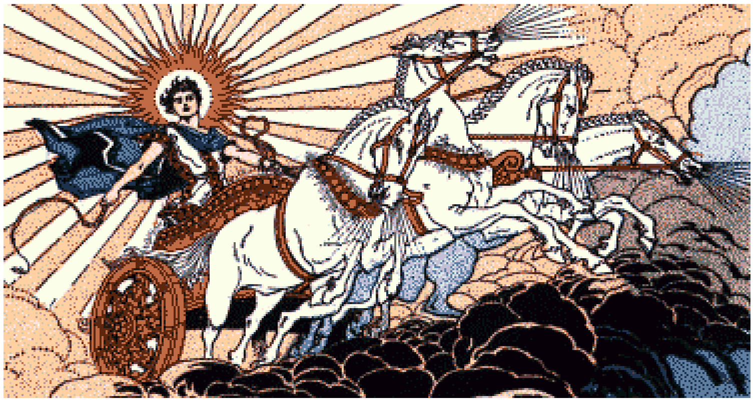

The Phaeton Project

Hardware Purchase Document
16.82
October 20, 2003

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1. Introduction

The project for the Fall 2003 Semester of 16.82 / 16.821 CDIO Capstone course involves designing an unmanned, autonomous quad-rotor craft, called the Phaeton. The objective of the CDIO Capstone 16.82 / 16.821 is to design and demonstrate the coordination and control of a small team of unmanned heterogeneous vehicles 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[1]. These vehicles have to be autonomous (with no human input within the control and stability loops), indoor, and based on a quad-rotor vehicle. Phase 1 of the project involves the conception and design of this vehicle and its control system.

This document describes the hardware selection decisions made by the team. The decisions refer to the requirements defined by the mission definition and interactions between the subteams. Cost analysis is undertaken with the eventual purchase of a second Phaeton system in mind. The second semester of the CDIO Capstone course will include the fabrication of a second Phaeton to compete in a robotic game of Capture the Flag.

2. Vehicle Design

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

2.1. 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 xrotor[2] 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 derived from xrotor allows the calculation of the stability derivatives of the vehicle. A full characterization of

[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] Created by Professor Drela at the Massachusetts Institute of Technology

the X-Pro rotor can be found in Appendix A. Once the new rotor geometry has been finalized the analysis will be repeated.

2.2. Structure Modification

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 o 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.

Initially concern was raised that we no longer have a big hollow space in the hub to put electronics. However, the upper part of the hub disc will still be protected as it will be below the rotors. We will also 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.

We are still waiting on a response, but we are currently hoping to get the sandwich structure from scrap materials in John Kane's lab (we only need about a square foot). Balsawood is readily available from the department stocks. Prof. Drela can provide carbon fiber extensions for the arms from scrap. As such, the expected cost is nothing. If we do need to purchase the Nomex – carbon fiber sandwich, the cost should not be more than $20 based on an internet search.

2.3. Power System

2.3.1. System Mass and Thrust Requirements

Table 1 shows the mass breakdown of the components. The total vehicle mass is estimated to be 2641 grams. Thus, the required thrust for hover is 25.9 Newtons and the required thrust for takeoff must be greater than 25.9 Newtons.

	Mass (grams)
Vehicle Subtotal	**2146**
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	**290**
Onboard computer	100
Ethernet card	55
3 A to D converters	60
Serial to PWM converter	25
Wiring, other hardware	50
Sens Subtotal	**207**
ArcSecond Sensor	156
Onboard Camera	14
Camera Transmitter	7
3DMG	30
TOTAL	**2641**

Table: 1 Mass Breakdown

2.3.2. Vehicle Propulsion

The Lithium Polymer battery that came with the Draganfly is 14.8V and 7.8 Ah. This battery will solely be used to power the motors. For the desired flight time of 10 minutes, this battery can output 46.8 Amps to the motors and provides 692.6 Watts of power. For a flight time of 15 minutes, this battery can provide 31.2 Amps for the motors and provides 461.8 Watts of power.

Current (A)	Thrust (N)	Power (W)
16	11.12	164.6
20	16.68	246.9
24	20.91	309.4
32	28.91	427.9
40	35.58	526.6

Table 2: Expected Thrust and Power and Current Draw for Four Motors

Table 2 shows the expected thrust and power at various currents for the current motors and propellers. This data is based on thrust results of one motor and propeller setup and has been multiplied by four. Based on the current weight of the system, 25.9 N of thrust are needed for hover. Thus, each motor will draw less than 8 amps to provide enough thrust for hover.

2.3.3. Component Power Requirements

Besides the motors, there are several other components that require power. Table 3 lists the voltage, current and power requirements for each component. This data shows that 1.5A at 5V and a total of 0.757A at 12V must be supplied. 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 the same battery that powers the motors powered this equipment, 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.

Component	Req'd Voltage (V)	Req'd Current (A)	Req'd Power (W)
Onboard Computer	4.75 - 5.25	1.500	7.13 - 7.88
ArcSecond Sensor	12	0.125	1.50
Onboard Camera	12	0.080	0.96
Camera Transmitter	12	0.500	6.00
3DMG	5.2 - 12	0.052	0.27 - 0.624

Table:3 Component Power Requirements

2.3.4. Choosing a Second Battery

The second battery must output a minimum of 2.257A for at least 10 minutes. Thus, at least a 376mAh battery must be used. The voltage of the battery can be changed for specific components by using voltage regulators. Table 4 shows three lithium polymer batteries that were considered. The 2LP608 lithium polymer battery was chosen because it provides a decent margin of current output for a 10 minute flight time. In other words, the battery will not run out after 10 (or even 15) minutes, but it does not have too much power remaining.

Li Poly Item #	Specifications	Current, 10min	Current, 15 min	Weight	Cost
KOK560-2S-FJ	7.4V, 560mAh	3.36A	2.24A	Not given	$ 23.50
2LP608	7.4V, 650mAh	3.9A	2.6A	28 g	$ 22.95
KOK880-2S-FJ	7.4V, 880mAh	5.28A	3.52A	Not given	$ 26.95

Table 4: Comparison of 7.4V Lithium Polymer Batteries

Next, nickel cadmium, nickel metal hydride and lithium polymer batteries were all compared before finalizing the decision. Table 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 for the second power source.

Item #	Description	Specifications	Current, 10 min	Current 15 min	Mass	Cost
B600AE6	NiCd 6cell battery pack	7.2V, 600mAh	3.6A	2.4A	128g	$20.90
PC720N7	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

Table 5: Weight and Cost Comparison of Different Battery Types

2.3.5. Voltage Regulators

Since the lithium polymer battery that will be used is 7.4V, voltage regulators are needed to obtain 12V and 5V for the components' power. The VRLI1-LPO regulator was chosen since it can change the voltage of a 7.4V lithium polymer battery to 5V, and also since it is only 5 grams and already assembled. The LM1557 voltage regulator was chosen since it can boost the voltage of a 3.5 to 40V battery up to 12 or 15V. This voltage regulator may output as much as 3 Amps, but the typical application pictured below shows that 0.800 Amps are outputted. This suffices since the components that need 12V require a current of 0.757 A. In addition, the lithium polymer battery is 7.4V, so it is in the voltage range that can be boosted to 12V. Unfortunately, the voltage booster must be assembled, and only the LM1577 is supplied on purchase. Currently, more information is needed whether the necessary equipment and components are available, and how to properly construct the device. Figure 1 shows these components and their arrangement.

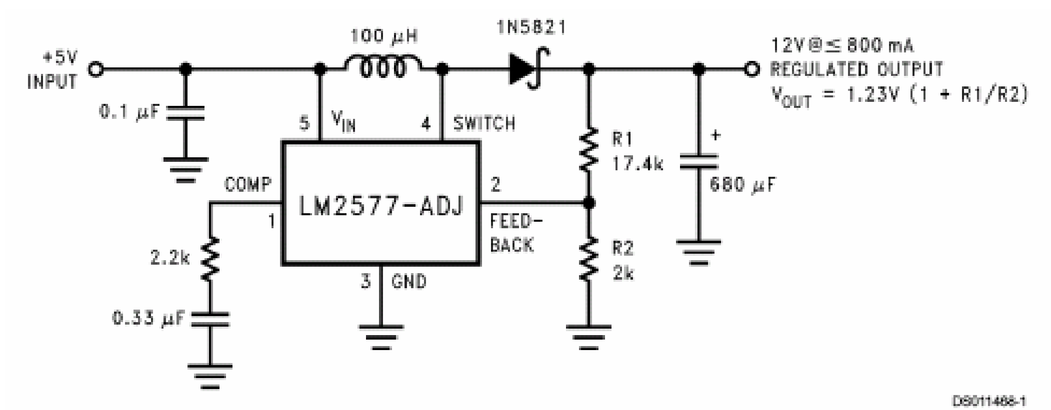

Figure 1: Setup of the Voltage Booster

2.3.6. Component Power Supply Summary

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 6 lists the items that will be purchased. In addition, a battery charger must be purchased. The QN-012BC charges 7.4V lithium polymer batteries at an average rate of 600mAh. It operates from a standard wall outlet and shuts off automatically when the pack reaches full charge.

Item #	Description	Purpose	Weight	Cost	Assembly Required?
VRLI1-LPO	down regulator	limit 7.4V to 5V	5g	$21.95	No
LM1577	up regulator	boost 7.4V to 12V	15g	$29.00	Yes
2LP608	Li Poly battery 7.4V, 650mAh	provide power for components	28g	$ 22.95	No
QN-012BC	7.4V Li Poly charger	charge battery	N/A	$ 19.95	N/A

Table 6: Items to Purchase for Second Power Source

3. Controller Approach

An off-board computer will control the travel of the vehicle. The ArcSecond position sensors (section 5.2) will send data to the computer which will then process the information to determine the position of the vehicle. The user input will be taken from the graphical user interface (GUI), and from that information, the desired position will be identified. Using both the location of the vehicle as well as its destination, a path will be created and motor commands will be calculated.

All other feedback loops will be closed onboard the vehicle. The roll, pitch and yaw movements will be constantly watched and corrected. In addition, readings from a magnetometer will help with the control of the vehicle by correcting for drift in the gyros (section 5.1). Finally, motor RPM may be monitored for the purposes of improving motor performance through feedback (section 5.3).

The controls team does not have a purchasing list because all controls code is written on hardware purchased by other subgroups.

4. State Sensing

4.1. Attitude Sensing

Hardware Solution:

Vendor	ID#	Description	Price
MicroStrain	**3DM-G**	**Orientation Sensor**	**$1,295**

The requirements for attitude sensing coming from the controls team stipulate that the minimum measurements needed are angular rates in three dimensions and heading angle in one dimension (yaw angle). The bandwidth for these measurements must be at least 30Hz and 1Hz, respectively. The controls teams says they can control the craft if the accuracy for these sensors is below 0.05 degrees per second per 100 seconds for the the angular rates and below +/-6 degrees for the angle.

Numerous vendors offer small highly accurate rate gyros that would suit our system. Tokin, Analog Devices, Systron, Gyration.com 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.

The device chosen by the sensing group is the Microstrain 3DM-G orientation sensor. This unit combines three rate gyros, three accelerometers, and a magnetometer. Numerous aspects of the 3DM-G make it the best option. By combining the various required sensing measurements it saves a lot of hassle that would be necessary with using individual gyros and magnetometers. It operates of the full 360 degrees of motion on all three axes. It outputs its data digitally via serial cable. And the output can be configured to provide the orientation data in martix or quaternion formats, or as raw data from the individual sensors. The 3DM-G outputs its data at 100Hz and has an accuracy of +/-5 degrees (though this number is likely to be much lower). It also has a temperature sensor to counter any drift due to temperature.

The 3DM-G takes advantage 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 complimentary 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 measurement (Microstrain.com). This product will require three weeks to obtain. So it should be ordered as soon as possible.

4.2. Position Sensing

Hardware Solution:

ArcSecond Constellation (Indoor GPS)

4.2.1. Sensor Components

- Cylindrical Tracking Sensor – to be purchased
- Position Calculating Engine (PCE) board – to be purchased
- 4 ground transmitters – borrowed from Professor How
- Workbench Control Center software - downloaded

Please refer to the purchase specifications for cost details. The system components are available immediately to start testing because spare sensors from the Aerospace Controls Laboratory can be borrowed.

4.2.2. ArcSecond System Configuration

- Four transmitters will be placed at known positions at least 4m above the ground.
- The cylindrical sensor, which will be mounted on top of the rotorcraft, will detect inclined laser beams from each transmitter and send this raw data to the PCE board that is also on board.
- This data will be partially processed on the PCE board and then input to the on board computer as a digital signal through a serial cable.
- The raw position data will be transmitted through a wireless link to the ground station (communications sub-team).
- Data on the ground station has to be interpreted as raw position data directly from the PCE board by the Workbench software on the ground station. The details of this step are currently being discussed among the sensing, communications and ground station sub-teams.
- Workbench will decode the position data and output the vehicle's location as (x, y, z) onto a memory location. This data can be called by the control sub-team with a specified C++ function.
- A velocity estimation will be performed using position data from the ArcSecond.

4.2.3. Top Level System Requirements Satisfied

Vehicle state characterization: This sensor will provide three dimensional position data at 20Hz and velocity data at a lower bandwidth (this is specified by constraint SENS0210). This information will contribute to the characterization of the vehicle's state for control and navigation.

Range: 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 system will be accurate to the order of millimeters when the maximum distance from the sensor to a transmitter is 25 m.[3]

Take off and hover at 3m above the ground: For all stages of the mission the sensor on board must have line of sight (LOS) to at least one transmitter 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 constraint VEHI0280. If the transmitters on the ground are below ~3 m, however, LOS would not be guaranteed when the vehicle is hovering 3 m above the ground.

[3] *Constellation3Di Error Budget and Specifications.* Available from www.constellation3di.com, accessed 20 September 2003

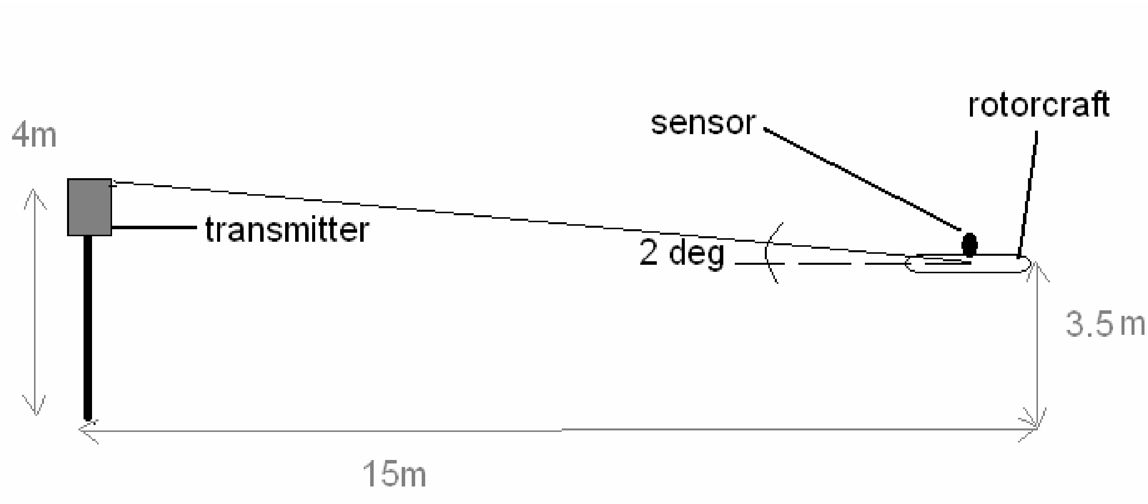

Figure 2: Transmitter location rationale

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 2 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 no to lose sight of any transmitter that is within 15m away. This is specified as constraint CONT0220 on the control subsystem by the sensing subsystem. Note that at least one transmitter can be closer than 15m from the vehicle at any given time given the limited area the rotorcraft is specifically required to navigate.

Accuracy: Constraint SENS0300 on the sensing sub-team requires position data to be accurate to 1cm for landing on a moving rover. As discussed above, given the maximum distance from the transmitters that the sensor is expected to operate at, the ArcSecond will satisfy this requirement by providing data that is accurate to within millimeters.

This requirement derives from the need to provide sensor data five times as accurately as the controller is expected to dominate the vehicle, which is 8cm during landing according to ~~constraint~~ CONT0200. In order to have a resolution of 100X100 pixels on a 20X20cm target at 2m above the ground, which is a top level requirement, the system camera has to 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 $h\tan\theta = 124cm$. 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 42cm, thus satisfying another top level requirement. By a similar analysis performed by the controls sub-team, this uncertainty has to be reduced to 8cm in order to ensure a safe landing.

Bandwidth: The ArcSecond sensor can update position data at rates up to 20Hz. Although there will be delay on this data because it has to be transmitted to the ground in order 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 can be done at a lower frequency of about 5Hz[4]. 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 velocity estimates from the vehicle's attitude that will be done on board.

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

The decision of whether the controller position loop would run on or off-board was affected because the ArcSecond software that decodes laser beam readings can only run on a Windows XP operating system. The decision to decode position data off-board was made after the following considerations:

- The Workbench software 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 B that reports observations made when the two-transmitter configuration was set up in Johnson for details.
- The communications sub-team was reluctant to decide on an on-board computer that could support Windows XP because of the increase in weight and the lesser real-time performance of Windows OS'.

4.2.5. Unresolved Issues and Work to Be Done

- Discuss details of the velocity estimator with the controls team
- Find a serial input emulator such that position data on the ground can be interpreted by the Workbench software (working with communications sub-team). Testing for the ArcSecond data path can be start as soon as the design is decided upon and any necessary software components are gathered.

4.3. RPM Sensing

It is still to be determined whether or not RPM sensing will be used on the aircraft. The sensing group has research various methods. The recommended method involves using optical interrupter switches at each rotor, outputting a varying hi-lo voltage corresponding to each rotation. These votages are sent to frequency counters which count the RPMs. Then the values can be sent to the OBC. After researching some various vendors, the combined setup using these devices will require an estimated 5 volts and 0.085 amps and under 50 grams. The details of this method will be hashed out in Tuesday's team meeting if the team decides to use RPM sensing.

[4] According to Arthur Richards, 16.82 Graduate TA; Aerospace Controls Laboratory

4.4. Video System

The following hardware components will be needed for onboard operation of the video system:

Component	Part No.	Cost	Vendor
Panasonic GP-CX171 (with lens mount)	GP-CX171-LM	$189	Rock House
Lens for GP-CX171, 35º field angle	BCL6C	$25	Rock House
Black Widow AV 2.4 GHz, 50mW transmitter	N/A	(sold as kit, see ground receiver)	Black Widow AV

The following hardware components will be needed for the ground station operations of the video system:

Component	Part No.	Cost	Vendor
Black Widow AV 2.4 GHz 50mW receiver	N/A	$140 (incl. transmitter)	Black Widow AV
Video adapter (optional, see below)	*Not finalized, see below*	*~$150-300*	*Not finalized, see below*

4.4.1. Explanation of hardware selections

The top level resolution requirement for video display is that a 20cm x 20cm square be displayed as 100px x 100px when the vehicle is at a height above 2m. This translates to a ratio of **250,000 pixels^2 / actual square meter**. Below is a table listing the calculated resolution ratios of the various camera lenses available for the 2 CCD board cameras that were under consideration:

Angle	Footprint radius (m) @2m	Footprint radius (m) @3m	Footprint area (m^2) @2m	Footprint area (m^2) @3m	Resolution ratio (px^2/m^2) @2m	Resolution ratio(px^2/m^2) @3m
41	0.747769	1.121654	1.75665	3.952462	199242.9	88552.4
53	0.997163	1.495745	3.123794	7.028536	112043.2	49797
115	3.139371	4.709057	30.96244	69.66549	11304.02	5024.008
17	0.298902	0.448353	0.280677	0.631524	1351665	600740.2
26	0.461736	0.692605	0.669789	1.507025	566420.1	251742.3
35	0.630598	0.945896	1.249265	2.810846	303684.2	134970.8
53	0.997163	1.495745	3.123794	7.028536	121449.1	53977.38
69	1.374562	2.061843	5.935789	13.35553	63914.33	28406.37
87	1.897929	2.846894	11.31644	25.46199	33524.85	14899.93
105	2.606451	3.909676	21.34268	48.02103	17775.74	7900.331

Note: Shaded rows indicate data for the Panasonic GP-CX**161** which was *not* chosen because it does not meet the resolution requirement with any of its available lenses.

From the table, only 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), which in turn will help decrease the search time of a given area, we chose the 35º lens, the widest angle lens that can meet the resolution requirement at a height of 2m.

In selecting an onboard transmitter for the video signal, the Black Widow 2.4GHz 50 mW transmitter was chosen. A 2.4 GHz transmitter has better reliability and range than the 900 MHz ones because of its stronger signal. We chose this particular transmitter (over the other 2.4GHz models) because of its small size, light weight, and low cost as seen in the table below:

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, it should be noted that all the transmitters above can transmit video signals in PAL as well as NTSC if we should desire a higher color quality in our output than typical American video standards. The Panasonic GP-CX171 can output either format.

The ground receiver has a built-in output jack of a 1/8" headphone-style combo AV plug (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 (a.k.a. digital video convertor). The interface to the ground station computer must be able to capture/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 following table presents other adapters being considered.

Adapter	Max. capture resolution	Interface	Cost	Comments
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	$1499	Too expensive
Dazzle Hollywood DV-bridge	720 X 576	IEEE 1394 (4-pin) Firewire	$299	Discontinued by Dazzle, but still available from retailers
Dazzle DV Creator 150	720x480	USB 2.0	$150	

Note: Only the Canopus adapters can handle both NTSC and PAL video formats.

5. 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 the Roboflag mission. The Communication subteam identified various hardware and system options and final selections were made based on the integrated system requirements and other factors.

5.1. Onboard Computer

The onboard computer was selected from a multitude of PDAs and embedded computer options. The parameters of interests 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; minimizing data transfer time. Additionally, PDAs generally have built in wireless devices making any necessary communication to the ground relatively simplistic. However, PDAs are comparatively massive 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. 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 opting for a PC 104-type computer were the operating constraint placed on the communication system by the sensing subteam and the maximum weight of 350 grams allotted by the vehicle team. PC-104s allow for easy expansion of functionality. For example, if the vehicle team determines they need the motor rpm data, a digital input board can be attached to the PC-104 with relative ease. 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 of at least 3 16-bit serial ports with an option for a fourth: 1 for rate information (MicroStrain device), 1 for position data (ArcSecond), 1 for the PWM signal outputted to the motors, and potentially 1 for motor rpm data (optical sensor). Additionally, the onboard computer will have to be capable of minimal altitude processing and be connected wirelessly to the ground station. The communications team transformed these requirements into specifications of an onboard computer: 32-bit x86 processor, 64 MB of SDRAM, 64mb 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.

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 7, 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.

Table 7: 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-520	UNK	0.9	32 std.	DiskOnChip	AMD SC520	UNK
Arcom Pegasus	96	0.8-1.0	64	Intel Flash (16mb max)	AMD SC520	UNK

5.2. Connectors/Converters

The magnetometer, ArcSecond sensors, and motors need to be attached to the PC-104 via 16-bit serial ports.

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. The MiniSSC was chosen for this role, being lightweight, readily available, and tested.

5.3. Ethernet Connection

In order to transmit data to the ground station, the onboard system is required to have wireless capability. There are 3 main options for connectivity to the ground station: wireless modem, WI-FI, and Bluetooth. In selecting the internet system, the selected onboard computer was considered. 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 were considered (Table 8), paying close attention to weight, data rate, range, and power consumption. The CompactFlash Asus and Zcom card are the lightest and require the least power. However, the advantages in weight and power of the CompactFlash cards do not outweigh reliability and ease of integration benefits of the Orinoco Cards. MIT computer services recommend the Orinoco cards and it works with both Linux and Windows. The Silver Orinoco card was selected, as it has a competitive range, average power consumption, and the desired 11 Mbps data rate.

Table 8: Wireless Cards – Figures of Merit

	Weight	Data Rate	Power Consumption/Reqmt	Range	Frequency	Thickness	Price
Orinoco Silver	55grams	11,5.5,2,1Mbps	T-576mA, R-341mA,S-15mA		5150-5350,5725-5825		79 (no tax)
Orinoco Gold	55grams	54,48,36,24,18,12,9,6Mbps	T-560mA, R-320mA,S-15mA		2400-2484MHz		85 (no tax)
Asus WL-110		11Mbps	T-300mA, R-200mA,S-110mA	120M	UNK	Type 2	40 (no tax)
Zcom XI-825	< 20grams	11Mbps	T-350mA, R-250mA,S-17mA	160M for 11Mbps	UNK	Type 1	90 "
		5.5, 2, 1					

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 (Table 9). 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 9: 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

In order to ensure that the wireless hub will work as intended a preliminary study on signal strength was conducted. A "websniffer" program was use to ping the wireless network in the Roboflag testing facility. The results are outlined in Table 10.

Table 10: Wireless Signal Strength

Location	Signals	Strengths (in bars)	
Upper Mezzanine	13-5026	NA	
	MIT	range 2 to 3	Good
Hangar 1	MYAP	NA	
	MIT	4 to 5	Very Good-Excellent
	HETE	(encrypted)	
	13-5026	NA	
Hangar 2	MYAP	NA	
	MIT	5	Excellent
	HETE	(encrypted)	
	13-5026	NA	
Hangar 1 = Walking all through the open area			
Hangar 2 = On the far right along the work tables			
*Signal Strength/Quality			
**Using Intel Proset			

5.4. 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, connect wirelessly to the rotorcraft's onboard computer, and to receive the video input. Although it is not a specified requirement, it is preferable if the ground station is relatively mobile to ease in transport between testing facilities and Johnson. Therefore, once it was established that laptops meeting and exceeding all requirements are available the team did not investigate desktop options.

In order to receive and process the Arc-Second data, the offboard computer requires the Windows XP-Professional operating system. 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, the two methods available to acquire the input to the laptop is to have the necessary analog inputs on the computer already built in, or 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 with the necessary analog inputs are available, they are rare. The decision was made to order a laptop with the required analog inputs, ensuring should the direct analog input should fail that it meets specifications for using an analog to digital converter. The digital video input of IEEE 1394 Firewire is standard on most laptops, including the Sony Vaio specified. 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 recommended.

The Sony Vaio GRT 250/270 was selected as the ground station computer. The five computers that were strongly considered had similar specifications except with respect to the video card. This group was already reduced from the limitless computer options on the market to include viable options. 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 C.

5.5. Video Adapter

The ground station requires that video from the sensing system (camera and receiver) be displayed on the screen, and then processed by the computer for navigational data. The camera will transmit the video signal from the rotorcraft to a receiver, and then in an analog composite video signal out. This signal must then be converted to digital video via and adapter. If the laptop has analog inputs (such as S-video or min-jack) then no adapter is needed; there may only be a cable 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 transmitted a video signal of greater than 640 x 480 pixels at a minimum of 30 frames per second.

Since the computer selected eliminates the need for a video adapter, there are not current plans for purchasing one. However, in the off chance that the analog input on the laptop does not function correctly, various adapter options were investigated and are outline in Appendix D.

5.6. System Design

The final components selected for the communications system are outlined in Table 11. As shown, the communications is both under budget and underweight. A detailed link diagram can be seen in Figure 3.

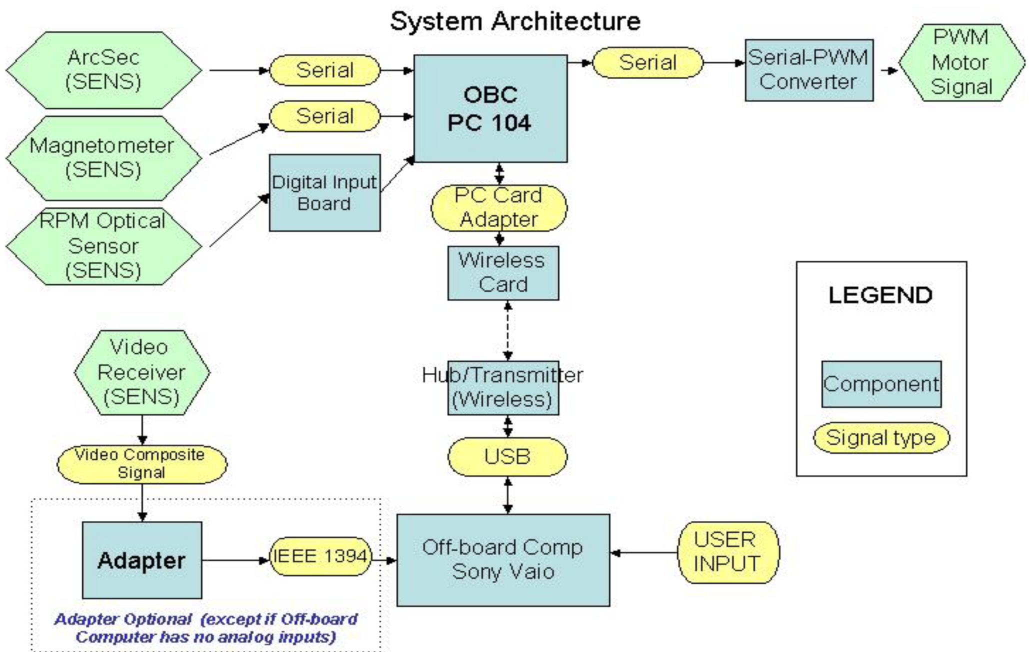

Figure 3: System Architecture

Table 11: Final Component Selection

Component	Description	Requirements	Specs - Chosen Hardware	Specs - Details	Est. Price	Est. Subtotal (Tax, S&H, Mit)
On-board Computer	PC104-type	Some attitude processing, not the ArcSecond 3-transmitter processing	VersaLogic Bobcat	400 MHz Intel	$802	$802
		1 serial port for magnetometer		64Mbytes SDRAM	?	
		1 serial port forArcSecond - 16 bit, - signal transmitted via Wi-fi		256Kbymes SRAM	?	
		1 serial port for PWM signal out (COMM0350)		3 serial ports (with options for a 4th)		
		(potential for 1 serial port for optical rpm sensor)		1 ethernet controller (4 pins)		
				2 USB ports		
Off-board computer	Laptop	Arc-Second GPS processing	Sony Vaio GRT 250/270 Series	Pentium 4, 2.4 Ghz	$2,050	$2,368
CG-Done		XP-Pro	*Website:*	512 Mb RAM	5% MA tax	
		Video signal input - IEEE 1394 input	*http://www.sonystyle.com/is-bin/INTE*	Windows XP-Professional	10% MIT tax	
		Ethernet 10/100 wireless ethernet	*http://www.sonystyle.com/is-bin/INTE*	2 USB 2.0 Ports	Free Shipping	
		USB Ports		Integrated Wi-fi (802.11)		
		User-input keyboard		1 IEEE 1394 Wirefire port		
		Programs for user-input		2 USB 2.0 Ports		
		Rec: Analog video input		1 PCI CardBus Slot		
				AV in (mini-jack, Mini Jack in (VHF/UHF) ports		
				S video input port		
				64 Mb Video Card, 16" screen		
				5-7 days to build		
				3-5 days ground shipping free		
10/100 base Ethernet	Transmitter/Base	Wireless transmitter hub	Belkin 802.11b Wireless Network Access Point Part #F5D6130	11Mbps	$100	$115
GH-Done			*Office Max*	802.11b wireless Ethernet	5% MA tax	
				range up to 1500ft	free shipping	
				OS: Windows 95, 98, 2000, NT, ME, or XP	10% MIT Tax	
	Receiver - onboard - wireless ethernet card	SMSC 91C111 - 8 pin connector to OBC	Proxim ORiNOCO 802.11a/b ComboCard Silver Version	11Mbps	$79	$106
		RJ-45 port on ethernet card	*www.wireless-computer-networking.c*	32bit interface	$12.99 S&H	
			http://www.wireless-computer-networ	3.3VDC from host (+/- .2V)	5% MA tax	
			30700 Carter Street, Suite B, Solon, (	frequency: 2400-2484 MHz	10% MIT Tax	
				Power Consumption: transmit mode = 576mA		
				receive mode: 341mA		
				Ground Shipping		
RCA video to digital video adaptor	DV Converter	RCA (Composite Video) Input	Canopus ADVC-100	Analog NTSC Color Bars For Reference	$299	$374
** Not needed if Laptop has Analog input*		IEEE 1394 FireWire Output	*http://www.promax.com/Products/Detail/22055*	Analog Input Connectors on Front and Back	3 day FedEx - $25 est	
CG-Done				6-pin FireWire Port on Back	5% MA tax	
				4-pin FireWire Port on Front	10% MIT Tax	
	IEEE 4-pin 1394 cable	Connect RCA-DV converter to laptop	Belkin Cable	6-pin to 4-pin OR 4-pin to 4-pin	$30	$35
			Bestbuy.com		Free Shipping	
					5% MA tax	
					10% MIT tax	
A to D converter (3 units) ?? AG?			?		$75	
Serial to PWM converter (D to A converter) AG?			?		$50	
Wiring/Misc Hardware					$25	$29
Note: N/A = Not Applicable				**TOTALS:**		**$3,829**

6. Budget

The first round of purchasing cost is listed below. Two estimates are given depending on each group's need for certain items. The communications team's lower range does not include the DV adapter. The sensor team includes the cost of two ArcSecond sensors for both X-Pros. Due to negotiation with prices, there is still an uncertainty in the cost for the sensing systems. For the vehicle team, shipping and tax are the only variables for the price range. Also, the X-Pro has not been included in the cost since it has already been bought. 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 12: Single Vehicle Cost Breakdown

Sub-Team	Lower Range	Upper Range
Communications Team	$3,418	$3,827
Sensor Team	$6,958	$7,510
Vehicle Team	$150	$160
Total	$10,526	$11,497

The following estimates are for the entire project and do not include the purchase of the second X-Pro. The upper range was the doubling of all of the parts. Since the sensor team already included a second ArcSecond sensor in the initial round of purchase, the cost of the ArcSecond was not doubled. For the communications team, the lower range does not include a second ground station computer since it is possible to use the first computer to run both aircraft simultaneously.

Table 13: Two Vehicle Cost Breakdown

Sub-Team	Lower Range	Upper Range
Communications Team	$4,470	$7,655
Sensor Team	$9085	$10,190
Vehicle Team	$300	$320
Total	$13,855	$18,165

In order to meet the budget requirement of $15,000, the lower budget figures must be used. There is still a small surplus of $1000 which should remain as margin as long as possible. 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. Doubling all of the parts for the project will exceed the budget of our project by over $3,000. Because the sensor equipment is required for each of the X-Pros, the communications team will have to work with one ground station computer for both X-Pros.

Appendix A

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_{tot} = 26.18 [N]. Because we have four rotors, the each propeller produces T_{oper} = 6.546 [N]. Fixing the thrust and the pitch of the blades describes the state.

Table 14 . 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:

V = velocity normal to rotor	[m/s]
ρ = standard air density sea level	[kg/m^3]
$\Omega = RPM * \pi/30$	[radians/s]
$Vref = Omega * R$	[m/s]
$Lref = R$	[m]
$Sref = \pi * R^2$	[m^2]

$$CT = T / (0.5 * \rho * Vref^2 * Sref)$$
$$CP = P / (0.5 * \rho * Vref^3 * Sref)$$
$$CQ = Q / (0.5 * \rho * Vref^2 * Sref * Lref)$$
$$\lambda = V / Vref$$

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 nondimensionalization. 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.

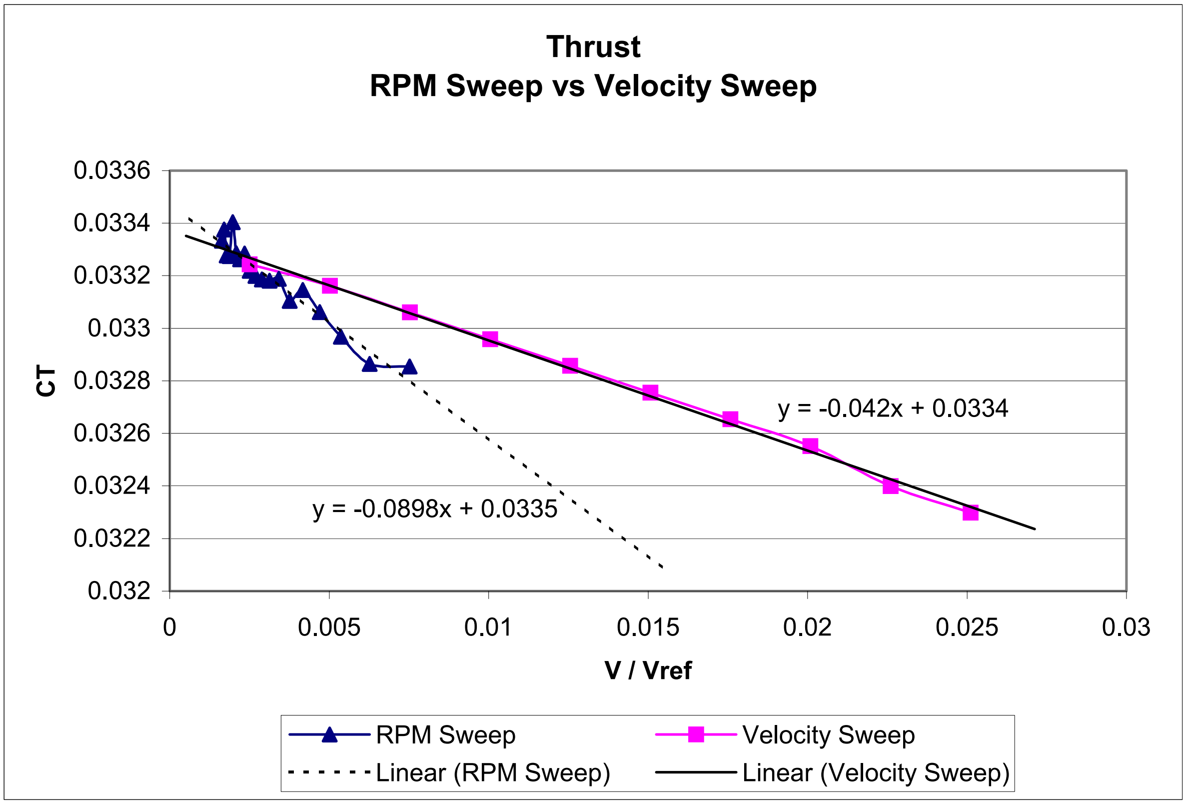

Figure 4: CT vs. V/Vref

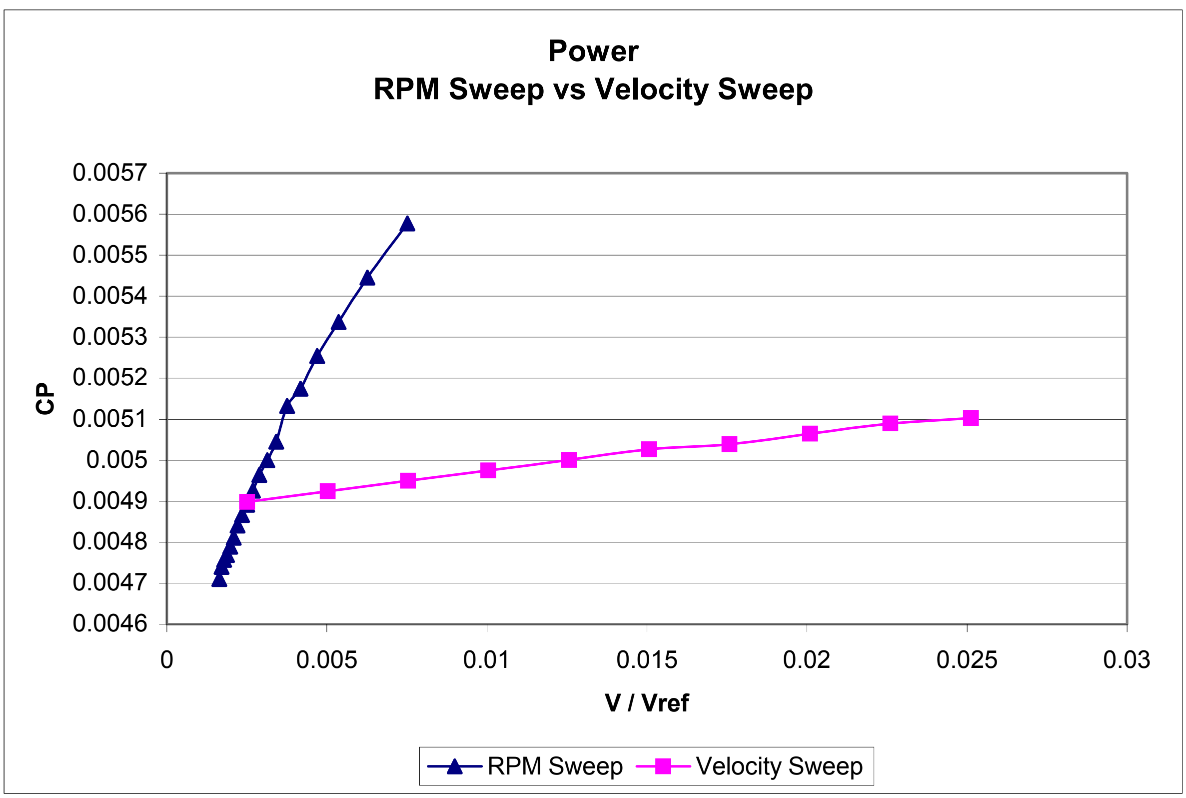

Figure 5: CP vs. V/Vref

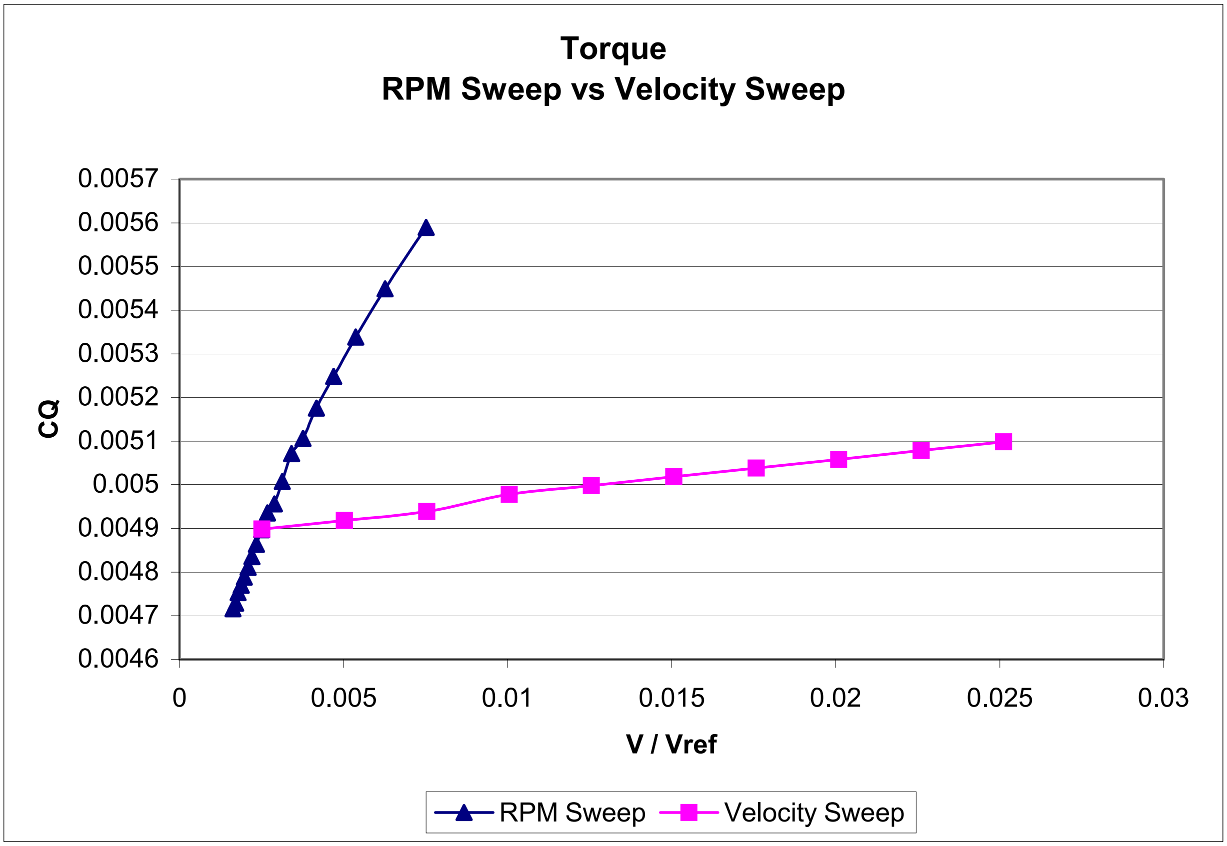

Figure 6: CQ vs. V/Vref

Appendix B

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 C

Table 15: Laptops – Figures of Merit

		Sony Vaio	***Sony Vaio V505***	***IBM Thinkpad X31***	***Sony Vaio GRT***	***Sony Vaio GRT***
Requirements	**Qty**					
IEEE 1394 input port	1	Yes	Yes	Yes	Yes, 1	Yes, 1
PCMCIA Card slots	1 (2 w/o Wifi)	1	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
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 Configurations)	2884JUU		
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 D

Table 16: Video Adapters – Figures of Merit

		JKN Electronics	*DVShop*	*ProMax*	*SP Comms*
Requirements	Qty				
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 - shippping only	Instock - shipping only
Shipping Cost		?	?	?	?
Total		$495	$399	$299	$325

References

Power System

2LP608, QN-012BC: http://batteriesamerica.com/newpage8.htm
KOK560-2S-FJ, KOK880-2S-FJ, VRLI1-LPO
https://www.fmadirect.com/site/fma.htm?body=Store
PC720N7 http://hobby-lobby.com/hydride.htm
B600AE6 http://hobby-lobby.com/nicads.htm
LM1577, Figure 1 http://www.national.com/pf/LM/LM1577.html