Team Manitoba 2006 AUVSI Student Competition Project Description

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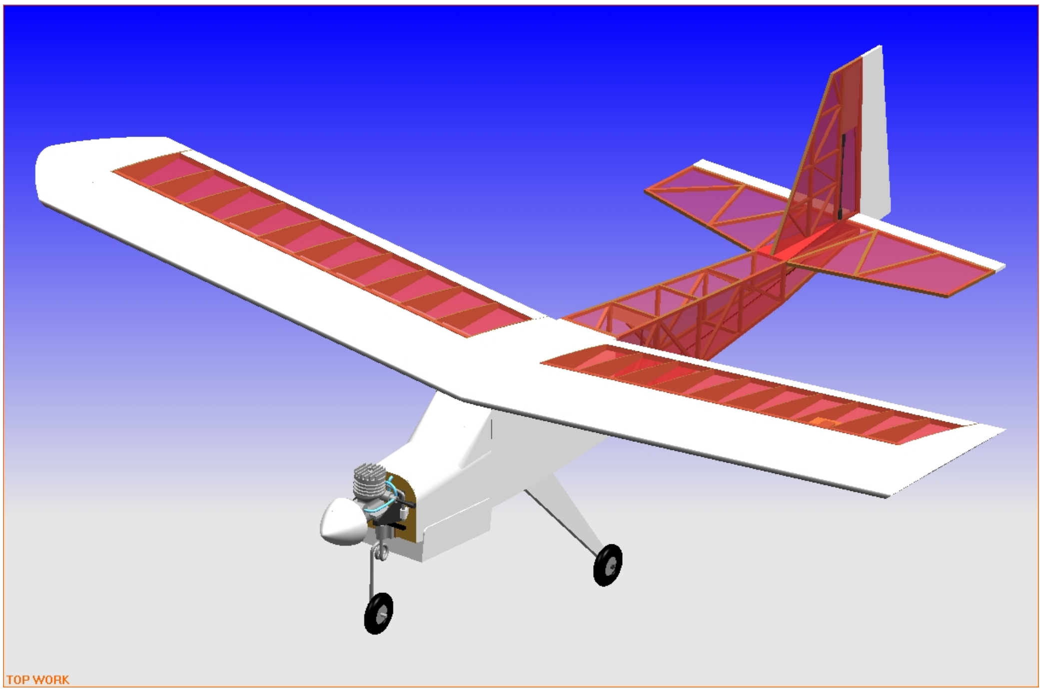

Abstract

This paper describes the Team Manitoba entry for the 2006 AUVSI Student UAV competition. After identifying major functional and non functional requirements, Team Manitoba designed a system based around four major subsystems: a fixed wing airframe, a Micropilot MP2027g autopilot, a ground station system, and an imaging system. These subsystems are mainly based around commercial off the shelf components that were assessed to fulfil the major functional requirements. Custom software was developed where no commercial solution was available or appropriate. For the ground station, custom software transforms a mission description into a script file for the Micropilot MP2028g. For the imaging station, custom software captures low resolution video during the flight and displays a VCR like interface which an operator may search for regions of interest. The regions of interest are marked and automatically linked to the high resolution images downloaded after the UAV has landed. To address the non functional requirements of robustness and safety, Team Manitoba adopted an iterative, incremental development strategy, fully testing each subsystem and integrating them one at a time. Throughout the development and integration process, a comprehensive safety checklist system was developed. Each subsystem shortcoming or failure resulted in a design change or checklist point. Through this iterative process, the daily and per-flight checklists account for all known safety and performance risks.

1 Introduction

1.1 Requirements

The Team Manitoba UAV Group entry for the 2006 AUVSI Student Competition began by identifying the major functional and non-functional requirements of the system. These requirements were used as guidelines throughout our development process.

1.1.1 Functional Requirements

Vehicle Control: The competition dictates four functional requirements regarding vehicle control. The vehicle should be capable of an autonomous takeoff; the autopilot system should be capable of changing flight parameters while the vehicle is in the air; the vehicle should be able to navigate GPS waypoints; and the vehicle should be capable of an autonomous landing.

Imaging: The imaging system has two functional requirements. It should be able to capture imagery of a search area that is of sufficiently high resolution to identify targets that are 4 feet squared. It must also be able to translate image coordinates to GPS coordinates based on the estimated position of the aircraft when the image was acquired.

1.1.2 Non-Functional Requirements

In addition to the functional requirements outlined by the competition rules, Team Manitoba assessed three additional non-functional requirements: The final system was to be robust, safe and exhibit autonomous behaviour wherever possible and appropriate.

1.2 Overview of system

1.2.1 Response to functional requirements

The Team Manitoba UAV competition entry is composed of 4 subsystems: airframe, autopilot, ground station, target identification. The airframe was chosen to be a kit plane that would be easily modifiable, have a large cavity in the fuselage to allow separation of components and offer stability of flight to reduce the pressure on the control systems. The autopilot chosen was a Micropilot MP2028g, an off the shelf autopilot system that, when well tuned, can perform all of the functional mission requirements regarding airframe control and has a flexible scripting language that may be used to build complete missions. The ground station software is composed of two parts: the Horizon software that comes bundled with the autopilot and custom mission generator software called Zenith. Zenith accepts mission definition parameters and builds a script file that is executable by the autopilot. The target identification system consists of a live video feed and a high resolution still camera. Target identification software offers a VCR-like interface for viewing the live video feed, it handles translation of image to GPS coordinates based on the telemetry of the airplane and it automatically finds high-resolution

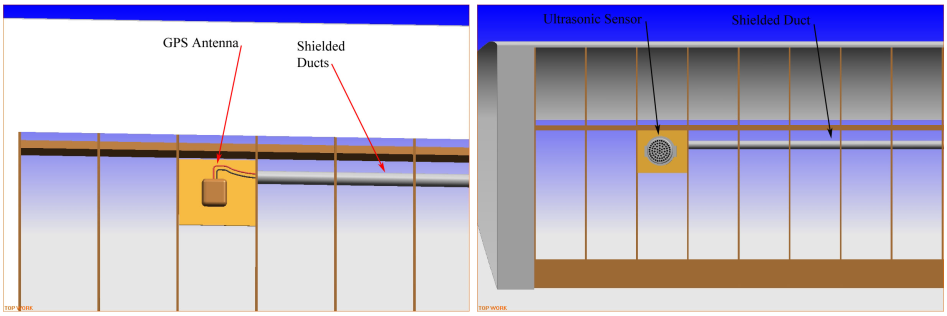

Figure 1: GPS antenna and ultrasonic AGL sensor mount points.

images that correspond to regions of interest flagged by the operator in the live video feed.

1.2.2 Response to non-functional requirements

To address the issue of robustness, the system was designed so that the subsystems interact as little as possible. To address the issue of safety, the system was developed using an iterative incremental development and integration strategy. Finally, each subsystem was designed to require operator involvement only at the highest levels, delegating tedious and error prone work to our custom software systems.

2 Airframe

The University of Manitoba UAV was created from a commercially available off the shelf remote control aircraft kit. The kit chosen supplied the raw materials for construction with no prefabricated components. This type of kit allowed for extensive modification of the airframe design. With no prefabricated sections, the team was able to mount components with special attention to potential RF interference. To this end, components and antennas were mounted with maximum separation distance within the airframe and wings and select components and cables were shielded.

The UAV was created from a modified SIG Kadet Senior kit. The Kadet Senior is a high wing monoplane consisting of built up balsa / spruce construction with a flat bottom constant chord wing. The intended configuration of the Senior called

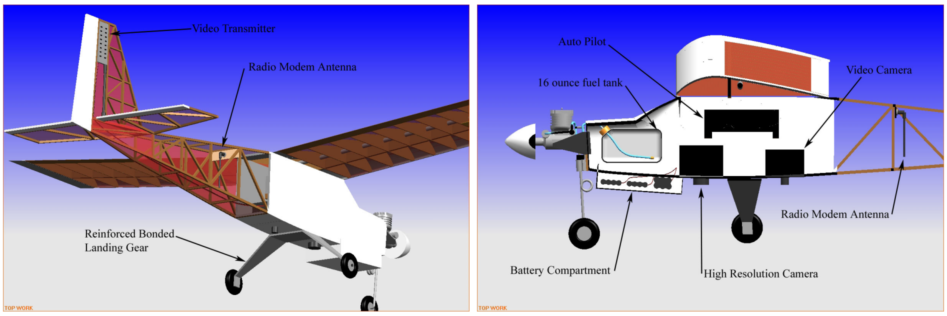

Figure 2: Aft and cutaway views of the airframe.

for three control functions: elevator, rudder, and throttle. The manufacturer's suggested power plant called for a .40-.50 cubic inch two stroke engine fed by a ten ounce fuel tank placing the intended take-off weight of the aircraft between six and seven pounds.

2.1 Modifications

In order to have a suitable platform for competition, a number of important modifications were performed during the construction of the airframe:

- Ailerons were installed for use with the micropilot.
- The wing was modified with a reinforced spar design as well as being made to be broken down into halves.
- The horizontal and vertical stabilizers were modified to be separable from the fuselage.
- The leading surfaces of the wing were reinforced with 1/32 balsa sheet enclosing the d-tube providing a more ridged structure.
- Wire landing gear was replaced with a two piece bonded aluminium main gear and a twin strut nose gear to compensate for the added weight of the modified configuration.
- The front section of the fuselage was left with the engine exposed and an access hatch was added provide access to fuel supply lines and pushrods.

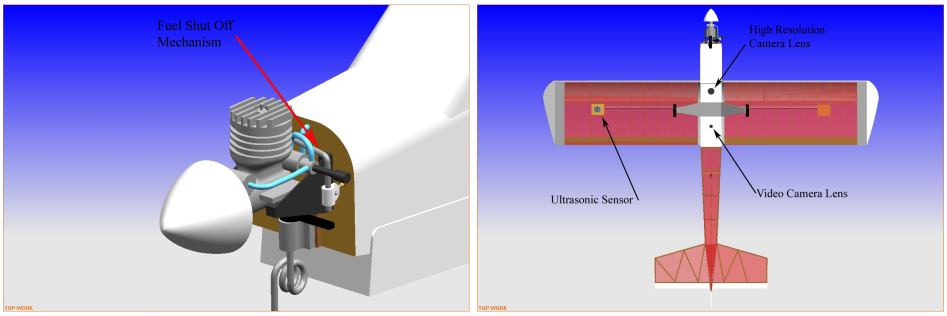

Figure 3: Fuel shutoff mechanism and airframe bottom view.

- An external battery tray was added to the front of the fuselage behind the nose gear.

2.2 Layout

The components were mounted within the airframe with a great deal of concern afforded to potential interference amongst the various antennas and transmitters. The GPS antenna and the ultrasonic sensor were mounted in opposing wings. Placing these two sensors in the wings, created good separation while maintaining a safe distance between the ultrasonic sensor and the engine during flight. The leads connecting the GPS and ultrasonic to the fuselage were run through shielded conduits mounted within the wings. The shielded conduits were fabricated from several alternating layers of aluminium foil and paper cured in an epoxy resin that was donated by local industry (Figure 1).

The radio modem antenna was mounted facing downward in the aft section of the fuselage (Figure 2) while the video transmitter was mounted within the vertical stabilizer. All wiring through the fuselage was shielded with aluminium. The fuel shutoff mechanism required to eliminate fuel flow to the engine should the aircraft lose communication with the base station was mounted directly to the front of the firewall (Figure 3).

During flight testing it was noted that battery packs required frequent charging and as a result a solution was required to minimize the amount of disassembly required to the aircraft to maintain battery power. All batteries were mounted in an external tray beneath the forward fuselage of the aircraft (Figure 2). The batteries mounted in the front of the aircraft effectively counteracted the effects of the added moment caused by having the video transmitter located so far aft in the vertical stabilizer. The external packs may be easily accessed by removing the forward tray without having to remove the wing from the aircraft. This minimizes operator stress and disruption to the radio compartment.

The high resolution digital camera represented the highest concentration of weight within the fuselage and was also amongst the most delicate components. The camera was mounted as close to the center of gravity as possible while maintaining a lens position between the reinforced landing gear struts (Figure 3). This minimized the chance of the lens striking the ground in the event of a failed landing. The lens of the camera was also protected by a glass filter mounted in the belly of the aircraft to protect against stone chips on take offs and landings. Similarly the video camera was mounted as close as possible to the center of gravity to minimize its movement relative to the aircraft and in turn provide more accurate telemetry of targets.

2.3 Range, performance and mission capabilities

The Kadet Senior Aircraft, once modified and mission ready, had 4.71 kilograms of extra hardware mounted within the airframe. The aircraft however, displayed excellent slow flight characteristics with stall speeds as low as 4.25 m/s. Estimated range of the aircraft at an average speed of 15m/s is 31.5 kms. This range corresponds to flight times in the range of 28-32 minutes in duration.

3 Autopilot

Mission requirements specified that our UAV must be capable of GPS waypoint navigation, autonomous takeoff and landing, and dynamic adjustment of the flight plan and flight parameters. The Micropilot MP2028g autopilot board was able to fulfil all of these requirements. The MP2028g peripherals include a GPS unit and antenna, three-axis gyroscope and accelerometer, relative airspeed probe, pressure altitude transducer, 2.4GHz radio modem, AGL ultrasonic altitude sensor, and external servo board.

The gyroscope, accelerometer, pressure altitude transducer and airspeed probe provide feedback at 5Hz. The data from these sensors supplement the GPS signal, which is updated at 1Hz. These feedback measurements are incorporated into twelve PID feedback loops shown in Table 1 which are used to control the UAV. The primary stability loops control the servos directly whereas the navigation loops control higher level parameters affecting navigation of the UAV.

Primary Stability Loops		
PID Number	*PID Name*	*Controls*
0	aileron from roll	aileron
1	elevator from pitch	elevator
2	rudder from Y accelerometer	rudder
3	rudder from heading	rudder
4	throttle from speed	throttle
5	throttle from altitude	throttle
Navigation Loops		
PID Number	*PID Name*	*Controls*
6	pitch from altitude	desired pitch
7	pitch from AGL	desired pitch
8	pitch from airspeed	desired pitch
9	roll from heading	desired roll
10	heading from crosstrack error	desired heading
11	pitch from descent	desired pitch

Table 1: Table of PID feedback loops.

The 2.4GHz radio modem provides the communication channel between the MP2028g and the base station. The modem is mounted outside of the autopilot casing and connects via an RG-223 SMA cable the antenna mounted behind the autopilot in the fuselage.

An ultrasonic AGL sensor provides landing assistance by accurately measuring the altitude of the UAV up to approximately 15 feet. The sensor is mounted in the aircraft wing to minimize interference from engine noise.

The MP2028g can also be programmed with flight failure patterns. These are flight patterns which are executed given a particular in-flight failure. There are seven possible failures, some of which are recoverable. The failures are ordered in terms of their priority shown in Table 2. Non-recoverable fatal errors assume a higher priority than the recoverable low priority failures.

Failure Number	Description	Pattern Name	Recoverable
0	Control failure	controlFailed	no
1	Fatal error	fatalErrorFailed	no
2	Loss of GPS	gpsFailed	yes
3	Loss of engine power	engineFailed	no
4	Low battery voltage	batVFailed	no
5	RC link failure	rcFailed	yes
6	Horizon communication link failure	gcsFailed	yes

Table 2: Autopilot failure patterns

4 Ground Station

4.1 In-flight software

The Micropilot MP2028g is bundled with the Horizon ground station software. Horizon, along with the “fly file” scripting system is capable of fulfilling the functional requirements of planned flight execution, dynamic flight parameter modification, and triggering a camera at specified locations.

4.2 Mission Planning Software

Hand scripting of the Horizon “fly file” based on mission requirements would be time consuming and error prone. The Zenith Mission Generator was created to handle this task. Zenith consists of modules which provide for input, processing, and display of mission component data, and for generating a final autopilot script to be executed by the Micropilot Horizon software. The design of the software was optimized for creation of new modules to allow us to easily integrate unanticipated tasks at the competition.

4.2.1 Application Framework

Zenith was developed in C# with the .NET framework because it allows for rapid development, testing, and debugging. Because of the need to remain flexible with mission components, the .NET reflection capabilities were used to create a plug-in architecture. Any class which inherits from the base MissionState class will be displayed for the user as a mission component. Relevant properties for each component are also displayed dynamically using reflection without requiring separate user interface code. In this way, each component is encapsulated and does not need code for setting up and processing the user interface controls.

4.2.2 Mission Viewer

The mission viewer control is a custom 2D mapping system designed to display a map of the operation area and the positions of mission components. It uses the .NET graphics classes for easy image display and creation. Each time the display is updated, the each mission component draws itself on the map in an appropriate way. This prevents the mission viewer from being filled with code to recognize and draw each of the mission components itself. Again, this promotes easy addition, modification, and removal of mission component classes at any time without adverse impact on the other modules or the system as a whole.

4.2.3 Mission Components

The *Takeoff* mission component serves as the starting point of every mission. It has no parameters and simply inserts the `takeoff` scripting command into the .FLY file. This places the autopilot in a mode that awaits takeoff instructions from the operator. Since the takeoff occurs wherever the aircraft is placed, there is no way to set the location of the takeoff in software and it is not drawn on the mission viewer.

The *Waypoint* mission component uses the latitude and longitude as the arguments to a `flyTo` scripting command. The `flyTo` command's goal is to get the aircraft to the specified point, regardless of the path required to do so. The autopilot system has rules for when it considers the aircraft to be at a waypoint which are designed to prevent it from getting stuck attempting to capture a waypoint exactly. For example, if the turning radius was too large to allow the aircraft to reach the waypoint, the rules would prevent it from circling indefinitely.

The *TakePicture* mission component is similar to the *Waypoint* component. However, it activates the high resolution camera when it reaches the waypoint, capturing imagery of the area.

The *Search Area* component takes a GPS center point, radius, and a number of other parameters and then creates the search pattern depicted in Figure 5. This is a wind-aligned pattern that makes passes over the search area such that the entire area is covered completely. Each pass begins with a setup waypoint in line with the entry to the search area. This is used to assist the autopilot in entering the search area in the correct direction. The next waypoint is the entry into the search area. At this point, the camera system is activated (see Section 5.1) and the aircraft flies across the search area until it reaches the exit waypoint and deactivates the camera system. In order to keep the aircraft close to the intended path, the `fromTo` autopilot script command is used which attempts to keep the aircraft flying along the line connecting the entry and exit points. Once the aircraft reaches the exit point, it proceeds to the collector point on the side farthest from the next pass. This is to allow for the greatest turning radius before beginning the next pass.

The *Landing* mission component is the final entry in a mission. Like the Takeoff component, it has no parameters and is not drawn on the mission viewer. It inserts the `circuit` scripting command into the .FLY file. The `circuit` scripting command causes the aircraft to descend to the altitude of the landing circuit, make a series of turns to align itself with the runway, and then land on the runway where the `takeoff` command was triggered. Since the autopilot sets the runway location and direction based on the direction of the autonomous takeoff, the manual suggests only using autonomous landings where an autonomous takeoff was performed in order to make a reliable landing.

5 Imaging Station

5.1 Target Identification Hardware

This section discusses the hardware and software that Team Manitoba used to meet the requirement to obtain high resolution images of the search area. In contrast to our 2005 platform, which had only a low resolution real-time video feed, this year's system includes a high resolution digital still camera. We realized this requirement when last year's performance was hampered by the difficulty that the target spotter had in distinguishing target-like objects from actual targets and in providing an accurate description of the targets. Many applications of unmanned aerial vehicles would require this kind of detail in the returned imagery.

There is one barrier that prevents obtaining real-time high resolution imagery from the aircraft - bandwidth. To make use of the highest resolution imagery possible, we decided the images were to be stored on the camera in the aircraft and processed after landing. The camera chosen was an off-the-shelf Sony DSC-V1. It was chosen based on customer reviews of a very short delay between the triggering of an image capture and the actual image capture as well as a short time to save the image to the removable media. These qualities both aid an accurate and complete coverage of the search area. In practise, we can obtain a capture rate of one picture every two seconds. To capture of an image, the Micropilot triggers a servo that is positioned to press the shutter button.

An unguided search of the high resolution imagery after the flight would be overwhelming for a small number of operators. We make use of the low resolution real-time video feed to allow the operator to flag regions of interest to be searched in the later high resolution images. Access to the high resolution images is through a panel-mount USB connection to the camera open to the outside of the airframe.

To allow transformation from a given image coordinate to a GPS coordinate, the position and orientation of the aircraft must be known. To achieve this, the output from the radio modem is split to both the base station and the image station.

The camera systems are completely separate systems from the autopilot and control systems. The processing of the video stream and images is done on a separate computer from the computer running the Micropilot Horizon ground control software. The only connection is a splitting of the serial signal from the radio modem to both the Horizon station and the imaging station. Failure of the imaging system (battery failure, communication failure) does not at all affect the performance of the other systems.

5.2 Target Identification Software

The target identification software comprises a telemetry capture module, an interpolation module, a video capture module, a video 'VCR' module, a camera calibration and transformation module, and a high resolution composite module.

The telemetry capture module records incoming telemetry from the Micropilot to a database. This information arrives at approximately 5Hz and requires interpolation for telemetry requests for times between actually received telemetry. The telemetry fields that are used for the transformation of image coordinates to GPS coordinates are longitude, latitude, altitude, pitch, roll, ground track, and airspeed.

The interpolation module provides telemetry at a requested time to the other modules. A module requests telemetry for time t. The interpolation module queries the database for a neighbourhood of telemetry around time t and returns an interpolated telemetry for the requested time. An important aspect of this interpolation is the ground track field. The ground track is reported by the Micropilot based on historical GPS position changes. Therefore, there is a lag between the start of a turn and the reported change in ground track. To avoid this, a feedforward prediction is made on the ground track based on roll and airspeed. If the aircraft's roll has been below a threshold for a minimum amount of time, the interpolation module simply returns a linearly interpolated ground track as the true ground track will not be changing rapidly for low roll changes. If the aircraft's roll is greater than the threshold, the ground track is forecast using the last reliable ground track and a calculation of yaw rate based on airspeed and roll [Smi96].

Future work on the interpolation module will include calculation of heading given the reported ground track, ground speed, airspeed, and estimated wind speed. Furthermore, it should be possible to calculate the wind speed online by analyzing the groundspeed, groundtrack, and airspeed if sampled through all 360 degrees of ground track.

The video capture module captures images delivered to the video capture card and stores them to a file, named according to the capture time.

The video 'VCR' module is the target spotter's main interface during the mission. It can playback in real-time the image stream being saved by the video capture module and be paused, reversed, fast-forwarded, or directed to display any time of interest to the spotter. Included with this module is a point and click interface to mark and record regions of interest to be examined later on the high resolution digital still images. The method of determining the GPS coordinate for the selected point of interest is described next.

The camera calibration and transformation module is the key to determining the GPS coordinates any point of interest in an image. The cameras are calibrated using an implementation of Tsai's camera calibration technique [Tsa86] Our implementation is a slight extension of a freely available implementation [Wil]. Calibration gives us a model of the intrinsic and extrinsic parameters of the cameras. The intrinsic parameters are the focal length, radial lens distortion coefficient, and the centre of the radial lens distortion on the camera's sensor aircraft. The external parameters are the rotation angles and translation components for the camera at the time of calibration. The extrinsic parameters can be used to determine the mounting angle of the cameras by calibrating the cameras while holding the aircraft so that the Micropilot reports 0 degrees of pitch, roll, and yaw.

Using the telemetry returned from the interpolation module and this camera model generated by our calibration, we calculate the GPS coordinate of any pixel on any image that is captured throughout the mission.

The high resolution composite module is used for processing of the high resolution images after landing of the aircraft. The images are first mounted to the filesystem on the image station. Next, each image's Exif data [EXI] is examined to determine it's capture time. Using this capture time, interpolated telemetry for this time, and the camera model, we determine the GPS bounds of each image. If any high resolution images encompass a point of interest selected by the spotter from the low resolution video feed, its bounding box is overlayed on an overhead view of the search area. The operator then only needs to review the relevant high resolution images. From these, the final confirmation, labelling, and recording of a target is performed.

6 Incremental development

In order to speed up and increase the safety of the system development process, Team Manitoba adopted an iterative, incremental development process. The integration schedule in Table 3 was designed to integrate decoupled components one at a time until the whole system was assembled. Each flight test, a log was kept including the wind and humidity, the duration of each flight, comments on each flight and a trouble log. The trouble log included the following columns: Problem Encountered, On Site Solution, and Follow-up Needed. This allowed us to compile a list of work to be done during the week in our lab after each flight, saving valuable flight test time. It also allowed us to track and deal with persistant problems that arose over the course of many tests. Finally, it allowed us to re-arrange our schedule to focus on trouble areas in the system. At the time of writing, Team Manitoba has completed all 9 scheduled flight tests. Further flight test plans will be dictated by our performance during simulated competitions.

Flight Day	Flight Plan
1	Tune inner PID loops
2	Tune outer PID loops (outer loops)
3	Control of high resolution camera. Manually triggered pictures.
4	Fly to and take a high resolution picture autonomously.
5	Autonomous takeoff and landing.
6	Autonomous takeoff and landing.
7	Fly wind aligned search pattern with high resolution pictures.
8	Integrate video system (added risk of RF interference)
9	Simulated competition.

Table 3: Flight test schedule.

7 Flight testing procedures and safety

During the flight testing process, Team Manitoba developed an extensive system of checklists. Both the groundstation team and the airframe team had daily and per-flight checklists. Any time a system failed or an unsafe situation was assessed (see the description of the trouble log in the section above), a check was added to the appropriate list to ensure that the situation would be detected should it arise again. Our checklists are included as Figures 6 and 7.

8 Conclusion

The Team Manitoba entry in the 2006 AUVSI Student Competition followed a requirements driven, iterative, incremental Systems Engineering approach that focused on ensuring the safety and performance of the process and product. Each of the four major subsystems (the airframe, autopilot, groundstation, and imaging system) have been fully tested and integrated. The completed system is capable of fulfilling all of the functional and non-functional requirements outlined in Sections 1.1.1 and 1.1.2 above.

References

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[Tsa86] Roger Y. Tsai. An efficient and accurate camera calibration technique for 3d machine vision. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 364–374, Los Alamitos, CA, June 1986. IEEE Computer Society Press.

[Wil] Reg Willson. Tsai camera calibration software. Website. http://www.cs.cmu.edu/afs/cs.cmu.edu/user/rgw/www/TsaiCode.html.

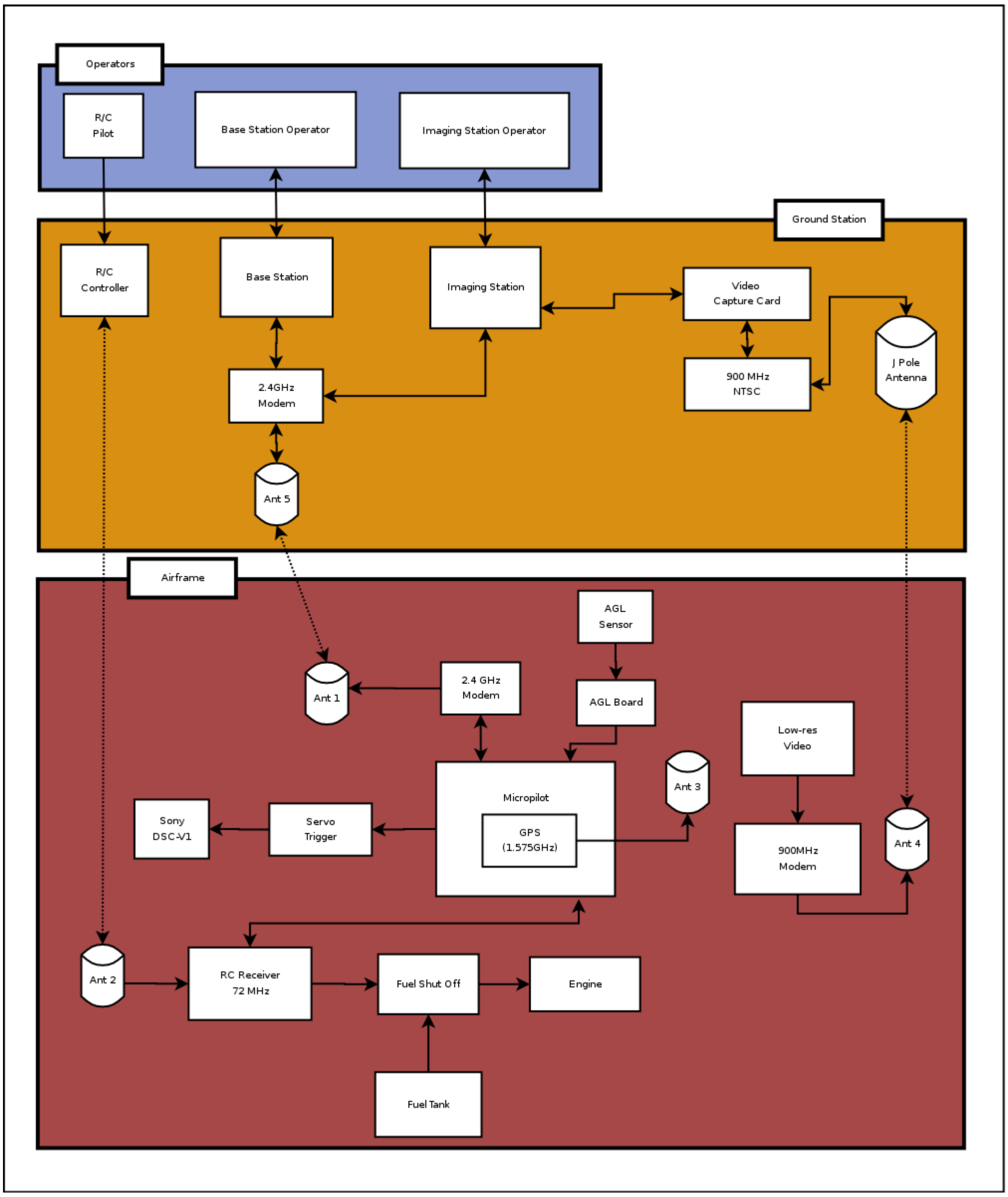

Figure 4: Full block diagram of system.

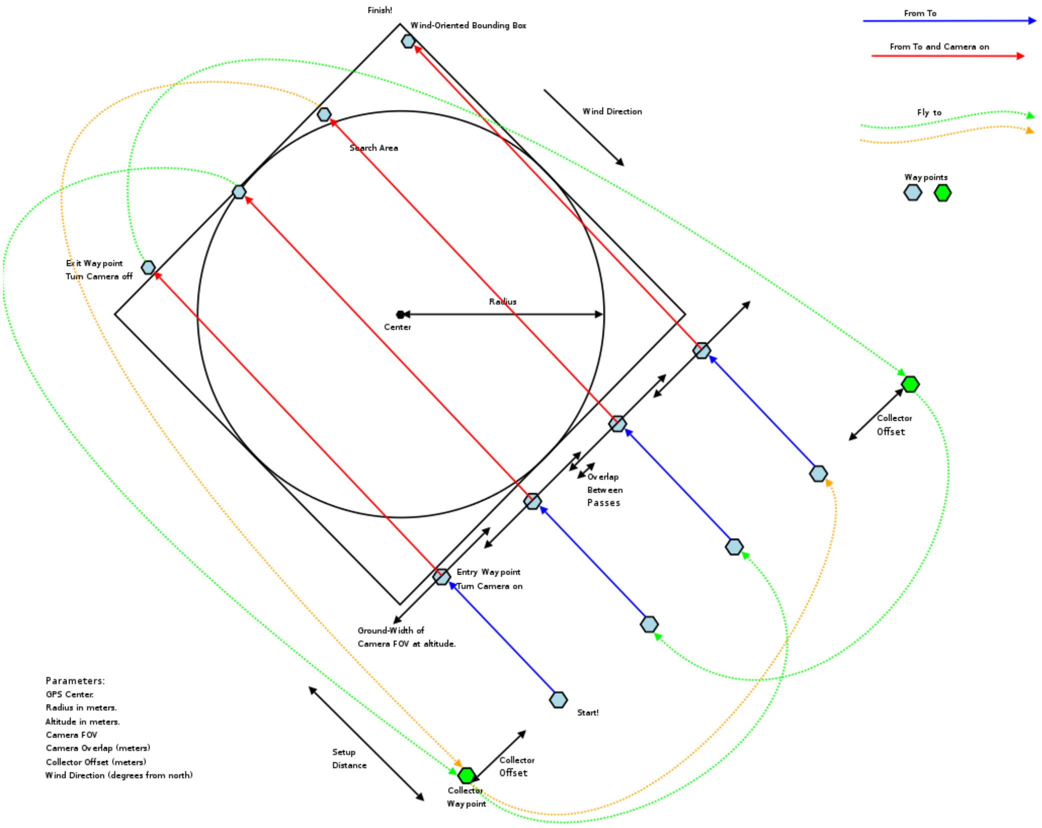

Figure 5: Search pattern definition

Daily flight checklist. ***Date:***								
Airframe and Autopilot.								
Pitch Response (elevator deflects correctly)								
Roll Response (ailerons deflect correctly)								
Yaw Response (rudder deflects correctly)								
Pitch Hold (hold at 45 degrees, sensor does not drift)								
Roll Hold (hold at 45 degrees, sensor does not drift)								
Micropilot Battery Voltage: (>5.6V)								
Servo Battery Voltage: (>6.1V)								
Airspeed Transducer:								
AGL:								
R/C								
Range (with all transmitters powered on):								
Control Deflection:								
Transmitter Voltage: (> 9.5V)								
RC pilot in control/ Computer in control switch.								
Engine								
Idle Setting:								
Full Throttle:								
Transition from idle to full:								
Pinch test:								
Vibration test (throttle to full and ensure sensors don't drift):								
Pitch up fuel test:								
Imaging								
Telemetry link:								
Video link:								
Camera time-synchronized with imaging station.								
Trigger and download high-res test pictures.								

Figure 6: Daily safety checklist

Per-Flight Checklist: ***Date and Time:***							
Ground Station							
Flight Plan Simulated:							
Radio Modem Link:							
GPS Lock:							
Micropilot Battery Voltage: (>5.6V)							
Servo Battery Voltage: (>6.1V)							
No Error Messages:							
Handedness of circuit landing pattern:							

Per-Flight Checklist: ***Date and Time:***							
Imaging Station:							
Receiving telemetry:							
Receiving video:							

Per-Flight Checklist: ***Date and Time:***							
Runway:							
Vibration test (throttle to full and ensure sensors don't drift):							
Airspeed:							
Transmitter Voltage: (> 9.5V)							
RC pilot in control/ Computer in control switch.							
Camera/video switched on:							
High res camera lens cap removed.							

Figure 7: Per-flight safety checklists