An economical approach to autopilot development and integration

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Autonomous Unmanned Aerial Vehicles (UAVs) are prohibitively expensive for use in civilian surveillance applications. This is in large part due to the manufactures need to recoup the costs of research and development. The more intelligence that is incorporated into unmanned vehicles, the more expensive it is to validate. At Cornell University an autopilot system for UAVs has been developed and integrated into a fixed wing aircraft on a budget of $15,000 and 3000 man hours dispersed over 6 months. This document describes the modern cost saving approaches used for developing the UAV, as well as the individual sub systems and the resulting UAV.

I. Introduction

Cornell University undergraduate students have developed a custom, autonomous, aerial vehicle package for use in local research activities as well as to enter in AUVSI's[1] second annual autonomous aerial vehicle competition. The package consists of off-the-shelf hardware components combined with custom software, placed in a standard fixed wing aircraft. The airframe is a SIG Rascal 110 ARF[2] with a wingspan of just over 9 feet and a dry weight of under twenty pounds. The aircraft is powered by a 3W 24CC[3] gas engine. The hardware package consists of a GPS receiver, a 3-axis orientation gyroscope, and a set of pressure sensors to measure air speed and altitude. The communications hardware consists of two radio modems, operating at 900Mhz and 2.4Ghz, allowing over-air speeds of up to 56kbs.

The aircraft handles all autonomous control onboard, however it is equipped with full telemetry systems to support ground monitoring, and if necessary, mission modifications. The telemetry system allows for caching on the ground through a single point of communication, as well as encrypted over the air communication. In addition to basic telemetry systems, live video is transmitted to the ground, which is used to gather target and object location information.

The paramount concern with Unmanned Aircraft is safety. The system utilizes many levels of fail safe, including system loitering, sensor failure detection and management as well as a system shutdown in the case of complete signal loss.

The autopilot system is capable of flying a series of GPS coordinates, calculating wind vectors and appropriate cropping angles, surveying large areas and is easily extended through its modular design.

This aircraft represents the second evolution of the project to develop an affordable, versatile autopilot system. The first generation project, detailed in the 2003 AIAA paper, achieved many of the target objectives, but was not as extendable, or as reliable as needed. This year the project has been completely reengineered, starting with a more suitable airframe, a more reliable component set, and a new software suite.

[1] AUVSI – Association for Unmanned Vehicle Systems International, http://www.auvsi.org/
[2] SIG Rascal ARF 110 – 110" wingspan almost ready to fly radio control aircraft kit, http://www.sigmfg.com/
[3] 3W 24CC – a 3W Modellmotoren engine, this engine provides 2.5 horse power at 1,500 – 8,500 RPM, and only weighs 2.96 lbs including the ignition system, http://www.3w-modellmotoren.de/

II. Design Objectives

The goal of this project has been to develop an autopilot system which is suitable for civilian applications, including forest fire surveillance, police traffic/search and rescue surveillance, weather sampling, etc. In order to develop a practical aircraft, it has to be affordable, safe, reliable, and capable of a diverse range of missions.

A. Economy

To be practical and affordable enough for integration into all levels of commercial and research need, the cost of autonomous flight control system had to stay below $5,000.00 USD. This figure was based on benchmarking of currently available autopilot systems, and costs associated with guidance and telemetry of baseline Remotely Piloted Vehicles (RPVs). Limited available resources also dictated a need to keep prototype system costs below this level. Equivalent commercial development costs also had to be kept below $500,000, as anything higher would not represent a practical business opportunity to make these vehicles available to the market.

B. Safety

An autonomous flight control system inherently removes human operator intervention from vehicle functionality. The capability of an aircraft of considerable mass, traveling at high velocity, to inflict damage to people or property is substantial. It was critical that the flight control system would include several modes of flight termination in case of emergency or flight control system failure.

C. Capability

The system must be able to navigate long and short distances with the ability to adapt to wind conditions and altitude constraints. This involves the ability to fly direct paths between waypoints, and accommodating for weather conditions to minimize cross track errors. The guidance package must be adaptable to allow for integration with a variety of fixed wing platforms. Furthermore, the competition requires that the vehicles be able to automatically take off and land, as well as carry a video surveillance payload.

D. Reliability & Maintainability

This is directly related to system safety, and critical to functionality. In order to offer a viable autonomous flight solution for any application, especially research applications where repeated data loss can setback a research program considerably, it is critical that the system be robust and capable of continuous functionality. Mission times of one hour with provisions for a thirty minute reserve, were established as the basis for operational capability of the prototype system. Previous experience with research data collecting was used to establish this constraint, which in turn helped with the design of a suitable power supply and distribution network.

E. Physical Constraints

The mass and physical dimensions of the flight control system had to be such that they were compatible not only with the prototype UAV, but also with a range of likely RPVs which were candidates for conversion to autonomous flight. Balancing the need for a sizable payload, but the convenience of a small airframe, a nominal package mass of 2kg was established. Physical size was not as critical, as it was assumed that dimension would be constrained by mass restrictions, but a maximum payload volume of 6000 cm^3 was established based on the UAV prototype airframe.

III. System Overview

The system is broken up into two areas of interest, the hardware, and the software. The hardware platform represents a diverse base of readily available components, assembled together to create a lightweight, reliable base for the autonomous software package. The software platform represents the most unique combination of the readily available Microsoft Windows operating system with the Microsoft.Net virtual machine runtime and our custom autopilot modules.

The choice of the Windows operating system often brings immediate concerns to such a critical application; however, the net result is not unlike the systems first employed inside of an Airbus commercial aircraft[4]. The Airbus

[4] Airbus commercial aircraft – Airbus was the first commercial airline company to introduce a fly by wire control system in 1988, in which a computer interprets inputs and adjusts the control surfaces accordingly, without the pilots controls being interfaced directly.

system utilized six i386 desktop processors, each running a custom operating system, abstracting machine operations with a virtual machine running each process. This system allowed the operating system to monitor each process's health, and in the case of failure, restart the process, without locking up the hardware. The windows embedded operating system is utilized in the aircraft to replace the custom operating system on the airbus autopilot, and the Microsoft .Net framework is used to replace the custom virtual machine. This combination is what allowed the project to be developed so rapidly, and has led to a reliable system.

A. Hardware Overview

The autopilot system is designed to be very modular and can be equipped in any given fixed-wing aircraft able to carry its payload mass within a matter of hours. Due to the high risk of flight, each component is heavily protected for hard impacts, and isolated from the vibrations of the engine and rigors of flight. Each electronic component is carefully faraday caged to prevent RF interference and is held in place by vibration resistant rubber mounts.

1. Airframe

The prototype airframe is a SIG Rascal 110[5], heavily modified RC aircraft. The Rascal comes as an unassembled kit, but has been constructed and adapted for this payload.

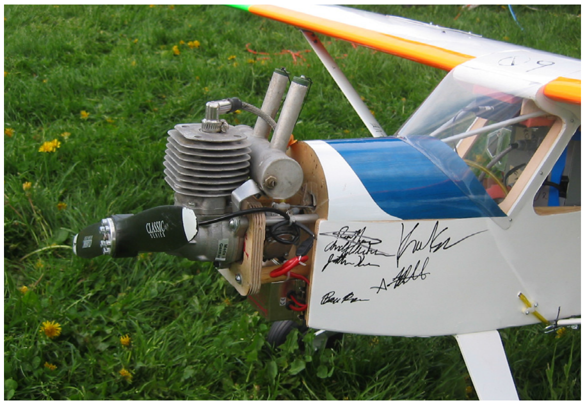
Modifications on the airframe include the replacement of the factory built tail with a custom lifting tail, moving the center of lift further towards the rear of the plane. Given the heavier than designed wing loadings this airframe is experiencing, we have installed large in-wing flaps to allow for a slower stall speed and improved takeoff and landing characteristics.

Airframe Specifications:
Wingspan: 110"
Wing Area: 1522 sq. in.
Length: 75-3/4"
Weight: 13 lbs.
Wing Loading: 16.6 - 19.7 oz./sq. ft.
7 RC servos

Table 2: Airframe specifications

The research and development phase of UAV development is extraordinarily risky, and often entails unpredictable accidents. In order to maintain steady development the project required four backup airframes, which could be used if an airframe is lost. This insures that development is not halted by an unfortunate accident, but rather that an accident can be analyzed and the project may resume without delay.

2. Engine



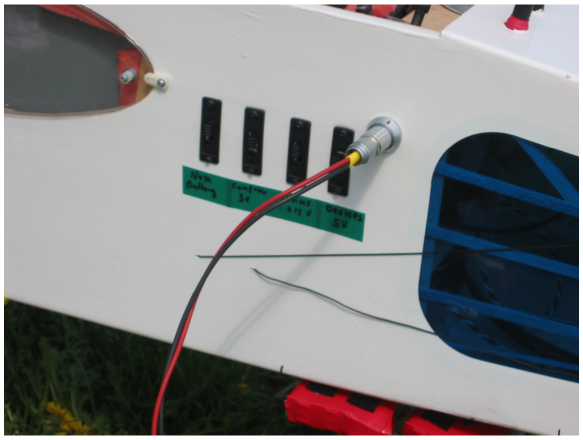
Picture 1. 3W-24i Engine Images

[5] SIG Rascal ARF 110 – 110" wingspan almost ready to fly radio control aircraft kit, http://www.sigmfg.com/

The prototype aircraft is powered by a 3W-24i gasoline engine manufactured by 3-W Modellmotoren[6]. This engine, designed for "giant-scale" sized airframes, has a cylinder capacity of 1.42 cu inches and weights just 2.65 lbs. The 18" 2-bladed propeller spins at 8,500 RPM, generating as much as 2.5 HP. This engine is powerful enough to easily carry the payload, while efficient enough to deliver flight times of up to an hour and a half.

3. Batteries and Power System

In order to power the large array of different sensors and computing equipment on the aircraft, a battery system with a significant capacity is needed. The total power draw of all the autopilot components is as much as 15W at 5V DC. When selecting a battery solution, a pack with high capacity and low weight was a necessity. Lithium Polymer technology provides the extremely high capacity needed to power our system, but in a lightweight, compact form factor. Kokam 3-cell lithium polymer[7] packs are used, each providing 3270mAH creating a combined 12V pack. Weighing less than 212g, this pack will power the system for as long as two hours.



Picture 2. Auxiliary Power Hookup

The majority of time during development test flights is spent with the aircraft on the ground. To prevent the loss of on board battery power, we have developed a system to circumvent the onboard packs and to provide external power. While on the ground, any 12V DC source, such as high capacity lead acid packs, can be plugged into a 2 prong Lemo Outlet (Picture 2) on the side of the plane, powering the entire system from auxiliary power.

In order to provide a regulated 5 Volts to our computer and sensitive electronic device, we selected a Beta Dyne[8] 25S5/12 high-performance isolated DC/DC converter, weighing just 59g and providing 86% efficiency, to power the computer and 5V sensor devices.

4. Computer System

The autopilot software runs on an onboard Technoland PC/104+ form factor computer[9]. The computer is an 800 MHz Crusoe[10] with 180 MB RAM, providing ample computing power while keeping power usage and heat

[6] 3W 24CC – a 3W Modellmotoren engine, this engine provides 2.5 horse power at 1,500 – 8,500 RPM, and only weighs 2.96 lbs including the ignition system, http://www.3w-modellmotoren.de/

[7] Kokam 3 cell lithium polymer – lithium polymer batteries offer energy densities of 5.6 grams / watt, with 3 cells in series, the nominal system voltage is 11.7 volts, and have a capacity of 76.5 watt hours, more than long enough to run all of our equipment. https://www.fmadirect.com/

[8] Beta Dyne DC/DC converter – this device used switching in order to regulate our ~11.7 volt system power down to precisely 5 volts for input to our electronics systems. http://www.beta-dyne.com/

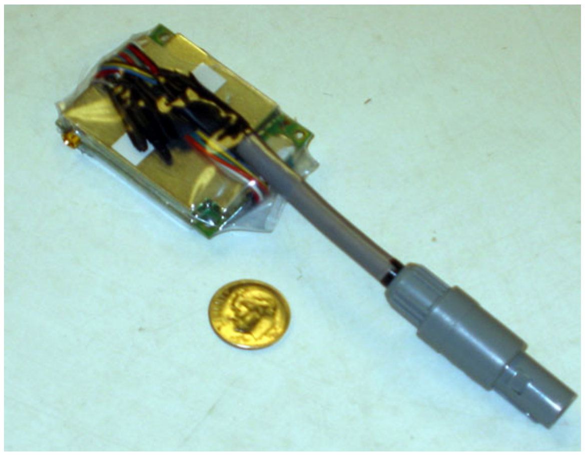
[9] Technoland PC/104+ form factor computer – this form factor measures just 3.75" in. x 3.54" in. and contains an i386 processor, hard drive interface, floppy drive interface, USB ports, two serial ports, two ps2 ports, an integrated network, and consumes just 12 watts. http://www.technoland.com/

[10] Crusoe – an i386 compatible processor, which implements several of the instruction sets in a software layer, allowing the processor to draw very little power. http://www.transmeta.com/

generation to a minimum. In addition, a USB[11] to serial device provides four additional RS232 communication ports[12] while avoiding IRQ conflicts[13].

The computer runs Microsoft Windows XP Embedded[14], allowing for a very small operating system footprint while maintaining the full functionality of the Microsoft .NET[15] architecture. The system runs off two 512 MB compact flash cards, providing a storage system with no moving parts, able to withstand up to 10,000 G's. One compact flash card holds the operating system in a protected write mode, while the other stores a real-time log of in-flight variables. In the case of an unknown failure, the problem can be diagnosed by examining the log files, even if the vehicle crashes.

5. GPS Receiver



Picture 3. Garmin GPS 15H

The plane obtains 3D positional data at 1Hz from a Garmin 15H GPS receiver[16]. The GPS module is extremely light and provides improved accuracy through the use of the Wide Area Augmentation System, and DGPS commands sent to the plane when available. Able to run off 8-40 VDC, the Garmin 15H weights just 15g and outputs its data in NEMA[17] standard over 4800 baud RS232 serial.

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[11] USB – universal serial bus provides a high speed interface to devices, and allows for up to 127 devices to be attached to a single port. This greatly expands the ability to attach future device through conversion or otherwise.

[12] RS232 Communication Ports – this is a serial protocol in which data is transferred over a three line system, send, receive, and a ground reference. This is a very common system, as it is easily implemented on small microprocessor devices, and is used as the medium of communications within the aircraft.

[13] IRQ – Interrupt request line – this is a computer resource, and provides a means for an input-output operation to notify the processor of its current actions. There are only 15 IRQ lines available on the Technoland computer, which limits the number of devices that can directly talk to the CPU.

[14] Windows XP Embedded – this operating system is derived from Microsoft Windows XP's kernel, and contains all of the elements of Windows XP Professional, however it has the ability to specify exactly which components of the kernel the end user would like to install, and allows the complete operating system to be installed on a small 200 mb foot print, with all of the needed capabilities of the full Windows XP kernel.

[15] Microsoft .NET framework – This is a virtual machine architecture, which runs within the Windows XP Embedded environment, and allows for a layer of abstraction between the flight application and the hardware.

[16] Garmin 15H GPS receiver – this is a small OEM Global Positioning System device, which is able to monitor up to 12 GPS satellites as well as to receive Wide Area Augmentation Systems (WAAS) updates. This provides a very high degree of accuracy in a GPS system in a package which weighs just 15 grams.

[17] NEMA - National Marine Electronics Association – organizing body, which has defined the protocol for communications between common devices including GPS, radar, plot charting, compasses, etc. The NMEA protocol 0183 defines the sentence structure used to communicate with the Garmin GPS, and is implemented over standard serial.

6. Orientation Sensor

Picture 4. Microstrain 3DM-G Gyro

The Microstrain 3DM-G gyro[18] is used to provide 3-DOF state information. This sensor combines three angular rate gyros with three orthogonal accelerometers and three magnetometers to provide pitch, yaw, and roll readings accurate to .10 degrees with .01 degrees of precision. The 3DM-G outputs all nine sensor values at 100Hz. A 9V DC regulator provides the 5.2V-11V power required by the gyroscope, and the entire package weighs 40 grams.

7. Altitude & Airspeed Sensor

In order to measure airspeed and altitude, two SenSys ACSX[19] analog pressure sensors are placed in the plane. One measures absolute pressure between 0 and 15 PSI, translating to the altitude, and referenced to ground level. The other measures differential pressure between the plane's static pressure reference and the kinetic pressure reference at a pitot tube located in the wing, translating to speed. We developed a custom analog to digital board, based on an Atmel microcontroller[20] and a 24-bit analog to digital converter. The microcontroller provides a filtered output at 20 hz to the computer for appropriate altitude conversions.

8. Communications and Trust

While the aircraft operates entirely independently, controllers on the ground require constant communication with the plane in order to monitor telemetry and surveillance information in real time. Furthermore, controllers may provide mission updates based on changing information, or they may need to take control of the aircraft if something should go wrong with the onboard sensors.

The largest issue with UAV development is the sense of trust. Before an aircraft may fly itself, ground operators must understand each component of the onboard decision management, and trust the aircraft to make correct decisions in flight. This process is very tedious because each module has to be integrated separately then finally allowed to operate on the aircraft under close supervision. It is the supervision phase which requires the greatest amount of ground interaction and extensive use of telemetry systems.

Each telemetry system has been carefully selected in order to insure that it will not cause interference with the other systems. Each device has been faraday caged and all transmission cables in the system have been shielded as not to broadcast any interfering signals.

[18] Microstrain 3DM-G gyro – This gyro provides a very reliable method to determine the pitch, yaw, and roll of the aircraft at any given time. The Microstrain gyro was selected for its use of all solid state equipment, extreme durability and weighs only 40 grams. http://www.microstrain.com/

[19] SenSys ACSX – These pressure sensors output a 5 volt analog output, allowing us to sample at 24 bit resolution.

[20] Atmel Microcontroller – inteagrates analog to digitial communications, and serial communications. http://www.atmel.com/

9. Communication Hardware

In order to maintain constant communication with the ground station, two radio modems are used. A Maxstream 9XStream[21] 900 MHz serial modem, capable of a 19.2 Kbps over-air transfer rates, is responsible for data packets sent to the plane. Working in conjunction with the Maxstream unit is Coyote Datacomm 2.4 GHz 56 Kbps radio modem, used for downstream communication from the plane. We are using two radios, as each modem is a half duplex unit, and we wanted to insure minimum interference for each link by using very different frequencies for upstream and downstream communication (2.4 GHz and 900 MHz). Both modems have an effective line of sight range of over 5 miles, allowing users on the ground to view in-flight variables as well as provide the ability to change mission parameters even if the plane is out of visible range.

10. Video and Imaging

A Panasonic CMH112[22] 470 line NTSC camera is mounted in the midsection of the airframe, providing a 53 degree overhead view of the area below the plane. This video is transmitted to the ground using a TXA5-RCb 1 watt ATV Transmitter board[23]. The ATV transmitter uses the 439Mhz HAM[24] band, with a cross-dipole antenna to provide a clear picture over channel 60 TV up to several miles away. The real time video system will allow the judges to verify the vehicle has flown directly over the targets. The video is digitized on the ground and indexed with the GPS telemetry received over the radio modems to quickly allow an operator to accurately pinpoint the location of objects on the ground.

11. Receivers and Failsafe

The airplane uses a pair of custom FMA Direct FS8 receivers[25] for dual redundant control from a transmitter on the ground. Each receiver controls half of the plane, allowing an emergency landing in the case of a failed component. The FS8 receivers have been modified to allow our autopilot computer to send commands to actuate the control surfaces, and the FS8 determines whether to pass the computer commands, or the manual commands, based on a switch on the ground transmitter. The FS8 receiver uses 8 channel digital signature recognition[26], reducing the possibility of radio interference, even from a transmitter on the same frequency. The receivers are also equipped with a programmable fail safe mode, which actuates the flight surfaces to a set position in the case of a lost signal. Furthermore, ground operators have the ability to force the transition between autonomous and manual flight via a channel on the radio. We have also added a secondary level of protection such if the plane flies out of range of the transmitter it immediately shuts down all other electronics on board in case they are interfering. This will provide the pilot a chance to recover the plane, as we can safely assume that the plane will only erroneously fly out of range during development.

[21] Maxstream serial modem – This device emulates an RS232 connection through a pair of wireless transceivers. http://www.maxstream.com/

[22] Panasonic CMH112 – This camera adjusts for light through frame exposure rather than adjusting the iris, critical for field of view calculations. http://rock2000.com/Company/CBC-Chugai/CMH112_-_CMH212_Datasheet.pdf

[23] TXA5-RCb 1 watt ATV transmitter board – a transmitter which sends a video signal through analoug means on Amateur radio frequencies. http://www.hamtv.org

[24] HAM – amateur radio, http://www.arrl.org

[25] FMA Direct FS8 receivers – FMA direct makes RC aircraft receivers, as well as small electronics for drone aircraft, and other applications. Their latest receiver, the FS8, provides a reliable mechanism to manually control the plane, and to switch between autonomous and manual control. – http://

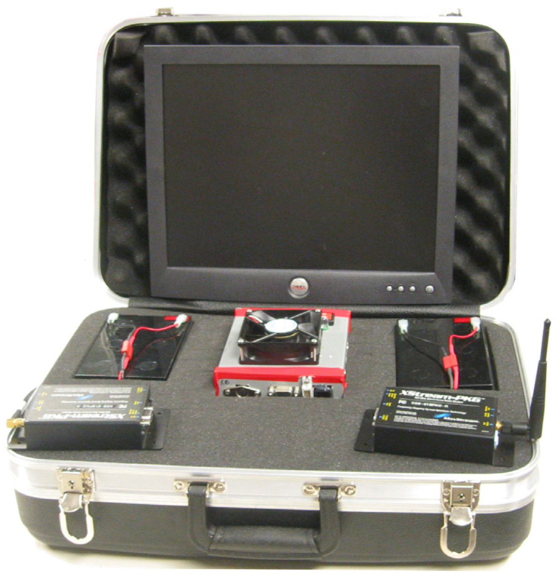
[26] Digital signature recognition – The FMA Direct FS8 receivers analyze the signal it receives and locks on to the particular signature of a given transmitter, and is able to overcome other signal sources, even if they are on the same channel.

12. Connectors

Picture 5. Lemo P-Series Connectors

In order modularize the electronic components within the airframe, Lemo P-Series 5-pin[27] connectors have been used to connect each device with the computer. Six sockets are mounted on the side of the computer box, allowing devices to plug into the system with just one cable. The five wire cable provides the varying voltage and signals necessary to connect to any of our devices. This has resulted in the ability to interchange any of the sensors or replacing them with a different device, without having to rewire the internal aircraft ports.

13. Ground Station



Picture 6. Ground Station Case

The ground station consists of a Versalogic Panther 400Mhz PC/104+[28] computer embedded in a 7" x 10" x 18" Platt heavy duty case. Connectors allow the two radio modems to be set up along side the case, and easy access to various I/O ports such as keyboard, mouse, Ethernet, and VGA. The computer and accessories are powered by two 12V 12Ah Lead-Acid batteries, providing more than six hours of power to the system. This allows for easy transportation and setup at a remote field location.

[27] Lemo P-Series 5-Pin Connector – small industrial connector, used to interface with our devices. http://www.lemo.com

[28] Versalogic Panther 400Mhz PC/104+ - Similar to the Technoland computer, this is a full i386 architecture motherboard in a 3.74" x 3.72" board. http://www.versalogic.com

B. Software Overview

At a high level, the software is divided into three separate components. First, there is the Prometheus aircraft software[29] which is run on the vehicle and is responsible for the actual control of the plane, including using Feedback algorithms to move the control surfaces.

As a result of the low speed and high latency of the telemetry connection it is necessary to introduce a ground station, which is the only piece of software that communicates with the plane directly. The ground station software runs a modified version of the aircraft software and acts as a gateway to allow many clients to connect to the plane, see appendix A for an object diagram. As such, the ground station is responsible for the caching of data coming down from the plane, as well as the propagation of commands from clients up to the plane.

The final application layer is made up by a number of client applications, each of which connects to the ground station via Ethernet. There are many choices for communication, including .NET remoting and Web Services[30]. The use of Web Services allows for platform transparency, communicating on a common network protocol. For example, there are clients for both the PC and the Pocket PC[31]. In short, the technologies that we utilize for ground connectivity enable the development of a wide body of heterogeneous clients to better the exchange of information to people that need it.

1. Serial Communications

As was already mentioned, communication between the plane and the ground station is through low speed serial modems. In order to facilitate this we developed a custom serial line protocol which is able to cope with the slow speed and the fact that the serial connection is potentially unreliable. To overcome loss issues, the data is streamed in packets, each of which is hashed to insure integrity. Each packet is then sequenced to ensure that missing packets can be detected, and saved on a network stack that allows dropped or corrupted packets to be resent. The packet design also contains quality-of-service bits to differentiate between command data, which needs to be received and "info" data, which if dropped is not a problem, because newer info will supersede it shortly. The packet design also contains a separate link control layer that makes it transparent to the rest of the Prometheus system when command packets are being acknowledged, or data resending is necessary.

Packets are handled by a series of classes which are designated Packet Handlers, and are responsible for encoding and decoding command information over the serial link. By using .Net reflection[32] at runtime, Prometheus automatically discovers these packet handlers and uses them; adding new command messages to the telemetry system takes minimal time and effort, and as such is highly extensible.

Additionally, the system has the capability to support pluggable encryption modules. Though currently the encryption scheme used is relatively simple, using single DES[33] as a proof of concept, any type of encryption can be plugged in by satisfying an interface. This will allow customers to implement any encryption scheme that they desire, including proprietary schemes in the case of military applications.

2. Interfacing with Hardware

In order to facilitate communications with the hardware devices, Prometheus supports a model for dynamically loadable drivers. This framework is currently used solely to interface with hardware, but this is not a design

[29] Prometheus aircraft software – this is the name for the application which runs on the aircraft, and is responsible for all autonomous actions, and for controlling real time flight.
[30] .NET remoting and Web Services – These technologies allow for communication between applications over a network. This is important as it allows for network transparency and platform independence.
[31] Pocket PC – a hand held computer capable of running Windows CE, and is used as a regular computer, running a version of the ground station software.
[32] .Net Reflection – This technology allows an application running within the .Net virtual machine framework to communicate with the virtual machine about object information and organization. This process allows the software to dynamically become aware of new modules, such as encryption.
[33] Single DES encryption – uses a 56-bit key in order to encrypt the data in packets for transmission. Each side must negotiate the key before communications may take place. This algorithm has been considered relatively weak by modern standards, as the speed of computers has made it possible to crack Single DES through the brute force method of trying every single combination.

restriction; drivers can be implemented for any purpose. For example, drivers which interface with log files are under development, in order to allow replaying of logged data within the same framework.

The driver system allows for the creation of driver profiles, so that for example, one set of drivers can be loaded when bench-testing, another on the vehicle, and yet another on a different aircraft, possibly using different hardware. This allows the system to be easily adaptable to many different configurations. This flexibility greatly improves the reusability of the platform, no longer making it hardware dependant, and allowing end users to implement this package on a larger variety of sensors.

Drivers are provided a common shared memory space, managed by a series of mutex[34] locks on the stored space. This provides the primary process for inter-thread communication, allowing drives to reflect their most recent data in the shared memory space, and control algorithms to respond to new data and to output new control surface positions.

3. *Mission Management*

Mission management is at the heart of the aircraft's autonomous behavior. It is responsible for defining the high level objectives for the mission; these objectives are then converted to lower level navigation commands and maneuvers, which are passed down to the inner control loops.

The mission management framework is centered on the abstract concept of a frame, which is a measurable segment of the mission, with decided criteria for termination. The mission is broken up into many frames and each frame is allowed to set intermediate goals for the feedback loops until it informs the mission manager that it is completed, at which point the next mission frame is loaded. Additionally, the current mission frame is allowed to specify which setup it requires for the feedback loops. This allows the software to perform many different types of maneuvers without requiring invasive changes. This will be discussed in more detail in the next section.

4. *Failover Modes*

Safety is of paramount concern in UAVs. The consequences of an out of control aircraft could be catastrophic, given the wrong circumstances. Our vehicle is targeted to be as cost effective as possible and as such, we have chosen not to utilize a large number of redundant equipment, but to use highly reliable components. In the case of failure, there is a very decisive mapping of failover modes. For example, if GPS lock is lost, the current mission frame is frozen, and the aircraft enters into a large radius circle until a signal is reacquired, or a manual pilot intervenes. If gyro information is lost, the aircraft attempts to roll over to a secondary (appreciably less expensive) gyro in the receiver. All of these situations are handled by the failover manager, which allows custom actions to be associated with failover conditions. When modules encounter these failure conditions, they inform the failover manager, which takes suitable action. When the failure situation terminates, then control passes back to the displaced modules normally responsible for the previously failed actions, and the mission resumes.

5. *Clients*

The information above describes how the system works in-flight, however for testing purposes, and also for the purposes of intelligence gathering, it has become necessary to develop a series of client applications.

The main client application is Hermes[35]. It allows us to see flight information coming back from the aircraft, monitor that information, and provides several useful visualizations of the information.

Mission objectives and geographic features of the area are mapped using third party Geographical Information System[36] (GIS) software. The current position and heading of the plane is overlaid on this map, allowing an operator to visualize the current status of the mission.

The client application provides functionality to view and sort the immense amount of log data that comes back from the aircraft. This log data comes from different subsystems giving reports of critical errors or status issues.

[34] Mutex – a data structure used to maintain inter thread locks on a memory object. This insures that memory is accessed in a synchronous manner.

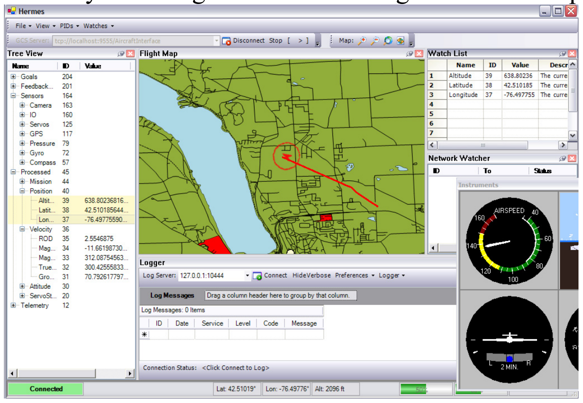
[35] Hermes – primary ground station client, used for monitoring aircraft position, and mission status. In the case of changing mission priorities it also allows for real time updates to the framework.

[36] Graphical Information System (GIS) – third party software, used to provide mapping functionality within the ground control station.

Hermes also provides a way for programmers to visualize the way that the feedback loops are acting on the current errors, so that they can verify the correct operation of these loops and be able to tune the loops more efficiently.

We have the ability to update flight variables that the system may require, and perform important in-flight actions, like saving changes in important configuration or feedback parameters to the hard disk so that they will persist past the current session. Other functionality of interest is the ability to engage and disengage the autopilot, reprogram its current mission in-flight and report on the current state of radio connectivity between the plane and the ground. As was mentioned previously, much of this complexity is implemented in the ground station or the plane, and the client merely requests that the ground station perform an action, or command the plane to do so.

Hermes also allows for the creation of custom views, which arrange the software in a specific way. As such, there is a pilot view which shows familiar gauges and log messages. There is a payload view, which provides the operator with current mission status, and payload controls and telemetry information. These views are customizable based on our core set of controls, and may be arranged and saved to a ground station operator's preference.



Name	ID	Value
Goals	204	
Feedback...	201	
Sensors	164	
Camera	163	
IO	160	
Servos	125	
GPS	117	
Pressure	79	
Gyro	72	
Compass	57	
Processed	45	
Mission	44	
Position	40	
Altit...	39	638.80236816...
Latit...	38	42.510185644...
Lon...	37	-76.49775590...
Velocity	36	
ROD	35	2.5546875
Mag...	34	-11.66198730...
Mag...	33	312.08754563...
True...	32	300.42555833...
Gro...	31	70.792617797...
Attitude	30	
ServoSt...	20	
Telemetry	12	

	Name	ID	Value	Descr
1	Altitude	39	638.80236	The curre
2	Latitude	38	42.510185	The curre
3	Longitude	37	-76.497755	The curre
4				
5				
6				
7				

ID	To	Status

Log Server: 127.0.0.1:10444 Connect HideVerbose Preferences Logger

Log Messages Drag a column header here to group by that column.

Log Messages: 0 Items

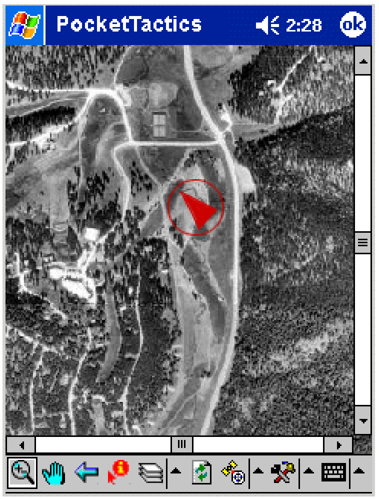
ID	Date	Service	Level	Code	Message

Connection Status: <Click Connect to Log>

Lat: 42.51019° Lon: -76.49776° Alt: 2096 ft

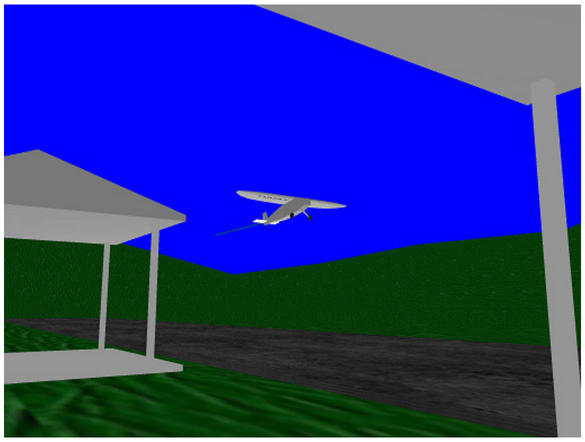
Picture 7. Hermes Client (Appendix D)

Another client of interest has been our PocketTactics client. Designed with the problems of modern UAV flight in mind, PocketTactics allows the intelligence chain to be shortened, so that the intelligence consumer can get important information directly from the plane, allowing decisions to be made in real time. The work in PocketTactics has centered around changes that should be made to the mission in response to intelligence presented by it. As such, it presents a simple mapping interface, which overlays the vehicle's current position and objectives on satellite images of the current terrain. This allows the intelligence consumer to easily cross reference current position with known landmarks, and modify the mission accordingly.



Picture 8. PocketTactics Client

Additionally, work is ongoing on a 3D visualization tool to plot the plane's position and environment. Initially this tool was designed only to be able to play back a flight after it had terminated, but the team has found value in having an in-flight visualization of the position of the aircraft in a 3D world. We foresee substantial usefulness for this software going forward to map the terrain below the vehicle in real time, which may allow the crew and intelligence consumers a better understanding of the area that they are interested in observing.


Picture 9. 3D Flight Visualization

6. Debugging

Debugging the software is a complex process; it is more difficult than implementing the functionality in the first place. We have attempted to minimize this difficulty in several ways. The first of these has been the development of specialized Graphical User Interfaces to view the status of different portions of the system. The autopilot code contains an automation framework, which allows every sub routine to be unit tested based on a well defined set of inputs and outputs. This process is far cheaper than using formal proofs, as the language to define inputs and outputs is the same as the language the software is implemented in. Unit testing does not provide the assurance that a formal proof does, however, a well designed unit test will test all of the corner cases of an algorithm, as well as repeated typical use cases, to verify the sub routine.

Flight testing all of the software based solely on unit testing, insures that the software components will each work as intended, but in order to develop the control algorithms, and to test the entire application framework together, it needs to be tested. Immediate flight testing of the software would place the aircraft, and control systems at unnecessary risk; instead the software has been interfaced into Microsoft Flight Simulator 2004, allowing for complete software in the loop testing.

Microsoft Flight Simulator 2004 - A Century of Flight with ...
Flights Aircraft World Options Views Help Modules
Sound Off
11999 ft
Picture 10. Flight Simulator Interface

Our aircraft is modeled in flight simulator to perform with similar characteristics in order to let us evaluate our control algorithms, and to tune them within a reasonable margin. This process is important to verify that the constraints placed and tested within the application are correct, and to determine reasonable constants for the control loops, such that the software may be prepared for flight evaluations.

IV. Flight Evaluations

Flight testing of the current platform is still ongoing. As of the time of this paper the airframe has flown manual valuation tests successfully. It has then flown with the autonomous package onboard, to validate the net weight, and distribution in the aircraft, and finally has demonstrated autonomous flight navigation. Ongoing work is being conducted in the areas of mission management, and payload development.

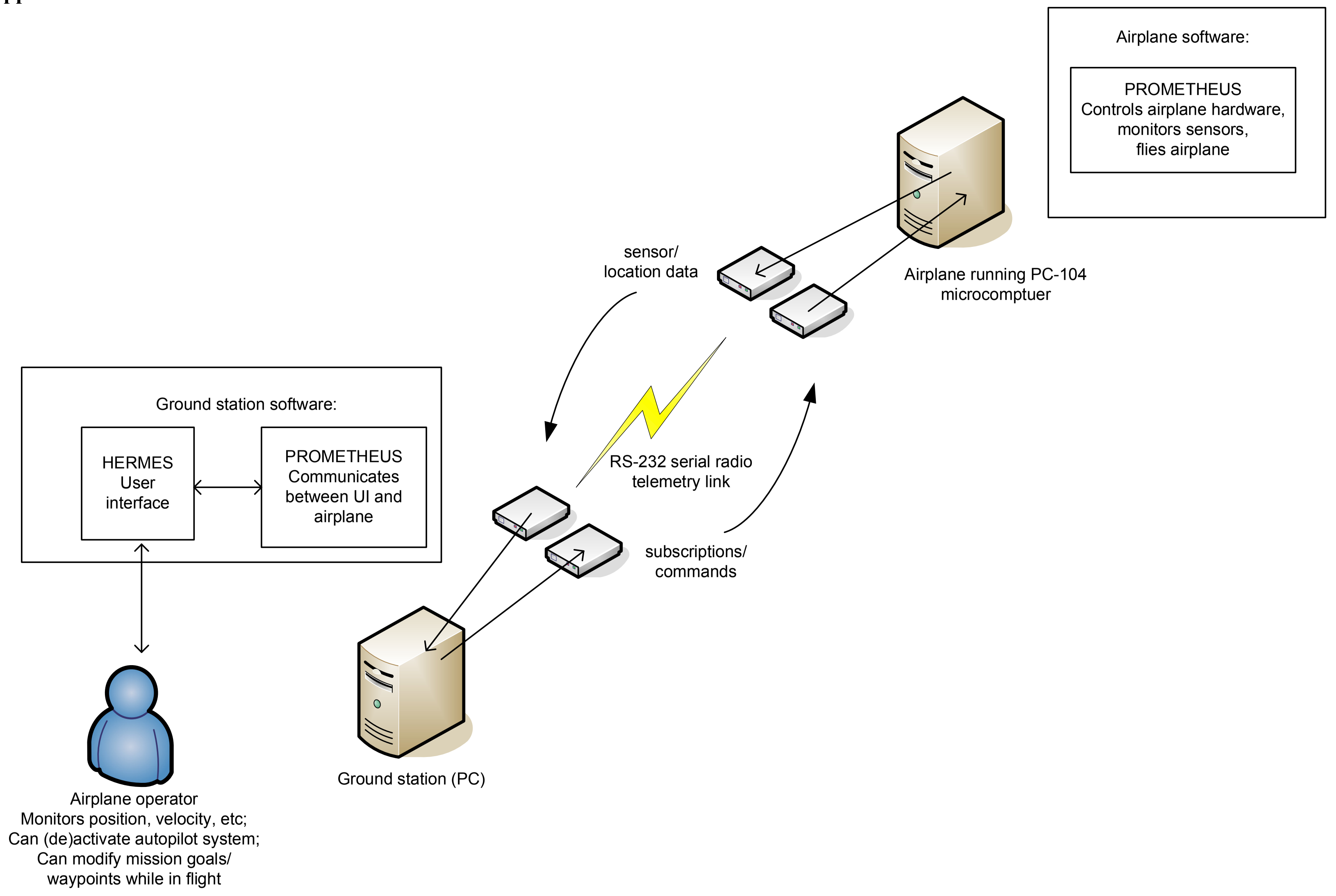
V. Conclusion

Given the demanding nature of real time flight control, the software and hardware choices have performed remarkably well. No aircraft has been lost since the initiation of the autopilot system in the hardware, and the software sub system has performed identical to simulations in each flight evaluation, allowing for flight controller tuning. The telemetry sub-system has been tested to one mile, and is rated for up to five miles. The packet protocol has resulted in an amortized 17% reduction of maximum throughput, but has been critical in maintaining data integrity. The encryption protocol selected does not restrict bandwidth in any way, as the key exchange for the encryption occurs on the ground, and in flight, both communication devices have ample processing power to translate the packets, such that the telemetry devices themselves are still the bottleneck.

The rapid progress in this second generation autopilot system has demonstrated the feasibility of using off the shelf software in a safety critical environment successfully. Given the extreme difficulty involved in formal proofs of such a large application and operating system, the use of off the shelf components has allowed for a very reliable system, which may be scaled to meet required safety standards through parallel implementations, still passing on the immense savings in development time of a custom architecture.

VI. Appendix

Appendix A

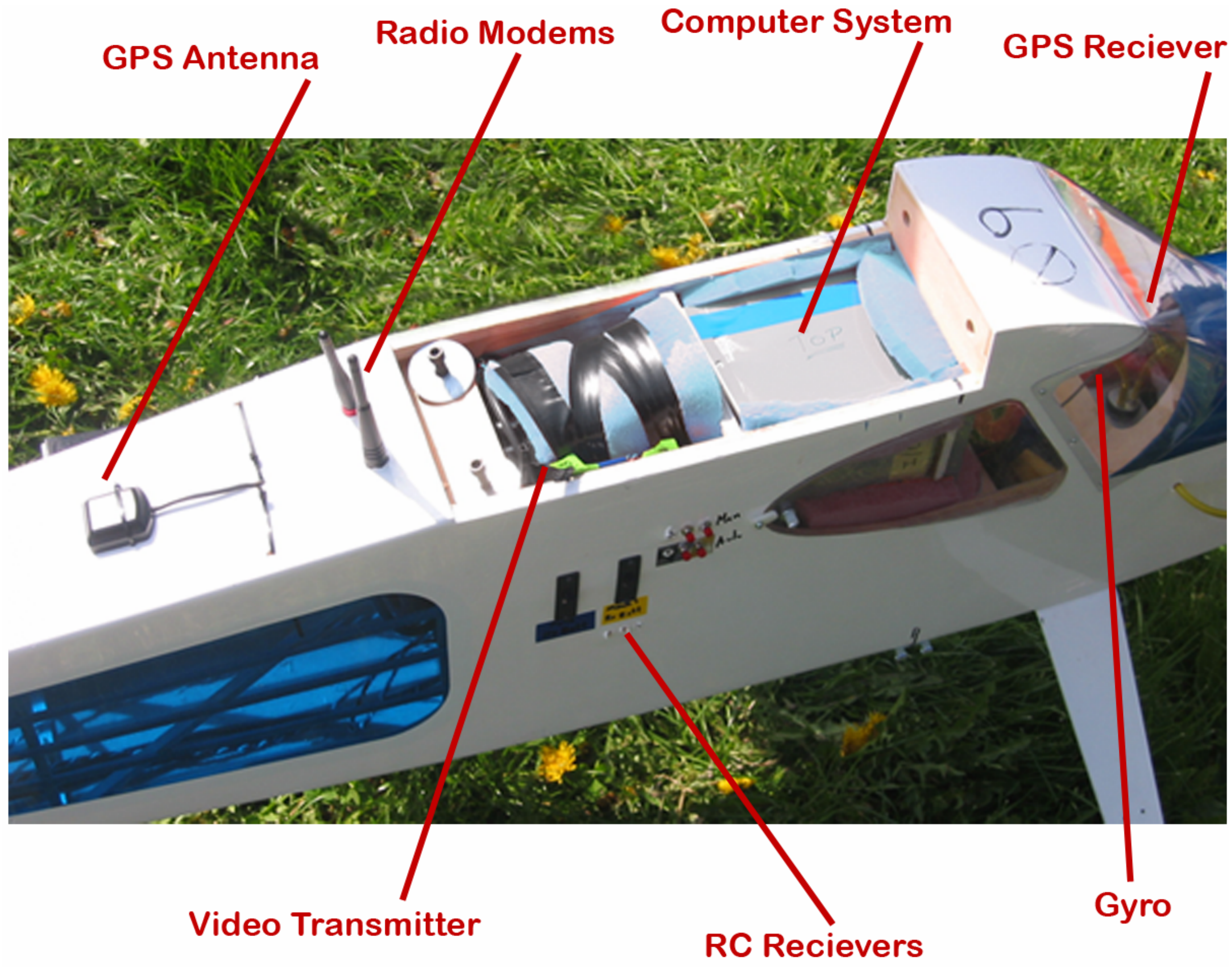

Airplane software:
PROMETHEUS
Controls airplane hardware, monitors sensors, flies airplane
sensor/ location data
Airplane running PC-104 microcomptuer
Ground station software:
HERMES
User interface
PROMETHEUS
Communicates between UI and airplane
RS-232 serial radio telemetry link
subscriptions/ commands
Ground station (PC)
Airplane operator
Monitors position, velocity, etc;
Can (de)activate autopilot system;
Can modify mission goals/ waypoints while in flight

Component Model

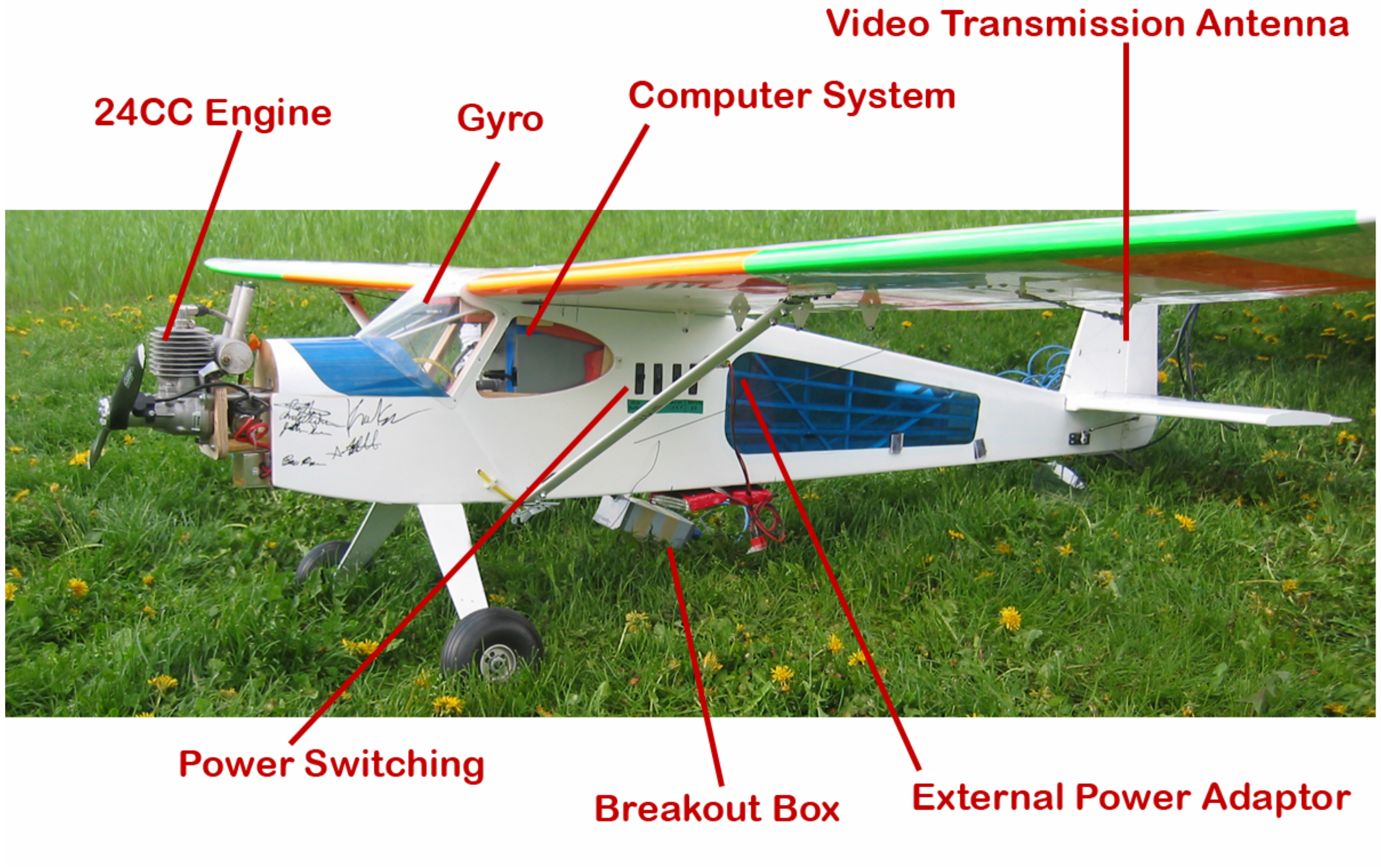
Appendix B.

In Flight Shot – February 14th, 2003

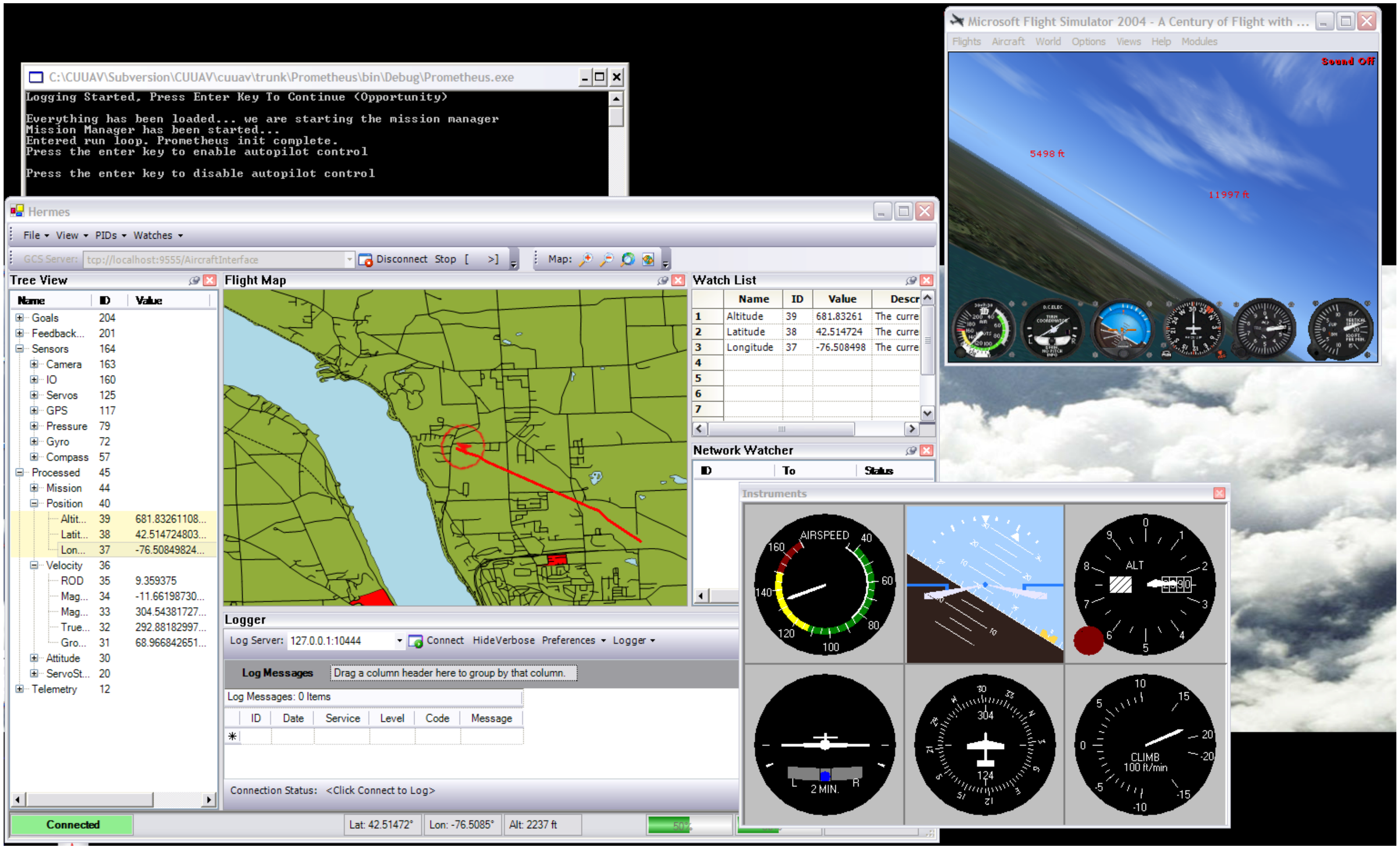
Appendix C1.


GPS Antenna
Radio Modems
Computer System
GPS Reciever
Video Transmitter
RC Recievers
Gyro

Appendix C2


Video Transmission Antenna
24CC Engine
Gyro
Computer System
Power Switching
Breakout Box
External Power Adaptor

Appendix D


C:\CUUAV\Subversion\CUUAV\cuuav\trunk\Prometheus\bin\Debug\Prometheus.exe
Microsoft Flight Simulator 2004 - A Century of Flight with ...
Flights Aircraft World Options Views Help Modules
Sound Off
5498 ft
11997 ft
Hermes
File View PIDs Watches
GCS Server: tcp://localhost:9555/AircraftInterface
Disconnect Stop
Map:
Tree View
Flight Map
Watch List
Network Watcher
Instruments
AIRSPEED
ALT
CLIMB 100 ft/min
2 MIN.
Logger
Log Server: 127.0.0.1:10444
Connect HideVerbose Preferences Logger
Log Messages
Drag a column header here to group by that column.
Log Messages: 0 Items
Connected

```
Logging Started, Press Enter Key To Continue (Opportunity)

Everything has been loaded... we are starting the mission manager
Mission Manager has been started...
Entered run loop. Prometheus init complete.
Press the enter key to enable autopilot control

Press the enter key to disable autopilot control
```

Name	ID	Value
Goals	204	
Feedback...	201	
Sensors	164	
Camera	163	
IO	160	
Servos	125	
GPS	117	
Pressure	79	
Gyro	72	
Compass	57	
Processed	45	
Mission	44	
Position	40	
Altit...	39	681.83261108...
Latit...	38	42.514724803...
Lon...	37	-76.50849824...
Velocity	36	
ROD	35	9.359375
Mag...	34	-11.66198730...
Mag...	33	304.54381727...
True...	32	292.88182997...
Gro...	31	68.966842651...
Attitude	30	
ServoSt...	20	
Telemetry	12	

	Name	ID	Value	Descr
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2	Latitude	38	42.514724	The curre
3	Longitude	37	-76.508498	The curre
4				
5				
6				
7				

ID	To	Status

ID	Date	Service	Level	Code	Message
*					

Connection Status: <Click Connect to Log>

Lat: 42.51472° Lon: -76.5085° Alt: 2237 ft

Hermes Client software monitoring a simulated flight (Flight Simulator shown in the top right).

VII. Acknowledgments

The following people and organizations have contributed greatly towards the success of our project and we would like to express our thanks: Kevin Kornegay, Microsoft Research, Cornell University, Learning Initiatives for Engineers (LIFE), FMA Direct, Lemo, Nathan Gwozdecki, Spacially Aware, Microstrain, glyFX, Syncfusion, Sax.net, XtremeSimplicity, HP InfoTech, Garmin, Dev Components, Cheryl Francis, Dorothy M Palladino, and James Buescher.

The following people directly participated on the team, William Aber, Andrew Abramson, Jake Felser, Ron Hose, Aaron Kimball, Jonathan Kron, Brian Rogan, Karl Schulze, Ryan Stenson, Joseph Sullivan, Dr. Kevin Kornegay.

VIII. References

[1]Jacky, J., “Programmed for Disaster: Software Errors that Imperil Lives,” *The Sciences, vol 29, num 5*, URL: http://staff.washington.edu/~jon/pubs/safety-critical.html [cited 16 Sept 2004].

[2]Schulze, K., Buescher, J. “A Scalable, Economic Autonomous Flight Control and Guidance Package for UAVs” 2nd AIAA "Unmanned Unlimited" Systems, Technologies, and Operations Volume 11750, San Diego, CA, September, 2003

[3]“Autopilot,” *Wikipedia* [online database], URL: http://en.wikipedia.org/wiki/Autopilot [cited 16 Sept 2004].