in Proceedings of the SPIE Conference on Sensor Fusion and Decentralized Control IV, vol. 4571, pp. 76-83, October 28-29, 2001

Collection of Environmental Data From an Airship Platform

George Kantor[a*], David Wettergreen[a], James P. Ostrowski[b], Sanjiv Singh[a]
[a]The Robotics Institute, Carnegie Mellon University; [b]Department of Mechanical Engineering and Applied Mechanics, The Univeristy of Pennsylvania

ABSTRACT

We believe that solar powered, autonomous airships with the capability to embark on extended duration sampling missions will serve as valuable tools for environmental science. In this paper, we outline our vision for an autonomous airship and discuss some of the applications for which such a craft would be well suited. We also report on our efforts to date to realize this vision. Specifically, we discuss the use of solar energy as a renewable source of power for airships. We also describe the configuration of a nine meter airship that we will use as a testbed for environmental sampling and autonomy research. We conclude by outlining directions for future research.

1. INTRODUCTION

Environmental scientists who develop policies for the effective management of human activity are often thwarted by a lack of accurate information about the state of the environment. Specifically volumetric data, sampled densely in a three-dimensional airspace, and reacquisition of the same data over time are not available. Satellites provide regional data summed through the air column, radiosondes provide a linear sequence of samples up the air column, and ground monitoring stations provide only ground level measurements. There is currently no cost effective means of accurately characterizing environmental properties throughout a volume of air. To address this need, we have embarked on the development of a solar powered airship with the capability of extended-duration autonomous environmental sampling. In this paper, we report our early progress in this endeavor.

Figure 1: Nine meter (30 foot) airship during test flights in Pittsburgh, PA. This airship has been equipped with an on-board computer and a suite of navigational and environmental sensors. It will be used as a testbed for autonomy research and environmental sampling.

Airships, or blimps, exhibit a number of characteristics that separate them from other types of aerial sensing platforms. They require less power to remain aloft than fixed wing aircraft and helicopters, making them good candidates for solar power. They are safer to operate, a fact that is especially important for operation at low altitudes. They are capable of hovering and stable, low speed flight, making them ideal platforms for sensing operations such as atmospheric particulate matter measurement that must integrate data over a relatively long sample time to attain an accurate result.

Airships have been capturing the imagination of the public for a long time. A significant body of research in airship engineering emerged in the early 20th century when it was believed that airships could provide inexpensive air transportation for both passengers and freight. Interest in airship

* Correspondence: e-mail kantor@ri.cmu.edu, phone (412)268-7084

research was renewed in the 1970's when rising energy prices drove the search for more fuel efficient methods of transport. Recently, airship research has merged with research in robotics and automation in an ongoing effort to develop a fully autonomous airship platform. Some results include path planning and visual servo control [7] and formation flight using GPS navigation [1] for small indoor airships. Additionally, researchers have developed models [6], navigation systems, and experimentally demonstrated a rudimentary automatic control system [5] for an outdoor airship.

This paper, which reports on our own efforts to expand this body of research, is organized as follows: Section 2 provides motivation for our research by listing a number of potential environmental applications for an autonomous airship. In Section 3, we present an argument for solar power and discuss some theoretical and practical issues regarding the use of solar power to drive an airship. Section 4 describes a 9 meter airship platform that has been configured with navigational and environmental sensors and on-board computing hardware. We conclude in Section 6 by outlining airship capabilities that will need to be developed in future research.

2. MOTIVATION

We envision an autonomous airship that can carry environmental sensors safely and accurately through an airspace of interest. Using solar power as an energy source, the airship will be able to operate over an extended period of time, allowing it to collect data over large geographical areas or large volumes of airspace. A sensing platform of this kind would be an asset to environmental scientists who seek to understand, remediate, and manage the environment. The following are some examples of potential impact:

Air pollution: Air pollution can cause breathing difficulties an other health problems in people, aggravating diseases such as asthma and contributing to the development of cancer and emphysema. Air pollution also harms plants and animals. The airship described in this paper would have the ability to map distributions of different types of pollutants over a 3-dimensional volume of space. Such a map could be used to help identify pollution sources and increase our understanding of pollution transport mechanisms. The resulting data could be used to enforce existing regulations and develop new policies to reduce the impact of air pollution on public health.

Forest Management: Gypsy moths defoliate trees in many parts of the United States causing a loss of timber and impoverished forests. Airship-collected data describing the extent of defoliation could be used to develop effective spraying programs to control outbreaks. In general, forests could be better managed if properly typed, i.e. if maps existed that represented the spatial distributions of different species of trees. This information could be used to develop optimal harvesting policies so that timber could be harvested in a way that does not adversely affect the health of the forest. Also, by typing forests, unique habitats that support endangered species can be identified and protected.

Wetlands: Beyond supporting numerous wildlife species, wetlands are critical to a clean water supply for humans. Today, wetlands are disappearing as they are drained to make room for development. Wetlands are difficult to monitor because they are often inaccessible from the ground. Airships that could delineate wetlands from nonwetlands could track wetland health, allowing for the development of environmentally sound policies regarding drainage for development and dredging for water traffic.

3. SOLAR POWER

Solar power provides a renewable energy source that is necessary for the extended airship operation. Photovoltaic cells can be used to transform solar radiation directly into the electric current that is required to operate on-board computing hardware and sensors. This also allows for the use of electric thrusters, which provide some operational benefits over propellers driven by combustion engines. Electric thrusters do not emit any exhaust, a fact that is extremely important in the context of environmental sensing. Additionally, electric thrusters simplify control issues by providing the capability of reverse and differential thrust.

There are some technical challenges that need to be overcome before solar energy can provide a practical power source for our application. The weight of the solar cells and the batteries necessary to store and manage the collected power poses serious difficulties for airship applications. The power required to propel an airship scales with the square of its length while the payload available scales with length cubed, so the weight consideration can always be accommodated if the airship is made "big enough". In this section, we consider a continuous flight scenario and examine some of the engineering requirements and trade-offs that exist.

3.1 Flight Scenario and Assumptions

In the following analysis, we consider the power requirements for an airship that flies in an environment where the available solar power is a constant 1000W/m^2 for a 12 hour day, followed by 12 hours of darkness. The airship maintains a constant forward velocity (V) during the entire 24 hour period, meaning that it must operate using power stored in on-board batteries during darkness. We begin this flight scenario at the beginning of the daylight period with the batteries empty. As a result, the ability of the airship to operate for the first 24-hour period implies the ability to operate indefinitely.

We assume that the airship has length L with width and height equal to $L/3$. For the purposes of computing volume and surface area, we assume that the airship is an ellipsoid. For the purposes of computing drag, we assume that the airship has a traditional aerodynamic airship hull shape such as the National Physical Laboratory (England) low drag airship body[4]. We also assume that the total airship drag is twice that of the hull drag. This assumption is in line with experimentally determined drag parameters for existing airships [4, p. 34].

3.2 Available Payload

The gross lift of the assumed airship is computed as the volume of the hull times the unit lift of 10.36 N/m^3. This yields

$$B_{gross} = \frac{10.36\pi}{54} L^3 \text{ (Newtons).}$$

The weight of the airship hull is assumed to scale linearly with surface area. If we assume that the hull is constructed of material with an areal density $\rho_{\text{skin}} = 0.4$ kg/m^2, then the hull weight is expressed as

$$W_h = A_s \rho_{\text{skin}} g = (0.3076L^2)(0.4)(9.8) = 1.2022L^2 \text{ (Newtons)}$$

We assume that the mass of the required computing hardware and sensor suite does not vary with the size of the airship. In our experience, this required payload is approximately 5kg. Factoring this mass in with the above equations provides a cubic polynomial expressing the net lift of the airship:

$$B_{\text{net}} = 0.6027L^3 - 1.2022L^2 - 49 \text{ (Newtons)}$$

3.3 Weight of Solar Cells and Batteries

The amount of power necessary to drive the airship at constant velocity V determines the required number of solar cells, battery storage, and motor mass. A formula for this power is

$$P_{\text{flight}} = 0.5C_D \rho_{\text{air}} A_s V^3 \text{ (Watts),}$$

where A_s is the surface area of the airship hull. Here we let the skin drag coefficient be $C_D = 0.0510$ and we let the density of air be $\rho_{\text{air}} = 1.225$ kg/m^3. The resulting expression for the power required for an airship of length L to fly forward at a constant velocity V is

$$P_{\text{flight}} = (0.0312)(0.3067L^2)V^3 = 9.57\times10^{-3} L^2V^3 \text{ (Watts).}$$

Integrating this number to get the energy required for 24 hours of flight yields

$$E_{\text{flight}} = 24P_{\text{flight}} = 0.2297L^2V^3 \text{ (Watt-hours).}$$

Assuming that the array of solar cells is configured as a flat surface pointing directly up, the amount of solar energy that strikes each square meter of array area over the 12-hour daylight period is

$$E_{\text{incident}} = \int_0^{12} 1000 \sin\left(\frac{\pi t}{12}\right) dt = 7639 \text{ (Watt-hours/meter}^2\text{)}.$$

The total solar array surface area then must be at least

$$A_{\text{array}} = \frac{E_{\text{flight}}}{\varepsilon E_{\text{incident}}} = 3.01 \times 10^{-5} \frac{L^2 V^3}{\varepsilon}$$
(meters^2),

where ε in the conversion efficiency of the solar cells. The efficiency for current solar cells ranges from 10-14% for commercially available silicon cells up to 28% for the highest quality triple-junction silicon or 23% for gallium arsenide cells. Higher efficiencies are possible but the mass of the cell and, typically, its concentrator rises dramatically. He we will use ε = 12.8%, which corresponds to the efficiency of the solar cells we have used in recent experiments. The areal density of these cells is approximately 1.5 kg/m^2, so we can write the weight of the minimum required solar array as

$$W_{\text{array}} = 2.637 \times 10^{-2} L^2 V^3$$
(Newtons).

In order to maintain forward flight in darkness, $\frac{12}{24} E_{\text{flight}}$ Watt-hours of energy will need to be stored in batteries. This gives a total battery weight of

$$W_{\text{batt}} = \frac{0.5 E_{\text{flight}}\, g}{\rho_{\text{batt}}} = 1.126 \frac{L^2 V^3}{\rho_{\text{batt}}} \text{ (Newtons)},$$

where ρ_{batt} is the specific energy of the battery in Watt-hours per kilogram. Some typical values of specific energy are show in Table 1 [2,4].

Table 1: Typical specific energy and specific power ratings for different battery technologies [2,4].

Battery Type	Energy Density, Whr/kg	Power Density, W/kg
Pb-Acid	30-45	200
Ni-Cd	40-50	190
NiMH	50-60	180
Ni-Zn	80	800
Li+	130	800
Ag-Zn	140-200	100-330
Ag-Cd	55-95	100-220
Zn-Air Fuel Cell	200-300	80-100
Al-Air Fuel Cell	350	500-600

We assume that the weight of the motors required to drive the blimp scales linearly with the power required for flight. Using data sheets for commercially available DC brushless motors designed for aerial applications, we estimate this scaling factor to be $\gamma = 2.835 \times 10^{-4}$ Newtons per Watt [http://www.aveox.com/motors.html]. This gives the following expression for motor weight:

$$W_{\text{motor}} = 2.835 \times 10^{-4} P_{\text{flight}} = 2.713 \times 10^{-6} L^2 V^3 \text{ (Newtons)}.$$

The total weight of the power system is given by the sum of the weights of the solar cells, batteries, and motors. This is

$$W_{\text{power}} = \left(2.637 \times 10^{-2} + \frac{1.126}{\rho_{\text{batt}}}\right) L^2 V^3 \text{ (Newtons)}.$$

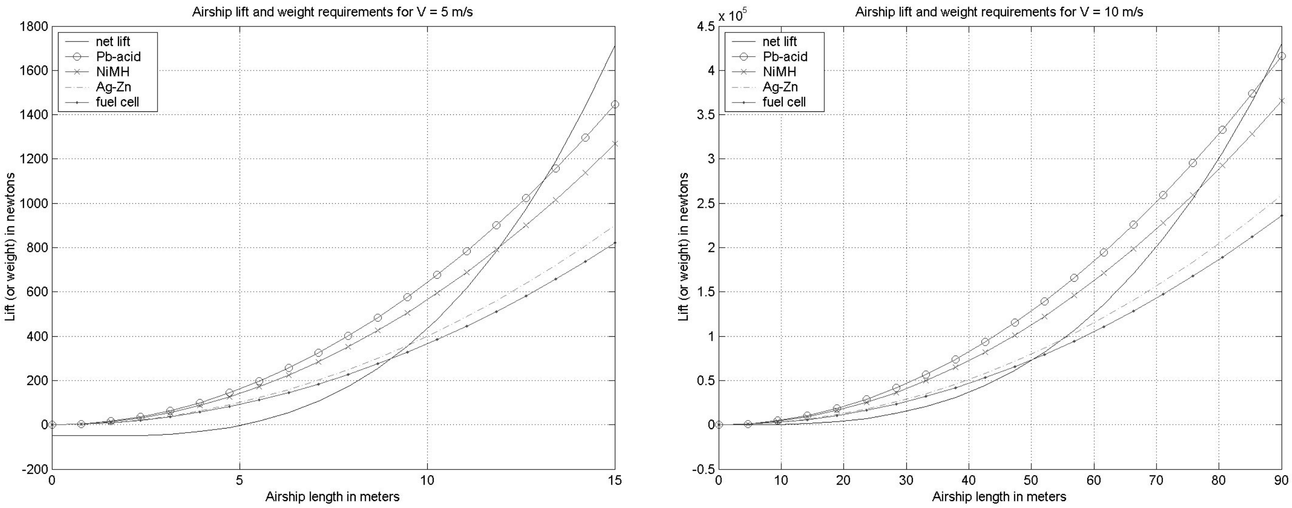

Figure 2: Net lift and solar power system weight are plotted together as a function of airship length. For each battery type, the weight curve intersects the lift curve as the minimum feasible airship length. The left plot assumes a continuous velocity of 5 m/s. The plot on the right assumes a velocity of 10 m/s.

3.4 Overall Feasibility

In order for an airship to be feasible, the net lift B_{net} must be at least as large as the weight of the power system W_{power}. This can be graphically depicted by simultaneously plotting B_{net} and W_{power} as a function of airship length *L*. The two curves cross at the smallest feasible value of *L*. Figure 2 shows these plots at velocities of 5 and 10 m/s for a variety of different battery types. As shown in the figure on the left, continuous solar powered flight of 5 m/s becomes feasible at a length of about 9 meters using silver-zinc batteries. A length of at least 12 meters is required for lead-acid batteries. The plot on the right shows that effect of the increased velocity on the required airship size is dramatic: a length of 50 m is required for silver-zinc batteries, and a length of almost 90m is required for lead-acid batteries.

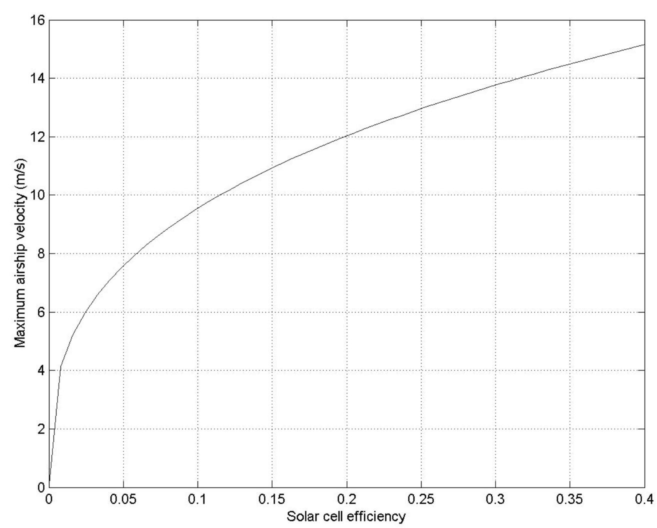

Figure 3: If an airship carries as big of a solar array as its surface area will allow, the maximum speed that can be maintained by power from the array is only a function of solar cell efficiency, not airship length. This figure plots maximum airship velocity as a function of solar cell efficiency.

In addition to weight requirements, a constraint is also imposed by the amount of area required for the solar array. Specifically, the area required for the array cannot exceed the area of the ellipsoidal cross section of the airship. This means that we must have

$$3.01\times10^{-5}\,\frac{L^2V^3}{\varepsilon}\le\frac{\pi L^2}{12}$$

Since both sides of this inequality are functions of L^2, this constraint becomes an absolute constraint on the velocity of the airship:

$$V\le 20.57\sqrt[3]{\varepsilon}$$

(meters/second).

The relationship between solar cell efficiency and maximum airship velocity is plotted in Figure 3. Commercially available silicon solar cells (12.8% efficient) allow a maximum velocity of just under 10m/s, with the governing factor being the cross sectional area of the blimp relative to the area of required cells. With slightly more efficient cells, 10m/s flight becomes feasible.

Since battery technology plays such an important role in the feasibility of solar powered airship flight, we take a closer look at the battery requirements for 20 meter airship, with specific interest in the mass available to carry batteries and the required energy density to support continuous 24 hour flight.

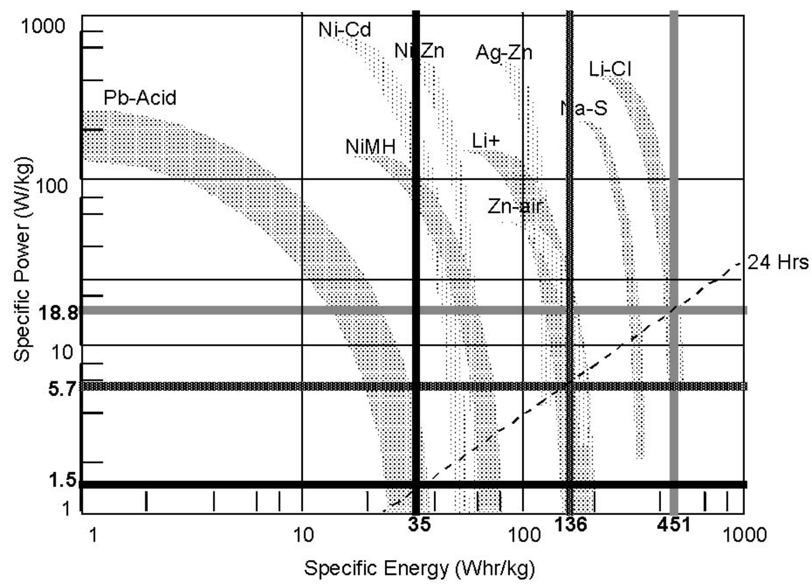

Figure 4: This figure plots the specific power and specific energy ranges for a number of different battery technologies [2]. The dashed line designates the section of the plot for which continuous 24 hour discharge is possible. The specific energies required for continuous flight of a 20 meter airship at 5, 7.5, and 10 meters per second are plotted in the figure. The intersection of these vertical lines with the dashed 24 hour line defines the specific power requirement as well as a suitable battery technology.

The mass available for batteries, with the simplifying assumption that there is no other payload, is:

$$\hat{W}_{\text{batt}} = B_{\text{net}} - W_{\text{array}}$$

The energy density is then $E_{\text{flight}}\,g/\hat{W}_{\text{batt}}$ and the power density for continuous operation is the energy density divided by 24 hours. So for a 20m blimp with 12.8% efficient solar cells, continuous flight at 5 m/s leads to 14720.3Whr of required energy and a panel area of 15.1m^2. The available battery mass is 420.2kg giving an energy density of 35Whr/kg. This falls within the capability of standard lead-acid batteries. For a flight speed of 7.5m/s, the panel area grows to 50.8m^2 and the energy density is 135.7Whr/kg, appropriate for lithium-ion batteries. At 10 m/s, 12.8% efficient solar cells are not sufficient for continuous flight both because the required surface area, 120m^2 is larger than the 20m blimp's plan-section, 105m^2, and because the available battery payload mass 261.1kg puts the required energy density into the range of non-rechargeable fuel cells.

4. AIRSHIP CONFIGURATION

In this section we describe a nine meter airship that has been configured with sensors and computing hardware. We have conducted some preliminary tests using this platform, and we will continue to use it as a testbed for our airship autonomy research. The work described in this section was conducted as a research project with the STWing Team at the University of Pennsylvania.

The airship sensing platform is constructed around nine meter radio controlled airship purchased from Mobile Airships, Inc. [http://www.blimpguys.com]. The airship is propelled by two gasoline powered engines and steered by 4 fins (2 elevators and 2 rudders) at the back of the craft. A photo of the blimp in flight is shown in Figure 1. As purchased, the airship has a net payload of about 5kg. A block diagram of the sensor and computing hardware configuration for is shown in Figure 5.

A Pentium laptop was selected for the on-board computing platform. The laptop was modified to reduce weight by removing the screen and reconfiguring the battery. STWing team members developed a JAVA based operating system that has the advantage of being easily interfaced to a number of different sensor types through a USB hub. The on-board laptop is also equipped with a wireless Ethernet connection that allows it to communicate with other computers on the ground. A shielded "subgondola" was mounted below the gondola to house the laptop and USB hub.

The airship employs GPS, rate gyros, and a web cam as navigational sensors. The GPS antenna is mounted on top of the airship in order to view the maximum number of satellites. The serial output of the GPS receiver is fed directly into the USB hub. Two sets of gyros configured to measure pitch, pitch rate, yaw, and yaw rate. They are mounted directly to the envelope instead of the gondola so that they are isolated from motor vibrations. Custom circuitry was built to translate the gyro outputs into serial signals, which is then fed into the USB bus. The web cam is mounted inside the gondola behind a clear plastic window. Its output is fed directly to the USB bus.

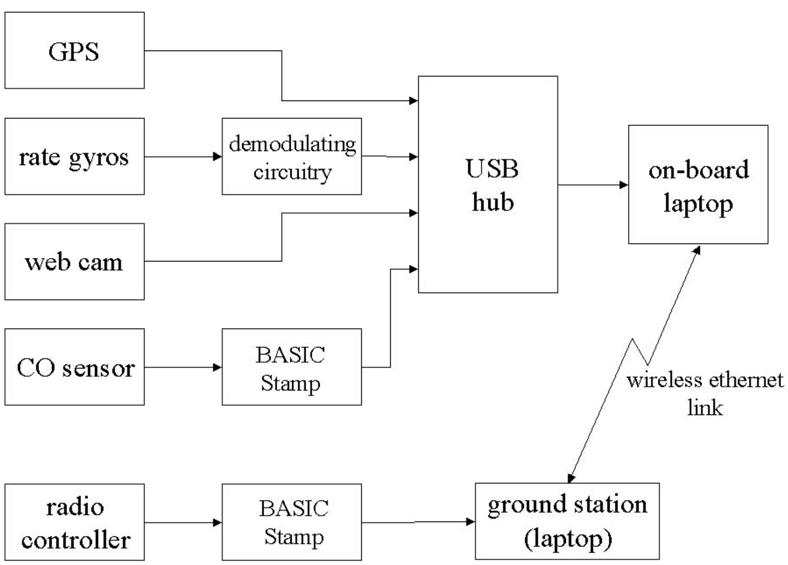

Figure 2: This block diagram depicts the configuration of the sensors and computing hardware for the nine meter airship testbed.

The airship is also equipped with a carbon monoxide (CO) sensor to measure air pollution. This sensor was selected because of its low cost, low weight, and reliable measurements. In the future, we will investigate the use of sensors that measure other gasses and particulate matter from an airship platform. The analog output of the CO sensor is translated to serial using a BASIC Stamp then fed to the USB hub. The CO sensor is mounted on top of the airship to minimize the extent to which the motor exhaust corrupts the collected data.

For future system identification experiments, it will be necessary to record the inputs supplied by the radio controller together with the outputs of the navigational sensors. To accomplish this, we use a BASIC Stamp to translate the pulse coded modulation signal from the radio controller to serial. This serial signal is then fed to a laptop on the ground, which relays it via wireless Ethernet to the on-board laptop.

5. SUMMARY AND CONCLUSIONS

Autonomous airships show potential as environmental sensing platforms, however a number of technical challenges will have to be met before their use can be realized. Powering an airship for extended missions is one such challenge. Solar power seems to be a suitable power source. The analysis in Section 3 demonstrates that continuous low speed flight is feasible under idealized conditions, however it is unlikely that the energy requirements necessary to operate in strong winds or execute complicated maneuvers could be supported for very long. It is clear from this analysis that realistic extended duration sampling missions cannot be supported by continuous solar powered flight alone. Rather, it will be necessary for the airship to find safe places to land when it runs low on power or faces strong winds. Accordingly, our future efforts will include research toward developing the intelligence necessary for airship autonomy.

We have configured a nine meter airship to be used as a testbed for research in airship autonomy and environmental sampling. We have developed a model for the airship using first principals, and we have designed a system identification experiment to tune the model parameters. Using model based methods, we will develop controllers for behaviors such as trajectory following, station keeping, and landing. We will also develop high level planners that piece the behaviors together to accomplish tasks such as feature following, volume sweeping, or land mapping.

The fact that the airship is underactuated poses some interesting problems from the perspective of control, as does the fact that the operating conditions of the airship are stochastic and time-varying. Numerous practical challenges arise due to the limited payload of the airship, especially when considering the use of solar power. The instrumentation and data processing necessary to collect and understand environmental data represents another set of research problems. These topics must be addressed together in order to realize the vision of an autonomous airship environmental sensing platform.

ACKNOWLEDGEMENTS

This work was funded in part by National Science Foundation grant # ECS-0086931.

We would also like to thank the STWing Team at the University of Pennsylvania for their continuing cooperation on this project.

REFERENCES

1. T. Corazzini, A. Robertson, J. C. Adams, A. Hassibi, and J. P. How, ``GPS Sensing for Spacecraft Formation Flying," Fall issue of the *The Journal of The Institute Of Navigation*, Vol, 45, No. 3, 1998, pp. 195-208

2. K. Dowling, “Power sources for small robots”, Carnegie Mellon University technical report CMU-RI-TR-97-02, 1997.

3. A. Elfes, S.S. Bueno, M. Bergerman, and J.G.Ramos, “A semi-autonomous robotic airship for environmental monitoring missions”, in Proceedings of the 1998 IEEE International Conference on Robotics and Automation, pp. 3449-3455, May 1998.

4. G.A. Khoury and J.D. Gillett, *Airship Technology*, Cambridge University Press, 1999.

5. J.G. Ramos, E.C. de Paiva, J.R. Azinheira, S.S. Bueno, S.M. Maeta, L.G.B. Mirisola, M. Bergerman, B.G. Faira, “Autonomous flight experiment with a robotic unmanned airship”, in Proceedings of the 2001 IEEE International Conference on Robotics and Automation, May 2001.

6. S.B. Varella Gomes and J.G. Ramos, “Airship dynamic modeling for autonomous operation”, in Proceedings of the 1998 IEEE International Conference on Robotics and Automation, pp. 3462-3467, May 1998.

7. H. Zhang and J.P. Ostrowski, “Visual servoing with dynamics and control of an unmanned blimp”, in Proceedings of the 1999 IEEE International Conference on Robotics and Automation, pp. 618-623, May 1999.

8. D.Wettergreen, B. Shamah, P. Tompkins, W. Whittaker, “Robotic Planetary Exploration by Sun-Synchronous Navigation,” i-SAIRAS, Montreal, Canada, June 2001