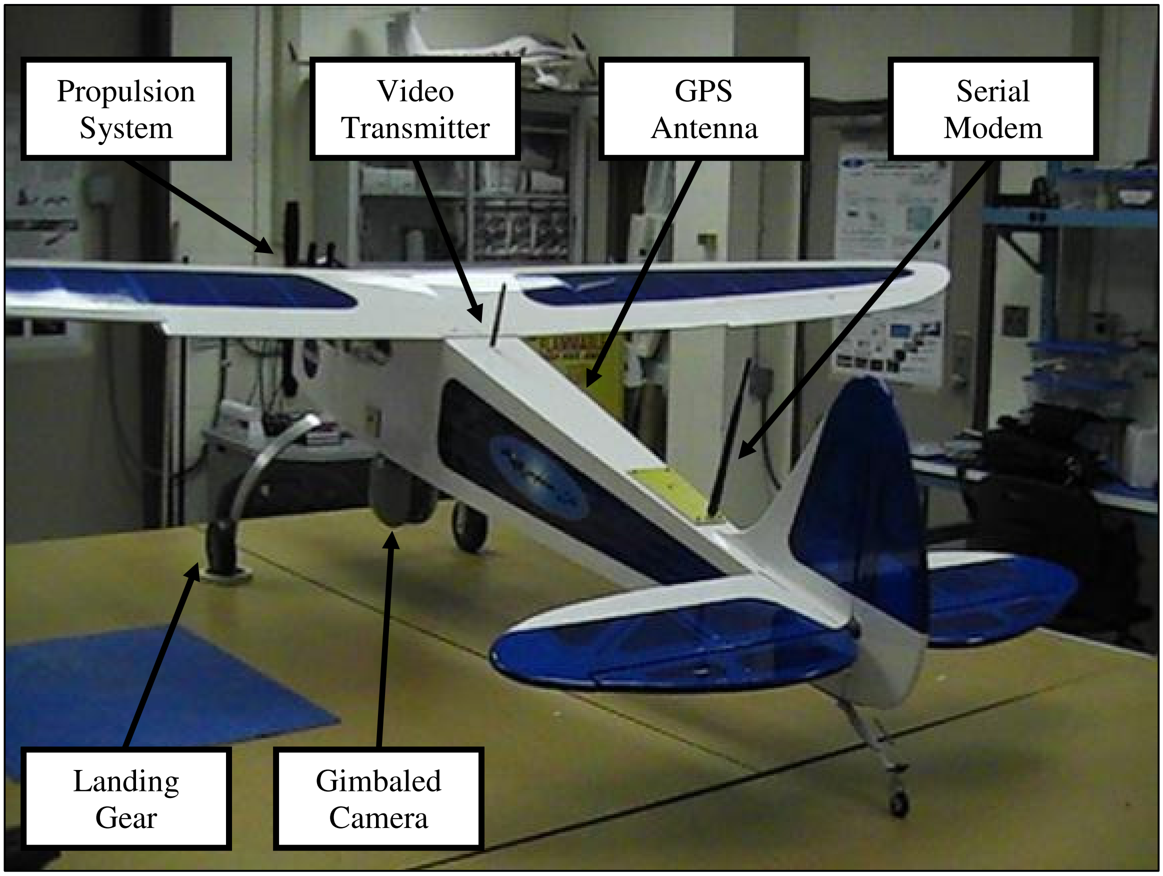


Figure 4.6: "MARP Mark I" assembled on tabletop.

This UAV was damaged beyond repair in a test flight in Hampton, VA in October 2009. Reconstruction of the UAV provided the opportunity to improve a number of aspects of the UAV.

Reinforcements were made to the installation point of the D-STAMP camera. The portions of the balsa fuselage surrounding the hole in the aircraft were strengthened with epoxied plywood and extended to include the mounting point of the landing gear.

The propulsion system was reconfigured with the ignition system placed directly beneath the engine and engine mount.

A service door was added beneath the nose to improve access to engine mounts and permit loading of the fuel tank.

The remote operations component of the aircraft testbed was improved by housing the XtremeLink receiver in a plastic test box with foam cushioning surrounding the device. All servo wires could be attached to the receiver through an access hole in the top. This was placed in the midsection of the aircraft on the floor of the fuselage to improve reception for most aircraft orientations.

The battery array was reorganized to mount the batteries on a removable battery shelf, installed in the main cabin area of MARP Mark II. Batteries were fixed in place with Velcro. The shelf was fitted with screw mounts so that the area underneath the batteries could be accessed, namely the Controp D-STAMP support structure and the Iftron Technologies video broadcast device. Batteries responsible for the aircraft testbed were affixed with Velcro behind the windshield on a special platform.

As noted, it was critical to power on the subsystems in the correct order. The remote operation system must be activated first, followed by engine ignition, then the serial command modem, then the video broadcast system, and finally the D-STAMP camera. To reduce the chance of operator error, a control panel was built on the left side of the fuselage with switches arranged in a top to bottom sequence for correct operation. The switches were oriented so that all systems were engaged when the switches were directed aft.

The final configuration of the MARP Mark II is illustrated in Figure 4.7

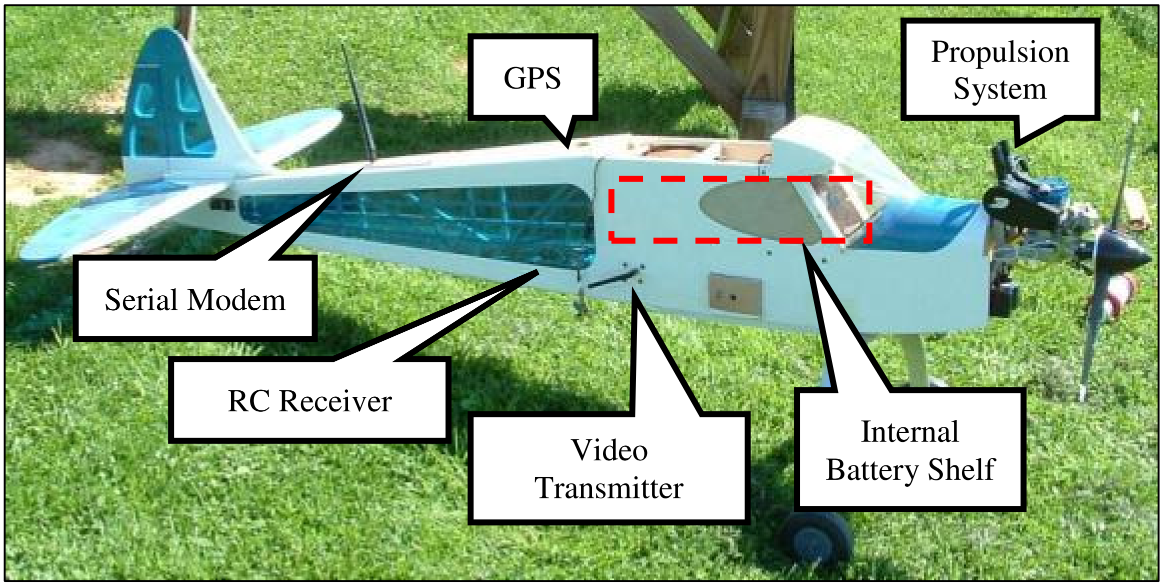


Figure 4.7: Onboard equipment locations for MARP Mark II.

4.1.8. Ground Station Equipment Upgrades

The GS equipment was upgraded based on lessons learned during MARP Mark I test flights. A television was added for live viewing of the D-STAMP's footage as well as to provide a backup data log with the built in Video Cassette Recorder (VCR). The GS Computer still commanded the D-STAMP with the Controp provided software. It also had a video-to-USB converter to record the video stream to the computer's hard drive. These devices were used with the existing radio modem and serial command modem. At this point, the GS Computer described in Section 3.7.3 was acquired and incorporated to replace the interim computer. Portable generator power was used to meet the substantial total power demand of the GS. Figure 2.3 shows the GS equipment as used in the field.

4.2. First Oxford, PA Flight Test

On this flight day, MARP Mark II was flown twice. The first test evaluated the aircraft testbed independently. The second test involved the entire the integrated system. The flight tests were run in Oxford, PA at the Cloud Kings of Oxford RC Park.

Figure 4.8: MARP ready for takeoff without D-STAMP.

4.2.1. Maiden Flight of MARP Mark II

The first fight was a shake-down test to prove the flight worthiness of the aircraft. In preparation for this flight, the Controp D-STAMP camera and support structure was removed and the insertion hole was covered with the same plastic skin material that wraps the majority of the aircraft. This covering helped reduce the parasite drag that would result from such an opening.

This flight demonstrated the air worthiness of the aircraft. Brian Porter of the Army Research Lab was the pilot for the MARP. He trimmed the aircraft in flight and performed a number of tests to get the "feel" of the aircraft. The plane went though several stall tests where the aircraft was pitched upward at high altitude, losing all airspeed and lift to demonstrate stall recovery.


(a) (b)

Figure 4.9: Successful (a) takeoff and (b) landing of the MARP during the maiden flight.

4.2.2. Equipment Integration Test Flight

The MARP was then transformed into a fully integrated system as a testing apparatus. The film covering the insertion point was removed so that the support structure of the Controp D-STAMP could be interfaced with the rest of the airframe. The holding rod locked the unit in place and all connections were made to the wiring tether for video broadcast and command through the radio modem. This flight fulfilled the long held desire to utilize this D-STAMP camera for aerial observation.

This was a very productive flight. The camera smoothly steadied itself as the plane pitched, rolled, and yawed, maintaining a constant inertial orientation. Video reception worked. Command of the D-STAMP worked. The airframe, propulsion system, and remote operations equipment all worked properly and passed post-flight inspection. This test also helped pinpoint three areas needing improvement: (1) D-STAMP responsiveness and modular interface, (2) communication link quality, (3) video acquisition.

4.3. Resolving Issues Identified During the First Oxford, PA Flight Test

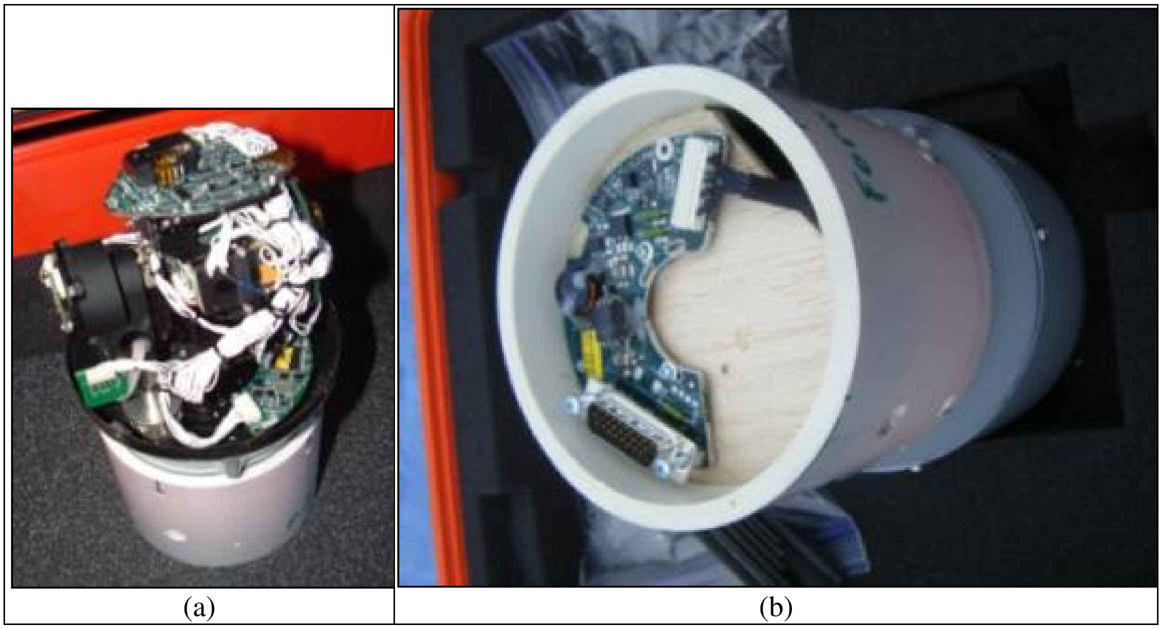
As addressed, there were three issues found from the test flight that needed to be remedied before the MARP's next flight test: the D-STAMP needed to be made responsive again, the communications link quality of the video broadcast needed to be improved, and the video acquisition process needed to be analyzed.

4.3.1. D-STAMP Responsiveness and Modular Interface

The Controp D-STAMP gimbaled camera had stopped responding to remote input, but would still provide video. After several days of testing, the problem was traced to the D-STAMP rather than a supporting system. The main gimbal for controlling the camera's azimuth angle from the base showed a significantly reduced slew rate at some portions of the 360° rotation.

Controp Precision Technologies offered to inspect the D-STAMP the following day at their United States office. The camera along with the rest of the equipment was taken to their office in Bethesda, MD. James Dotan and Roberto Rivas of Controp found that there was a mechanical problem with the bearings supporting the azimuth gimbal servo rotation. An iterative process of adjusting the bearings, reassembling the D-STAMP, and commanding motion through a powered harness gradually restored proper operation.

The camera was further improved by installing the Controp power supply to the upper portion of the support structure. This enabled the payload to be quickly added and removed from the remainder of the UAV for servicing and safe transportation.



(a) (b)

Figure 4.10: Controp D-STAMP (a) internal view when undergoing repairs and (b) with power supply integration to support structure.

4.3.2. Communication Link Quality

During the test flight, the video signal would cut in and out as the aircraft moved farther away from the GS. The GS was even moved out from underneath the shelter in attempt to improve the signal strength, but this was to no avail. New antennas and a revised antenna placement were used to strengthen the broadcast signals.

The Iftron Technologies YellowJacket Pro 5.8 GHz video broadcast receiver is normally equipped with a pair of omni-directional antennas that can receive a signal when the aircraft is anywhere in the 360° region surrounding the receiver, but within a limited functioning distance. A stronger connection was obtained by replacing the omni-directional antennas with a pair of directional antennas that each focus in a cone shape radiating from each antenna. The resulting reception shape extends to a much farther distance, but it must be aimed in the general direction of the aircraft to work. To this end the video broadcast receiver was augmented with a manual aiming turret to enable to maintain the video connection.

The manual aiming turret was composed of three main components: the receiver, an interface mount, and a camera tripod. The interface mount was made from a wooden Section fitted with a 1/4”-20 blind nut. This is the standard dimension for many camera tripod bolts. The interface mount was strapped to the receiver with Velcro and zip ties. It attached to the tripod by screwing in the quick release Section of the tripod. The video receiver assembled with the pair of directional antennas on the adjustable turret is shown in Figure 4.11a.

(a) (b)

Figure 4.11: New antenna arrangement: (a) assembled directional video receiver turret and (b) serial modem mount construction.

The serial command modem was improved by creating a mount so that the modem could be raised off the ground to reduce the effect of ground-based multi-pathing. Like the video receiver modification, the modem was placed on top of a camera tripod to keep it stable and elevated. When covered, this modification protects the radio modem and allows it to be attached to a tripod for field use as part of the GS. The field unit is shown assembled in Figure 4.11b.

4.3.3. Video Acquisition Improvement

When reviewing the footage of the test flight at the GS there was oddly no video present on the laptop's hard drive. The digital recording setup did not work and there was not a simple method present to confirm that video was indeed recording. Fortunately, footage was caught on the backup VCR. Careful review of video images from the First Oxford, PA Flight Test suggested there might be flaws in the video recording equipment initially employed. This was confirmed by feeding a test pattern to the existing equipment as shown in Figure 4.12. The pattern was originally composed of only black and white pixels; instead greens, reds, oranges, and many shades of gray are incorrectly recorded onto the hard drive.

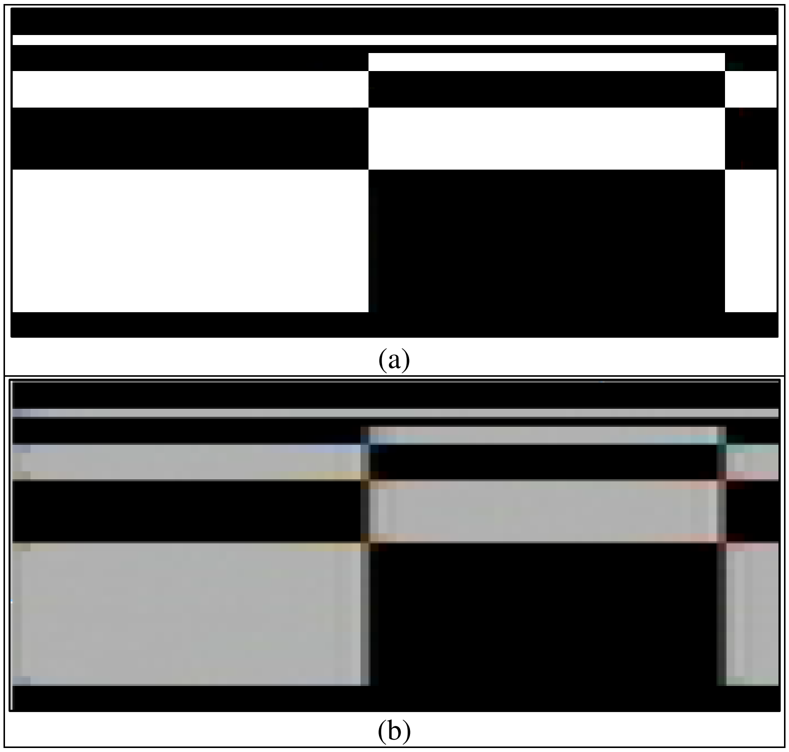

(a)
(b)

Figure 4.12: Black and white video test pattern (a) expected value and (b) pattern incorrectly recorded by old hardware.

The hardware and software were replaced by using the Imaging Source's Video-to-USB Converter DFG/USB2-lt and software. The system is capable of producing crisp images of each video frame received in real time according to the manufacturer [49]. Testing was required to confirm this capability.

Figure 4.13: Imaging Source DFG/USB2-lt Video-to-USB Converter.

4.3.4. Ground Station Testing

After improvements were made to the video receiver, the video acquisition equipment, and the serial command modem, the system was tested and configured independently from the aircraft. The two main components considered in this testing were the serial command modem and the video equipment. The serial modem worked properly when transmission power was raised slightly to a 500 mW output level. The video equipment, on the other hand, required a deeper evaluation method. It was tested for functional distance and endurance.

The functional distance test was done outdoors along the shore in Annapolis, MD where a stretch of road curved in an arc allowed for a clear line of sight between most points along the road. Video was transmitted from a small camera, included with the Iftron Technologies hardware, to the video broadcast receiver turret. This video then passed to the DFG/USB2-lt converter where the raw video frames were recorded on the computer. Landmarks in the video were marked on a map with a handheld GPS. These coordinates were compared with those of the GS to determine the distance at which the video signal deteriorated. When there was a clear line of sight, the video was of good quality at 3200 feet away (the longest test distance available)! When obstructed, the connection was satisfactory at a range of approximately 200 feet.

An additional lesson was learned that helped shape the video acquisition process. At one point during the procedure, the transmitter passed by a large transformer whose electro-magnetic interference knocked out the communication temporarily. The software then stopped recording without indication and had to be manually restarted. A highly visible command clock was incorporated into the graphical interface in order to monitor the health and functionality of the recording system.

Figure 4.14: Distance test for video ground station equipment.

The endurance time test used the same physical setup. The transmitter and receiver were left on for 25 minutes while the laptop's memory and CPU resources were monitored. The computer experienced no change with respect to either variable after the first minute of the digital video recorder initialization. The limiting factor from this test was deemed to be the size of the hard drive. Space was made on the hard drive for 16 hours of recorded video.

4.4. Second Oxford, PA Flight Test

A second series of test flights were conducted at the Cloud Kings of Oxford RC Park in Oxford, PA. The goal of this flight test day was to prove the full integrated functionality of all subsystems of the MARP in preparation for a final test and live video recording exercise at the Fort Indiantown Gap urban environment, scheduled to be completed three days later. All components of the MARP were tested for flight: the GS was tested to confirm that the camera could be commanded while the UAV was airborne and that the MARP could provide the high quality video essential to comply with the consolidated MARP requirements. The MARP was set up for flight, the aircraft was flown as the camera was commanded, and the video acquisition system received video from the UAV with a high strength signal. This section also covers the events that lead to the crash of the MARP Mark II UAV at the conclusion of the flight evaluation.

4.4.1. Setup of the Maryland Academic Research Platform

The GS of the MARP was comprised of a serial command modem and a video receiver turret to communicate with the UAV, a laptop to control the onboard camera's motion as well record digital video, a TV VCR for live viewing and back up recording, and a video camcorder for documentation. A diesel generator provided AC power for the electronic systems. This GS was setup as pictured in Figure 2.2.

The GS was to be manned by a team of four individuals: a Pilot, one Camera Operator, an Antenna Operator for the video receiver turret, and a Flight Documenter.

The Pilot would command the RC transmitter in full view of MARP Mark II to conduct safe flight of the UAV. The Camera Operator would sit at the laptop and access the Controp D-STAMP command software interface and pilot the aircraft using the joystick while also observing the Imaging Source DFG/USB2-lt software interface to view the live video stream from the D-STAMP. The backup TV VCR was to be placed in view of both the Camera Operator and a turret operator. This turret operator was to responsible for aiming the video receiver turret with the Iftron Technologies Stinger Pro 5.8 GHz device with the directional antennas pointed toward the aircraft. The final member of the team, the flight documenter, was to operate the video camcorder to log the flight from the ground. On the day of the test flight, only two crew members were available: the pilot and the Camera Operator. This did not pose a problem, because each element of the total system operation was to be tested separately.

The UAV was then prepared for flight. The wings were installed on the fuselage with wing struts attached to the hard points to secure the wings in flight. The voltages of the batteries were checked. The batteries were installed inside the fuselage with Velcro in the preset positions for weight balance. Power was activated to the onboard systems for an initial check. First the serial command modem was activated and communication was established between the GS and the UAV. Second, the video modem was powered. Third, the Controp D-STAMP camera payload was activated, providing the video modem with a signal. This signal showed the start up and calibration process for the camera gimbals. With all systems go, the aircraft was fueled with the gas-oil mixture and the aircraft was balanced to confirm its center of gravity position for stable flight. The UAV is shown at its preparation station in Figure 4.15.

Figure 4.15: MARP Mark II in final configuration.

4.4.2. Flight Footage

The engine of the aircraft was started and MARP Mark II was ready for takeoff. Correct control of the onboard camera was demonstrated as the system successfully transmitted video data to the GS. During the 15 minute flight, the pilot directed the UAV in a constant elliptical circuit around the flying field. This allowed the GS operator sufficient experience to improve his handling skills to control the D-STAMP camera. The skill acquisition began with simple operating modes where the operator provided direct input to steer the camera up, down, left, and right. This later moved on to manually tracking objects on the ground and then in utilizing more of the advanced operating modes of the camera payload. During this portion of the flight evaluation, the camera's Heads Up Display (HUD) overlay was activated to provide critical information regarding the camera's position, orientation, and its current operating mode. The HUD is shown in Figure 4.16.

(a) (b)

Figure 4.16: Heads Up Display in D-STAMP video stream with camera facing (a) right landing gear and (b) RC Park Facilities.

The camera was also put through a series of tests. During the latter portion of this flight, the camera was qualitatively evaluated for its performance in responding to different real world scenarios. The HUD was deactivated to provide an unobstructed view of the environment, depicted in Figure 4.17. The Controp D STAMP is equipped with inertial stabilization. This was tested by positioning the camera at an arbitrary angle as the fuselage of the UAV was put into oscillating rolls by the pilot. As the body of the aircraft moved, the rate gyroscopes of the camera payload detected the motion and triggered the gimbal motors to compensate for the motion. This allowed the inertial facing angle of the camera to stay constant as the aircraft moved. The features of the camera's optical zoom and coordinate holding were also tested and shown to be satisfactory.

(a) (b)

Figure 4.17: View provided by the MARP of (a) the farm composing the flight field and (b) the bordering forest.

4.4.3. Crash of MARP Mark II

For fifteen minutes, the Second Oxford, PA Flight Test proceeded as planned, demonstrating a successful test of many system and subsystem requirements of the MARP. It appeared that all was in readiness for the final test and video recording exercise at Fort Indiantown Gap in three days. However, as the pilot began descending for the final circuit before landing, the wing bolts sheared and failed and the wings detached from the main fuselage of the plane. The pilot attempted to recover the aircraft, but elevator deflection and throttle usage could not reorient the plane from its nose dive. MARP Mark II fell along its ballistic path to the ground. See Figure 4.18.

Figure 4.18: Crash photo of aircraft testbed and onboard equipment.

The wings had fluttered to the ground approximately 30 yards from the crash site of the fuselage. The majority of the components were found at this location. The force of the impact buried the engine into the ground, shearing the thick aluminum mounting bracket into pieces. The front half of the aircraft was decimated. Several of the Lithium Polymer batteries had their cells ruptured in the crash. They were contained in a metal firebox overnight to prevent additional harm from a potential explosion. The D-STAMP base was still attached to the support structure of the airframe, unmoved in the crash, but the head of the D-STAMP camera had sheared off of its base, approximately 20 yards from the crash site.

It was determined from examining the wreckage that the wing bolts holding the wings to the fuselage snapped at the head, releasing the wings into the air as the fuselage fell as a projectile. These nylon wing bolts are the standard hardware provided as part of the Sig Rascal 110 kit. This test flight showed that they were inadequate to carry out their function.

4.4.4. Video Capture and Corruption

Because the testing apparatus had a live communication link, the video data from the Mobile Video Platform of the MARP successfully arrived at the GS. This is how video frames could still be retrieved, despite the crash of the aircraft. During the 15 minutes of the Second Oxford, PA Flight Test, video was recorded live to the computer, via the video capture device, and to the backup Video Cassette Recorder, providing two records of the flight from the perspective of the Controp D-STAMP camera payload. The thesis researcher walked into the field to locate the crash site while the video capture software was finishing its save of the digital video file to the hard drive of the GS Computer. A well meaning observer turned off the GS computer before the system had completed saving the video. This corrupted the video file.

Fortunately, the VCR provided a VHS cassette video tape of the flight footage. The cassette footage was a little grainy, blurring a few pixels and preventing the extraction of the motion data information from the video frames. Nevertheless, the flight footage provided from the VHS backup is a valuable asset. It confirms that the MARP could successfully provide full resolution video at the full frame rate in the video format required by the consolidated MARP requirements; it shows that the fixed wing UAV provided a smooth flight, improved by the gyro-stabilized D-STAMP camera payload; and it demonstrates the value of a backup video recorder.

4.5. Resolving Issues Identified During the Second Oxford, PA Test Flight

The flight evaluation at Fort Indiantown Gap was intended to be flown with MARP Mark II, but because of the Oxford test flight crash three days before the scheduled urban environment test, this was not possible. ARL kindly loaned the use of one of their helicopter Unmanned Aerial Systems so that the Ground Station of the MARP could be run through a set of tests to verify is adherence to the consolidated requirements of the MARP.

The Second Oxford, PA Test Flight revealed a need to protect the video data upon acquisition by the GS hardware. The corruption of the captured video motivated a full switch in the way the DFG/USB2-lt video capture device was to be used. Instead of saving the video at the conclusion of the test flight, the video acquisition system was modified to save video frames individually so that a similar system malfunction would not destroy the whole of the video data. A ground test of the revised GS configuration was conducted. It confirmed that the MARP GS could continuously save video frames individually for at least 25 minutes (the tested endurance time of the previous configuration). This 25 minute recording ability of the MARP GS was greater than the longest reported flight time of the ARL helicopter UAV and thus marked as satisfactory for testing at the Fort Indiantown Gap flight location.

4.6. Verification of Ground Station Equipment

The flight evaluation at the ARL Fort Indiantown Gap, PA site had been planned months in advance. This was a sophisticated location containing a mock city with 14 buildings of a variety of shapes, several streets, walls, towers, and hills as picture in

Figure 4.19. The hybrid Unmanned Aerial System was setup to mix ARL equipment with the surviving equipment from the MARP Mark II. Seven flights were performed on May 11th, 2010.

Figure 4.19: Aerial photograph of Fort Indiantown Gap site provided by the Army Research Lab.

This thesis researcher brought the GS computer; video capture equipment; tripods to hold documentation equipment and ARL's video receiver; several spare parts such as wires and adaptors to interface the two sets of equipment; and furniture to protect the equipment, including chairs, a table, and large canopy. The GS was setup along the pavement of one of the streets of the urban environment on the edge of the imaginary flight line established to protect bystanders from a potential crash. The equipment from ARL and the University of Maryland were integrated to form the GS.

The GS video receiver was composed of a Yagi directional antenna, receiving the 100 mW signal on the 1.2 GHz band and paired with the ARL helicopter UAV. It was integrated to the MARP Mark II GS video capture device and processing computer. The antenna was mounted on a camera tripod. The processing computer had been upgraded to use the DFG/USB2-lt video capture device and software from The Imaging Source to capture and save each video frame one at a time.

The GS computer and other devices were protected by large tent canopy. It was expected to begin raining early in the day. The canopy protected the equipment when it began to rain after the seventh flight. It helped keep the equipment dry as the system was packed away in the vehicles. A folding table kept the computer off the wet ground and placed the display at eye level so that the Camera Operator could view the perspective of the camera, steer the camera to aim at new orientations, and monitor the video saving status of the computer. The GS also included two tripods to hold a digital photography camera and a video camcorder to document the flight evaluation process. The assembled GS is presented in Figure 4.20.

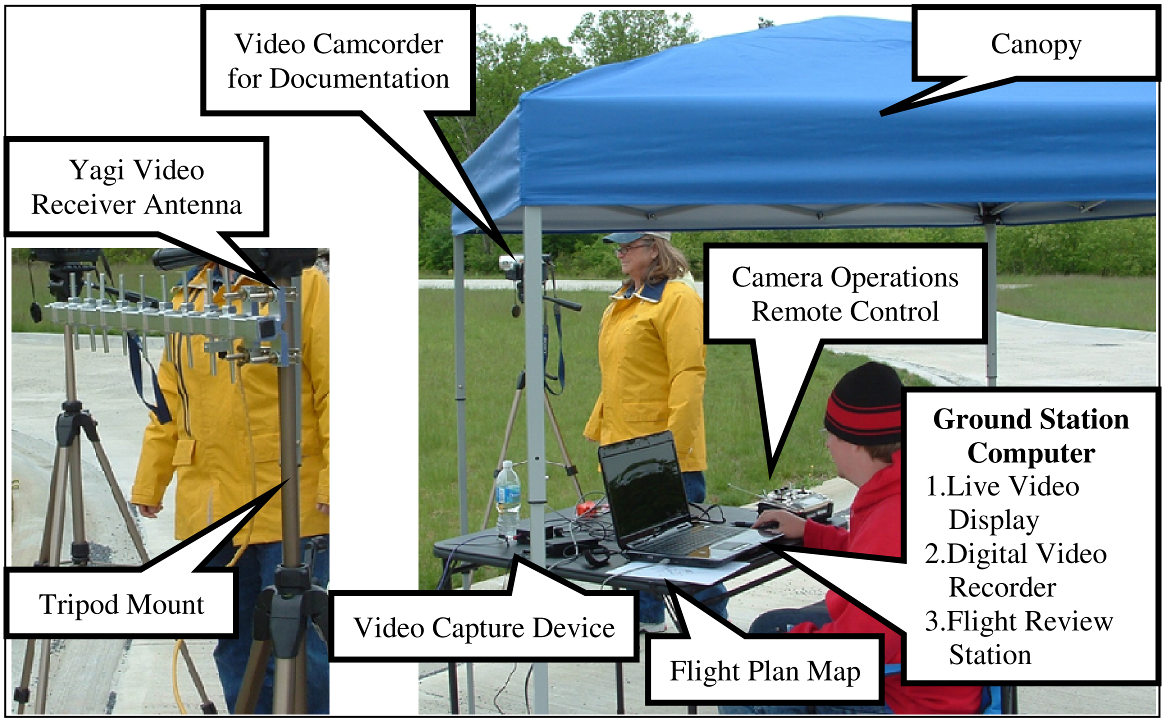


Figure 4.20: Ground Station configuration for Fort Indiantown Gap flight evaluation.

Figure 4.21 samples a few of the video frames of the flight evaluation as well as the locations at which they were taken.

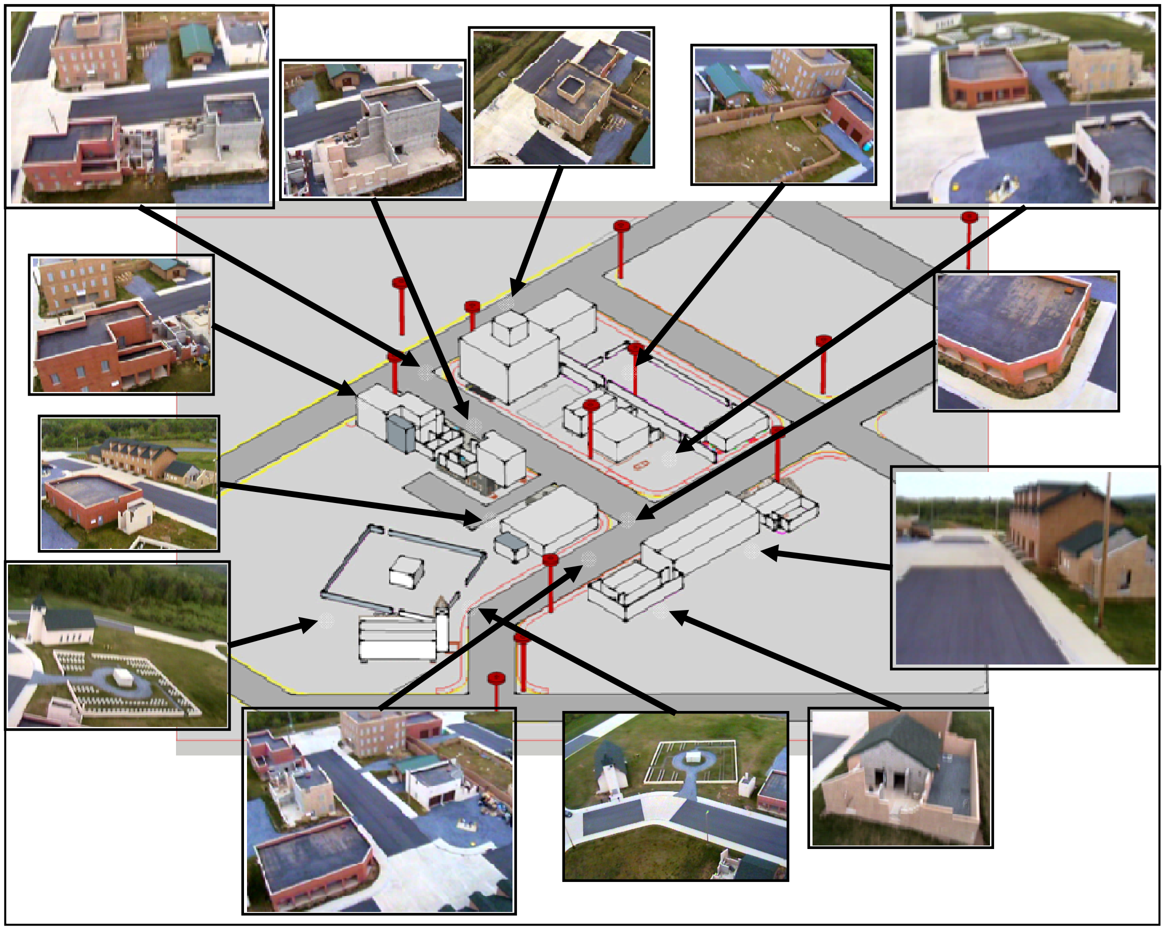


Figure 4.21: Video frames collected observing many different buildings referenced on 3D map of Fort Indiantown Gap site.

The Fort Indiantown Gap flight evaluation produced lots of video. The system stored the raw, uncompressed video frames at the full 640 by 480 pixel resolution at the full rate of 29.97 frames per second. These video frames were deinterlaced into odd and even fields as discussed in Section 3.3.3.2. This produced two separate progressive videos that could serve and input to the execution of ISR research application algorithms performing real time video processing. More than 120,000 images, containing 51.5 gigabytes of data were written onto 14 data DVDs after the ground station test. The video was paired with Camera Calibration data of the ARL helicopter UAV camera, according to the procedure referenced in Section 3.3.3, to measure the lens distortion of that camera.

This endeavor successfully tested the functionality of the MARP GS in the acquisition and live recording of video. It also showed that the MARP GS Computer had sufficient resources remaining to execute ISR research algorithms had they been loaded onto the GS Computer.

Chapter 5. Conclusions and Recommendations

This thesis successfully completed the objective to design, construct, and flight test the Maryland Academic Research Platform (MARP) to satisfy the consolidated requirements of the selected Intelligence, Surveillance, and Reconnaissance (ISR) research applications. In this chapter, those fulfilled requirements are enumerated as requirements derived from the ISR research applications and requirements inherent to Academic Research Platforms, then a presentation of the lessons learned is presented, and finally future work is recommended.

5.1. Fulfillment of Requirements Derived from ISR Research Applications

The requirements derived from the ISR research applications pertained to four categories: the sensor payload, the airframe, the processing equipment, and the communications equipment.

5.1.1. Sensor Payload Requirements

The MARP sensor payload requirements include stabilization, high resolution video output, computer processable imagery, a camera that is vectorable, and inertial motion measurement. The Controp D-STAMP camera used in this thesis research inherently satisfied many of the sensor payload requirements. It is a stabilized, vectorable, high resolution camera system, with built-in motion measurement devices. However, significant effort was required to extract the data from those internal motion measurement devices and to format the raw video output of the D-STAMP to become computer processable imagery.

5.1.2. Airframe Requirements

The MARP requirements dictate that the airframe is to be very stable and be able to sustain the weight of the UAV in flight. The customized Sig Rascal 110 aircraft powered by the 1.6 cubic inch Evolution 26GX gas engine provided the turbulence rejection necessary to aid in the stabilization of the D-STAMP camera and provided the lift necessary to support the 15 pounds of onboard equipment, including the D-STAMP, the communications systems, fuel, and batteries. Control, stall recovery, and handling remained adequate to maneuver the UAV after heavy modification, including extra drag from the placement of the belly mounted camera.

5.1.3. Processing Equipment

The selected GS Computer was a COTS ASUS Notebook N51Vn Series laptop, featuring a NVidia GeForce GT 240M CUDA 1 GB Graphics Processing Unit (GPU) measured to be several times as fast as a GPU that had previously accomplished real time video processing in Section 3.7.3. The GS Computer was configured and tested to run multiple applications including full resolution, uncompressed digital video recording, while demonstrating remaining available system resources to complete more tasks.

5.1.4. Communications Equipment

Communications equipment was necessary in the MARP to establish a four links between the UAV and GS: camera attitude control, camera pose reporting, aircraft control, and video broadcast. A significant time was spent configuring hardware and software on several candidate communications link devices with problems ranging from incompatible bit level input/output to gross simplifications of advertised functionality of components. In the end, devices were chosen to provide an adequate connection between the UAV and the GS. Camera attitude control and camera pose reporting were supported by the two-way FreeWave Technologies MM2 900 MHz serial modem. Aircraft control was performed by Futaba remote controller with the XtremeLink FHSS 2.4 GHz transmitter. Video broadcast was handled by the Iftron Technologies Stinger Pro 250 mW video transmitter and YellowJacket Pro video receiver with directional antennas.

5.2. Fulfillment of System Level Requirements Inherent to the Academic Research Platform

As a total system, the MARP must be affordable, legal to fly, and operable by a small, relatively untrained crew.

5.2.1. Affordable

A key objective of this research was to design, build, fly an affordable ARP. The most expensive component of the MARP was the Controp D-STAMP camera, which retails for about $30,000. This unit was available at the beginning of the research effort and has the high-end sensor capabilities needed for the execution of ISR research. As demonstrated by conversion of the ARL helicopter UAV (see Section 4.6), the tools and techniques assembled by the researcher allow the rapid calibration and adaptation of any digital camera as a sensor for ISR research. The particular sensor system for future research can be chosen based on resolution, stabilization, vectorability and pose reporting characteristics required by the chosen ISR research application.

Total cost of the Sig Rascal airframe, the propulsion system, communications equipment, batteries and miscellaneous wiring, connectors and supplies to modify and assemble the entire MARP was an order of magnitude less than the cost of this sensor payload. The use of COTS equipment for the Ground Station proved an economical and effective solution. The total cost of the entire MARP was substantially less than the prices of military and corporate UASs, including the ones highlighted in Table 1.1. This level of affordability makes the MARP and systems like it feasible for academic research institutions.

5.2.2. Legal to fly

As discussed in Section 3.1.1.2 and especially in 3.5.3.1, there are strict legal requirements constraining the operation of UAVs by civilian researchers in the general U.S. airspace. The particular UAV was selected to provide adequate flight characteristics for ISR research while remaining within these constraints. The operation of the MARP at two flight parks within the standards and respective ordnances of the parks demonstrates achievement of this objective.

5.2.3. Manageable by a Small, Relatively Untrained Crew

As noted in Section 2.4, the MARP resulting from this research effort is best operated by a crew of four, although for several test flights it was operated with less. Most operational roles can be fulfilled by amateurs (e.g. research assistants); however, the responsibilities of the Pilot are best suited for someone with training and experience. RC training simulators and trainer aircraft exist to teach an amateur how to fly, but there is substantial risk involved entrusting the UAV to the hands of a novice.

5.3. Lessons Learned

Through the undertaking of this thesis research, several important lessons were learned. By taking account of these lessons, future researchers can significantly expedite development of future ARPs and devote more of their time to ISR research.

The first and foremost observation is the supreme importance of a rugged UAS for testing. The equipment must be highly reliable with redundant subsystems to protect against failure. It is recommended that more time be allocated to flight with dummy payloads to prove out the UAV.

It proved difficult to maintain the required level of video quality with respect to signal strength, bandwidth, and freedom from transmission artifacts. The researcher was able to obtain satisfactory communication quality by dedicating a crew member to constantly aim the video receiver antennas toward the UAV. Research conducted in a military environment would have access to military communications equipment with broadcast capabilities exceeding those of legal civilian wireless devices.

Vibration prevention and mitigation is necessary to provide a smooth trajectory for successful real time video processing. The combination of the large wingspan of MARP Mark I and MARP Mark II with the gyroscope stabilization of the gimbaled camera helped to provide a trajectory that has been qualitatively evaluated as "very smooth". It has not yet been established quantitatively what smoothness is required for real time video processing of aerial footage.

A final conclusion is that the archaic NTSC video format, used from 1941 to the present, is a significant hindrance to efficient implementation of video processing on a UAS, such as is planned for various ISR research applications with the MARP. Many video cameras, like the gimbaled camera used in this research, record progressive video and are forced to internally convert it into interlaced frames to satisfy the NTSC standard. The methodologies described in Section 3.3.3.2 will help researchers work around this constraint until an all-progressive format is adopted by more video hardware.

5.4. Recommended Future Work

5.4.1. Use Thesis Work as Baseline for ARP Production

It is recommended that the procedures and experiences of this thesis research be treated as a baseline in the creation of an Academic Research Platform.

5.4.2. Quantify Vibration Tolerance Levels for ISR Applications

Vibration prevention and mitigation is necessary to provide a "smooth" trajectory for many of the identified ISR research applications. At present there are no objective measures of what constitutes "smooth" or any criteria for how smooth is smooth enough. The large wingspan of the MARP UAV combined with the gyroscope stabilization of the gimbaled camera helped to provide a trajectory that has been qualitatively evaluated as "very smooth". This suggests a topic for future research, perhaps in a simulated environment of a chosen ISR research application requiring real time video processing. The output could be quantifiable compared with the true simulation values, showing the boundaries of tolerance levels on vibration magnitudes.

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