Team Manitoba Project Description

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Abstract

The Team Manitoba Unmanned Aerial Vehicle Group's entry in the 2007 AUVSI Student UAS Competition was developed in response to the competition requirements and built on our previous entries in an incremental fashion. Combining an appropriate airframe, autopilot, control station, and imaging system will allow our team to perform with confidence at the competition. By following a requirements-driven approach, we were able to dedicate our resources to the most important aspects of the project while keeping safety, robustness, and autonomy in consideration for all of our design choices. Our main driving requirement was the competition objective for real-time target data. To address this requirement, we added an on-board computer and wireless transmission system to provide a new data link between the air vehicle and imaging station. The need to accommodate the additional size of the on-board computer caused the use of a larger airframe and power distribution system with increase capacity and capability. Our improved connectivity opens the door for future development of autonomous target detection software for use as a part of our unmanned air system.

1 Introduction

The technological advancements in robotics, avionics and surveillance equipment have widened the usage of Unmanned Aerial Vehicles (UAVs) not only in military application but also in civilian applications such as weather monitoring, fire fighting, support of rescue missions during natural disasters or even agriculture. The Team Manitoba Unmanned Aerial Vehicle Group started the project for the 2007 AUVSI Student UAS Competition by identifying the major functional and non-functional requirements of the system based on

Figure 1: 2007 Entry Photo

the competition rules and objectives. These requirements were used as guidelines throughout the design and construction process of the Unmanned Air System (UAS).

1.1 Functional Requirements

The team identified the following functional requirements:

Vehicle Control During the design stage, the team considered the competition objectives and identified four functional requirements pertaining to vehicle control: autonomous takeoff, ability to change flight parameters during flight, navigation of the air vehicle through GPS waypoints, and autonomous landing.

Imaging The functional requirements of the imaging system are to capture imagery of a search area that is of sufficiently high resolution to identify targets and translate image coordinates to GPS coordinates based on the estimated position of the aircraft when the image was acquired.

1.2 Non-Functional Requirements

Besides functional requirements, the team identified robustness, safety and autonomous behavior of the system as non-functional requirements. Being a robust system, the air vehicle must be capable of encountering varied environmental conditions without degraded performance. This has the added benefit of increasing the geographical area over which our system can operate.

A number of measures were taken to ensure safe operation of both the air vehicle and the system as a whole. Components were selected and implemented based on the projected worst case whenever possible. The electronic components were tuned and tested individually before being integrated with the rest of the system to limit the number of issues related to a new component. An autopilot was configured and tested to verify autonomous navigation operated within the competition rules.

2 Airframe

The design of the air vehicle used plans from a commercially-available Sig Kadet Senior kit which were then enlarged by 5% in order to increase both the space available for, and ease of access to, the payload. With no prefabricated sections, the design gave us the freedom to locate electronics as we saw fit. To this end, components and antennas were installed with maximum separation. Our airframe provides four control functions: ailerons, elevator, rudder, and throttle. An OS .70 cu. in. four-stroke engine fed by a 20 oz fuel tank provides our air vehicle's thrust.

2.1 Modifications

Due to the special needs of the air vehicle created by the competition requirements and objectives, the following modifications were made to the stock Sig Kadet Senior to arrive at our design:

- Airframe size was enlarged 5% overall and the fuselage was widened by 25% in order to permit easy access to the payload compartment. This enlargement increases the wing area and, subsequently, maximum payload weight by 10%.
- Outboard ailerons were installed for easier control.
- The stock "flat" horizontal and vertical stabilizers were redesigned as airfoils.

- The leading-edge surfaces were covered by 3/32 inch balsa sheet to reinforce the wing structure.
- The main landing gear is made from 7075 aircraft-grade aluminum as the stock gear was deemed unsuitable for our air vehicle. According to modelers who have flown this model, the stock landing gear design is not very robust. In order to accommodate our payload and to facilitate landing in less than ideal conditions, the landing gear for our air vehicle was redesigned to increase its robustness.
- The team redesigned the nose section of the airframe. Instead of a cockpit shape, the firewall was connected with the top of the fuselage directly to reduce construction effort.
- An OS .70 cu. in. four-stroke engine was installed to achieve an adequate power-to-weight ratio and provide a good clime rate, better fuel economy, and better throttle response than a two-stroke engine.
- A battery bay and spring-loaded access hatch were integrated into the nose of the aircraft. Experience last year with frequent changing of the battery pack led us to incorporate a quick and easy way to change out the battery packs.

2.2 Layout

The layout of the electronics suite inside the airframe is critical to prevent interference between devices and to properly balance the aircraft. Of particular importance is maximizing the distance between the antennas on the aircraft. Therefore, the GPS antenna was mounted on top of the tail boom near the vertical stabilizer while the ultrasonic sensor was placed on the bottom of the left wing and the radio modem antenna was mounted vertically inside the tail boom. The vertical orientation of the radio modem antenna was chosen in order maximize the signal strength.

The autopilot board was placed at the approximate center of mass of the vehicle to ensure that the aircraft motion and acceleration it measured were as accurate as possible. The camera was installed below the autopilot in the belly of the aircraft to maximize viewing angle and avoid obstruction of the camera view by the landing gear.

Flight testing raised concerns that exceptionally long servo leads could cause radio control (RC) interference. Therefore all servo leads were kept to a minimum by placing servos close to the payload bay. Servos inside the payload bay were located at the corners to minimize their impact on access to the bay.

There were two requirements for the mounting method selected for our electronics. It was important to provide a solid attachment to the airframe while allowing for easy removal for development and testing. In addition, some components are particularly sensitive to vibration. To meet all of these requirements, a novel method was employed. Larger devices like the autopilot and on-board computer were first attached to balsa rails through their corner mounting holes. Velcro was applied to these rails as well as to equivalent rails inside the fuselage. Smaller components had Velcro applied directly to their outer cases. This satisfied the requirements for easy access and solid attachment. To prevent vibration from affecting the autopilot's operation, we added a small platform on top of the rails and added a layer of foam between the platform and autopilot board. This acted to isolate the autopilot while also positively attaching it to the airframe.

For safety reasons, an engine kill servo was mounted in a front corner within the fuselage. The servo is attached to a set of pushrods which will pinch the fuel line if activated.

2.3 Range, Performance and Mission Capabilities

From data collected during test flights, the endurance of the air vehicle is about 30 minutes. RC operation was possible to a range of about 1.5 km.

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 fulfill all of these requirements. The MP2028g peripherals include a GPS unit and antenna, three-axis gyroscope and accelerometer, relative airspeed transducer, pressure altitude transducer, 2.4 GHz radio modem, AGL ultrasonic altitude sensor, and external servo board.

The gyroscope, accelerometer, pressure altitude transducer and airspeed transducer 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 air vehicle. The primary stability loops control the servos directly whereas the navigation loops control higher level parameters affecting navigation of the air vehicle.

The 2.4 GHz radio modem provides a telemetry data link between the MP2028g and the base station. The modem is mounted in the rear of the fuselage behind the main wing in

Table 1: Table of PID feedback loops

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

order to obtain maximum distance from both the GPS antenna and the antenna for the 900 MHz imagery system.

An ultrasonic AGL sensor provides landing assistance by accurately measuring the altitude of the UAV when it is within approximately 15 feet of the ground. The AGL sensor is used primarily during landing to provide an accurate altitude measurement. This negates any error in the GPS altitude and allows the aircraft to flare at the correct altitude. The sensor is mounted in the aircraft's wing in order to minimize interference from the engine.

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.

In the event that the RC link fails (failure #5) there are several failsafe systems which are automatically activated by the autopilot. After 30 seconds of no RC signal, the autopilot

Table 2: Autpilot failure patterns

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 Link Failure	gcsFailed	Yes

forgoes the preprogrammed flight-path and returns to the takeoff point. If, after 3 minutes, there is still no RC signal, the flight is immediately terminated.

In the event of a catastrophic autopilot failure which rendered the RC pilot unable take command of the aircraft, we have equipped the vehicle with an emergency fuel shutoff system. This system is fully independent of the autopilot to ensure that it can always be activated by the RC pilot.

4 Electrical Systems

4.1 Batteries

Mission requirements specify that the flight and target identification must be completed within 40 minutes. Since part of the mission time will be used for ground based activities, a minimum flight time of 30 minutes was used to determine the system battery capacity requirements.

The air vehicle has a number of electrical components which are powered by the main battery including:

- Autopilot (4.2 - 26V)
- Flight Servos (4.8 - 6.0V)
- 2.4GHz Telemetry Radio (5.0V)
- Onboard Computer (12 - 18V)

- Camera (4.3V)
- 900 MHz Data Radio (3.3V)

Approximately 14 watts is required to power these components during flight. Based upon the team's desire to be able to conduct multiple test flights without having to swap or recharge our batteries, a minimum battery capacity of 30 watt-hours (WHr) was specified.

The second consideration given to battery selection was weight. Previous UAVs have used Nickel-Metal Hydride (NiMH) batteries due to their ease of use, reliability, and relatively high power density compared to Nickel-Cadmium (NiCd) batteries. Unfortunately, due to this year's increased power requirements, weight became a major issue. A NiMH battery pack which met the minimum requirements consumed approximately 30% of the airframe's maximum payload, limiting the other components that could be carried. Instead a Lithium-Polymer (LiPo) battery pack was chosen which weighs only 1/3 of the equivalent NiMH battery. The PolyQuest PQ-2600-4S battery contains four 2600 mAH LiPo cells producing a nominal voltage of 14.8 V. The 38.5 watt-hours provided by this battery yields well over 2.5 hours of flight time as the maximum 14 watt load occurs only when all of the imaging and wireless components are active.

With LiPo batteries, safety is a concern unless several factors are considered during the battery's use including:

- During Charging
  - Over voltage protection
  - Over current protection
  - Over temperature protection
- During Discharge:
  - Over current protection
  - Over temperature protection
  - Under temperature protection
  - Under voltage protection

In order to ensure the safe operation of our LiPo batteries, the health of the battery packs is continuously monitored during both charging and usage. In the event that the operational limits of a battery are exceeded, usage is automatically terminated in an effort to prevent damage to both the battery and the air vehicle.

An ElectriFly Triton battery charger was chosen as the primary battery charger due to its ability to charge a multitude of battery chemistries and sizes. This charger is ideal for charging LiPo batteries as it uses a combination current source / voltage source charging profile rather than a simple current source. This charging profile can be modified to suit the voltage and capacity of the battery being charged. For the PolyQuest battery, a nominal charging voltage of 14.8 V, maximum voltage of 17.0 V, and current limit of 2.0 A (0.77C) were used.

During charging, a PolyQuest PCM-Guard battery monitor is used to monitor the voltage of each individual LiPo cell in the battery pack. If any one of the cells exceeds 4.35 ± 0.025 V, the PCM-Guard disconnects the battery from the charger in order to prevent a potentially dangerous over-charge from occuring. The combination of the charger monitoring overall battery pack voltages and limiting the maximum charging current provides a safe charging method.

During discharge, both the battery voltage and fuselage ambient temperature are monitored by the autopilot and transmitted back to the base-station via the 2.4 GHz telemetry data link. This allows the battery health to be monitored at the base station and the flight to be terminated should the operational limits be exceeded. In addition to voltage and temperature, the battery must also be protected against an over-current condition. The PolyQuest battery used is rated at 10C continuous and 15C instantaneous current draw, where C designates the capacity of the battery pack. The worst-case load, with all of the components in the aircraft operating and all servos in a stall-condition, is only 3.5 A: well under the maximum 26 A continuous current draw. Thus, even under extreme operating conditions, the battery will never be subjected to an over-current condition. However, as an added layer of protection, the two 5 V power regulators used in the aircraft are both limited to 2 A output current. This will fully protect the battery even if a fault were to occur on one of the 5 V busses.

4.2 Regulation

Due to the differing power requirements of the aircraft's electrical systems, four separate power busses are used. Two unregulated busses power the autopilot and on-board computer, respectively. Additionally, two Texas Instruments switching power regulators provide 5 V busses which power the servos, radios, and camera. The components were separated out onto individual busses in order to allow them to be turned on and off individually as required. On the exterior of the aircraft fuselage there are two power switches. One powers the critical flight systems and the second powers the non-critical imaging and wireless systems. This allows aircraft flight testing to be conducted without powering unnecessary components, greatly increasing the flight time per battery charge and reducing the down-time between flights.

4.3 Embedded Computer

The onboard imaging system is designed around the Wireless Router Application Platform (WRAP) .2E embedded computing platform. This system is based on a 233MHz SC1100 AMD Geode processor and contains 64 MB of RAM, 2 miniPCI slots, and a Compact Flash (CF) card slot for storage. The WRAP board was chosen due to its small footprint, minimal power requirements (3-5 W), and miniPCI expandability. One of the miniPCI slots is used for a USB 2.0 host bus adapter to control the camera and the second is used for a wireless adapter for data communications. The WRAP board also includes 10/100 Ethernet and RS-232 ports for basic communication.

The advantage of having four industry standard expansion busses available (USB, miniPCI, RS-232, 10/100 Ethernet) is that it greatly increases the types of instrumentation and equipment that can be incorporated into the air vehicle. This allows the vehicle to be highly modular and quickly adaptable to other mission roles such as data relay, radar, or search and rescue.

4.4 Wireless

The air vehicle carries two parallel wireless modems operating in the 900 MHz and 2.4 GHz ISM spectrums. Initial flight path programming is done through a Maxstream 24XStream 2.4 Ghz radio modem operating at 9600 baud. This datalink is also used during flight to transmit telemetry data to the ground control station and to send flight path updates to the aircraft for dynamic re-tasking.

A second high-bandwidth 900 MHz Ubiquity SuperRange9 (SR9) modem is used to transmit camera imagery to the ground station. This high-power 900 MHz modem was chosen due to the difficulty of obtaining a reliable high-bandwidth 2.4 GHz radio link with an aircraft in flight. The 700 mW SuperRange9 provides a maximum data throughput of 54 megabits/sec and averages around 3 megabits/sec full-duplex at ranges of over 1 mile. This provides enough bandwidth to allow imagery from the onboard camera to be transmitted to the base station in near real-time.

Similarly to 802.11g, the SR9 allows the use of multiple transmission frequencies or 'channels' to be utilized within the 902-928 MHz ISM band. There are four non-overlapping 5 MHz channels which may be used independently or multiple channels may be bonded together for higher bandwidth. In order to achieve the highest possible bandwidth, we have configured the SR9 to use one of two overlapping 20 MHz channels.

Simple 3 dBi omni-directional antennas are used on the aircraft and at the base station in order to minimize the effects of the aircraft's location and orientation with respect to the base station. Due to the much longer range of the 900 MHz signal (versus 2.4 GHz), it was determined that there was no need for the use of directional antennas on either the aircraft or the base station. If necessary, the use of directional antennas would allow the operational range of the aircraft to be greatly increased.

4.5 Camera

In-flight imagery is captured using a Canon A620 digital camera controlled by the onboard computer. Full electronic control of the camera opens up a variety of imaging roles that the UAS would be otherwise unsuitable for. For example, if a target of interest is identified during a flight, high resolution imagery of a target may be obtained using the camera's zoom, without having to alter the aircraft's flight altitude. Alternatively, the camera's zoom could be dynamically controlled from aircraft altitude in order to maintain a consistent ground resolution (pixels/ft) throughout the flight.

The desire to use a fully controllable (and well-documented) camera significantly limited the cameras from which the team could choose. Ultimately, the Canon A620 offered the highest resolution and best supporting drivers and was therefore chosen as the main imaging camera.

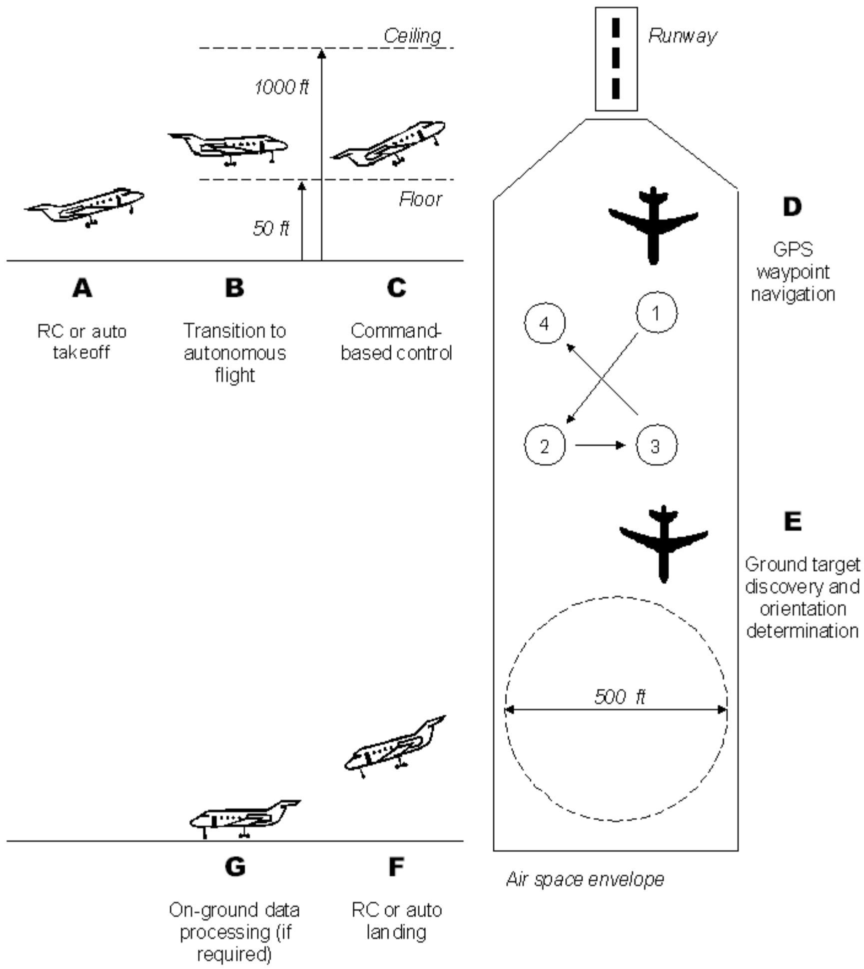
5 Zenith

Micropilot's Horizon software was supplemented with flight planning software called Zenith developed by Team Manitoba.

Zenith provides additional functionality to that included with Micropilot's Horizon application. Specifically, Zenith includes a map display and mission component sequencer for planning missions. It allows for point-and-click location of mission components (such as a waypoint navigation command) and easy pre-visualization of missions. After an operator has designed their desired mission sequence, Zenith outputs an autopilot script which is executed by the Micropilot autopilot and Horizon.

Zenith includes a set of mission components (see figure 2) which allows an inexperienced operator to assemble a mission. The major included components are takeoff, waypoint navigation, image capture, search area processing (with built-in image cature), and landing.

Figure 2: General Mission Overview [1]



Agility in our ability to respond to mission assignments is a key part of the competition, so Zenith was designed to be easily modified. Because new mission components can be created in response to changing needs with a minimum of effort, unexpected events are not fatal from a mission planning point of view.

6 Imaging Software

6.1 General Design Overview

The software used in this year's system for collecting, organizing, and processing imagery and telemetry is largely unchanged from last year. Because its performance during the 2006 competition was excellent, there was no need for more than incremental changes to the imaging software. A review of the imaging software is provided below. A more detailed description can be found in [2].

The imaging system consists of hardware and software components. The hardware required includes a digital still camera as described in section 4.5, a photo storage device, and a communications channel for transferring photos. The communications channel for the imaging system was upgraded. Previously, a simple USB cable was used to download photos upon landing. This was replaced with a wireless transmission option which will be detailed in section 7.3. This improvement retains the current imaging software's performance while allowing the imaging operator to collect target data during the flight. This will allow image processing to be completed in near real time.

The software component will remain unchanged from last year with the exception of an interface to the wireless transmission channel. As the air vehicle is flying, the digital camera will cover the search area with still photos. The imaging station software will collect a copy of the autopilot's telemetry packets via a split RS-232 cable and add them to a database. When images are later being processed, the timestamp of the image will be used to locate the relevant telemetry packet(s) from the database. By manipulating an unused data field included in the autopilot telemetry, the system can signal the imaging software that a particular packet has data for a particular image and achieve an even better coupling between the image and telemetry data. This process is described in more detail in section 6.3.

By including client software on the imaging station which will communicate with an onboard computer, the team can retrieve photos in nearly real-time. This client software adds received images to a queue for processing by an imaging operator. The use of a queue will allow the imaging operator to process images at a comfortable pace as well as allow them to focus on locating targets instead of being forced to keep up with the rate of data acquisition. As soon as the operator declares an image as processed, the next image will be displayed. This will continue until there are no images remaining to process.

6.2 Removal of Video Interface

In previous years, live video interfaces have been attempted. However, since the imaging software performed very well with only static image processing, the team decided that live video display was not necessary and removed it from this year's design. Other operational considerations contributed to this decision:

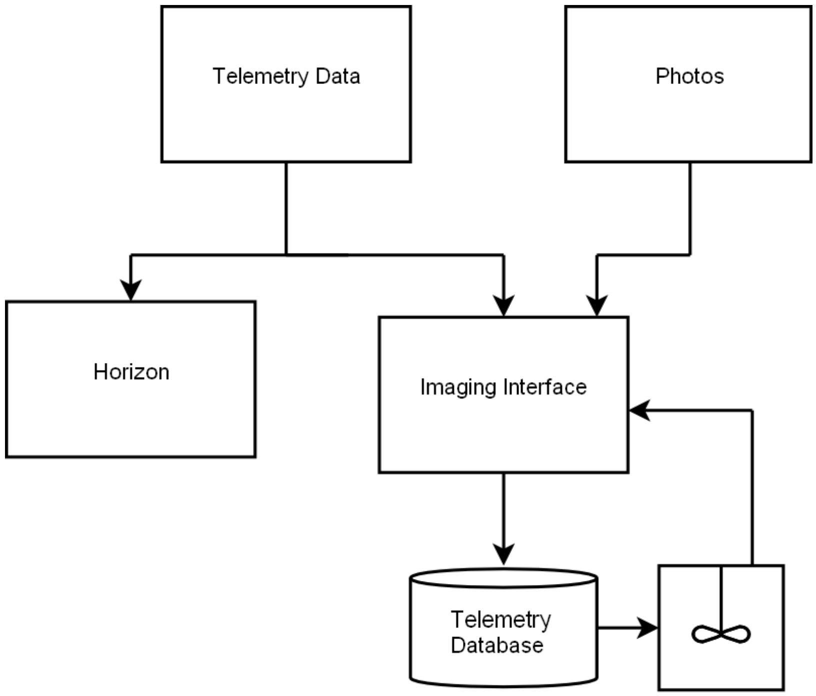
- RF interference with other vital sensors made the video subsystem difficult and dangerous to operate continuously.
- The proposed user interface and use-case descriptions for the video subsystem placed a heavy burden on the imaging operator to, first, notice a target in a fast-moving, low-quality video display and, second, re-locate it by rewinding the recorded video to mark the target for a second high-quality pass.
- Mission time would increase due to the need for multiple flights over one area in order to obtain high-quality photos of the noticed targets.

6.3 Image and Telemetry Correlation Method

The telemetry returned by the Micropilot MP2028g is spread over multiple packets sent at a rate of 5 Hz. Therefore, for the purposes of determining the current orientation of the air vehicle, it is not adequate to query the telemetry database for the single packet with a timestamp closest to the image timestamp. Instead, the imaging software must retrieve telemetry data from the database for a time interval around the requested time and build an interpolated data set from the received telemetry packets.

Once this has been completed, the next step is to decide where in the course of the telemetry data the photo was taken. The obvious choice is to match based on the time the photo was taken. However, this requires that the camera and imaging station clocks be perfectly synchronized. The 2006 system evolved from using a servo to trigger the camera. It was observed that an extra data field present in the autopilot could be included in the telemetry packets to relate photos to telemetry data. By incrementing the field whenever a photo was taken, we could locate the specific instance when a photo was taken and correlate this to the telemetry data at that instant without the need for clock synchronization.

Figure 3: Imaging System Block Diagram



7 On-Board Computer

Stemming from the objective to provide images and location data during flight, we have included a subsystem to convey photos from the still camera to our ground station.

7.1 Hardware Description

As other teams have experienced issues with on-board processing in the past, we made sure to select a hardware platform which included basic safety features such as a watchdog timer (failure to reset the watchdog timer within a specified period of time will cause it to reset the processor) and thermal monitor. These features will allow safe operation of our on-board system while preserving autopilot control in the event of a catastrophic failure.

As peripherals to the WRAP, we have added commercial USB and 802.11g-based wireless interfaces and a 1 GB Compact Flash card which is capable of storing all required system files as well as serving as backup storage for photos.

7.2 Operating System

The WRAP board manufacturer provides a Linux distribution (called iMedia WRAP Linux) designed to run on its hardware. The use of open source software makes integration problems easier to deal with. If a new operating system component is required but not available, the option to develop such a component independently of the software manufacturer allowed the team to remain agile in the development cycle.

7.3 Application Software and Libraries Used

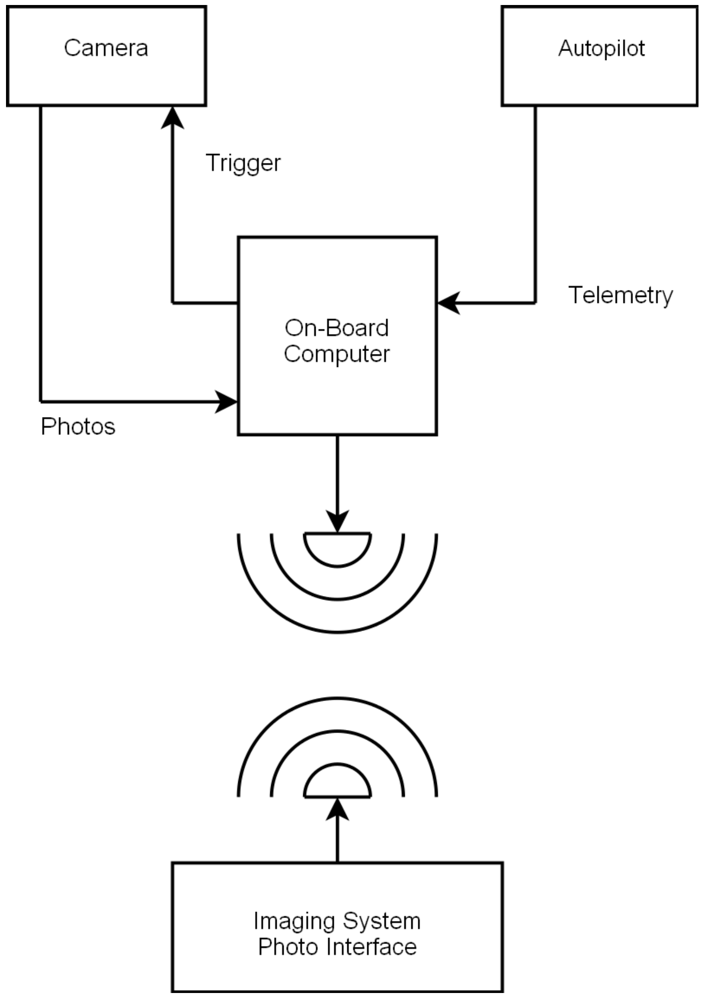
The application which runs on the on-board computer to handle payload tasks is straightforward. It performs the following operations until terminated:

1. Wait for telemetry from autopilot
2. When telemetry is received
    (a) If telemetry contains a "signal value"
        i. Send a command to the digital still camera via USB to capture an image
        ii. Download image from the camera to the on-board computer and save to compact flash
        iii. Transmit image to imaging station software using wireless network
3. Go to step 1

The software interface between the digital camera and the on-board computer is provided by an open source library called gPhoto[3]. The gPhoto software development kit (SDK) exposes a number of functions for many cameras including, most importantly in our case, a trigger for capturing an image and a file transfer mechanism for retrieving photos stored on the camera. With these functions, we are able to both capture an image and transfer it to the on-board computer for further processing.

Once the image is stored on the on-board computer, we initiate a transfer of the image from the on-board computer to the imaging station using standard TCP/IP file transfer protocols. Because the embedded error detection and correction mechanisms in the TCP/IP protocol are satisfactory, the only error detection we must include is one which ensures an entire image has been transferred. To accomplish this, we can simply compare the expected file size with the amount of data received.

Figure 4: On-Board System Block Diagram



In the event of signal loss which prevents an image transfer from completing, a timeout will cancel wireless transmission of an image after a specified period of time. The backup copy of the image stored on compact flash will be retrieved upon landing and processed at that time. This arrangement prevents a backlog of images from forming which would reduce the system's ability to react to targets in a timely manner. As soon as wireless connectivity is restored, the system will continue processing images as captured.

7.4 Expected Performance

One of the goals of our system is to receive images from the camera in real-time. Assuming an average photo size of 2 MB, the time required to transfer a photo is approximately 3.8 seconds (based on data provided by the SR9 manufacturer). If the time between consecutive photos being captured is greater than 3.8 seconds, the photos will arrive in nearly real-time without creating a data backlog on-board the air vehicle. The process of locating and marking targets in a photo will likely be finished after additional photos have arrived, but the operator will still have a head start compared to waiting for the vehicle to land before beginning. Future work will include developing an autonomous target detection system which can detect and identify targets more quickly than a human operator, further increasing the speed of processing.

8 Conclusion

Team Manitoba's design process for our entry in the 2007 AUVSI Student UAS Competition has followed a requirement-driven, iterative and incremental systems engineering approach. Each of the four major subsystems (airframe, autopilot, ground station, and imaging system) have been fully tested and integrated. The completed system meets each of our identified requirements and satisfies all mandatory competition requirements.

References

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[2] Paul Furgale, Sancho McCann, Jim Majewski, Andrew Bugera, Kory Zelickson, and Jon Kurtas. Team Manitoba 2006 AUVSI Student Competition Project Description. In *Association for Unmanned Vehicle Systems International (AUVSI): 4th Annual Student Unmanned Aerial Vehicle Competition, Lexington Park, MD*, June 2006.

[3] gPhoto.org. gPhoto and related resources. Website. http://www.gphoto.org/.