

The Phaeton Project

Hardware Document

16.82

October 30, 2003

EXECUTIVE SUMMARY

This document explains the hardware design of an autonomous aerial vehicle, called the Phaeton that will later be coordinated with other unmanned vehicles to participate in a mission of capture the flag. In the capture the flag mission, an autonomous quad-rotor vehicle equipped with sensors, a computer and a camera will search for and find a target, or flag. An unmanned ground vehicle will obtain the position of the flag from the Phaeton and then retrieve it. The purpose of this project is to demonstrate the capabilities and utility of this type of autonomous vehicle.

The document describes in detail the hardware components and responsibilities of the four subsystems: vehicle, sensing, communication, and controls. The vehicle team is responsible for the structure, power for the motors and components, and test apparatus. The sensing team chose the camera to determine the location of the flag and the sensors used to monitor rpm, position, angles, and angular rates of the vehicle. The communications team provides a means of data exchange between subsystems, the hardware necessary for navigation calculations, and the supporting ground station. The control team provides algorithms to stabilize and maneuver the vehicle.

The test plan outlined in this document focuses on the completion and testing of the control loops. By using the chosen hardware and adhering to the test plan and schedule, the Phaeton will be operational and demonstrated on December 4, 2003.

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1. INTRODUCTION

The project for the fall 2003 semester of the CDIO Capstone course (16.82 / 16.821) involves designing an unmanned and autonomous quad-rotor craft called the Phaeton. The objective of the overall CDIO Capstone 16.82 / 16.821 is to “design and demonstrate the coordination and control of a small team of unmanned heterogeneous vehicles”¹ that could be used to perform missions such as persistent surveillance and harbor protection, where the teams will have to coordinate in uncertain, dynamic, and potentially hostile environments with very low data communication.

This document describes the hardware design decisions for Phase 1 of the project, which concerns an air vehicle that would be part of the aforementioned vehicle team. As an autonomous aircraft, the Phaeton can have no human input within the control and stability loops. It must also operate indoors and its design must be based on an existing quad-rotor vehicle, which is shown in Figure 1.1. The team of fourteen students who are designing the Phaeton is separated into four sub-teams that are responsible for the four major subsystems of the project: the physical vehicle, the control algorithms, the sensors and the communications.

The spring semester of the CDIO Capstone course will include the fabrication of a second Phaeton to compete in a robotic game of Capture the Flag.



Figure 1.1: Baseline vehicle: Draganflyer X-Pro²

The following section is a discussion of the project’s top level requirements and of the requirements that developed between sub-teams. These were reported in the Requirements Document that the class presented on October 21. Section 3 is a summary of the overall design, which is followed by a detailed discussion of the analysis and the decisions involved in the design of each sub-system in section 4. Section 5 explains the team’s testing and component integration plans for the project duration. The team budget and schedule follow section 5, and previous work is referenced in the appendices.

¹ How, Jonathon P., “Flight Vehicle Design, 16.82 / 16.821 New CDIO Capstone Course, Subject Syllabus, Fall 2003/Spring 2004,” Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 2003.

² Image available from <http://www.draganfly.com/draganflyerxpro.php>

2. HIGH LEVEL REQUIREMENTS

The Phaeton vehicle will help demonstrate the utility of heterogeneous vehicles by satisfying multiple high level requirements. The project is divided into two phases: one to be completed during the fall term of the Capstone course and another in the spring. The overarching requirement for Phase I is to conceive, design, build, and implement an autonomous control system for an indoor flying vehicle. The team must “achieve the objective of takeoff, hover in place for 5 minutes 2 m above the ground, continuously pointing an onboard camera at a fixed target (20cm x 20cm) with sufficient stability (min 100 x 100 pixels) that an operator can easily identify (85% of the time) the color, shape, and orientation of the target, and then land within 1m of the target¹,” by December 5, 2003.

In order to satisfy the top level requirement of a resolution of 100 x 100 pixels on a 20 x 20 cm target at 2 m above the ground, the system camera must be equipped with a lens with a field of view no greater than 35 degrees. This will provide a footprint with a radius given by $h \tan \theta = 124\text{cm}$. The target will therefore stay within the camera’s field of view if the vehicle is commanded to position itself directly above the target and the lateral stability of the rotorcraft is controlled to within 42 cm, thus satisfying another top-level requirement.

Additionally, the team must demonstrate that the Phaeton design will be able to accomplish several more tasks to be implemented in Phase II. The first is to “take-off, fly (3 m off the ground) to a specified point (covering a 10 m distance in less than 1 min), then hover in place for 2 min, return to the original point and land.” Next the rotorcraft must “take-off, fly to a known point (covering a distance in less than 1 min.), search for a nearby ground target (20 cm x 20 cm) that is moving very slowly (speed < 5 cm/sec) in a specified region (2 m x 2 m) in less than 1 min. When found, have the UAV track the target (height > 2 m) and display the target’s progress to the operator for a period of 2 minutes.” Finally, “to extend the flying range of the UAV, this vehicle must be designed to autonomously take-off and land on one of the rovers¹.”

The subsystem teams (communications, controls, sensing, and vehicles) each have individual requirements outlined in the Requirements Document in Appendix A that must be met in order to satisfy the mission requirements. The subsystems are constrained by each other and by the high level requirements. The high level requirements dictate that the missions will take place in MIT’s Johnson Athletic Center and that Draganfly quad-rotor UAV be used as the baseline vehicle. Modifications can be made to the rotorcraft, but the cost of the entire project must not exceed \$15K with a goal of \$12K.

¹ How, Jonathon P., “Flight Vehicle Design, 16.82 / 16.821 New CDIO Capstone Course, Subject Syllabus, Fall 2003/Spring 2004,” Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 2003.

3. OVERVIEW OF DESIGN

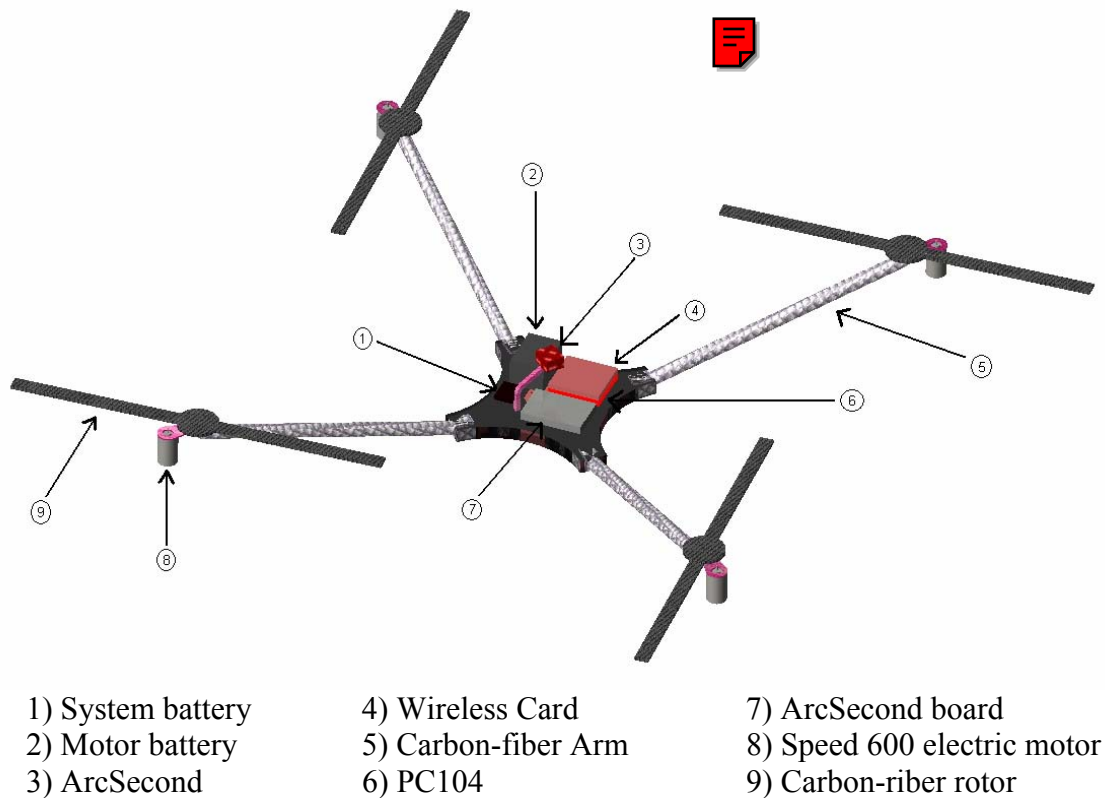


Figure 3.1: Vehicle Design

The final vehicle design will be a quad-rotor craft similar to the Draganfly. Figure 3.1 shows a picture of the vehicle design and the location of the main components. (Microstrain is also on the vehicle, but it is not pictured since it is embedded in the platform and covered by the batteries and PC104.) The center section of the vehicle will be reconstructed with carbon fiber composite with a Nomex core and new rotor blades will be built, but the original arms and motors of the Draganfly will be used. For the propulsion of the vehicle, the 14.8V and 7.8Ah lithium polymer battery included in the Draganfly package will be used. An additional 7.4V lithium polymer battery will be used to power to the computers and sensors on the vehicle. Voltage regulators will be used to provide power at certain voltages for these components.

The vehicle also includes sensors, controls, and communication equipment. In general, the sensors obtain information, which is sent to the computers. Next, this information is processed in control loops on the computers. The control loops output new information, which is then sent from the computer to direct the vehicle. All information travels through the communications equipment. This process continues for the duration of the flight. The overall system architecture, as seen in Figure 3.2, is more complex than in the above description. The next section explains the purpose and function of these components in great detail.

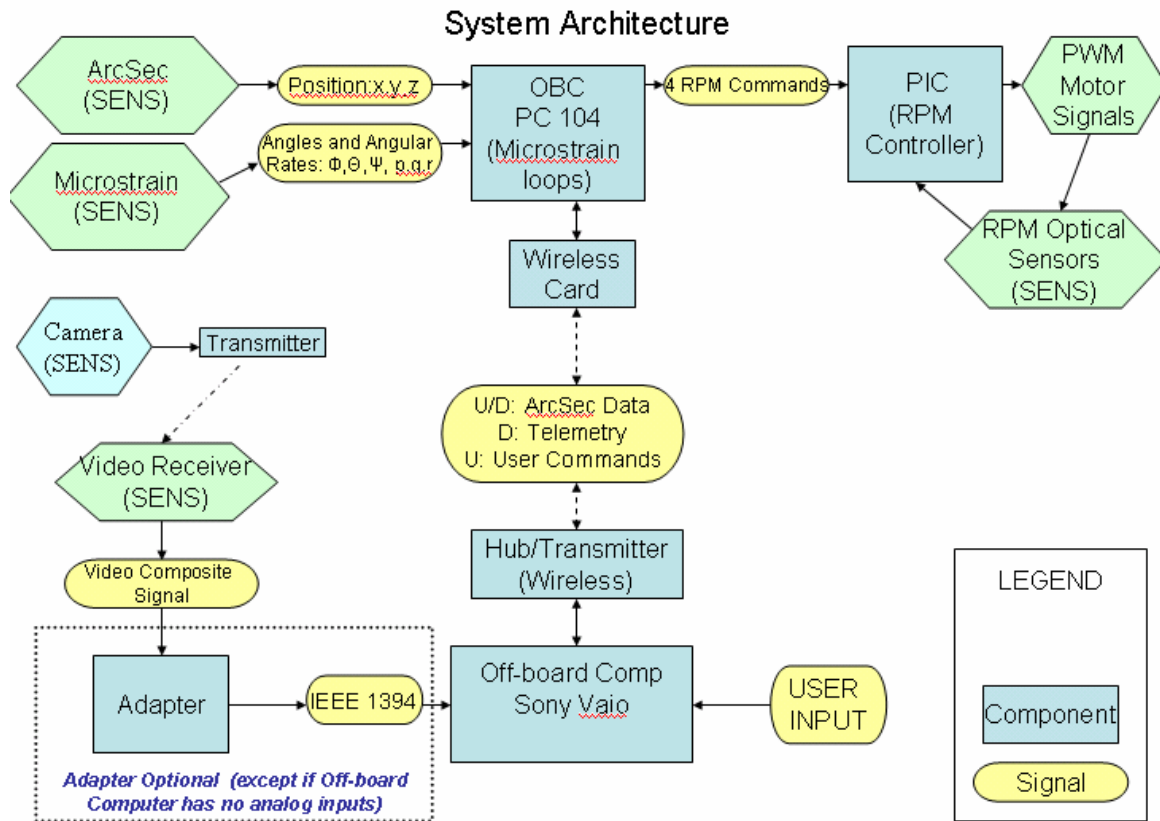


Figure 3.2 System Architecture

4. DETAILED DESIGN, ANALYSIS AND DISCUSSION

4.1. Vehicle

The Phaeton is based off a commercially available vehicle called the Draganflyer X Pro. The commercial design is not optimized for the heavy lifting that the mission requires. Changes to the commercially supplied structure are required to make the entire system functional.

4.1.1. Rotor Replacement

The rotors currently used on the Phaeton have an efficiency close to 40%. The rotor blades are stalled with an estimated C_l of 1.7 except at very low RPM. Because the Phaeton is lifting more than a pound of payload, the rotor geometry of the x-Pro must be improved. Using a Unix based rotor analysis and design tool called xrotor¹ a much more efficient rotor geometry can be obtained. This new rotor geometry is converted to G-code in order to create a mold of the rotor on a CNC milling machine. Carbon fiber is then laid in the mold and vacuum wrapped to create a new rotor.

A full understanding of the dynamics of the rotor is crucial for the control of the Phaeton. The xrotor program is used to analyze the characteristics of the rotor. The data

¹ Created by Professor Drela at the Massachusetts Institute of Technology

derived from xrotor allows the calculation of the stability derivatives of the vehicle. A full characterization of the X-Pro rotor can be found in Appendix B. Once the new rotor geometry has been finalized the analysis will be repeated.

4.1.2. Structure Replacement

The current Draganfly body is not optimal for our purposes. First, the arm connections to the central hub are very fragile, and when they break, a replacement arm costs \$500. Second, one of the crucial components of the central hub is the current control board (which we are planning to scrap). Because of this, we have decided to scrap the current central hub and replace it with a new design that solves both of these problems while increasing rigidity, robustness, light weight, and protective storage space.

We initially considered simply strengthening the current central hub, but that is not a good solution as weight would be too high. Then we considered using two sheets of PC board in a similar configuration to the current hub with tabs on which to mount the motor arms by Kevlar wraps. That is a better solution but still heavy, and any fracture would mean building a new hub.

Our final decision was to use a sandwich construct of one inch thick Nomex honeycomb between sheets of 1/32 inch thick carbon-fiber. This sandwich disc weighs less than the current central hub. It is incredibly strong and rigid. We will be able to insert the arm into the sandwich by removing sections of the Nomex and replacing it with balsawood mounts. In the event of a crash and joint fracture, only the balsawood will need replacing. We will also be able to make the disc slightly larger than the current hub and extend the arms farther from the center. This allows for the larger rotors that we are fabricating.

The sandwich disc will also be advantageous for the placement of onboard components. The upper part of the hub disc will still be protected as it will be below the rotors. Additionally, we will be able to place some of the smaller, more sensitive components inside the sandwich structure. This will save space and make center of gravity adjustments more flexible. The flat disc design will also allow for a lower center of gravity.

There will not be any cost associated with this modification. We will be fabricating it out of scrap material in John Kane's lab (Nomex and Fiberglass) and general department stocks (Epoxy and Balsawood). If we decide to extend the motor arms, Prof. Drela can provide carbon fiber extensions from scrap.

4.1.3. Mass and Power

4.1.3.1. System Mass

Table 4.1 shows the mass breakdown of the components. The total vehicle mass is currently estimated to be 2641g. A 10 percent margin was added to the total mass to account for estimation and the mass of any future components. Therefore, the mass of the system will be considered as 2905g.

Table 4.1: Mass Breakdown

	Mass (grams)
Vehicle Subtotal	2144
Battery for motors	594
4 arms (no motors)	576
4 motors	656
center structure	270
Battery for components	28
Voltage down regulator	5
Voltage up regulator	15
Comm Subtotal	240
Onboard computer	100
Ethernet card	55
3 A to D converters	60
Serial to PWM converter	25
Sens Subtotal	207
ArcSecond Sensor	156
Onboard Camera	14
Camera Transmitter	7
3DMG	30
Other Wiring/Hardware	50
Total Mass	2641
Total + 10% margin	2905

4.1.3.2. Power for Propulsion

Table 4.2 shows the expected thrust and power at a range of currents for the original motors and propellers of the Draganfly. This data is based on test results of one motor and propeller setup and has been multiplied by four.

Table 4.2: Expected Thrust and Power from Applied Current

Current (A)	Thrust (N)	Power (W)
16	11.1	236.8
20	16.7	296.0
24	20.9	355.2
32	28.9	473.6
40	35.6	592.0

The required thrust for hover, where thrust equals the mass times gravity, is 28.5N. Comparing this thrust to the expected thrust, Table 2 shows that a thrust of 28.9N requires 473.6W of power. A 10 percent margin was added to this obtain a power requirement of 520W. The lithium polymer battery that came with the Draganfly will solely be used to power the motors. This battery is 14.8V and 7.8Ah. Figure 4.1 shows a

comparison of the required power and the available power from the battery for a certain flight time. The estimated flight time is 10 minutes, and this is based on the high level requirements. Yet the available power for 12 and 15 minutes is also included in Figure 4.1.

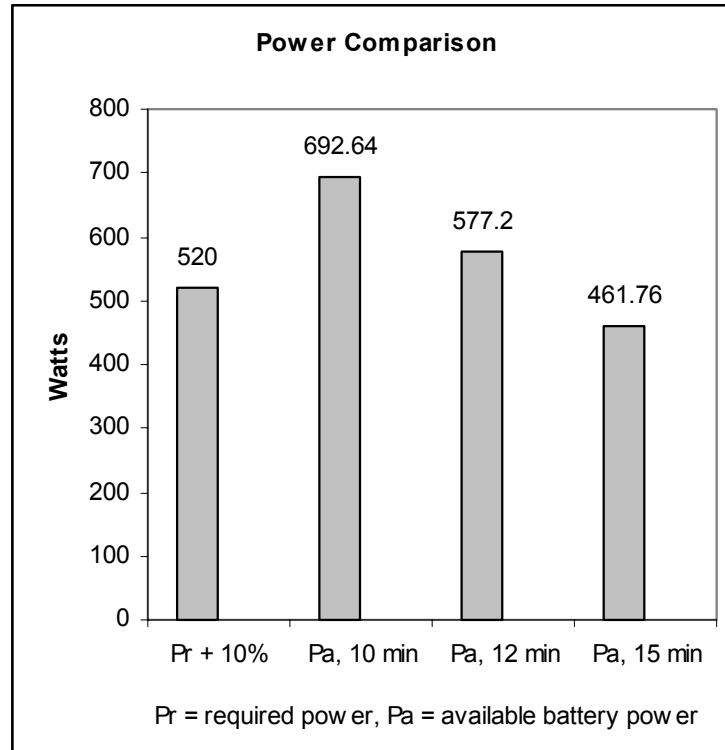


Figure 4.1: Comparison of Required Power and Available Battery Power

As seen in Figure 4.1, the lithium polymer battery will be able to provide enough thrust for the estimated flight time of 10 min ([VEHI0230]). This battery can also power a 12 min flight time, but it cannot provide enough power for a 15 min flight time. However, additional power is required for maneuvering. Thus, the remaining available power from the battery will be used by the controls group to position the vehicle and maintain stability. For a flight time of 10 minutes, 172.64W are available for control. Less power is available for control at a flight time of 12 minutes; only 57.2W are available.

4.1.3.3. Power for Components

Besides the motors, there are several other components that require power. Table 4.3 lists the voltage, current and power requirements for each component. Overall, a power source that provides 5 and 12V is needed. Also, the required power for the components is 17.18W. The required power with a 10 percent margin is 18.90W.

Table 4.3: Component Requirements

Component	Voltage (V)	Current (A)	Power (W)
Onboard Computer	4.75 - 5.25	1.5	7.13 - 7.88
ArcSecond Sensor	12	0.125	1.5
Onboard Camera	12	0.08	0.96
Camera Transmitter	12	0.5	6
3DMG	5.2 - 12	0.052	0.27 - 0.624
RPM Sensor	5	0.044	0.22

An additional battery and regulators will be purchased to provide power for these components. Although another battery adds complexity and weight to the system, there are advantages to having a separate power supply. The sensing equipment requires a constant voltage and current in order for the equipment to work properly. If this equipment was powered by the same battery that powers the motors, it would be subjected to motor-induced noise as well as voltage and current sags due to sudden bursts of power during vehicle maneuvering. Thus, a separate battery for these components is beneficial. Table 4.4 shows three lithium polymer batteries that were considered.

Table 4.4: Lithium Polymer Batteries

Li Poly Item #	Specifications	Weight	Cost
KOK560-2S-FJ ¹	7.4V, 560mAh	Not given	\$23.50
2LP608 ²	7.4V, 650mAh	28 g	\$22.95
KOK880-2S-FJ ¹	7.4V, 880mAh	Not given	\$26.95

Figure 4.2 compares the available power from these batteries to the required power for the components. The 2LP608 lithium polymer battery was chosen since it can power the components for about 15 min. Although the expected flight time is 10 min, additional time on the ground will be needed to prepare and check the equipment. The KOK880-2S-FJ battery provides much more power than is needed.

¹ <https://www.fmadirect.com/site/fma.htm?body=Store>

² <http://batteriesamerica.com/newpage8.htm>

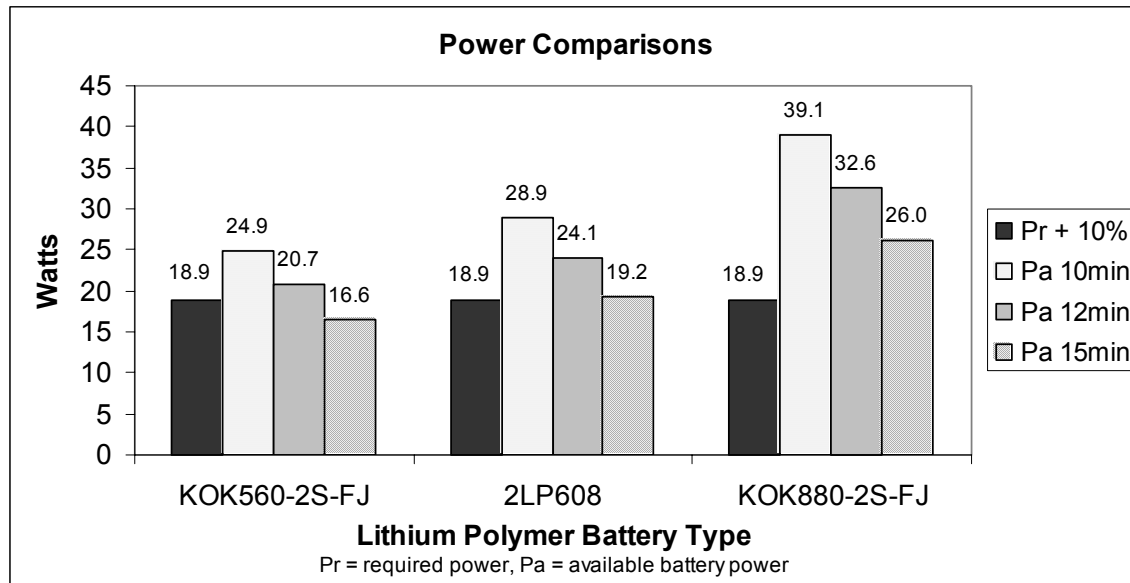


Figure 4.2: Power Comparison of Required Power and Available Power of LiPo Batteries

Next, nickel cadmium, nickel metal hydride and lithium polymer batteries were all compared before finalizing the decision. Table 4.5 shows a weight and cost comparison of these batteries with similar specifications. Clearly, the cost of each battery type is similar, but the lithium polymer battery has a significantly lower weight. Since weight is critical to this project, the lithium polymer battery will be used as the power source for the components.

Table 4.5: Weight and Cost Comparison of Different Battery Types

Item #	Description	Specifications	Current, 10 min	Current 15 min	Mass	Cost
B600AE6 ¹	NiCd 6cell battery pack	7.2V, 600mAh	3.6A	2.4A	128g	\$20.90
PC720N7 ²	NiMH 7cell battery pack	8.4V, 720mAh	4.32A	2.88A	96g	\$32.90
2LP608	LiPo 2cell battery pack	7.4V, 650mAh	3.9A	2.6A	28g	\$22.95

Finally, since the lithium polymer battery that will be used is 7.4V, voltage regulators are needed to obtain 12V and 5V for the components. The VRLI1-LPO regulator³ was chosen since it can change the voltage of a 7.4V lithium polymer battery to 5V and outputs 10W of power, which is more than the required 8.0W for the 5V equipment. In addition, the VRLI1-LPO is only 5 grams and is already assembled. Another useful feature of the regulator is that it continuously measures the battery pack voltage and provides a clear warning of the battery condition. The LM2557 voltage regulator⁴ was chosen since it can boost the 7.4V lithium polymer battery up to 12 or 15V. This voltage regulator may output as much as 36W, but the typical application shows a 9.6W output. This will suffice since the components that need 12V require

¹ <http://hobby-lobby.com/nicads.htm>

² <http://hobby-lobby.com/hydride.htm>

³ <https://www.fmadirect.com/site/fma.htm?body=Store>

⁴ <http://www.national.com/pf/LM/LM1577.html>

9.1W. The voltage booster must be assembled as shown in Figure 4.3. Besides the LM2557, the 100 μ H inductor, diode, and 680 μ F capacitor are needed. Two of each of these items will be purchased from digikey.com. The remaining components are available in the MIT's Gelb Lab.

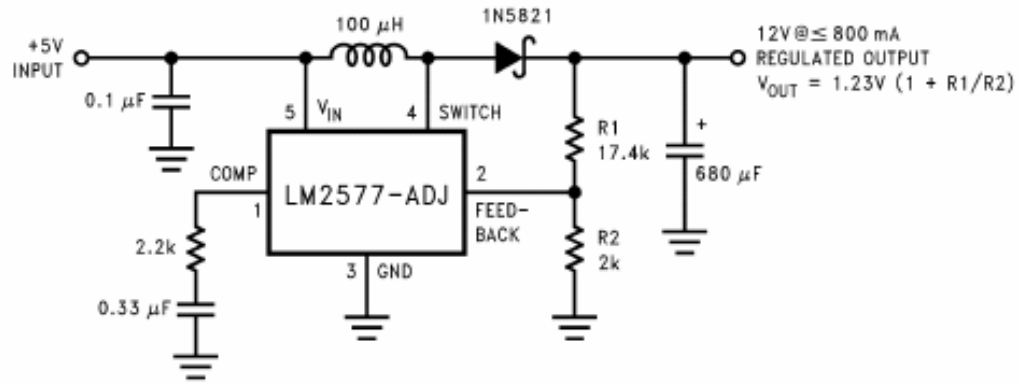


Figure 4.3: Setup of the Voltage Booster

4.1.3.4. Items to Purchase

The second power system for the components will be comprised of a 7.4V, 650mAh lithium polymer battery, a step-up voltage regulator, and a step-down voltage regulator. Table 4.6 lists the items that will be ordered. In addition, a battery charger must be purchased. The QN-012BC charger¹ is for 7.4V lithium polymer batteries. It operates from a standard wall outlet and shuts off automatically when the pack reaches full charge. Once these items are purchased and delivered, the up regulator must be assembled and eventually the power system for the components must be connected.

Table 4.6: Items to Purchase for Second Power Source

Item #	Description	Purpose	Cost
2LP608	Li Poly battery 7.4V, 650mAh	provide power for components	\$22.95
QN-012BC	7.4V Li Poly charger	charge battery	\$19.95
VRLI1-LPO	down regulator	limit 7.4V to 5V	\$21.95
LM2577-12-ND	up regulator	boost 7.4V to 12V	\$10.62 (for 2)
P10250-ND	680 μ F, 16V capacitor	up regulator component	\$1.66 (for 2)
DN2424-ND	100 μ H, 4A inductor	up regulator component	\$12.10 (for 2)

4.1.4. Remaining Issues to Resolve

Currently, the vehicle team needs materials and the code of the rotor geometry to begin construction of the new propeller blades. The specific details of the size and type of the materials, the cutting tools, and the geometry code should be provided by Professor Drela by the end of the week.

¹ <http://batteriesamerica.com/newpage8.htm>

4.2.Sensing

The sensing subsystem has two overall responsibilities. First, it must provide the controls subsystem with the vehicle's state information. To successfully control the aircraft the controls subsystem needs to know the position of the aircraft and the orientation of the aircraft (both an angle of rotation and the rotation rate). The position and orientation will be measured by separate sensors. Also, the RPM values for each motor will be measured and given to the controls subsystem. The second responsibility of the sensing subsystem is to obtain a video image from the view of the vehicle and transmit that image to the ground station. This will be accomplished with a wireless camera and transmitter which meet the necessary view and resolution requirements, thus achieving the high level requirements outlined for the project.

4.2.1. Video Sensing

The primary objective of the video system is to provide a real-time analog video signal to the ground controller (which is specified in [SENS0200]) displayed at a resolution no less than 250,000 square pixels/actual square meter (which is specified in [SENS0270]). To achieve this, the component configuration in Figure 4.4 will be needed.

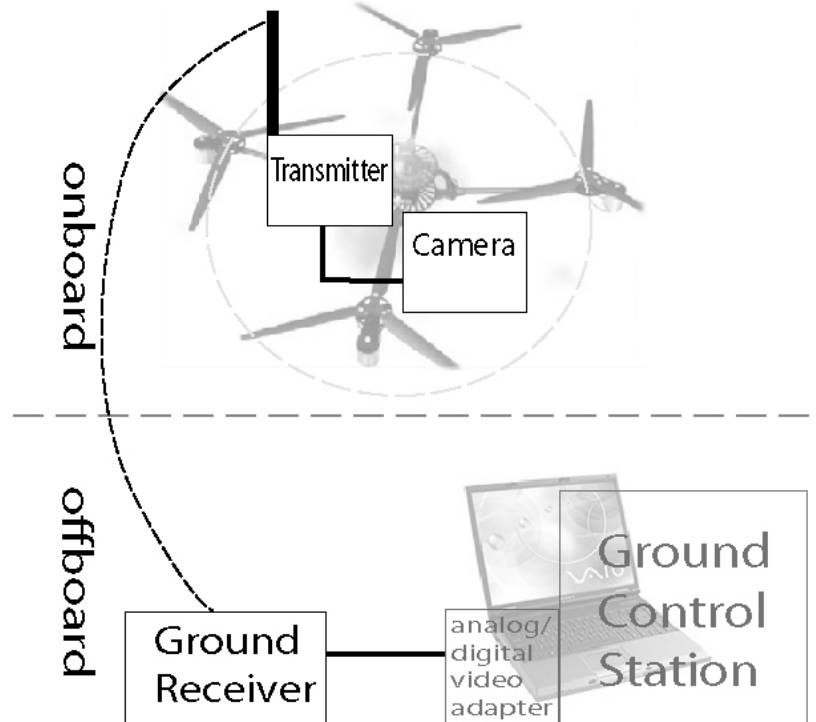


Figure 4.4: Video system components

4.2.1.1. Camera Selection

The principal tradeoff in camera selection was between resolution and camera weight or size. Larger cameras, designed for either consumer home video use or

commercial surveillance, would have adequate, if not exceptional, picture quality and imaging capabilities, but would be far too massive to be carried on board¹.

Therefore the only viable camera options for consideration were the Panasonic GP-CX161 and GP-CX171. Both are small, lightweight, CCD board cameras with relatively higher-end imaging capabilities. Table 4.7 below lists the calculated resolution ratios with the lens field angles available for both of these cameras. Appendix D explains how these resolutions were calculated.

Table 4.7: Comparison of camera resolution ratios for various lenses

Angle (degrees)	Footprint radius @ 2	Footprint radius @ 3	Footprint area @ 2	Footprint area @ 3	Resolution ratio@ 2m	Resolution ratio @ 3m
41	0.75	1.12	1.76	3.95	199,243	88,552
53	1.00	1.50	3.12	7.03	112,043	49,797
115	3.14	4.71	30.96	69.67	11,304	5,024
17	0.30	0.45	0.28	0.63	1,425,123	633,388
26	0.46	0.69	0.67	1.51	597,203	265,424
35	0.63	0.95	1.25	2.81	320,188	142,306
53	1.00	1.50	3.12	7.03	128,049	56,911
69	1.37	2.06	5.94	13.36	67,388	29,950
87	1.90	2.85	11.32	25.46	35,347	15,710
105	2.61	3.91	21.34	48.02	18,742	8,330

The shaded rows in Table 4.7 indicate data for the Panasonic GP-CX161 which does not meet the resolution requirement with any of its available lenses at either altitude, and thus was not selected for this project.

The GP-CX171 meets the requirement and only with its 3 smallest angle lenses. Since larger view angle yields a larger footprint (i.e. viewing area), this in turn will help decrease the search time of a given area. The 35° lens is the widest angle lens that meets the resolution requirement at a height of 2m, so it is preferred.

Another feature of the GP-CX171 over the GP-CX161 is the ability to capture video data in both NTSC and PAL formats. NTSC is the standard color system for US broadcast, while the most of the rest of the world uses PAL. It is a widely held belief of many video-philies that PAL is a superior color format.

4.2.1.2. Transmitter and Receiver Selection

The primary concern in selecting a transmitter and receiver set is range and reliability. There are basically two types of transmitters on the market today that operate in the 900 MHz and 2.4 GHz bandwidths, respectively. The differences in range and reliability between these two basic types are negligible when used in consumer products such as cordless phones, but since the goal is for optimal performance, operation at a higher bandwidth is preferred. It is generally accepted that higher bandwidth transmissions have greater range and reliability properties, thus 2.4 GHz-type transmitter/receiver sets were considered.

¹ Chang, Catherine, *Sensing Team Trade Studies (with a focus on camera trade studies)*, Section 3.3.1-3.3.5

Various internet vendors for small transmitters were researched, however, the majority of them appeared to be untrustworthy. The most legitimate looking vendor found was Black Widow AV¹, a provider of small transmitters for unmanned aerial vehicles. They have a selection of 2.4 GHz transmitter and receiver sets which are compared in Table 4.8 below. Of these, the 50mW set appears to be most ideal because of its small size and weight as well as their low cost.

Table 4.8: Comparison of transmitters from Black Widow AV

Transmitter Power	Transmitter Weight	Cost of set (w/ receiver)
50 mW	7g (0.2 oz)	\$140
200 mW	25g (0.88 oz)	\$150
600 mW	38g (1.2 oz)	\$189

There was some concern regarding possible interference with the Communications team's 802.11b signal which also operates in the 2.4 GHz range. However we believe this will not be a problem because the chance of interference on the 2.4 GHz band is reasonably low and all transmitters from Black Widow AV have a set of switches built-in for changing channels in such an event.

Also, all the transmitters above can transmit video signals in PAL as well as NTSC if a higher color quality in video output is desired.

4.2.1.3. Video Adapter Selection

The ground receiver has a built-in output jack of a 1/8" headphone-style combo AV plug, which is more commonly found built into Apple iBooks. A cable with a composite video RCA-style plug on one end makes it easily interfaced with a computer video adapter also known as a digital video converter. The interface to the ground station computer must be able to capture and convert video at a resolution of 720x480 pixels or higher to maintain resolution sufficient to meet the top-level requirement.

At this time the Communications team's selection for a ground station computer has a built-in S-video interface. However we were not able to get capture resolution specifications from the computer manufacturers. In the event that the resolution of the computer's built-in adapter is insufficient the adapters in Table 4.9 are being considered.

¹ <http://www.blackwidowav.com/>

Table 4.9: Comparison of analog-to-digital video adapters

Adapter	Max. capture resolution	Interface	Cost
Canopus ADVC100	720x480	IEEE 1394 (4- or 6-pin) Firewire	\$299
Canopus ADVC500	? (but most likely higher than ADVC100)	IEEE 1394 (4- or 6-pin) Firewire	\$1,499
Dazzle Hollywood DV-bridge	720 X 576?	IEEE 1394 (4-pin) Firewire	\$299
Dazzle DV Creator 150	720x480	USB 2.0	\$150

Canopus is a manufacturer of analog-to-digital video converters (and software) for the high-end consumer and professional markets. The ADVC500 is far too expensive when the ADVC100 is adequate for this project and retails for a fifth of its cost.

Dazzle makes similar products to Canopus that cater to the typical home consumer. Its Hollywood DV-bridge is comparable to the Canopus ADVC100, however it has been discontinued and is no longer supported by the manufacturer despite its significant availability among internet vendors. A recommended equivalent to, and replacement for, the DV-bridge is the DV Creator 150. The principal difference between the two is the interface to the computer; IEEE1394 is slightly faster.

4.2.1.4. Final Decision

To meet the top-level resolution requirement the Panasonic GP-CX171 CCD board camera with a 35° lens, as shown in Figure 4.5, is the optimal choice. That lens will provide the largest view area among the few lens and camera combinations that fulfill the resolution requirement.

The 2.4GHz, 50 mW transmitter and receiver set from Black Widow AV, as shown in Figure 4.6, provides the smallest, lightest and cheapest on-board transmitter among those of comparable range and reliability.

In the event that the ground station's built-in video adapter does not provide sufficient capture resolution the Canopus ADVC100 shown in Figure 4.7 is a good choice for an analog-to-digital video converter because it provides an adequate capture resolution as well as a highly reliable IEEE 1394 interface. However because of the ADVC100's slightly high cost, the Dazzle DV Creator 150 shown in Figure 4.8 should be considered a viable lower cost alternative because it provides a similar capture resolution through a USB 2.0 interface.



Figure 4.5: Panasonic GP-CX171 CCD board camera without lens or lens mount



Figure 4.6: 2.4 GHz, 5mW transmitter & receiver set from Black Widow AV



Figure 4.7: Canopus ADVC100 analog-to-digital video converter



Figure 4.8: Foreground, Dazzle DV Creator 150

4.2.2. Rotor RPM Sensing

The controls sub-team suggested the possibility to artificially reduce the motor lag if they were provided with rotor RPM data on-board. In order to address this suggestion, the sensing team has been exploring RPM sensing options. The most likely design at this time is an optical interrupter switch at each motor that is intercepted several times per revolution by blinders rotating on the motor shaft. As the light beam through these switches is intercepted, they output high or low voltage to a digital binary counter. The on-board computer would call these counts at 40Hz (which is the frequency at which the control algorithm will run) and then reset the counters. This configuration is sketched in Figure 4.9.

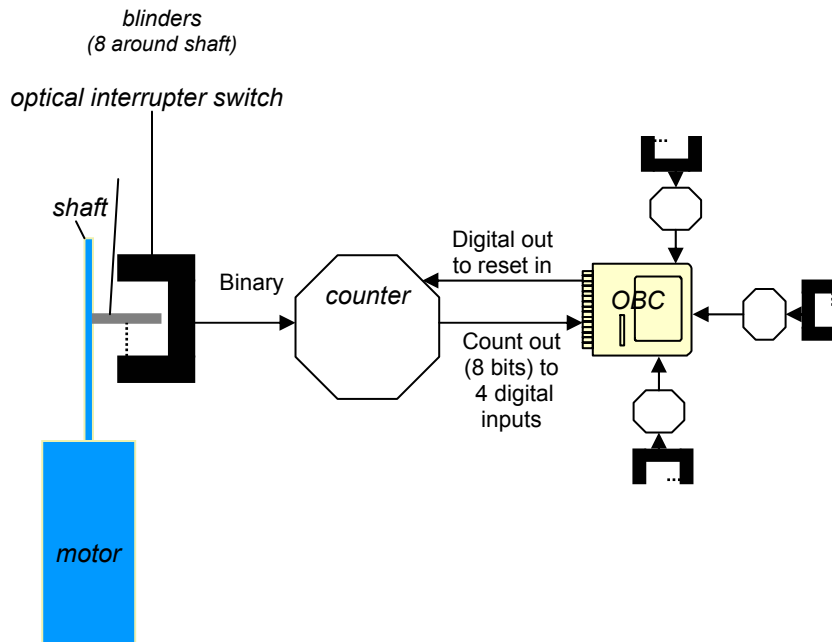


Figure 4.9: RPM sensing configuration

The Fairchild Optologic Optical Interrupter Switch has a typical voltage rise time of 70ns every time the beam is interrupted¹. The delay can be approximated as a factor of ten above this², which would be 0.7 microseconds. Considering that the rotor RPM is of the order of 1500, that is around 9000 revolutions per second, one revolution will take about 111 microseconds. This optical interrupter is therefore suitable to record up to one hundred interruptions per rotor revolution.

The granularity or resolution with which RPM measurements will be provided then has to be considered. If eight blinders are fixed onto the motor shafts, which are on a ten to one gear setup with respect to the propellers, the switches would be interrupted

¹ Optologic Optical Interrupter Switch H21LOI-H21LOI, available at www.fairchildsemi.com, accessed 19 October 2003.

² According to Arthur Richards, 16.82 Graduate TA, Automatic Control Laboratory

80 times per revolution. The RPM counts could thus be accurate to 1/80 or 0.0125 of a revolution.

However, if the count granularity is too high and the switches are interrupted too often, the counters may overflow and start counting again from zero before being reset by the on-board computer. The counter that the sensing team is considering is a Texas Instruments 8-bit counter with a choice of tri-state register outputs (SN74LS590)¹. The maximum counts (N_{\max}) that an 8-bit counter can handle will be $(2^8 - 1)$ or 256, which, with the switch blinder setup described above, would account for 3.2 rotor revolutions. At 1500 rpm, the counter will be full at 7.8Hz, or every time period T_{\max} , where

$$T_{\max} = \frac{60 \text{ min/sec}}{1500 \text{ rpm}} * 3.2 \text{ rev} = 0.128 \text{ s}$$

If the counts are called every 40Hz, neither granularity nor overflow should be a problem.

The optical interrupter switches will be connected directly to the clock input of the counters. Since the counters have a tri-state output option, 2*8 digital inputs will be needed on the on-board computer to read the four 8-bit RPM counts. Finally, four digital outputs on the on-board computer will be needed to reset the counters after each reading. The components of this rotor RPM sensing configuration are 4 Fairchild Optologic Optical Interrupter Switches and 4 Texas Instruments 8-bit counters with tri-state register outputs (SNJ54HC590AN).

4.2.3. Attitude Sensing

The requirements for attitude sensing coming from the controls team stipulates that the minimum measurements needed are angular rates in three dimensions and heading angle in one dimension [SENS0230-0240]. The bandwidth for these measurements shall be at least 40Hz [SENS0330-0350]. The controls teams can control the aircraft if the accuracy value for the orientation angle is no more than +/-2 degrees [SENS0340].

Numerous vendors offer small highly accurate rate gyros that would suit our system. Tokin, Analog Devices, Systron Donner, Gyration and more produce very similar single-axis rate gyros that could be used in combination to provide a three dimensional angular rate. Similarly, various companies like Crossbow produce accurate magnetometers which would provide the heading angle to meet our requirements. Finally, a few companies market integrated orientation sensors that are able to provide angular rates and heading angles with a single device. Vendors researched include Tokin, Xsens, and Microstrain as shown in Table 4.10.

¹ 8-bit Binary Counters with Output Registers SNJ54HC590AN, available at www.digikey.com, accessed 24 October 2003

Table 4.10: Attitude Sensor Vendors

Vendor	Part No.	Description	Price
Crossbow	CXM113	3-axis magnetometer	N/A
Gyraton	MG100	3-axis Microgyro rate gyros	\$450
Analog Devices	ADXRS150	Angular rate sensor	\$50
Davidson Measurement	CRS-03	Silicon VSG Rate Gyroscope	N/A
Systron Donner	BEI GyroChip II	Angular rate sensor	\$1350
XSENS	MT9	3-D inertial measurement unit	\$2000
NEC/Tokin	MDP-A3U7	3-D motion sensor	N/A
MicroStrain	3DM-G	3-D orientation sensor	\$1295

The device chosen by the sensing group is the Microstrain 3DM-G orientation sensor. This unit combines three rate gyros, three accelerometers, and magnetometers. Numerous aspects of the 3DM-G make it the best option. By combining the various required sensing measurements, it saves work that would be necessary with integrating individual gyros and magnetometers. The sensor operates over the full 360 degrees of motion on all three axes. It outputs its data digitally via serial cable as the Communications Team requires [SENS0230-0240]. And the output can be configured to provide the orientation data in matrix or quaternion formats, or as raw data from the individual sensors. The 3DM-G outputs its data at 100Hz and has an accuracy of +/-2 degrees¹, thus meeting the previously stated requirements.

The 3DM-G utilizes the integration of its sensors in the following way: The processor first processes the output from each individual sensor and calculates an estimate of its orientation in space. The processor then applies complementary filtering that combines the high frequency response of the rate gyroscopes and the long-term low frequency response of the accelerometers and magnetometers. By processing the data in this way, we achieve robust orientation measurement¹.

4.2.4. Position Sensing

The ArcSecond Constellation3Di is the indoor GPS position sensing system that was chosen for the Phaeton mission. Considerations leading to the choice of this subsystem involved top level requirements of navigation, lateral and vertical stability and range capacity within the operating environment, which is MIT's Johnson Athletic Center. The ArcSecond configuration and operation specifics were a major factor in the decision to take the position loop computation off-board the rotorcraft and to the ground station – a decision that affected the controller's design and the communication requirements of the overall system.

An overview of the position sensing configuration is depicted in Figure 4.10 to facilitate a discussion of how the subsystem satisfies requirements and factors into the

¹ www.microstrain.com

design of other subsystems. The cylindrical sensor mounted on the vehicle will intercept tilted laser beams from the four transmitters on the ground and will pass this raw data to a position calculating engine (PCE) board. Data will then be input through a serial port to the on-board computer and sent through a wireless link to the ground station. Finally, the ArcSecond software in the ground station will calculate and output position from this data.

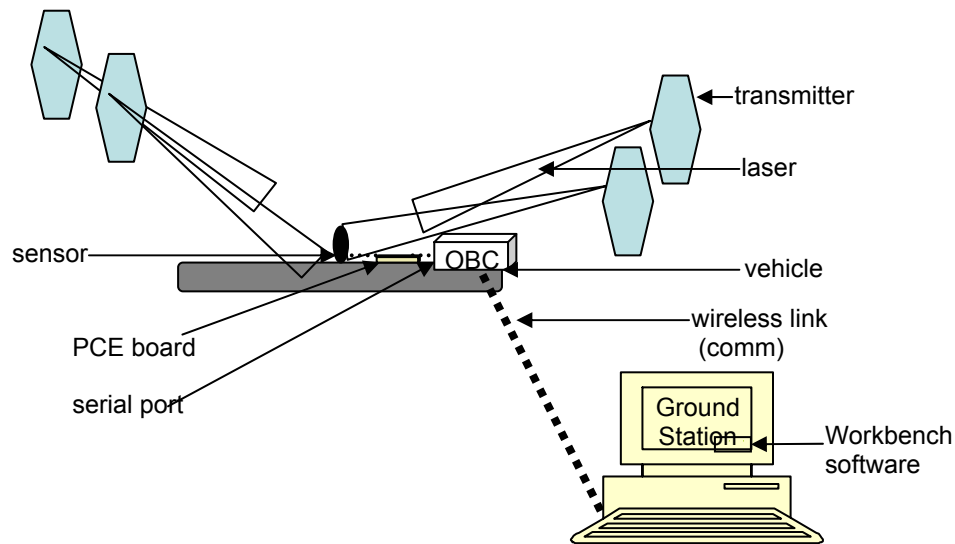


Figure 4.10: Overview of position sensing configuration

4.2.4.1. Vehicle State Characterization

The ArcSecond will provide three dimensional position data at up to 20Hz¹ and velocity data at a lower bandwidth (which is specified in [SENS0210]). This information will contribute to the characterization of the vehicle's state for control and navigation. Note that, although there will be delay on this data because it has to be transmitted to the ground to be decoded, this rate is acceptable to correct an on-board position estimation derived from the vehicle's attitude.

Since the ArcSecond position data does not have a time step associated to it, a velocity estimation derived from it can only be done at a lower frequency of about 5Hz². This will ensure that, if at some point the delay is larger than the ArcSecond time step and there is no position update, an erroneous velocity will not be input to the controller. This velocity data can be called at a lower frequency by the controller to correct on-board velocity estimates that are based on the vehicle's attitude.

4.2.4.2. Range and Accuracy Considerations

The system's range is dictated by the need to operate in the Johnson Athletic Center, which is a specified project requirement. Using four ground transmitters, the

¹ "Constellation – Navigation and Control," www.constellation3di.com, accessed 20 September 2003

² According to Arthur Richards, 16.82 Graduate TA; Aerospace Controls Laboratory

system uncertainty will be on the order of millimeters¹ when the maximum distance from the sensor to a transmitter is 25m. This will satisfy constraint [SENS0300], which requires position data to be accurate to 1cm for landing on a moving rover. This requirement derives from the need to provide sensor data five times as accurately as the controller is expected to command the vehicle², which is 8cm during landing according to constraint [CONT0200].

4.2.4.3. Sensor and Transmitter locations

For all stages of the mission the sensor on board must have line of sight (LOS) to at least two transmitters on the ground. When the rotorcraft is taking off and landing, this dictates that the sensor must be mounted on top of the rotorcraft, which is specified by [VEHI0280]. If the transmitters on the ground are below ~3m, however, LOS will not be guaranteed when the vehicle is hovering 3m above the ground.

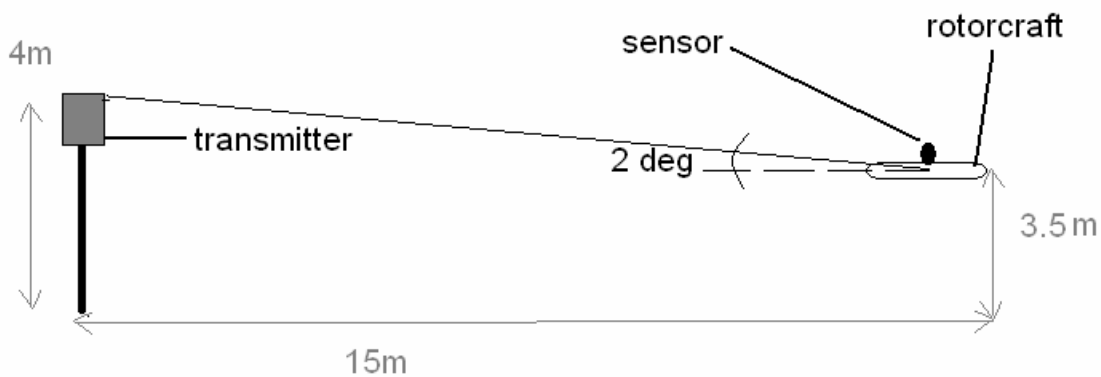


Figure 4.11: Transmitter location rationale

The maximum altitude that the rotorcraft is required to reach according to top level requirements is 3m. Furthermore, the vehicle is not required to travel more than 10m plus whatever distance it must track the target for – presumably not more than a few meters taking into account that the target, which is located within a 2X2m area, will travel at less than 5cm/s. As Figure 4.11 illustrates, if the vehicle does not go above 3.5m at any given point, and the transmitters are located 4m above the ground, the attitude of the rotorcraft should be maintained within 2 degrees of the horizontal so as not to lose sight of any transmitter that is over 15m away. This is specified as constraint [CONT0220] on the control subsystem by the sensing subsystem. Note that at least one transmitter is likely to be closer than 15m from the vehicle at any given time given the limited area the rotorcraft is specifically required to navigate.

¹ Constellation3Di Error Budget and Specifications. Available from www.constellation3di.com, accessed 20 September 2003

² According to Jonathan P. How, 16.82 Professor; MIT Department of Aeronautics and Astronautics

4.2.4.4. On-board vs. Off-board Position Loop Decision

A factor in the decision of whether the controller position loop would run on or off-board was that the ArcSecond (Workbench) software that decodes laser beam readings can only run on a Windows XP operating system.

Workbench is necessary to process position data if more than two transmitters are used, but it was decided that a two-transmitter configuration would not be robust (please refer to the memo in Appendix C that reports observations made when the two-transmitter configuration was set up in Johnson). The communications sub-team decided not to have an on-board computer that could support Windows XP because of the increase in weight and the lesser real-time performance of Windows OS'. After these considerations, the decision was made to decode position data off-board.

All the components of the position sensing subsystem that was chosen are listed in Table 4.11 along with on-board mass, current and voltage requirements, which were critical parameters for the vehicle design and resource allocation decisions.

Table 4.11: Position Sensing Subsystem Components

Part	Mass (g)	Current (A)	Voltage (V)	Cost (\$)	References
Cylindrical Tracking Sensor and PCE board	156	0.125	12	2000	Mass was measured directly, power requirements were obtained by inspection
4 Ground Transmitters	N/A	N/A	N/A	borrowed from Prof. How	N/A
Workbench Control Center Software	N/A	N/A	N/A	free download	N/A

4.2.5. Remaining Issues to Resolve

One remaining sensing issue is that the ground station's built-in video adapter must be assessed as to whether it will provide sufficient capture resolution. Thus, the ground station equipment must be tested. If not the built-in adapter is not sufficient, there are other analog-to-digital video converter options, as previously mentioned.

4.3. Communication

The communication subteam's role in the overall UAV system is to provide means of communication between the other subsystems, the hardware necessary for sensing and control calculations, and a ground station to support Phaeton's mission. The communication subteam identified various hardware and system options and final selections were made based on the integrated system requirements and other factors.

4.3.1. Onboard Computer

The onboard computer was selected from a multitude of PDAs and embedded computer options. The parameters of interest in achieving the basic onboard

communication requirements are connector types, power, weight and size, programmability, and connectivity to ground station.

The PDAs processors offered the capability of doing all calculations onboard, which would minimize data transfer time. Additionally, PDAs generally have built in wireless devices making any necessary communication to the ground relatively simple. However, PDAs are heavier and are limited in hardware connectivity options. The system requirements dictate that the communication system be able to receive input from the sensing team, transfer the input to the controls team, perform control calculations, and send information to the vehicle team. In order to satisfy **this requirement**, an onboard computer with at least 3 serial ports is needed [SENS0210-0240]. The PDA would require a USB-serial converter in order to have the required input and output ports. These converters would add additional weight to the already heavy PDA system.

The primary driving forces in selecting a PC 104-type computer were the operating system constraint placed on the communication system by the sensing subteam [COMM0250] and the maximum weight of 350 grams [COMM0200] allotted by the vehicle team. PC-104s allow for easy expansion of functionality. For example, the control team's additional requirement for the motor rpm data can be met by attaching a digital input board to the PC-104. The ArcSecond Indoor GPS System requires Windows XP to extract meaningful data from its sensor array. Although there are options for embedded XP or generating code to perform the calculations on a non-XP system, the benefits of doing all calculations onboard do not offset the additional weight, cost, and effort needed to implement such a system.

The requirements outline the need for at least 3, 16-bit serial ports with an option for a fourth: 1 for rate information (MicroStrain device) [SENS2300-2400], 1 for position data (ArcSecond) [SENS0210-0220], **1 for the PWM signal outputted to the motors** [COMM0350], and potentially 1 for motor rpm data (optical sensor). Additionally, the **onboard computer must be capable of altitude processing** and be connected wirelessly to the ground station. The communications team transformed these requirements into specifications for an onboard computer: 32-bit x86 processor, 64 MB of SDRAM, 64 MB of storage, and wireless Ethernet connectivity.

To begin the selection of a PC-104, the AMD Elan SC520 processor was selected. This 5x86 chip offers the most performance for current drain, and provides a 32-bit bus for faster network connectivity. There are numerous PC-104 options built on this processor that conformed to the above requirements. In addition, there are boards that employ the same processor as a more stripped-down unit. These would require board fabrication in order to interface a wireless unit to their onboard bus. While this could be done, it was decided that the work required was beyond the scope of this project and would severely impact the team schedule.

Table 4.12: PC104 Comparison – Figures of Merit

Make/Model	Mass (g)	Current (A)	RAM (mb)	Storage Type	Processor	D-Kit Price
VersaLogic Bobcat	86	0.96	64	DiskOnChip	AMD SC520	\$802
WinSystems PPM	UNK	0.9	32 std.	DiskOnChip	AMD SC520	UNK
Arcom Pegasus	96	0.8-1.0	64	Intel Flash (16mb max)	AMD SC520	UNK

The PC-104 that best fits these requirements while minimizing weight and cost is the VersaLogic Bobcat and was selected as the onboard computer. Specifications are shown in Table 4.12, along with those of two other alternatives. The VersaLogic Bobcat is 10 grams lighter than its Arcom Pegasus counterpart and has the more desirable DiskOnChip storage type. The WinSystem board was competitive, but only has 32 Mb of RAM, which is insufficient for Roboflag applications. The Bobcat board will be ordered with the standard development kit and 64mb DiskOnChip module, as well as a PC Card adapter for the wireless option selected.

4.3.2. Connectors and Converters

The microstrain, ArcSecond sensors, and motors need to be attached to the PC-104 via 16-bit serial ports [SENS0210-0240]. The PWM signal to guide the motors is sent via a serial port. The voltage level is an analog signal sent to each of the four motors and thus the digital signal produced by the controls team must be converted. This will be done via a PIC programmed to convert the signal and convert RPM sensing data.

4.3.3. Ethernet Connection

A wireless connection will be used to transmit data from the onboard computer to the ground station. There are 3 main options for connectivity to the ground station: wireless modem, WI-FI, and Bluetooth. The onboard computer selected impacted the internet connectivity selection. Had a PDA been part of the selected system, the Bluetooth option may be more viable. However, for ease of integration with the PC-104 a wireless card was selected. The card will mount on an adapter board connected to the PC-104 processing board. Various options shown in Table 4.13 were considered, paying close attention to weight, data rate, range, and power consumption. MIT computer services recommend the Orinoco cards and it works with both Linux and Windows. Sources online also indicate that the miniPCI cards are compatible with most distributions of Linux.

Table 4.13: Wireless Cards – Figures of Merit

	Weight (g)	Data Rate	Power Consumption/Reqmt	Range	Frequency	Interface	Price
Orinoco Silver	55	11,5.5,2,1Mbps	T-576mA, R-341mA,S-15mA		5150-5350,5725-5825	Type 1 PC Card	79
Orinoco Gold	55	54,11Mbps	T-560mA, R-320mA,S-15mA		2400-2484MHz	Type 1 PC Card	85
Agere Systems	< 20	11,5.5,2,1Mbps	UNK	160m	2400-2484MHz	miniPCI	UNK
IBM High Rate miniPCI	< 20	11,5.5,2,1Mbps	UNK	160m	2400-2484MHz	miniPCI	113

When speaking with company representatives from Agere Systems, it was discovered that their wireless card has been discontinued. Therefore, the IBM High Rate Card was selected. The miniPCI form factor offers the lightest weight and a great ease of hardware and software interface with the PC104.

Interfacing the miniPCI card will require a simple adapter board (essentially only a voltage regulator). Mesa Technologies manufactures such a device, and its weight will

still keep the total mass of the Wi-Fi interface to well under 55grams. The cost for this board is \$75 for individual units.

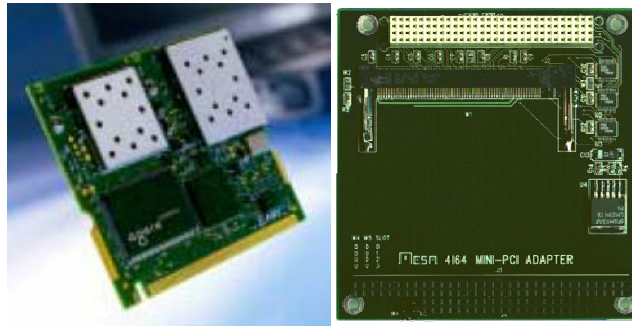


Figure 4.12: IBM miniPCI Wi-Fi Card and PC104 Adapter Board

The ground station will have a wireless transmitter hub. Since the transmitter base will be offboard, the weight of this item is irrelevant. A modem connection is more reliable in timed package information. However, the attitude data, which is time critical, is being processed onboard. The position data and other information being relayed to the offboard computer is not as time sensitive. Therefore, an Ethernet hub was selected since it has more bandwidth. Therefore, it meets the data transfer rates and reliability constraints set forth by the other subteams.

The base hubs were assessed based on range, price, and reviews which are shown in Table 4.14. The Belkin hub has a good history with the MIT network and received good reviews. Both options have comparable prices, but the Belkin is available from a mainstream supplier, Office Max. Therefore, the Belkin hub was selected.

Table 4.14: Ethernet Hubs – Figures of Merit

	Price	Data Rate	Op Range	Frequency	Operating Channels	OS
Belkin	100 (no tax)	11Mbps	590ft(180M) at 11Mbps	ISM Band, 2400-2483.5MHz	11	Windows 2000/NT
			984ft(300M) at 5.5Mbps			
NetGear ME102	95 (no tax)	11Mbps	500ft(150M) at 11Mbps	UNK	NA	Windows 2000

4.3.4. Off-board Computer

The requirements for the ground station are the ability to process the Arc-Second GPS data, accept user input via a keyboard [COMM0340], connect wirelessly to the rotorcraft's onboard computer, and to receive the video input. Although it is not a specified requirement, it is preferable for the ground station to be mobile, in order to ease transportation between testing facilities and Johnson. Therefore, laptop-type computers were chosen, and specified to meet the requirements. The team did not investigate desktop options in detail since the purchase cost would not be much less than an equivalent laptop, and the amount of time required for the team to build a less expensive desktop computer in-house would delay the project.

In order to receive and process the Arc-Second data, the off-board computer requires the Windows XP-Professional operating system [COMM0280]. To ensure the programs are executed reliably, the minimum requirements are for a Pentium 4 class chip, with 1.6 Ghz, 20Gb of hard drive space, and 512 Mb of RAM memory. In order to connect the internet hub to the computer, the computer needs a USB port, which is standard with most laptops (USB 2.0).

With regards to the video input, there are two methods available to acquire the input to the laptop: the first is to have the necessary analog inputs on the computer already built in; the second is to use a digital video analog-to-digital adapter. Using a computer with a built in analog input is preferable, as it would minimize the additional hardware needed to transmit the video. Although computers (desktops or laptops) with the necessary analog inputs are available, they are rarer and more expensive than standard versions.

The decision was made to order a laptop with the required analog inputs. The team also ensured that should the direct analog video input should fail for some reason, that the laptop ordered meets specifications for using an analog to digital converter. The digital video input type IEEE 1394 Firewire is the specified digital video signal, and is standard on most laptops including the Sony Vaio specified [SENS0200]. Additionally, to process the video data, a video card with a minimum of 32 Mb of memory is required, with a 64 Mb video card recommended¹.

The Sony Vaio GRT 250/270 was selected as the ground station computer. The five computers that were strongly being considered all had similar specifications, except with respect to the video card. This group was already by selecting laptops that were known to be stable and relatively standardized throughout industry. The Sony Vaio GRT was the only computer to meet the 32 Mb specification and the sensing team strongly encouraged the upgrade to the 64 Mb card. A full description of the laptop options can be found in Appendix E.

4.3.5. Video Adapter

The ground station requires that video from the sensing system (camera and receiver) be displayed on the screen [SENS0200], and then processed by the computer for navigational data. The camera will transmit the video signal from the rotorcraft to a receiver, and then on an analog composite video signal out. This signal must then be converted to digital video via an adapter. If the laptop has analog inputs (such as S-video or mini-jack) then no adapter is needed; there may only be a cable with the correct connectors needed to connect the receiver to the laptop.

If the laptop doesn't have the required analog inputs, an adapter is needed to convert the video signal, digitize it, and then send the digital video signal (over a cable) to the computer. This adapter must have the requisite analog video input (composite video), and a 1394 Firewire digital output port (a cable is then needed to connect the adapter to the computer). The adapter must be capable of transmitting a video signal of greater than 640 x 480 pixels at a minimum of 30 frames per second.

Since the computer selected eliminated the need for a video adapter, there are no current plans for purchasing one. However, should the analog video input not function

¹ According to Catherine Chang, who has experience in this area.



correctly, various adapter options were investigated, are outlined in Appendix F, and one adapter was chosen: the Canopus ADVC-100 (from ProMax). This adapter is also available on the MIT campus for testing, prior to ordering one, should the need arise.

Our goal and specification is to complete Option C shown in Figure 4.13 below. Option A and B require the video adapter, should we find it is necessary. The connectors/cables required can be purchased locally.

Video to Off-board Computer Connections

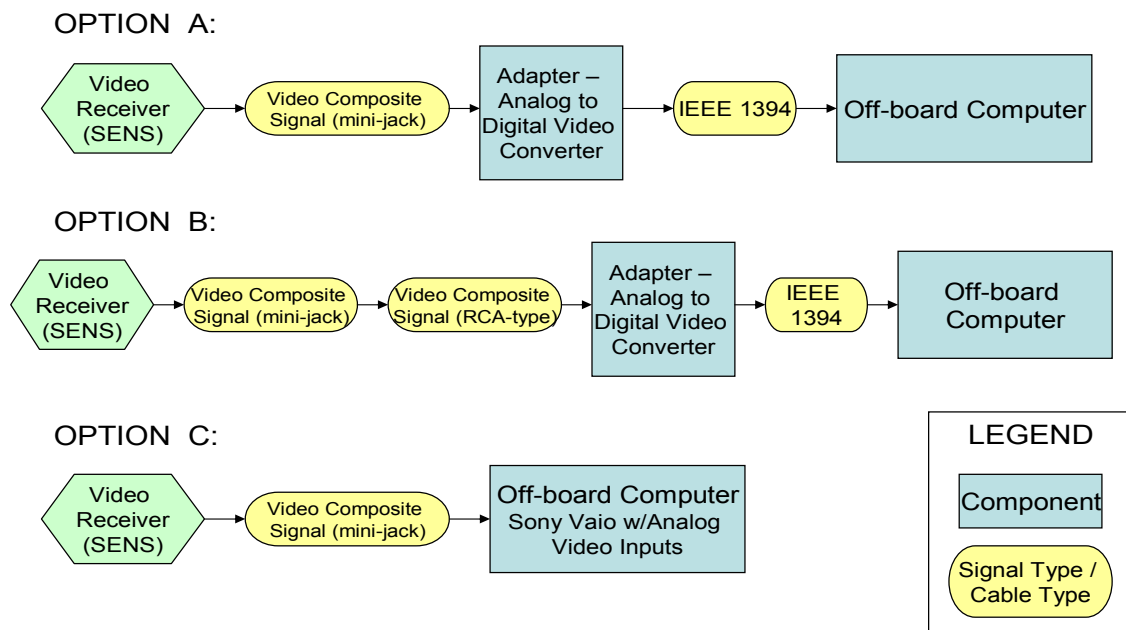


Figure 4.13: Video to Off-Board Computer Connection Options

4.3.6. Remaining Decisions and Issues to Resolve

The computer must be ordered, and once it arrives, needs to be tested with the video receiver. Once this is accomplished, the requisite software can be installed, and then the computer can be implemented and tested in the control loops. Final testing should be done using this computer. Once one operational craft is successfully being flown, data should be collected and then a decision should be made regarding the video card specification, and whether or not more craft can be controlled using the computing power of the computer.

Should the direct analog video input on the laptop fail to work, we have a Canopus Unit available on the MIT Campus with which we will be able to test the set-up before ordering another unit for the project.

4.4.Controls

The controls subgroup is responsible for writing the controls algorithms necessary to complete the top-level requirements. The team will first model the dynamics of the vehicle and use the model to predict a controller. The controller is then implemented onto the vehicle and perfected through the different tests presented in the test plan (section 5).

4.4.1. General Controls Overview

The vehicle will be controlled by both an on-board computer and an off-board computer. Using the feedback of the position, rotor speeds (omegas), yaw angle, and rotation rates along all three axes, as well as user-defined position input, the on-board and off-board controllers will determine the necessary attitude, elevation, and travel of the vehicle and output that information in the form of commanded omegas.

The on-board computer will be used to close the pitch, roll, and yaw loops, whereas the off-board computer will function to close the travel loop. A user script on the off-board computer calculates desired position based on a user input to the graphical user interface. Using actual position information from the ArcSecond sensor along with the desired location based on the user input, the off-board computer calculates the position error and translates that information into commands of pitch, roll, and yaw angle, as well as elevation. These commands are then transmitted back up to the on-board computer where the angles are fed into the respective pitch, roll, and yaw controllers.

On-board angle estimators use the measured pitch and roll rates to estimate the true angles. The true yaw angle is measured by the Microstrain sensor. These true angles/angle estimates are fed into the pitch, roll, and yaw controllers along with the angle commands from the ground station. The controllers determine the angle errors and calculate the necessary relative omegas for correction. The pitch and roll controllers output the relative rotor speeds (delta omegas) between the two rotors on the x- and y-axes, respectively. The yaw controller outputs the delta omega between the sum of the pitch rotor speeds and the sum of the roll rotor speeds. These delta omegas are sent to a final solver, which also takes the elevation command as the overall omega of all the motors and then calculates the omega of each specific rotor and sends the commanded omegas to the motors.

A rotor-speed feedback loop takes the commanded rotor speeds and subtracts the measured speeds to find the error. This error is inputted to a motor controller which then sends the necessary PWM signals to the motors. The overall schematic of the controls system is in Figure 4.14. Components in yellow and gray are ground-based controllers, blue are on-board controllers, and black items are those that will be modeled in the development of the controls law.

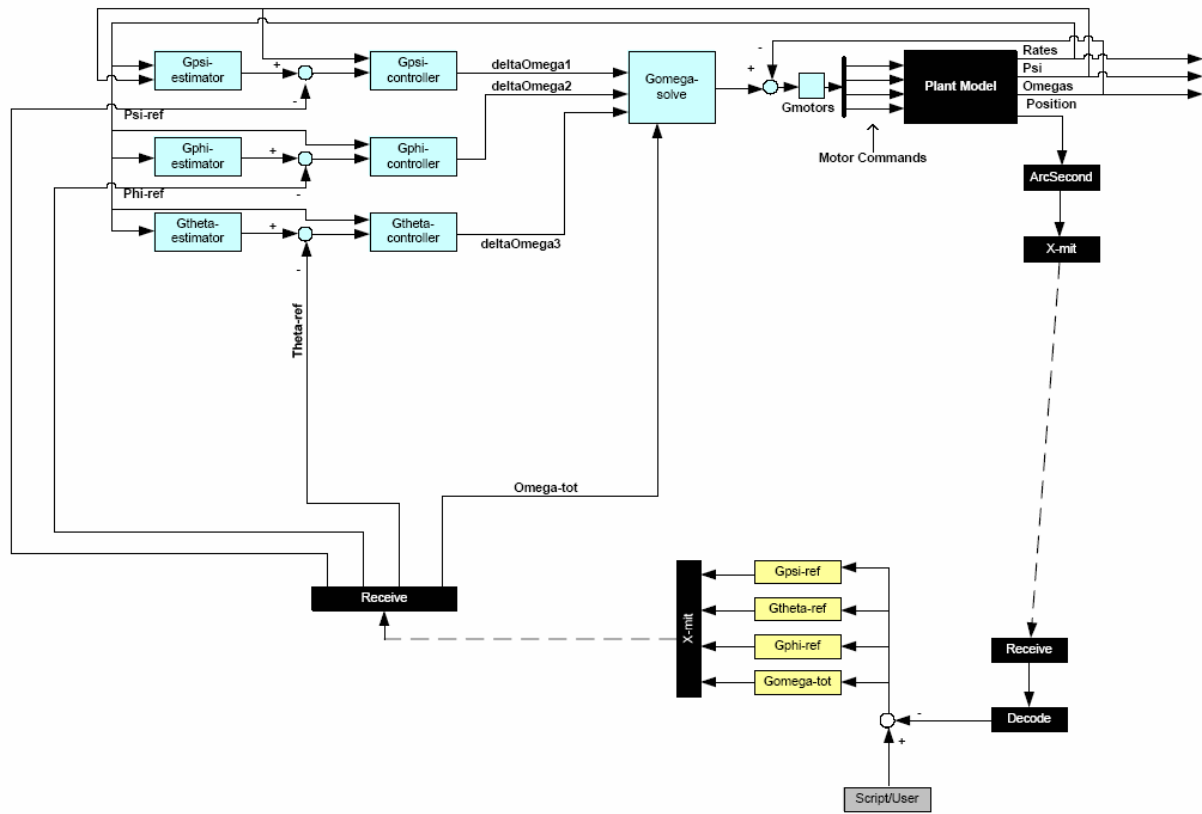


Figure 4.14: General Controls Schematic

4.4.2. On-board Controls

The control loops contained in this section are those processed entirely onboard the aircraft. The data flow, therefore, comes direct from the sensors and is considered to be real-time and zero-order-hold in its acquisition. The controls system is implemented as a series of functions, called by the communications team's software running on the on-board computer at a rate of 30hz. Outputs of the function $G_{\text{omega-solve}}$ are the motor speed commands and is the last function called on the main computer. G_{motors} , the motor control loop will be implemented on a separate PIC controller.

4.4.2.1. $G_{\text{psi-estimator}}$

The function $G_{\text{psi-estimator}}$ receives the **ArcSecond angular rate** and angular position data and returns the measurement of Ψ , the yaw angle, to be used by the yaw controls law. If the estimation contained within the ArcSecond proves sufficient, this function may simply become a transfer function of 1. If additional filtering or smoothing is required, it will be inserted here. It will also be used to perform any conversions between the data provided by the communications system to the form required by the later controls laws.

4.4.2.2. $G_{\phi\text{-estimator}}$

The function $G_{\phi\text{-estimator}}$ receives the ArcSecond angular rate and angular position data and returns the measurement of Φ , one of two pitch angles, to be used by the pitch controls law. If the estimation contained within the ArcSecond proves sufficient, this function may simply become a transfer function of 1. If additional filtering or smoothing is required, it will be inserted here. It will also be used to perform any conversions between the data provided by the communications system to the form required by the later controls laws.

4.4.2.3. $G_{\theta\text{-estimator}}$

The function $G_{\theta\text{-estimator}}$ receives the ArcSecond angular rate and angular position data and returns the measurement of θ , one of two pitch angles, to be used by the pitch controls law. If the estimation contained within the ArcSecond proves sufficient, this function may simply become a transfer function of 1. If additional filtering or smoothing is required, it will be inserted here. It will also be used to perform any conversions between the data provided by the communications system to the form required by the later controls laws.

4.4.2.4. $G_{\psi\text{-controller}}$

The function $G_{\psi\text{-controller}}$ receives the difference in output from $G_{\psi\text{-estimator}}$ and ψ_{ref} , the yaw reference angle received from the ground station. It returns $\Delta\Omega_z$, the difference in commanded rotational velocity between pairs of counter-rotating rotors. This difference results in a torque acting about the z-axis (yaw) of the vehicle. Initial modeling suggests that control of this loop can be achieved through a simple proportional controller.



4.4.2.5. $G_{\theta\text{-controller}}$ and $G_{\phi\text{-controller}}$

Each of these functions will control its corresponding pitch angle. The control law of each will be identical due to the symmetry of the flight vehicle. It will receive the difference in pitch reading between $G_{\phi\text{-estimator}}$ or $G_{\theta\text{-estimator}}$ and θ_{ref} or Φ_{ref} . It will also receive the angular rates for its respective loop. Applying those values to the control law, it will return either $\Delta\Omega_x$ or $\Delta\Omega_y$, the difference in applied motor commands between motors across the corresponding pitch axis. Should it be necessary, this function will also return an array of state variables that need to be remembered across instances of it being called. These would, in that case, be added to the parameters passed to the function.

4.4.2.6. $G_{\omega\text{-solve}}$

This function receives the three $\Delta\Omega$ values and the Ω_{total} received from the ground-based elevation loop. It then solves for Ω_1 , Ω_2 , Ω_3 , and Ω_4 , the individual motor command settings.

4.4.2.7. G_{motors}

This function, implemented on a PIC, receives the commanded motor rotation speeds. It then receives a polled count from the optical sensor on each motor and a

corresponding time step. From these two values, it determines the current angular velocity of the motor. Based on this value and the reference value, it determines the motor command to send to the motor's speed controller for optimal control. The goal is to artificially reduce the time constant of the motors to allow for better performance.

4.4.3. Off-board Controls

The off-board control loops are those that require the ArcSecond data. They return references for Φ , θ , and Ψ as well as the value of Ω_{total} . These are functions of the error in position from the ArcSecond data and the reference values from the User Command Script. For modeling purposes during the development of the controls laws, this set will be subject to a transport delay representing the communications times present from the time the ArcSecond concludes a reading to the time that the corresponding reference signals are returned to the vehicle. As a result, these functions are those which can be made delay tolerant.

4.4.3.1. Script/User Command

This function returns the desired position of the vehicle in world-coordinates and determine either through direct user input, or through the use of a script written for the flight. In the event that a script is operating the vehicle, this function will also receive the ArcSecond data in order to determine if a current state has been met in order to move on to the next. The difference between this value and the position returned by the ArcSecond constitutes the position error signal used to determine the reference values for Φ , θ , Ψ , and Ω_{total} . Later, enriching this in the form of a scripting language will allow for more complex motions of the vehicle to be performed autonomously.

4.4.3.2. $G_{\psi\text{-ref}}$

This function receives the error in position and returns the desired yaw angle (Ψ) for the craft. It will possess limiting to prevent unreasonable yaw commands from being sent to the vehicle.

4.4.3.3. $G_{\theta\text{-ref}}$ and $G_{\phi\text{-ref}}$

This function receives the error in position and returns the desired pitch angle (θ or ϕ) for the craft. It will possess limiting to prevent unreasonable pitch commands from being sent to the vehicle.

4.4.3.4. $G_{\Omega\text{-tot}}$

This function uses the error in elevation to generate a command for the total thrust to be commanded to the motors. This function will possess limiting to ensure the that total thrust value allows margin for the inclusion of other potential thrust differences across sets of motors.

4.4.4. Remaining Issues to Resolve

Since the controls team does not purchase any items, there are no outstanding issues.

5. TEST PLAN AND COMPONENT INTEGRATION

The test plan for the vehicle is centered about the closure of the different control loops. The tests provide a schedule for all subgroups to have the necessary hardware and software ready for each test. The sequence of the control loops to be closed will be yaw, pitch and roll, elevation, and travel. Each test will fix all axes except the one being tested. The yaw loop will be closed first because it is the easiest loop to model and control. The pitch and roll loops are modeled and controlled the same way because the vehicle is symmetric, therefore they are tested concurrently. These two loops are tested before the elevation loop in order to ensure necessary control of each pair of motors separately, before attempting to control all four in unison. Finally, once the vehicle is controllable at hover, the travel loop will be closed.

5.1. Yaw Controller Test

The yaw test will consist of the Phaeton attached to a turntable such that it cannot pitch, roll, or change elevation. Heading angle and yaw rate will be measured by the Microstrain. All computation will be done on the ground station directly wired to the vehicle on the test stand. The ground station will read the Microstrain data and run the control code. Motor speeds will be output to a Micro SSC controller which will convert the digital signal to PWM and drive the four motors.



Figure 5.1 Yaw Controller Test Setup

This test requires the Phaeton to be mounted to a turntable, the Microstrain to be mounted on the Phaeton and the Micro SSC to be connected to all four motor speed controllers. The laptop is required receive data from the Microstrain over a serial cable, run a program that uses that data as its input, and transmit the program output over another serial cable to the Micro SSC.

5.2. RPM Controller Test

The RPM controller test will be concurrent with the yaw controller test. The RPM test requires an optical interrupter switch at each motor connected to a PIC to count the interrupts. The PIC will dump the count to the ground station which will record the

data. The ground station will also output command rotor speeds to the PIC which will convert the signal to PWM and drive the four motors.

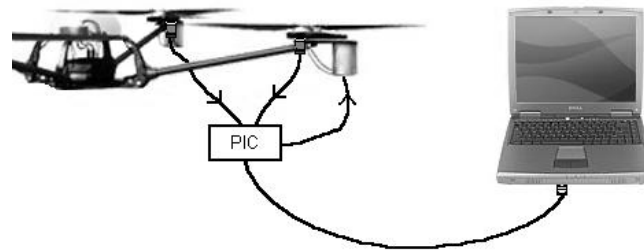


Figure 5.2: RPM Controller Test Setup

For this test the Phaeton should be fully restrained. The PIC must be programmed to execute the RPM controller. The laptop is only responsible for creating rotor speed commands and recording the RPM data. The rotor command and the actual rotor speed will be indexed with time so that the PIC performance can be analyzed.

5.3. Pitch / Roll Controller Test

The pitch and roll axes of the Phaeton are symmetric, thus the pitch and roll controllers are identical. During the test, the controller will be run on the OBC. Both the Microstrain and the RPM sensors will be used to provide feedback to the controller. The Phaeton will be suspended on a Kevlar rope strung between two fixed points, allowing rotation **around on** axis. This axis will be along one of the motor arms.



Figure 5.3: Pitch/Roll Controller Test Setup

The choice of rope direction will affect which axis the controller attempts to stabilize, thus the naming convention for the Phaeton body axis system must be established prior to the test. The rope must sustain enough tension to ensure that there is no contact with a propeller. All computation will be done with the ground station laptop as in the previous tests. The laptop must be able to read the data from the Microstrain and the PIC, execute the controller code and output rotor speeds to the PIC. The PIC must be properly executing the RPM controller as demonstrated in the previous test.

5.4. Elevation Controller Test

Having proven the ability to control yaw, pitch, and roll, the elevation controller will attempt to maintain a constant height above the ground. This test requires the inclusion of the ArcSecond sensor to give provide a 3D position measurement. The OBC **will be included for the first time** along with an improved set of rotor blades. The Phaeton will be in its final configuration for the testing of the elevation controller. The

Phaeton will be tethered to the wall by ropes off all four motor arms (much like the pitch/roll controller test). The ropes will be slack enough to allow the Phaeton to move freely in a small region, but will pull taught if the craft begins to stray.

Windows XP is required to run the ArcSecond software which cannot be run on the OBC. Thus the OBC must be connected to the ground station, preferably over Ethernet. All onboard systems must be operating using power supplied by the system battery.

5.5. Travel Controller Test

The final test is to prove that the Phaeton can hold a given 3D position within tolerance and travel to a given waypoint while remaining stable. This test will be fully hands off with no restraints. All waypoint commands will be input to the ground station. All controller code will be executed on the OBC excepting the position calculation from the ArcSecond. Success is defined as meeting the system requirements established in the 16.82 Requirements Document.

5.6. Sensing and Communications Testing Plan

The first device required for the overall vehicle testing is the Microstrain. It will be integrated with the vehicle right from the start for the yaw tests. Before the yaw tests begin the sensing team will put the Microstrain through a few individual simulations. First some computer code will be created to run a basic startup, test, and shutdown of the device. Then this code will be expanded to involve polling the Microstrain for various sensor outputs. Next, the device will be put on a turn-table or similar device to observe its functionality as it is put through various motions. Following this, the next test will involve setting the Microstrain up between the vehicle's operating motors. This will verify that the sensor's magnetometers will not be affected by the electric motors. At the conclusion of these simulations the device will be integrated with the vehicle for the scheduled yaw tests.

The video system will not be integrated with the whole vehicle system until the aircraft is ready for the travel tests. In preparation for this integration the video devices will be setup and tested in successive configurations that approach the final vehicle design. Since the camera will use a dedicated transmitter for the video signal the original test will be to setup the camera with the wireless transmitter and receiver and have the receiver plug straight into a television. The camera can be moved around to various positions to view the corresponding field of view sizes and footprint resolutions. The next step will be to connect the receiver to the ground computer's video card and configure the computer to display the video image. Finally, a point-and-click program will be setup that will calculate the actual position of the cursor's selected location on the video image.

The Arcsecond is scheduled to be integrated with the group vehicle testing at the beginning of the altitude tests. It is necessary to verify the functionality of the Arcsecond's data transmission setup before the altitude tests take place. To do this the device will be run through a series of successive tests. The first step will be to configure the Arcsecond with a test laptop. This laptop will be setup to stream the Arcsecond data through a network cable to another computer. The second step is to replace the network cable between the two computers with a wireless network connection and verify that this

is successful. The next step then is to introduce the PC104 onboard computer. The Arcsecond will be setup to run on the PC104 and the PC104 will transmit the sensor data through a network cable to the ground computer. The ground computer will use the Arcsecond data to calculate an exact position. Finally, the last step will be to again replace the network cable with the wireless network connection and verify that the data stream to the ground computer is still functional.

Testing and implementation of the PC104 will run in parallel with sensor testing, until the Arcsecond is used for position data. To begin, the PC104 DiskOnChip will be loaded with Linux, and boot tests will be run. After the system boots reliably, simple programs will be written in C++ to test serial input/output, the built-in watchdog timer, and other basic functions. After this, the necessary drivers for wireless Ethernet will be installed and a test program will be written to send and receive packets of data over the wireless link. The software developed by the sensor team to route the Arcsecond data over Wi-Fi will then be tested. The PC104 will also be tested briefly with the Microstrain, and then fully outfitted with the Arcsecond for position feedback during that phase of control.

6. BUDGET

The first round of purchasing cost is listed below. It is divided into each sub-teams purchase requirements and the exact price or a range of prices. The ten percent MIT tax and shipping and handling have been added to the final price. For any case in which the MIT tax and the shipping have not been factored, a scaling factor of 1.15 was used to get a cost estimate.

Table 6.1: Communications Cost Breakdown

Communications Components	Price
Sony Vaio Laptop	\$2,368
PC104 On-board Computer	\$1,032
Video to Digital Adaptor	\$410
IBM Network Adaptor Mini PCI-Wifi	\$136
Transmitter/Base	\$110
PC104 Mini PCI 3 Adaptor	\$94
PWM Converter	\$56

Table 6.2: Sensors Cost Breakdown

Sensors Components	Price
ArcSecond	\$1,980
3DM-G Orientation Sensor	\$1,433
Ground Station	\$290-\$440
Camera	\$242
RPM Sensor	\$26

Table 6.3: Vehicle Cost Breakdown

Vehicle Components	Price
7.4 V Battery and Charger	\$55
Record Player	\$50
Propeller Material	\$50
Voltage Down Regulator	\$33
Step Up Regulator and Parts	\$20

Two estimates are given depending on each group's need for certain items. The communications team's lower range does not include the DV adaptor. The new

Draganfly has not been included among the vehicle team's cost estimate since it has already been bought.

Table 6.4: First Round Cost Estimates

Sub-Team	Lower Range	Upper Range
Communications Team	\$3,796	\$4,206
Sensor Team	\$3,971	\$4,121
Vehicle Team	\$210	\$260
Total	\$7,977	\$8,587

The following estimates are for the entire project and do not include the purchase of the second quad-rotor. The upper range was found by doubling the cost found of the first round's upper range. For the communications team, the lower range does not include a second computer or a second transmitter since it is possible to use the first computer and transmitter for the second Draganfly.

Table 6.5: Second Round Cost Estimates

Sub-Team	Lower Range	Upper Range
Communications Team	\$5,114	\$8,412
Sensor Team	\$7,942	\$8,242
Vehicle Team	\$420	\$520
Total	\$13,476	\$17,174

In order to meet the budget requirement of \$15,00, it seems the lower range of the budget has to be used. There is still a surplus of \$1,500 which could be used for extra parts. Doubling all of the parts for the project will exceed the budget of our project by over \$2,000. We must conserve the remaining budget. Once cost negotiations with companies and the shipping and handling costs have been settled, the exact spending of the project may decrease. Since the sensor equipment is necessary for each of the X-rotors, the communications team will probably just have one computer for both X-rotors. However, with the surplus, it is possible to buy a second computer for less. All of the funds acquired for the project will then be used.

7. SCHEDULE

Figure 7.1 shows the detailed schedule for Phase I of the project from now until November 25. Since November 27 through November 30 is Thanksgiving weekend and the Phaeton must fly the following week, the project must be completed by November 25. The first few days of December will be spent putting the finishing touches on the design.

Currently, the team is working diligently to complete various aspects of the project. The schedule is based on the design and testing of the control loops. By November 4, the yaw and rpm loops must be finished. The pitch and roll loops, the elevation loop, and the travel loop must be completed by November 13, 18, and 25, respectively. On December 4, the quad-rotor must fly.

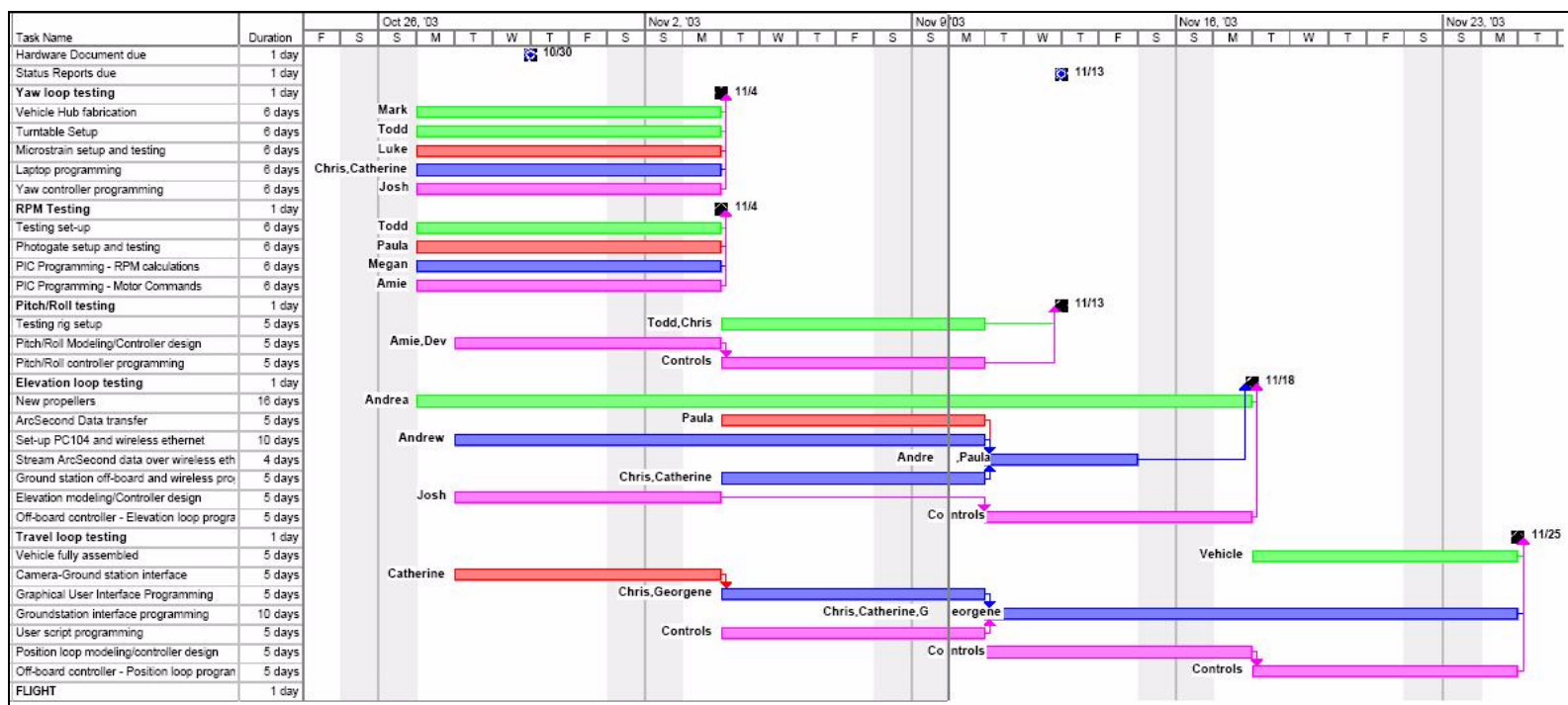


Figure 7.1: Schedule

8. CONCLUSION

The Phaeton project is making good progress thus far. At this point the team has created and revised the Requirements Document. In addition, a preliminary Hardware Purchasing Document and this final Hardware Document, which describes the hardware analysis and selection, have been completed. Currently, all hardware orders are being placed and processed, and some have already arrived. Members of the vehicle, communications and sensing subteams are currently awaiting the arrival of remaining hardware. In the interim, individual and integrated test plans are being refined, the controls subteam has been working on their current controller design, and the vehicle team has been constructing the testing rig and the new center structure for the vehicle. For a successful completion of the Phaeton project by December 5, 2003, the team must strictly follow the schedule and produce the deliverables on time. To ensure success, the team structure will be modified to focus on the schedule milestones. Individual team members will be assigned specific responsibilities, and a leader for each milestone will be appointed.

APPENDIX A

REQUIREMENTS DOCUMENT

Communication

Performance:

[COMM0200] The onboard communication system, including all wiring, shall weigh less than 350 grams.

[COMM0210] The onboard communication system's power will come from a 12-volt bus and is limited to .15 amps.

[COMM0220] The control team's algorithms must be executed at a frequency of 30 Hz.

[COMM0230] Sensing delay information transferred from the sensing team to the controls team should not exceed a delay of more than .05 seconds in pitch and .1 seconds in travel.

[COMM0240] Sensing bandwidth for the rate gyro shall be 500 degrees per second.

[COMM0250] The hardware must be able to run C++ or a version thereof.

Function:

[COMM0300] The communications system shall read in position data via 1 16-bit serial port. The data will be received at a frequency of 20 Hz.

[COMM0310] The communications system shall receive 3 analog voltages from the rate gyros and convert them to direct signals.

[COMM0320] The off-board communications system shall receive a video feed from the sensing team to be displayed on the off-board computer.

[COMM0330] The communications system shall receive an angular rate vector via a 8-bit serial port.

[COMM0340] The communications system shall receive user input via the ground station.

[COMM0350] The communications system shall send PWM signals to the four propulsive motors. The frequency of the signal shall be 25 Hz with no more than .05 seconds delay.

[COMM0360] The communications system shall transfer the user input to the controls group to generate a user-command vector.

[COMM0370] The communications system shall transfer the command vector between onboard and off-board computers.

[COMM0380] The communications system shall transfer altitude, position, and angular rate vectors to the controls system.

Implied Constraints:

[VEHI0260] The vehicle system shall centrally locate the communication board to decrease the wiring of the system and the weight.

Explanation:

The primary concern of the communications subsystem is to transfer data between the other subsystems and provide the hardware on which to compute sensing and control algorithms [COMM0300 – COMM0380]. The specific functional requirements outline the data rates and delay acceptable for each data transfer and calculation.

The communication team is constrained in the physical size of the onboard system [COMM0200] and power [COMM0210] by the vehicle team. There are other constraints placed on the communications subsystem, which address actual computing power and efficiency [COMM0220 – COMM0240]

Controls

Performance:

[CONT0200] The controls system shall maintain a position accuracy to within an 8 cm sphere of the commanded position for landing, as measured by the state vector.

[CONT0210] The controls system shall maintain a position accuracy to within a 42 cm sphere of the commanded position during hover as measured by the state vector.

[CONT0220] The controls system shall maintain the attitude of the rotorcraft to within 2 degrees of horizontal in all axes during hover and landing as measured by the state vector.

[CONT0230] The controls system shall be capable of commanding stable translation at speeds of 10 meters per minute as measured by the state vector.

[CONT0240] The controls system shall maintain an elevation accuracy to within 8 cm of the commanded elevation for translation as measured by the state vector.

[CONT0250] The controls system shall be capable of commanding a search in a 2 m by 2 m space of a 20 cm by 20 cm object in less than one minute as measured by the state vector.

[CONT0260] The controls system shall not command thrust values to the motors exceeding the maximum values TBD by the vehicles subteam as measured by the state vector.

[CONT0270] The controls system shall not command pitch angles exceeding the maximum allowable values TBD by the vehicles subteam as measured by the state vector.

[CONT0280] The controls system algorithms shall be implemented in the C++ programming language.

Function:

[CONT0300] The controls system shall read from memory a binary formatted state vector generated from raw sensing data.

[CONT0310] The controls system shall read from memory a user-command vector generated from the user input.

[CONT0320] The controls system shall determine a flight plan based on the user-command vector.

[CONT0330] The controls system shall produce a motor command vector containing a 16-bit floating-point power setting for each of the four propulsive motors.

[CONT0340] The controls system shall run functions on both the onboard and off-board computers.

Implied Constraints:

[COMM0220] The control team's algorithms must be executed at a frequency of 30 Hz.

[SENS0340] Yaw angles shall be accurate to +/-2 degrees.

[SENS0300] Position data shall be accurate to 1cm.

[SENS0320] Angular rates shall be accurate to +/- 2 degrees/second.

[VEHI0240] - The vehicle system shall provide a second order approximation of the transfer functions that relate motor commands to the pitch and yaw at elevations of 0 meters, 0.5 meters, 1 meter, and 2 meters.

[VEHI0250] - The transfer functions from the pitch to travel at elevations of 0 meters, 0.5 meters, 1 meter, and 2 meters will be provided.

[COMM0230] Sensing delay information transferred from the sensing team to the controls team should not exceed a delay of more than .05 seconds in pitch and .1 seconds in travel.

[SENS0330] The bandwidth of the angular rates shall be greater or equal to 40Hz.

[SENS0350] The bandwidth of the yaw angle shall be greater or equal to 40Hz.

Explanation:

The primary concern of the controls system is to fly the vehicle to within the parameters given by the problem statement. Because the controls team is the final step between the vehicle and meeting its performance requirements, most of its requirements are derived from the top-level requirements, as shown by [CONT0200] through [CONT0250]. These are mainly direct translations of the top-level requirements translated into controls requirements. In the case of [CONT0220], it is a combination of the video sensing requirements and the predicted camera properties.

[CONT0260-0270] are limitations imposed by the vehicle team on how aggressively the controls system attempts to command the vehicle. These are expressed in terms of maximum thrusting commands that can be applied to the motors and the maximum pitch angles the vehicle can move to while maintaining line-of-site for the navigation system, which is a function of the sensors' position on the vehicle, and other flight concerns.

[CONT0280-0340] are interfacing requirements. They briefly define the functions that operate the controls system to be called by the communications systems, and describe the vectors to be used by the communications and controls systems to share information. [CONT0280] exists as C++ has been agreed upon to be the standard programming language across the communications and sensing systems.

Although the controls system requires various performance parameters of the sensing and communications systems, those are listed as requirements on those systems and as implied constraints of the controls system. Hence the controls requirements are primarily performance and interfacing requirements.

Sensing

Function:

The sensing sub-team shall provide the system with the following:

[SENS0200] An analog video signal to the ground station as composite video.

[SENS0210] Position data in three dimensions on board as a digital signal through a serial cable.

[SENS0220] A C++ function for the communications team to call the position data in three dimensions on the ground station.

[SENS0230] Angular rates in three dimensions as a digital signal through a serial port.

[SENS0240] Yaw angle data as a digital signal through a serial port.

Furthermore, the sensing sub-team will operate within the following mass and power specifications:

[SENS0250] A total mass of less than or equal to 220g.

[SENS0260] A power supply of 12V and drawing a total current of 0.9A.

Also, the following top-level requirement applies:

[SENS0270] The video resolution shall be greater than 250,000 pixels² per actual square meter on the ground.

Performance:

[SENS0300] Position data shall be accurate to 1cm.

[SENS0310] Position data shall be updated at 20Hz.

[SENS0320] Angular rates shall be accurate to +/- 2 degrees/second.

[SENS0330] The bandwidth of the angular rates shall be greater or equal to 40Hz.

[SENS0340] Yaw angles shall be accurate to +/-2 degrees.

[SENS0350] The bandwidth of the yaw angle shall be greater or equal to 40Hz.

Implied Constraints:

[VEHI0270] The vehicle system shall point the camera downwards and outwards near the center of the vehicle.

[VEHI0280] The vehicle system shall place the indoor global position system at the top of the vehicle as close to the center as possible within the line of sight.

[VEHI0290] The vehicle system shall place the Microstrain on three axes within 4 centimeters of the center of gravity.

[CONT0200] The controls system shall maintain a position accuracy to within an 8 cm sphere of the commanded position for landing, as measured by the state vector.

[CONT0210] The controls system shall maintain a position accuracy to within a 42 cm sphere of the commanded position during hover as measured by the state vector.

[CONT0220] The controls system shall maintain the attitude of the rotorcraft to within 2 degrees of horizontal in all axes during hover and landing as measured by the state vector.

Explanation:

The primary objectives of the sensing system are twofold: 1) to provide accurate and real-time navigation and orientation information required to successfully control the flight of the vehicle, and 2) to provide real-time video data at sufficient resolution in order to identify and track ground objects.

The only top-level requirement imposed on the sensing subsystem is that the video output resolution be sufficient to display a 20cm x 20 cm object as no less than a 100 pixel by 100 pixel object when operating at an altitude of more than 2m. Thus, it is necessary for the camera to have a resolution of no less than 250,000 square pixels per actual square meter [SENS0270].

As directed by the vehicle subsystem, the sensing package's total mass cannot exceed 220g [SENS0250] and its power consumption cannot exceed a total current of 900 mA on a 12V power supply [SENS0260].

[SENS0300,0320,0340] are accuracy constraints imposed by the control subsystem. Providing data that meets these requirements allows the vehicle to be controlled with the appropriate stability. [SENS0310,0330,0350] concerns the rate at which the controller requires the data from the various sensors. If these constraints are met the description of the motion of the vehicle received by the controller will be accurate.

The nature of the hardware outputs requires a specification of the various interfaces involved. [SENS0200,0210,0230,0240] define the interfaces dealing with video, position, and orientation outputs. [SENS0220] is the software interface between the indoor positioning system and the controller.

Vehicle

Performance:

[VEHI0200] The vehicle system shall have a thrust greater than the weight of the vehicle during takeoff.

[VEHI0210] The vehicle system shall have a thrust greater than the weight of the times a factor of alpha during hovering.

[VEHI0220] The vehicle system shall have a manual control response if the automatic system fails.

[VEHI0230] The vehicle system shall endure a flight time of ten minutes.

[VEHI0240] The vehicle system shall provide a second order approximation of the transfer functions that relate motor commands to the pitch and yaw at elevations of 0 meters, 0.5 meters, 1 meter, and 2 meters.

[VEHI0250] The transfer functions from the pitch to travel at elevations of 0 meters, 0.5 meters, 1 meter, and 2 meters will be provided.

[VEHI0260] The vehicle system shall centrally locate the communication board to minimize the wiring of the system and the weight.

[VEHI0270] The vehicle system shall point the camera downwards and outwards near the center of the vehicle.

[VEHI0280] The vehicle system shall place the indoor global position system at the top of the vehicle as close to the center as possible within the line of sight.

[VEHI0290] The vehicle system shall place the Microstrain on three axes within 4 centimeters of the center of gravity.

Function:

[VEHI0300] The vehicle system shall receive four pulse width modulation signals, one for each motor from the communications team.

Implications:

[COMM0200] The onboard communication system, including all wiring, shall weigh less than 350 grams.

[COMM0210] The onboard communication system's power will come from a 12-volt bus and is limited to .15 amps.

[CONT0260] The controls system shall not command thrust values to the motors exceeding the maximum values TBD by the vehicles subteam as measured by the state vector.

[CONT0270] The controls system shall not command pitch angles exceeding the maximum allowable values TBD by the vehicles subteam as measured by the state vector.

[SENS0250] The total mass for sensing equipment will not exceed 220g.

[SENS0260] Sensors will use a 12V power supply and are limited to a total current of 0.9A.

Explanation:

The primary objectives of the vehicle team originate from the top level requirements. [VEHI0200-0210,0230] show that the vehicle team must develop an efficient quad-rotor design that will be able to take off, hover, and sustain flight for 10 minutes. Thus, the vehicle team must constrain the weights of and allot power for the subteams' components. In addition, the vehicle team must include a system that will warn the operator of vehicle peril and that will provide a switch between automatic and manual control as shown in [VEHI0220]. This is critical for the safety of the vehicle and any nearby individuals.

[VEHI0240-0250] show that transfer function models regarding the quad-rotor's flight behavior must be given to the controls team. These models will be computed based on data from flight tests of the quad-rotor craft.

The vehicle team must also place communication and sensing equipment in certain locations. The communications board must be centrally located to minimize wiring as shown in [VEHI0260]. As directed by the sensing team, the vehicle team must orient the camera and the indoor global position system in a certain way as shown in [VEHI0270] and [VEHI0280]. The camera must have a clear view in order to find the flag, and the indoor global position system must be within the line of sight in order to determine the craft's position. As shown in [VEHI0290], the gyros must be placed near center of gravity on three axes in order to work properly.

The only function of the vehicle team is to receive pulse width modulation signals that will control the outputs of each motor and this is shown in [VEHI0300]. These signals will come through the communications and tell a specific motor to speed up, slow down, or remain the same based on the current and desired position of the craft.

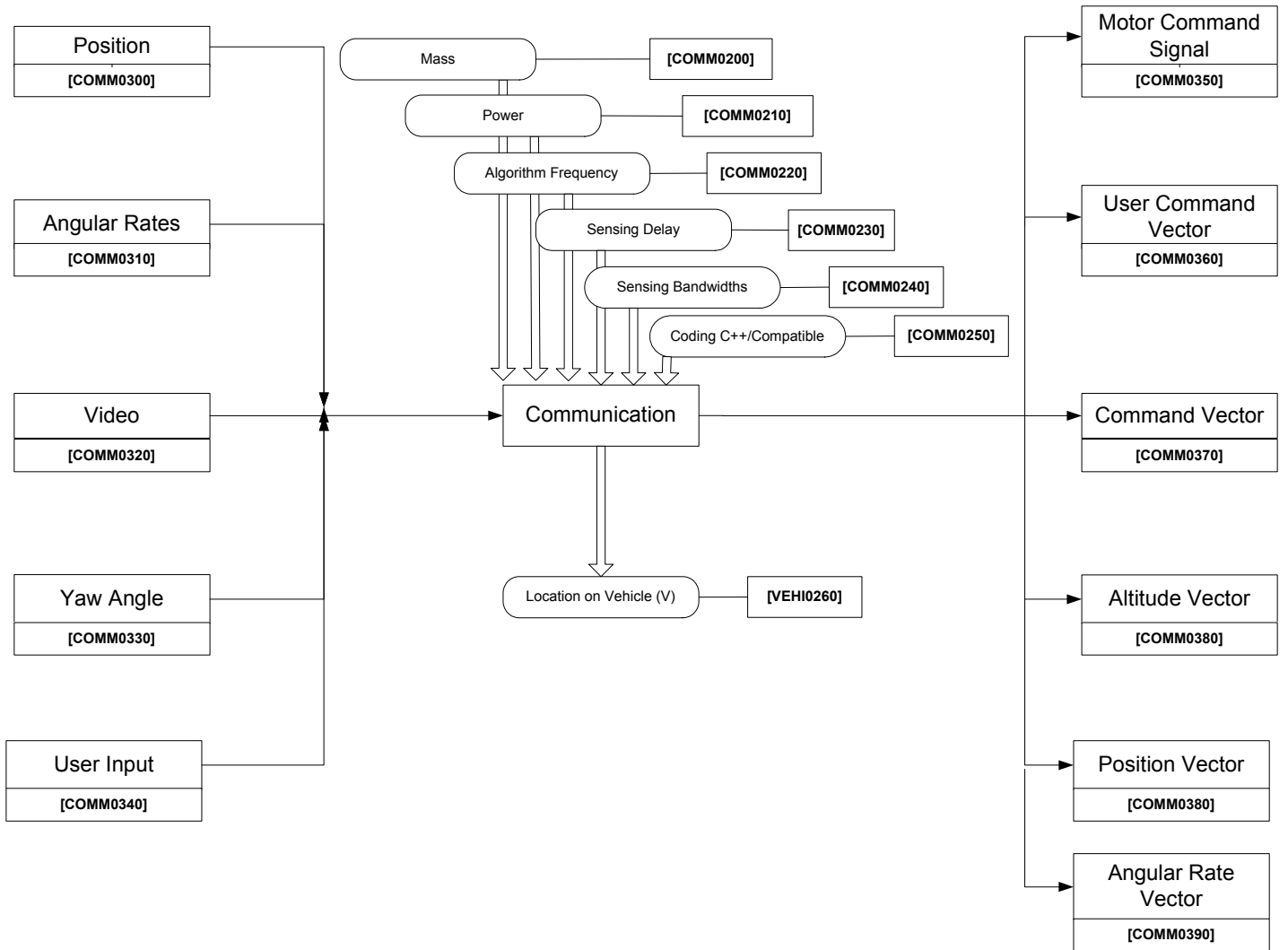


Figure A.1: Communication Chart

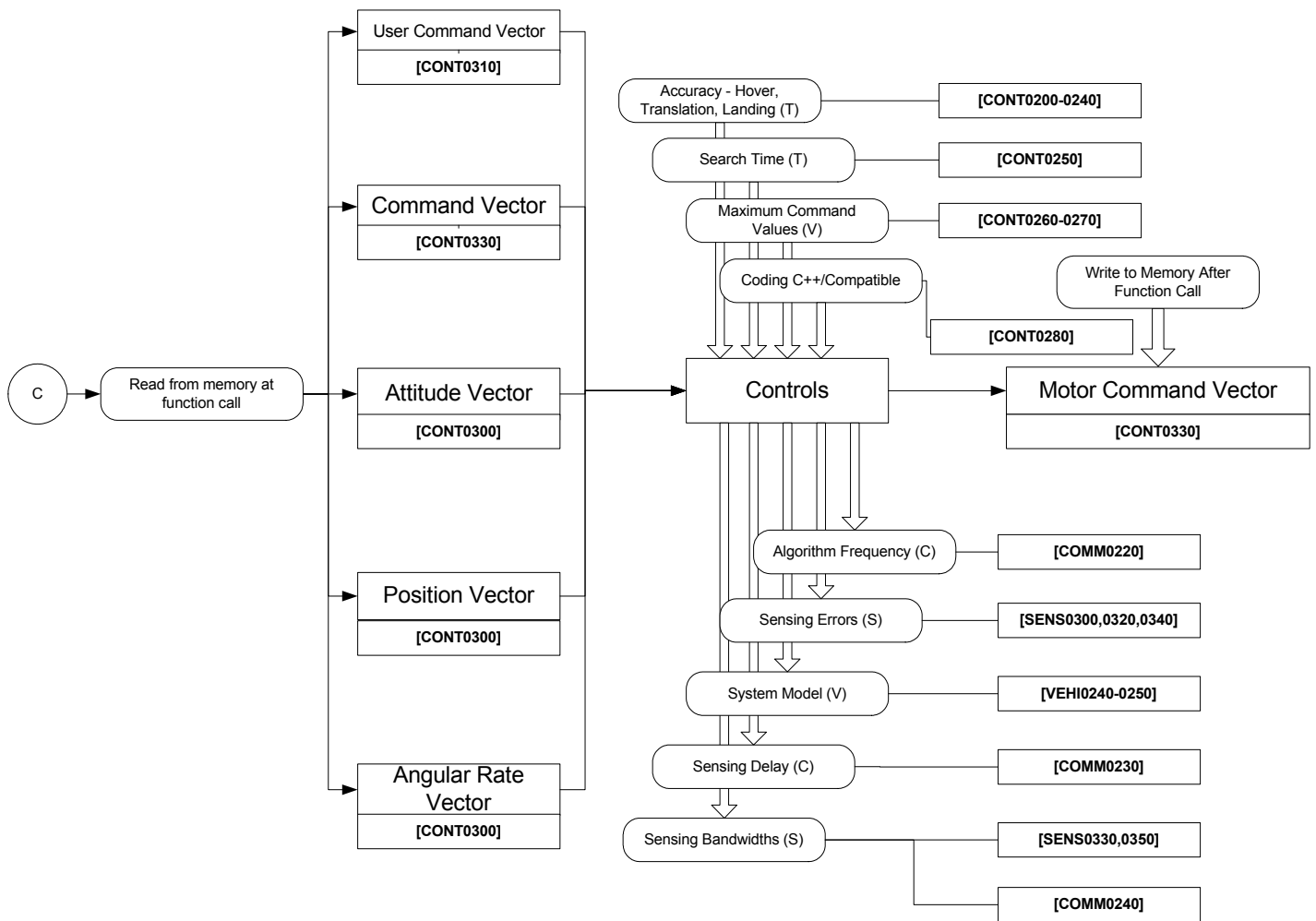


Figure A.2: Controls Chart

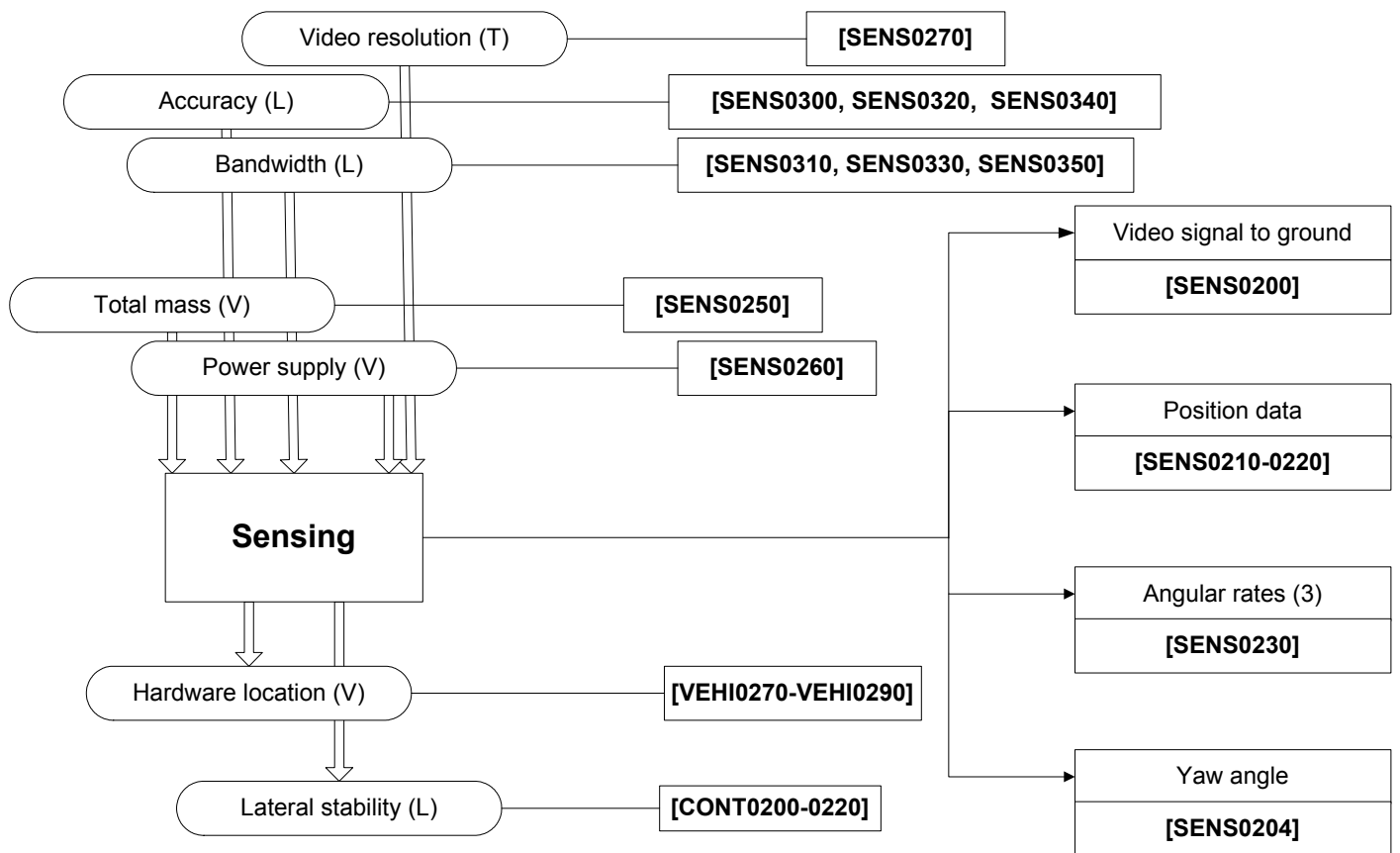


Figure A.3: Sensing Chart

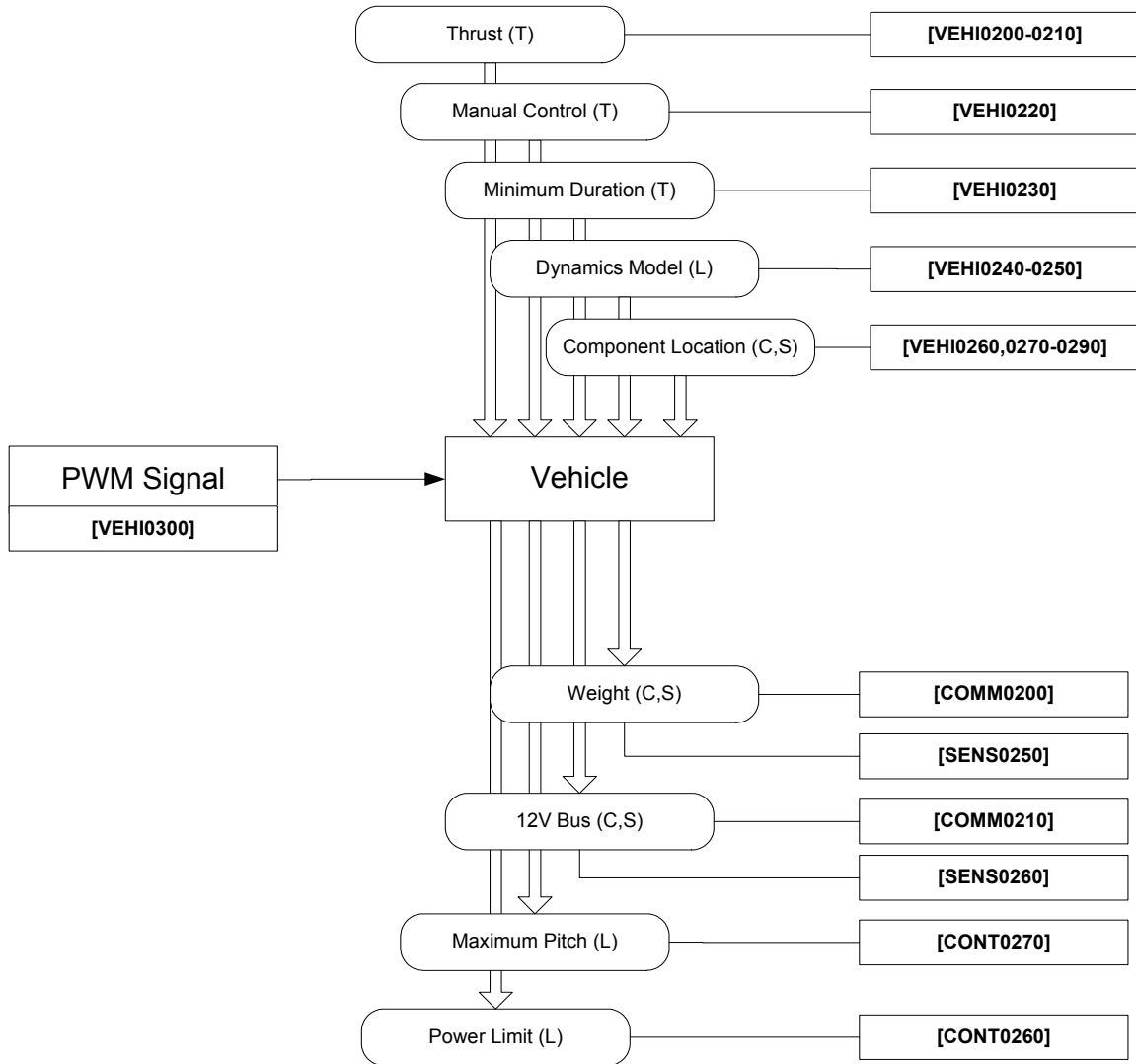


Figure A.4: Vehicle Chart

APPENDIX B

From: Vehicle Team
To: Controls Team
Re: xrotor calculations and derivatives
Date: October 14th, 2003

First we define the operating point of the vehicle by stipulating the thrust required to hover out of ground effect. From previous mass estimates we have $T_{\text{tot}} = 26.18$ [N]. Because we have four rotors, the each propeller produces $T_{\text{oper}} = 6.546$ [N]. Fixing the thrust and the pitch of the blades describes the state.

Table B.1: Operating Point State Variables

RPM	T [N]	P [W]	Q [N-m]
1496.7	6.546	38.4	0.245

Xrotor program requires an input for the velocity normal to the propeller – in our case vertical velocity. The program allows a minimum value of 0.1 [m/s] before the solution fails to converge. Thus this state is defined at a velocity of 0.1 m/s.

Three sweeps were then conducted in order to fully characterize the rotor.

1. The normal velocity held constant at 0.1 m/s while the rotor RPM varied from 1420 to 1580, stepping by 10. This describes the characteristics of the rotor very close to the hovering condition.
2. RPM varied from 500 to 2300, stepping by 100. The broad range describes the rotor in the outlying operating conditions.
3. RPM constant at 1496.7 while the normal velocity was varied from 0.1 to 1.0 m/s, stepping by 0.1 m/s. Any faster velocity can not be controlled.

The variables were then nondimensionalized and plotted. The transforms used are as follows:

$$\begin{aligned} V &= \text{velocity normal to rotor} & [\text{m/s}] \\ \rho &= \text{standard air density sea level} & [\text{kg/m}^3] \\ \Omega &= \text{RPM} * \pi/30 & [\text{radians/s}] \\ V_{\text{ref}} &= \Omega * R & [\text{m/s}] \\ L_{\text{ref}} &= R & [\text{m}] \\ S_{\text{ref}} &= \pi * R^2 & [\text{m}^2] \end{aligned}$$

$$\begin{aligned} C_T &= T / (0.5 * \rho * V_{\text{ref}}^2 * S_{\text{ref}}) \\ C_P &= P / (0.5 * \rho * V_{\text{ref}}^3 * S_{\text{ref}}) \\ C_Q &= Q / (0.5 * \rho * V_{\text{ref}}^2 * S_{\text{ref}} * L_{\text{ref}}) \end{aligned}$$

$$\lambda = V / V_{\text{ref}}$$

CT, CP and CQ are plotted versus λ . The CP vs λ and CQ vs λ curves prove to be identical (xrotor rounding errors are present) given this form of nondimensionalization. There is still some question as to why the curves from the velocity sweep and the RPM sweep do not lie on top of each other. Questions should be posed to Professor Drela. The plots can be found at the end of this document.

Derivatives with respect to Velocity and Ω can be obtained by dimensionalizing the derivative with respect to λ .

$$d() / dV = d() / d\lambda * d\lambda / dV = d() / d\lambda * [1/(\Omega R)]$$

$$d() / d\Omega = d() / d\lambda * d\lambda / d\Omega = d() / d\lambda * [-V/(\Omega^2 R)]$$

The value of $d() / d\lambda$ changes between the RPM sweep and the velocity sweep. The derivative is calculated from the xrotor data using the linear regression tool in Excel. The values are as follows:

RPM Sweep

$$dCT / d\lambda = -0.0898$$

$$dCP / d\lambda = 0.1894$$

$$dCQ / d\lambda = 0.1956$$

Velocity Sweep

$$dCT / d\lambda = -0.042$$

$$dCP / d\lambda = 0.0091$$

$$dCQ / d\lambda = 0.0090$$

A possible explanation for the difference in the slopes is Reynolds number effects that were neglected in the non-dimensionalization. The change in the Reynolds number for the rotor can be neglected for the velocity sweep because the normal velocity component is so small compared to the tip speed. However, the variations in RPM cause a much larger in the velocity of the rotor and thus a larger change in Reynolds number.

Moments created by thrust differential due to rotational velocity can be calculated by using $dCT / d\lambda$ to predict what the thrust will be with a negative normal velocity. Xrotor cannot converge on a solution with negative velocities. The moment arm can be found from the rotor craft itself or the drawings provided from the patent information.

Finally, it should be noted that the rotor blades are expected to be change on the vehicle. These numbers should be used for a close approximation of the final rotor dynamics. Once the new rotor geometry has been finalized, new data will be provided. The central hub of the current rotorcraft may be enlarged, increasing the moment arm on which the rotors act. When final plans have been made, new inertia and geometric values will be provided. Current values can be used as a close approximation.

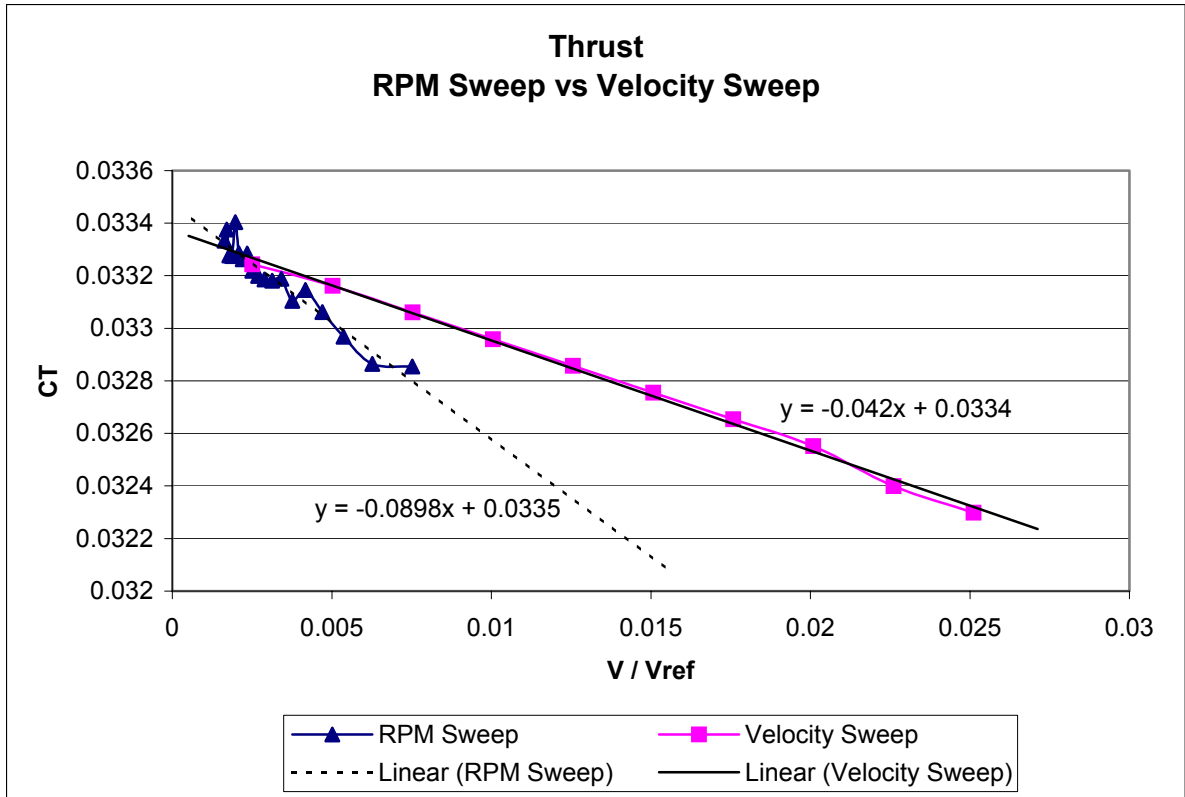


Figure B.1: CT vs. V/Vref

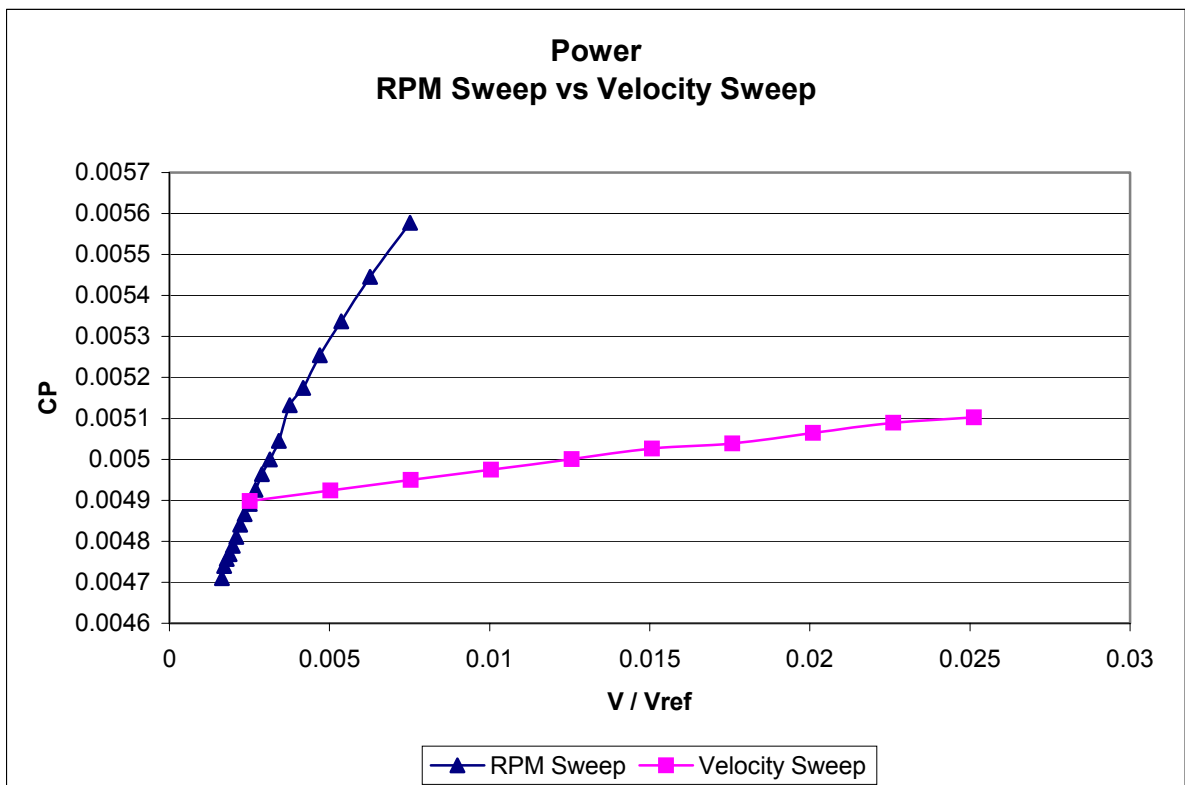


Figure B.2: CP vs. V/Vref

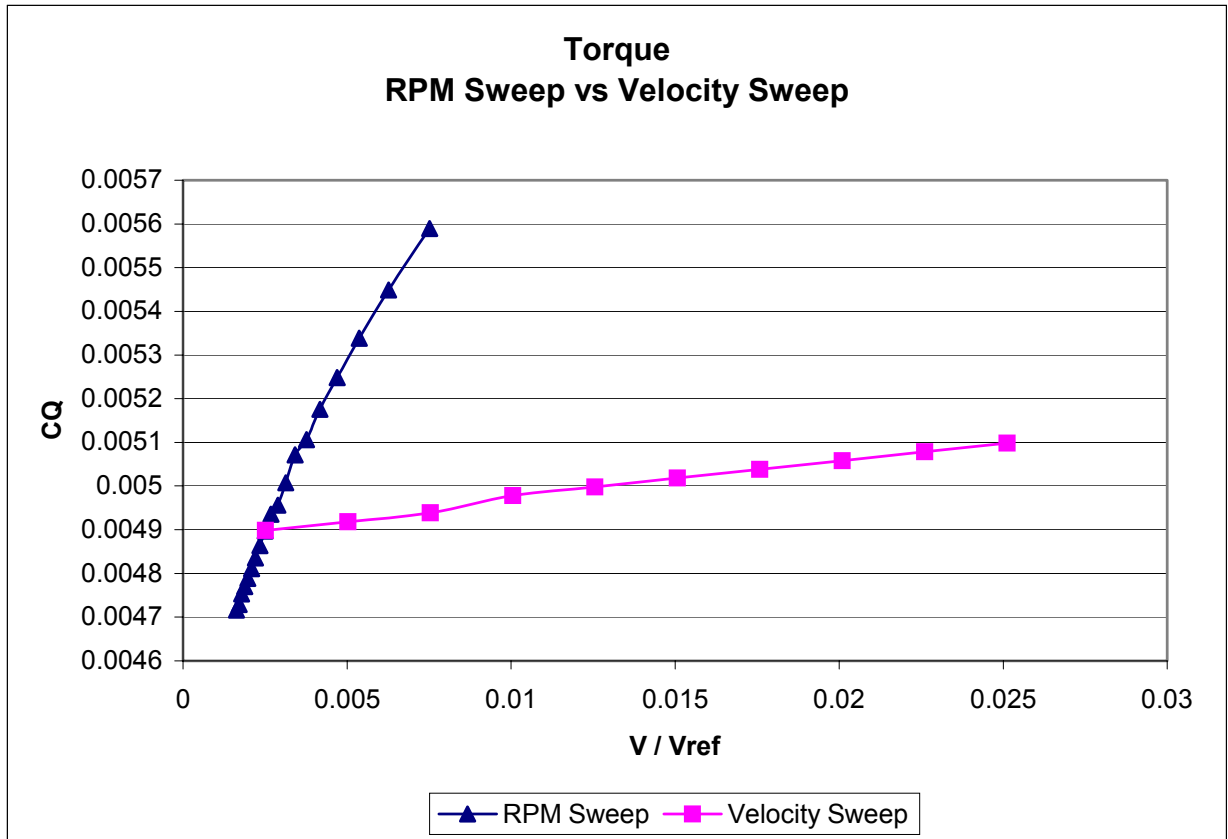


Figure B.3: CQ vs. V/Vref

APPENDIX C

To: 16.82
From: Sensing team
Re: ArcSecond performance with two transmitters
Date: October 3rd, 2003

The sensing team met with Arthur and Luca on Friday morning to test the performance of the ArcSecond Indoor GPS system using only two transmitters on the ground. This test was performed after the request of the communications team, since data from only two transmitters can be processed on the PCE board that is connected to the sensor without the need of the ArcSecond software, which only runs on Windows XP.

Windows XP cannot realistically be run on-board, so if four transmitters are used, position data would have to be processed off-board. This raises concerns as to the robustness of the system since a loss of communication with the ground would result in a loss of position data to the controller.

The Arcsecond performs to the required accuracy and range if only two transmitters are used on the ground. However, this configuration is very delicate: a slight tilt makes the sensor lose its line of sight with one of the transmitters and position data stops being available immediately. Flying the rotorcraft with two transmitters may be a viable option if:

- The vehicle team can mount the ArcSecond high above the body of the vehicle to maximize the angle at which the line of sight with the transmitter is lost; and
- The controls team can reliably control the pitch and roll of the rotorcraft to remain within this angle range.

Note that, after it is lost, a line of sight to the transmitter is not likely to be recovered using other information available to the controller. This is because, if the controller is designed to the appropriate stability, losing the line of sight means that there has already been a fault in the controller.

We must try to define whether this configuration is more reliable than the communications link to the ground (on which position data would depend if four transmitters are used).

APPENDIX D

Calculation of camera resolution ratios

The viewing area or “footprint” of a given camera is dependent on the altitude or height and the lens field angle, as seen in Figure D.1 below.

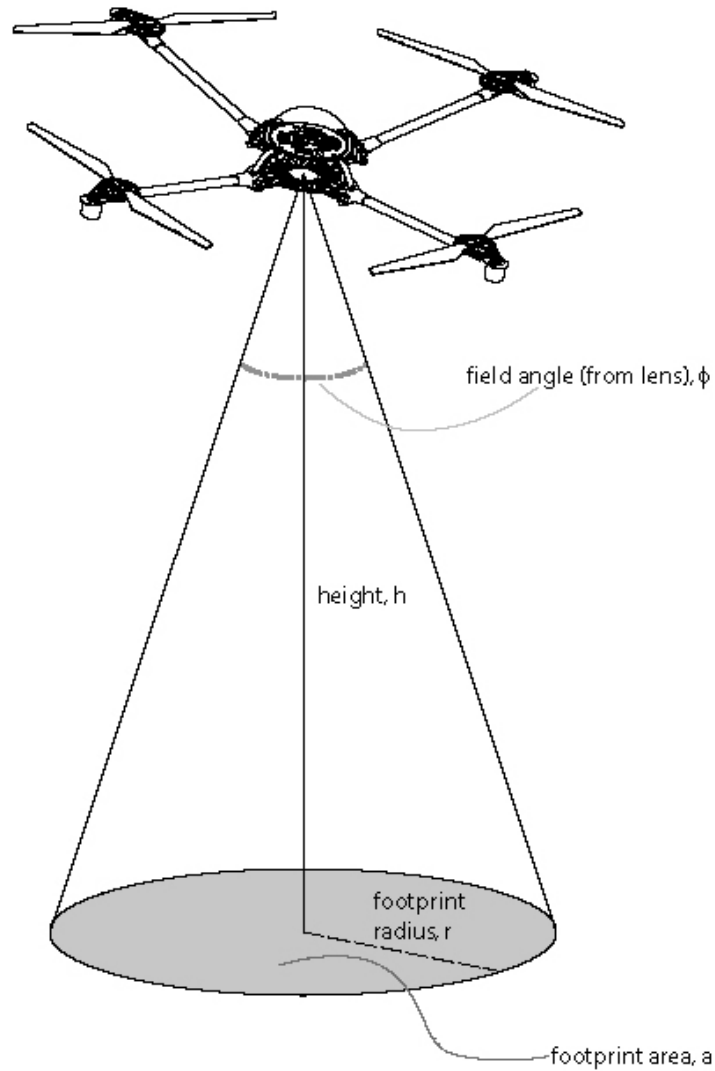


Figure D.1: Footprint of onboard camera

Using basic trigonometry, the relationship between the footprint radius (r), the lens angle (ϕ) and the altitude (h) is:

$$r = h \tan\left(\frac{\phi}{2}\right)$$

Thus, the footprint area (a) is:

$$a = \pi h^2 [\tan(\frac{\phi}{2})]^2$$

The resolution ratio is the pixel resolution (p) given for each camera in the specifications, over the footprint area (a):

$$resolutionratio = \frac{p}{a} = \frac{p}{\pi h^2 [\tan(\frac{\phi}{2})]^2}$$

For the GP-CX171, $p \approx 400,000 \text{ pixels}^2$; for the GP-CX161, $p \approx 350,000 \text{ pixels}^2$.

APPENDIX E

Table E.1: Offboard Computer

Off-board Computer

		Sony Vaio	Sony Vaio V505	IBM Thinkpad X31	Sony Vaio GRT	Sony Vaio GRT
Requirements	Qty	http://www.sonymstyle.com	NA	http://www-132.ibm.com	http://www.sonymstyle.com	Same as previous
IEEE 1394 input port	1	Yes	Yes	Yes	Yes, 1	Yes, 1
PCMCIA Card slots	1 (2 w/o W)		1	1	1	1
USB Ports	2	2 USB 2.0	2 USB 2.0	2 USB	2 USB 2.0	2 USB 2.0
Integrated Wi-Fi		Yes, IEEE 802.11b	Yes, IEEE 802.11b	Yes, 11 a/b Wi-Fi and Bluetooth	Yes, IEEE 802.11 g	Yes, IEEE 802.11 g
Relevant Connections					AV in (mini-jack), S video in, Mini Jack in (VHF/UHF), i.LINK® (IEEE 1394) interface ³ , 3 USB 2.0, AV, out (mini-jack9), RJ-45 Ethernet, Memory Stick® media slot ¹²	AV in (mini-jack), S video in, Mini Jack in (VHF/UHF), i.LINK® (IEEE 1394) interface ³ , 3 USB 2.0, AV, out (mini-jack9), RJ-45 Ethernet, Memory Stick® media slot ¹²
Win XP OS	Pref. Pro	XP Pro	XP-Pro	XP-Pro	XP-Pro	XP-Pro
Memory		512 MB	512 MB	256 MB	512 MB	512 MB
Hard Drive		40 GB	40 GB	40 GB	40 GB	40 GB
Processor		P4 2 Ghz	P4 2.0 Ghz	P4 M 1.4 Ghz	P4 2.4 Ghz	P4 2.4 Ghz
Video Card		16 Mb	16 Mb	16 Mb	32 Mb, 15" screen	64 Mb 16" screen
Model No.		PCG-V505BXP	V505DC2 Series (CTO)	2884JUJ		
Description		Sony VAIO® V505BXP Notebook	V505D Series	ThinkPad X31 (IBM Think Express Program)	GRT 250/270 Series	GRT 250/270 Series
Price		\$1,800	\$1,650	\$1,680	\$1,700	\$2,050
Lead Time		3-5 days shipping	5-7 days building, 3-5 days shipping	In stock, 3-5 days shipping	5-7 days building, overnight (free) shipping	5-7 days building, overnight (free shipping)
Shipping Cost		\$0	\$0	\$0	\$0	\$0
Total		NA	\$1,650	\$1,680	\$1,700	\$2,050
Total w/MIT Tax		NA	\$1,815.0	\$1,848.0	\$1,870.0	\$2,255.0

APPENDIX F

Table F.1: Video Adaptor

Video Adaptor		<i>JKN Electronics</i>	<i>DVShop</i>	<i>ProMax</i>	<i>SP Comms</i>
<i>Requirements</i>	<i>Qty</i>	http://www.jknelectronics.com	http://www.dvshop.ca/pe	http://www.promax.com/	http://www.spcomms.com
RCA (Composite Video) Input	1	2	1	1	1
IEEE 1394 FireWire output	1	1, need 6 pin to 4 pin adaptor (\$70)	2	2	1
Video signal	30 fps	640x480 pixels @ 60 Hz	?	?	
Model No.		DFG 1393 1	CANOPUS ADVC-100	CANOPUS ADVC-100, PN: 22055	DV Converter ProTM, Part No: DVN
Description		Video to Firewire Converter for Windows 2000 and Windows XP	Analog to Firewire converters	Analog to Firewire converters	D/A A/D converter, bi-directional
Price		\$495	\$399	\$299	\$325
Lead Time		Shipping time only	Instock - Shipping only	Instock - shipping only	Instock - shipping only
Shipping Cost		?	?	?	?
Total		\$495	\$399	\$299	\$325
Total w/MIT Tax		\$544.50	\$438.90	\$328.90	\$357.50