Technical Paper for the
Autonomous Unmanned Vehicle Systems International
2004 Student Unmanned Aerial Vehicle Competition

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Abstract

North Carolina State University is competing in the 2004 Student UAV Competition. NC State's Aerial Robotics Club has developed an autonomous fixed wing aircraft capable of flying GPS points over a distance of 3 kilometers and carrying a payload of cameras for aerial imagery. This paper outlines the design of the systems.

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Introduction

Mission Requirements

The purpose of this project is to compete in the AUVSI Student UAV Competition. The 2004 competition involves designing and building a UAV to fly through a set of known GPS coordinates with a possible flight path of several kilometers. The competition judges will provide several coordinates of interest. Aerial imagery will be taken at these locations and stored onboard the aircraft. After landing, the quality of the imagery will be assessed by judges. This mission is to be completed within 30 minutes.

Design Overview

Early on, it was decided to use a fixed wing aircraft. A fixed wing aircraft is fast, can carry an appreciable payload, and can fly in light to medium weather. From previous experience, it was discovered that a rotorcraft is far too mechanically complex to provide the reliability, payload capacity, or endurance needed. Lighter-than-air vehicles do not have the ability to effectively maneuver when exposed to moderate winds and do not have the speed required to reach all GPS coordinates. As a result, the team selected a conventional fixed-wing platform.

Navigation is the next major requirement. Since GPS coordinates are provided and are part of the mission requirements, GPS is used for navigation. Inertial navigation systems were therefore not considered. The coordinates will be provided the day prior to competition, so GPS induced error was determined to be relatively small.

The overall goal of the competition is to obtain quality images of target coordinates. A multi-faceted camera system was chosen to ensure satisfactory images and provide multiple image formats for the judges. Three independent camera systems were utilized to maximize coverage of target locations. The team considered less costly imaging systems, deciding finally on quality and quantity to ensure good imagery.

Safety is also an important consideration, as demonstrated clearly at the 2003 Student UAV Competition. One such safety feature is dual, redundant receivers installed for extra protection against loss of transmitter signal. However, in the case of loss of transmitter signal, the plane is programmed to initiate a hard-over maneuver as the fail-safe. This fail-safe will occur even if the plane is in autonomous mode so the vehicle can not fly outside of manual safety override distance. On the ground, extensive checklists are used to ensure correct procedures are followed.

The team decided to use commercial off-the-shelf products whenever possible. There was no reason to spend time reinventing a product if it could be purchased. The disadvantages of commercial products included accepting the limitations of those products, which were not necessarily meant for aerial operation. When commercially available products were too costly or their applications too limited, the club resorted to designing custom systems.

System Design

The team selected the commercial components based on performance, size, weight, ease of integration, and availability. Design decisions involved compromises and tradeoffs between components, and their contribution to the success of the mission. The major systems required for a successful reconnaissance UAV include: vehicle, navigation, aerial imagery, wireless communications, controller hardware, controller and navigator software, and ground station support.

Vehicle Design: *Daedalus*

The main aircraft is *Daedalus*, a low wing, T-tail, conventional aircraft designed and constructed by seniors in the 2001 Aerospace Engineering Senior Design program, and modified with landing gear by the club. This vehicle was selected because of its large payload bays inside the fuselage and heavy lifting capability of approximately 15 pounds over airframe weight. The landing gear was designed for twelve inches ground clearance in order to allow for a deployable vehicle in the future. Currently, the clearance is being used for two pan-tilt mounts installed on the underside of the wings just outside of the main gear. *Daedalus* has a maximum speed of approximately 85 miles an hour, which allows quick travel time between GPS waypoints. For ease of landing, *Daedalus* can slow to a 35 mph landing speed and can stop quickly with pneumatic brakes applied.

Daedalus has a wingspan of 8 feet and is 6 feet from spinner cone to tail. It is powered by a 180 Saito four stroke engine that runs on standard RC glow fuel. This oil, water, and alcohol fuel was chosen because of its stability and low fire risk.

Construction of *Daedalus* is Kevlar and Korex for fuselage and wing skins with carbon and Korex internals. Prepreg carbon dual wing spars take aerodynamic and landing loads. After a crash, the front bay was rebuilt with Korex and carbon fiber. Hard mounts were installed into the skin of the front bay and internal ribs replaced by thicker carbon skins to create additional room in the main cargo compartment. A removable wing, T-tail, and landing gear allow for easy transport in a special travel box that protects the vehicle from impact damage.

Navigation

Navigation through the GPS waypoints requires the use of a GPS receiver. The system selected is a Royal Tech GPS receiver with a Mighty Mouse II active antenna. This combination provides fast acquisition, low power consumption, small size, low weight, and ease of interfacing with the PC 104.

The navigation algorithm (described in more detail in the Controller Section) automatically plots a course to intercept a predetermined path while avoiding an arbitrary, closed boundary.

Aerial Imagery

For the reconnaissance aspect of the mission, three systems are used to capture images of the target locations. Still images from the digital photography system are recovered after landing with aid of a memory card reader and a laptop. Live video is transmitted to the ground and captured on VHS tape for later analysis.

Still Photography

Three Aiptek SD 1.3 Megapixel digital cameras each with a 128 MB memory card are mounted on a modular payload board. The cameras are tilt calibrated for 30% image overlap at 300 feet altitude. One camera looks directly downward for undistorted ground images while the other cameras provide oblique images to ensure a large area can be covered quickly. All three cameras are triggered simultaneously during flight over target coordinates. An inline BASIC stamp looks for three PWM pulses of the same length before triggering the camera array, ensuring a quality triggering signal. The BASIC stamp is bundled on the camera tray.

Dual Pan-Tilt Cameras

Two Channel Vision mini-cameras with 380 lines of resolution are attached to a custom pan-tilt mount. A controller program runs on an Atmel Mega128 microprocessor that interfaces with the PC 104 to get the plane's current position, the position of the next waypoint, and the Euler angles of the aircraft. The controller calculates needed sweep and inclination angles to point cameras to the ground at the next GPS waypoint. The Atmel handles all of the PWM signals for the four servos in the pan-tilt mounts. Together, the two cameras provide an unobstructed view of the target for most logical plane orientations. The video from the cameras are transmitted back to the ground station providing a live view of the target location.

Pilot's View Camera

A Channel Vision bullet-camera with 380 lines of resolution is mounted on top of *Daedalus*' T-tail looking out over the nose of the aircraft. The images from this camera can be given to the pilot to supplement his ground view.

Communications

There are several communications systems in simultaneous operation on the aircraft during any flight. They are the RC inputs from the pilot to the vehicle, the video link from the vehicle to the ground station, and the two-way communication via wireless modem between the ground station and the PC 104 onboard the aircraft. Also, a dual receiver set-up has been implemented to guard against radio interference and RC receiver failure.

Radio Interface Board

The radio interface board sits between the PC 104, the RC receivers, and the servos. It was designed by Dr. Hall to optically isolate the servos from the PC 104 and switch control of the aircraft from remote control mode to computer control mode. The board monitors the gear channel of the receiver. When the gear channel is in the up position, "Clicked Out," the pilot has complete RC control of the aircraft. When "Clicked In", the servos are commanded by the PWM signals from the PC 104. If the RC receiver losses signal from the pilot's transmitter, then the receiver fail-safe automatically triggers the gear channel to the "Clicked Out" position, initiating a hard-over maneuver. (See Appendix: Radio Interface Schematic)

Video Transmission

A single 2.4 GHz video transmitter made by Black Widow AV is mounted inside the fuselage and provides approximately 3km range of live video downlink. The three onboard mini video cameras sends input to an onboard 4-1 encoder which encodes four video feeds into one feed and transmits using the single channel transmitter. A single channel receiver from Black Widow AV picks up the signal and outputs to a 1-4 decoder that parses the signal into four separate images on the ground. These images are then passed into a separate multiplexer so that the best image can always be displayed full screen to the judges while all four images are simultaneously recorded onto VHS tapes. A GPS overlay board displays the plane's current GPS location and our pilot's HAM operator call sign overtop the transmitted camera image. (See Appendix: Video System Schematic)

The 2.4 GHz transmitter does not interfere with the 72 MHz remote control signals, but it does overlap with some of the frequencies used by the RS232 wireless modem. The two types of transmitters are set to use different channels in the 2.4 GHz band, reducing interference when flown together.

Wireless Modem

A wireless Aerocomm RS232 modem is installed with the PC 104 inside the vehicle. This modem allows for communication with the vehicle while in flight or on the ground without requiring the removal of hatches and computers.

Controller Hardware

PC 104

The embedded PC chosen was the MZ-104 from Tri-M Systems. The computer is a standard x86 computer running Real Time Linux, in a small, modular form factor. The PC 104 stack has a 20GB Travel Star hard disk as well as 32 MB memory. The processor on board is 133 MHz and draws less than 500mW of power.

The PC 104 is responsible for controlling the servos as well as input and output for all of the sensors. Servo signals are generated using a Real Time Devices DM6804 timer board, which converts counts into PWM signals. Analog signals are sampled by a Real Time Devices DM6420 digital to analog converter board.

The GPS, gyro, and magnetometer units send senor information to the PC 104 using asynchronous serial communication. (See Appendix: Control System Schematic)

Crossbow Solid State Gyro

The PC 104 interfaces with a solid state gyro for all of the plane orientation data. The system is made by Crossbow Technology and records movement in all six degrees of freedom. The Crossbow unit will integrate roll and pitch for both velocities and angles, but not for yaw due to the lack of an internal magnetometer. Yaw angle has to be integrated on the PC 104 through use of a Kalman filter and magnetometer.

PNI Digital Magnetometer

Precision Navigation Instruments (PNI) donated a digital magnetometer to the NCSU Aerial Robotics Club in the fall of 2003 for use with the club's controller. Alone, GPS heading does not allow accurate waypoint navigation. The magnetometer gives instantaneous readings of heading with wings level. Onboard sensors compensate for bank and pitch of up to sixty degrees to give accurate readings during turns. The controller checks magnetometer heading prior to making turning, ensuring accurate waypoint navigation.

Alpha-Beta Vanes

Space Age Controls donated an Alpha-Beta vane probe for use on our vehicle for competition. The Alpha vane relays the plane's glide slope and the Beta vane gives sideslip of the airplane. These two sensors greatly help the controller make smooth, coordinated turns and changes in altitude. Both vanes relay analog data that is converted to digital format by an Analog-to-Digital board in the PC 104 stack.

Pitot-Static Probe

A Pitot-Static probe was made by the machinists at NCSU for use on the UAV. This probe gives both altitude and air speed in analog format. The analog signals are converted to digital format by an Analog-to-Digital board in the PC 104 stack.

Controller and Navigator

Attitude control for the aircraft is done using five closed-loop controllers (pitch rate PID, bank angle PID, velocity PID, yaw damper, and flight path controller). With the control of these five states and with the use of turn coordinators, complete attitude control is possible. The turn coordinators for the pitch rate controller and the yaw damper calculate the necessary change in those states to execute a coordinated banked turn. For a given bank angle and velocity, the necessary pitch rate and yaw rate are respectively calculated as:

$$q = abs\left(\left(\frac{g}{V}\right) * \tan(\phi) * \sin(\phi)\right) \qquad \text{(Eq 1)}$$

$$r = \left(\frac{g}{V}\right) * \sin(\phi) \qquad \text{(Eq 2)}$$

Where q is the pitch rate, r is the yaw rate, g is the acceleration of gravity, V is the velocity, and ϕ is the bank angle.

Heading control is accomplished through the use of a navigator. The navigator algorithm is broken into 4 subroutines: *Waypoint*, *Pathfollower*, *Userturn*, and *Realtimeturn*. The *Waypoint* subroutine uses a list of preprogrammed waypoints and the current latitude and longitude. First, *Waypoint* calculates the distance from the present location to the current waypoint (AB) and determines whether or not the waypoint has been reached. If not, then *Waypoint* calculates three headings, as shown in Equation 3, using the flat earth approximation. The three headings are from the current position to the current waypoint (course), from the last waypoint to the current waypoint (path), and from the current waypoint to the next waypoint (nextpath). These headings along with AB, current velocity, and current heading are sent to the *Pathfollower* subroutine. The *Pathfollower* routine first determines which path to follow based on AB and λ_1 and λ_2. It then calculates the necessary heading change to get onto the path using a lateral path controller. Using λ, AB, velocity, and Ψ_{ref}, the lateral offset and the lateral offset rate can be calculated using the following

$$d = AB * \tan(\lambda) \qquad \text{(Eq 3)}$$

$$\dot{d} = k * V * \sin(\Psi ref) \qquad \text{(Eq 4)}$$

Where k is defined as –1 when the path is to the left. The equation for the guidance law is given by the following

$$TC = d * \left(\frac{G_1}{AB}\right) + \dot{d} * \left(\frac{G_2}{abs(d) * AB}\right) \qquad \text{(Eq 5)}$$

Where G1 and G2 are the offset and offset rate gains respectively. Before the track correction is sent on to the *Userturn* subroutine it is limited to sixty degrees. This is done to keep the aircraft from intercepting the path too steeply. *Userturn* converts the track correction from a heading change into three numbers, which define a banked turn: maximum bank angle, total time for the turn and the time at maximum bank angle. Due to the limitations of the aircraft's performance, the maximum bank angle is held to under sixty degrees. The *Realtimeturn* subroutine then takes the maximum bank angle, total time, and time on top and builds an array of φ_{req} and time which is sent into the real time space for implementation by the attitude controller. The array is built at a frame frequency of 50 Hz. Both the attitude control and navigation control were modeled in Matlab's Simulink simulation package. Included in the appendix is a screenshot of the final simulated controller (Simulink Screenshot).

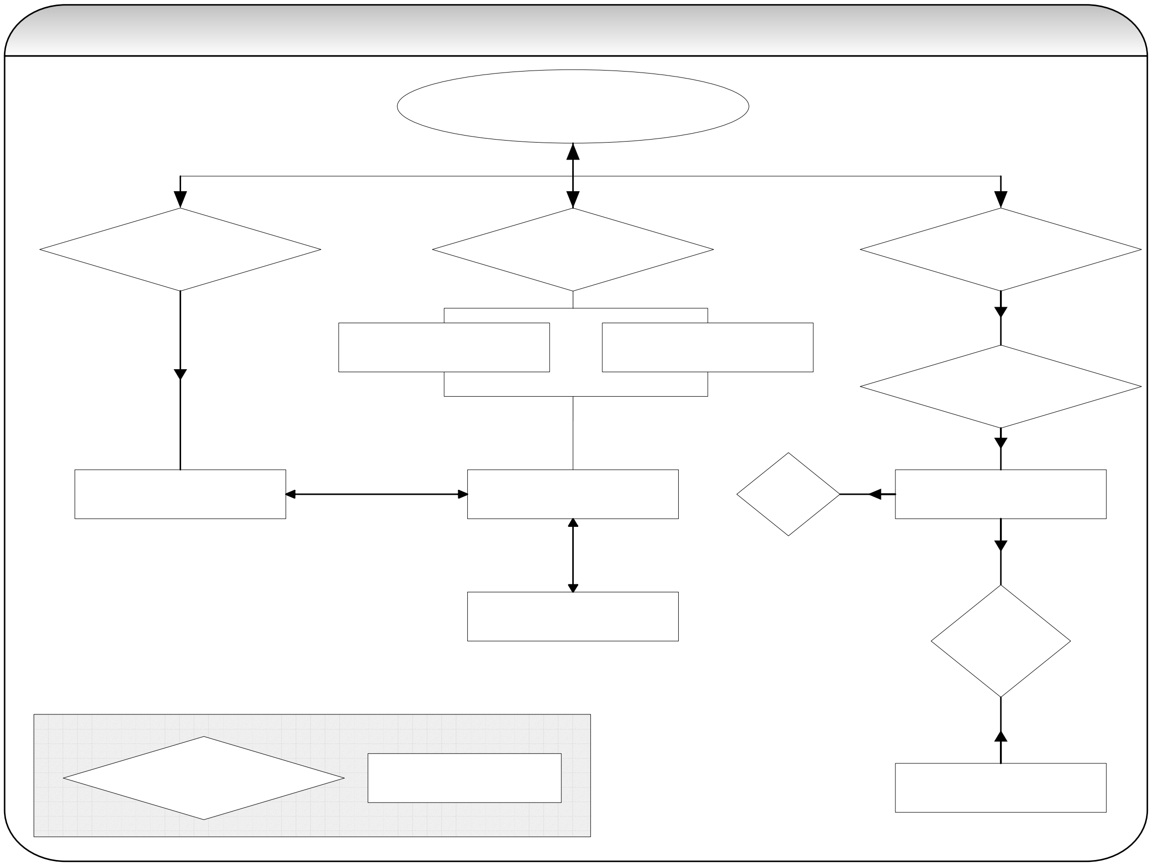
Ground Station

The ground station provides support of the UAV. It consists of the pilot with RC control, the laptop station for ground programming, and the Video Monitoring Station (VMS) for watching and recording aerial imagery feeds.

The pilot and manual control ground station consists of necessary equipment for UAV operation. This includes fuel, electric starter, tools, and spare parts. The manual ground control station is portable in two wooden flight boxes and needs no external power.

The laptop station is used for ground programming of GPS coordinates to the onboard PC 104 via an Ethernet port. The laptop can also be used to simulate a flight path prior to take-off. It requires a laptop battery or auxiliary power source for operation.

The VMS includes all receivers and ground video displays for viewing live video feed. The internal video receiver sends a single signal to a 4-1 decoder. The 4-1 decoder sends four signals to a multiplexer which allows simultaneous recording of the three video feeds and allows viewing of any or all video feeds. A VCR records the images for future reference. The VMS is contained in a small portable box and requires only external power for operation.



Safety

Of primary concern is operator and spectator safety. There are safety protocols in place to ensure safe operation of the UAV, safety of the support team, and early detection of catastrophic computer failure. In addition to the protocols and safe design practices, there are redundant receivers as an extra safety feature.

Wireless Modem

Standard Operating Procedures (SOP)

A comprehensive set of SOP checklists has been developed to ensure safe vehicle operation. These checklists are followed for every activity involving the plane after it is taken out of the travel box. (See partial SOP in appendix)

Before every flight, radio communications are thoroughly checked via system tests of worst case scenarios. A range check is performed with communication antennas collapsed to simulate worst case conditions.

Flight Line Chain of Command

A strict chain of command is established so that everyone that is on the flight line knows his or her job. Anyone that is not one of the set jobs is not allowed on the flight line and must watch the flight as a spectator.

Any time there is a vehicle flying there is always a back-up pilot standing next to the primary pilot. The back-up pilot's job is to take over control of the aircraft in the case the primary pilot becomes unable to fly the vehicle. Once the situation has passed the primary pilot can take over control of the aircraft or the back-up pilot can finish piloting the flight.

There is a spotter for the pilots that stands behind both the primary and secondary pilot. The spotter has three jobs while the vehicle is in the air. His first job is to watch the plane and give directions as needed for vehicle orientation or position. The spotter's second task is to help the pilots move into positions for landing and after take-off by checking for any debris that might cause the pilot to trip and guiding the pilot to the proper place so that the pilot never needs to take his eyes off of the vehicle while he is flying it. The spotter's third job is to be the communication link with the rest of the team so that the pilot is not distracted.

The scribe stands behind the spotter and records all vital flight comments made by the pilots and spotter. These notes help the team to adjust the vehicle for the next flight and keep a record of each flight. The scribe also keeps track of flight time and avionics time so that battery life and fuel consumption are monitored.

The telemetry monitor is set back off the flight line, but in communication with the pilot spotter. The telemetry monitor views the data being transmitted back via the RS232 wireless modem from the PC 104 onboard the aircraft. His job is to provide an early warning to the spotter should computer problems arise. This early warning system allows the pilot to attempt a recovery before a critical, non-recoverable situation develops.

Redundant Receiver Switch Board

A redundant receiver set-up was designed so that redundant receivers could be flown in the vehicle without compromising safety. The redundant receiver switch board monitors an unused channel on the primary receiver. The fail-safe on the primary receiver is set to all hold except this channel, which is set to full value from a default of zero. When this occurs the switch board then switches to allow all the signals from the secondary receiver to transmit to the radio interface board. The fail-safe on the secondary receiver is set to be a hard-over maneuver as required by competition rules. Along with the hard-over the secondary receiver's fail-safe will trigger the gear channel to the "clicked out" position thereby giving the fail-safe priority over the autonomous controls.

Back-up Vehicle

The team has a back-up vehicle and has had it for the last year. This vehicle is capable of everything that *Daedalus* is, but uses a different computer for the controller and can not carry the pan tilt mounts. The vehicle is a 15 pound canard design named *Duck* that is controlled via the MicroPilot 2028 that was donated to the team. The team will rely on this vehicle in the case of any problems with *Daedalus* that cause it to receive a "no fly" status. This vehicle was chosen as a back-up after realizing that though it is further along in its flight testing, it is limited in its carrying capacity. It uses the same Aiptek camera array, pilot's view camera, 2.4 GHz video transmitter, and redundant receiver switch board that are in *Daedalus*.

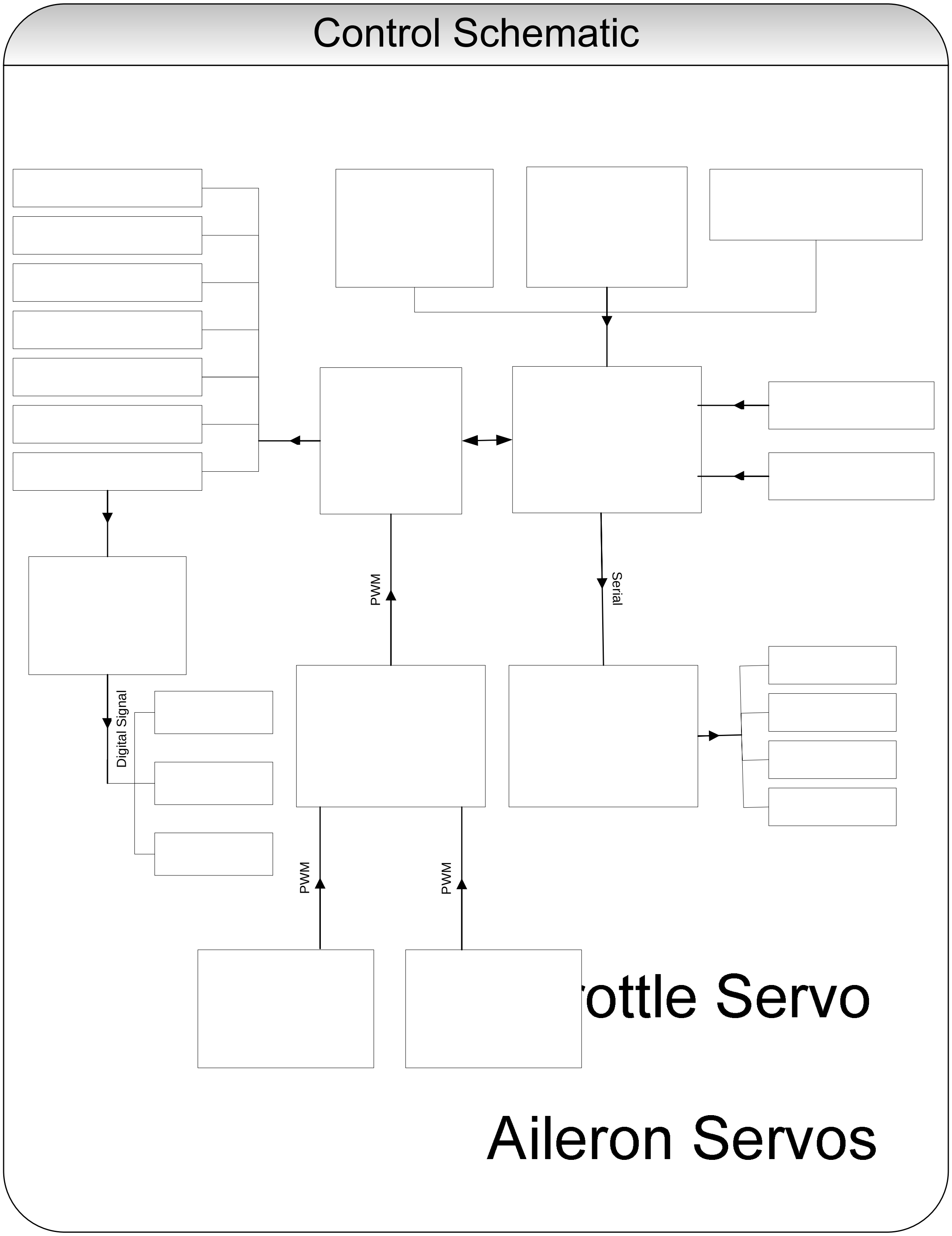
Conclusion and Expected Performance

The advantage of using commercial products reduces the complexity of building an UAV from a design problem to a systems integration challenge. Many aspects of the UAV have been tested, yet other aspects are still in the process of being refined. Vehicle and computer systems are expected operate as designed giving *Daedalus* 20 minutes of autonomous flight, which at cruise speed will easily cover the needed 3 kilometers of waypoints. The video system is expected to provide live video as well as quality still pictures. The pan-tilt mounts will allow for more extended viewing time of the target area as opposed to fixed cameras and the GPS overlay board will allow for the exact coordinates of each target object to be determined.

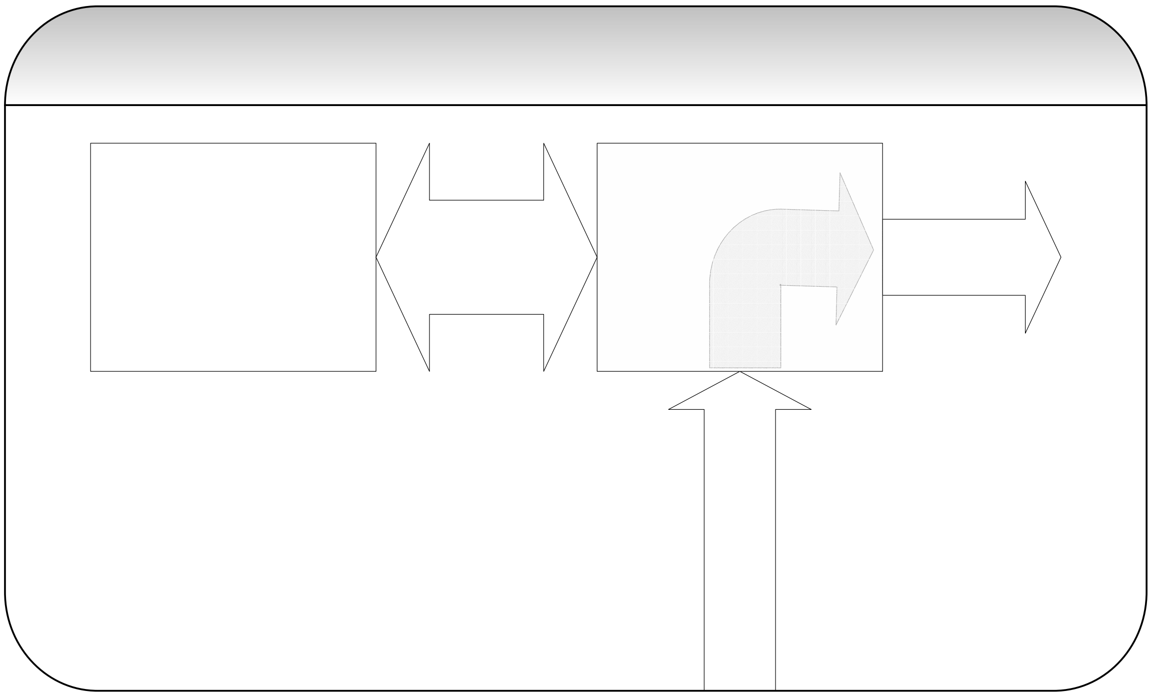
Appendix

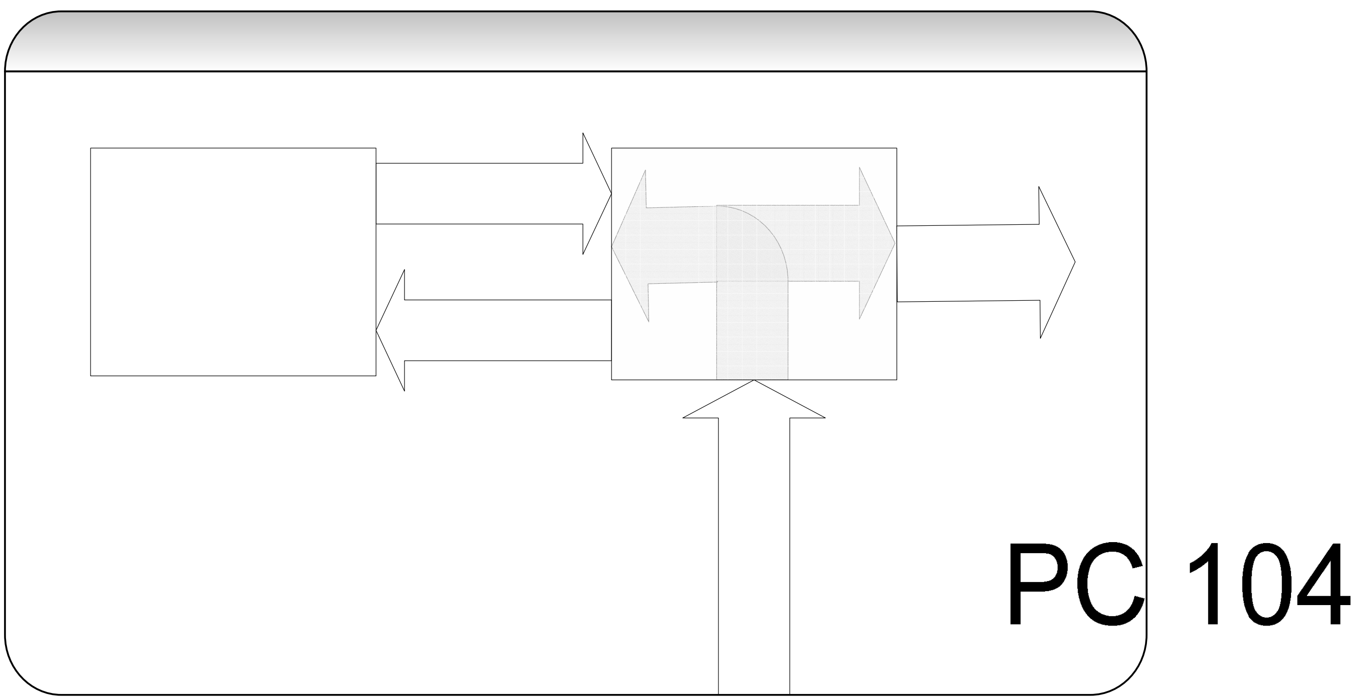
Photo of “*Daedalus*”

Control System Overview

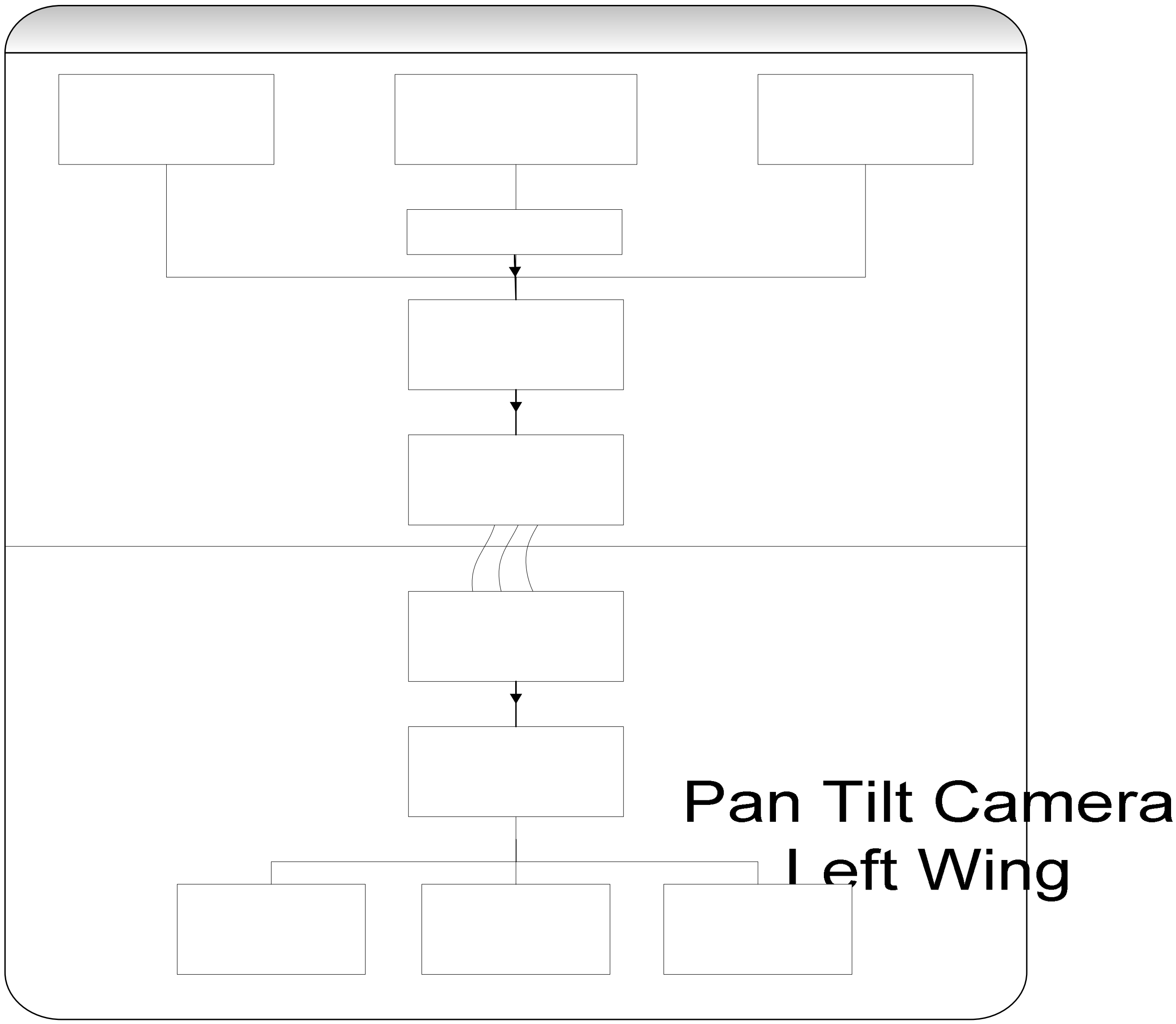


Radio Interface Board Flow Charts

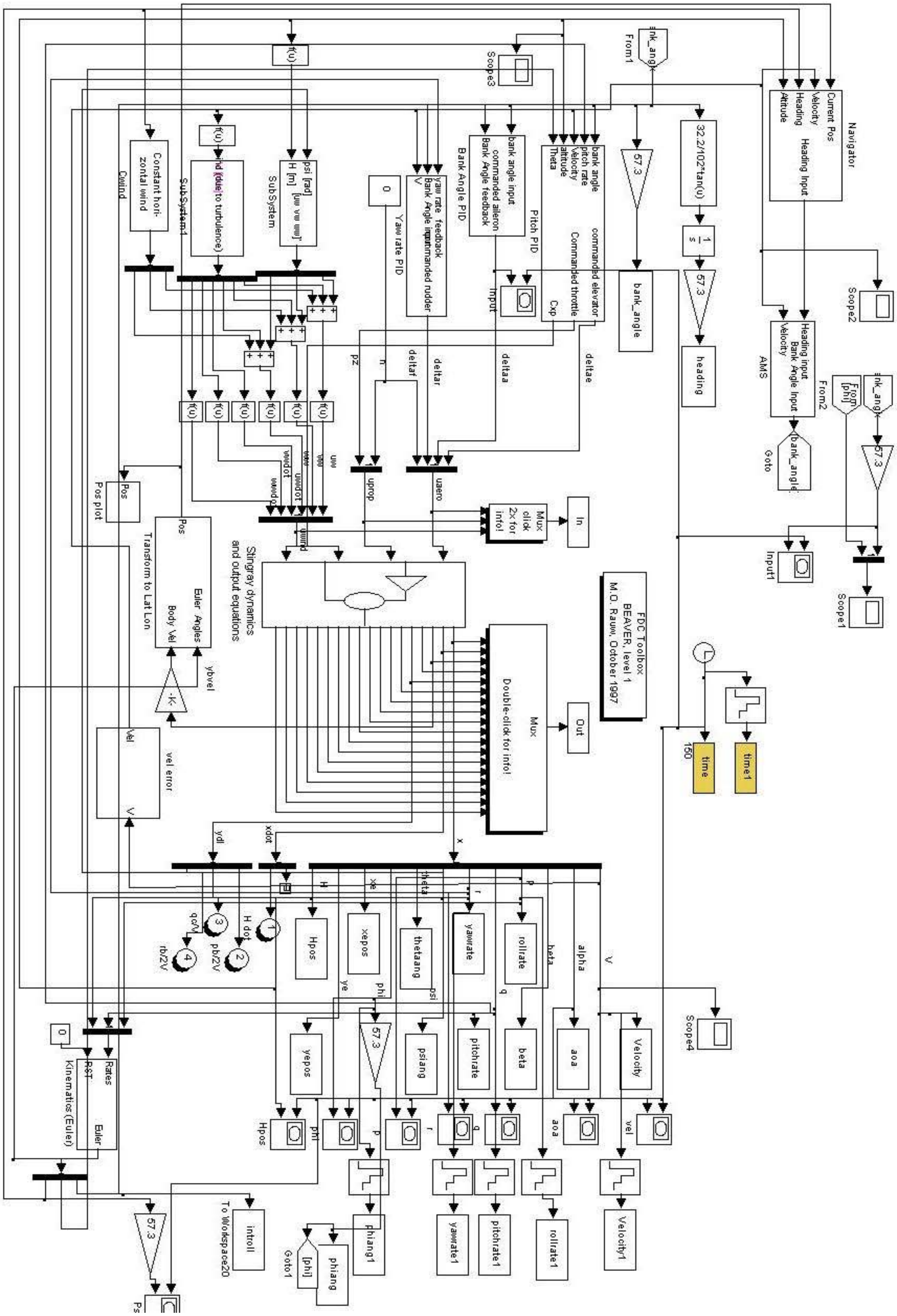




Video System Overview



Simulink Diagram of Controller



Sample Daedalus Checklist

Preflight (at field):

Inspector: ________________________________ Date/Time: ______________

- ☐ **Assembly:**
  - Check runway for FOD (foreign object debris)
  - Check all switches OFF
  - Check glow driver UNPLUGGED from glow plug
  - Install pitot tube (10-32 bolt)
  - Bolt on landing gear
  - Zip-tie brake lines onto gear legs
  - Connect brake lines onto gear brake nipples
  - Bolt in wing (¼ -20 bolts, washers)
  - Check all switches OFF
  - Check aileron pushrods
  - Connect wing wiring plug inside fuselage with screws
  - Connect brake line from air cylinder to wing plate plug
  - Connect battery for receiver and tape connection
  - Connect battery for avionics and tape connection
  - Secure batteries into fuselage
  - Check T-tail mounts inside fuselage
  - Insert T-tail
  - Bolt tail into pockets (¼ -20 bolts, washers, locknuts)
  - Connect rudder/elevator plug to hard mount in fuselage with screws
  - Close tail hatch
  - Connect antenna to top of tail
  - Check servos connected to elevator and rudder pushrods

- ☐ **Systems Check:**
  - Check glow driver UNPLUGGED from glow plug
  - Turn transmitter ON
  - Check transmitter on Daedalus model
  - Turn avionics switch ON
  - Turn servo switch ON
  - Check flight controls, free and correct
  - Turn transmitter OFF
  - Check for correct fail safe procedure
  - Turn transmitter ON
  - Recheck flight controls
  - Range check

- ☐ **Final Assembly:**
  - Fill Brake Air cylinder (100 psi)
  - Tape hatches and wing joints
  - Fill fuel tanks

Recognition of Sponsors

Micropilot: donation of a MP2028g autopilot system
Space Age Controls: donation of alpha-beta vanes for 2005 implementation
Channel Vision: price breaks on three mini video cameras and multiplexer
Black Widow AV: price break on a 2.4 GHz video transmission system
Precision Navigation Instruments: donation of a magnetometer for 2005 implementation
North Carolina State University: monetary donations from the Mechanical and Aerospace Department; monetary donation from Engineers' Council; and time and equipment donations from NCSU Flight Research