Guidance, Navigation and Control of High-Altitude Airships

White Paper
by Joseph Mueller

Executive Summary

Recent developments in lightweight materials and renewable energy technologies have sparked a renewed interest in an old concept. Airships have been flying since 1852, and have been serving the U.S. military since 1908. Since their inception, they have been used for sightseeing, civilian and military transport, and most recently, advertising. However, the potential of these lighter-than-air vehicles has not yet been fully tapped. With recent advances in ultra-lightweight fabrics, composites, and thin-film solar cells, airships can now reach the stratosphere and sustain powered flight using only solar energy. This concept of a high-altitude airship (HAA) represents a new service platform that compliments, and in many ways, outperforms satellites.

Flying in the calmest region of the atmosphere, above all cloud cover and all regulated air traffic, the HAA is designed to station-keep at an altitude range of 65-70 km, or 19-21 thousand feet. Unlike satellites, airships can maintain any geostationary position; their close-proximity offers improved uplink capability; they are serviceable and easily re-stationed; and they do not carry the burden of high launch costs. Some broad examples of the potential applications include data relay stations for the military and telecommunication industry, mobile observatories for weather and scientific study, and surveillance platforms for activities such as border patrol, disaster relief, and private security. While the potential benefits of the HAA concept are clear, it does remain a concept.

To advance from the design stage to an operational platform, the HAA must demonstrate reliable, controlled flight for days, weeks, and eventually months at a time. The unique dynamics of the HAA vehicle make this a challenging task, with widely varying mass properties, significant effects from added mass and inertia, and high sensitivity to wind. Ultimately, success hinges on the performance of the autonomous guidance, navigation and control (GN&C) system that flies the vehicle. It is critical that this system achieves the tracking requirements imposed by the mission while flying energy-efficient trajectories, so that a daily energy balance is maintained. Without meeting these objectives, the airship cannot accomplish its mission. Because the HAA is such a tightly integrated system, a successful design requires a detailed understanding of the complete vehicle.

Through previous SBIR contracts with the Missile Defense Agency and the Air Force Flight Test Center, Princeton Satellite Systems (PSS) has developed a comprehensive set of modeling, analysis and control design tools for airships, along with a prototype GN&C design that demonstrates autonomous station-keeping subject to random wind variations [1]. A linear, $\mathcal{H}_\infty$ optimal control law is designed for an array of flight conditions that span the airship's entire operational envelope. The point controllers are gain-scheduled with altitude and airspeed to provide smooth, robust feedback control throughout the flight envelope. Results from non-linear, closed-loop simulations demonstrate the capability of the system to provide reliable station-keeping performance and to track any rate-limited trajectory defined by the guidance law. Further research has shown the benefits of applying trajectory optimization methods for guidance, resulting in dynamic station-keeping flights that utilize wind energy to minimize power consumption [2].

This white paper outlines the general requirements of a high-altitude airship mission, presents the software tools that have been developed, and provides an overview of our GN&C design for autonomous airships, with simulation results from an example airship mission.

1   Example Airship Mission

The Air Force Flight Test Center is currently working to improve its communication infrastructure at Edwards Air Force Base in southern California. The existing system is a ground-based network of towers spread out across hundreds of miles. Telemetry is transmitted from the aircraft to the local tower, which then routes the data stream over a microwave signal to the control center. The ground-based system, which is inefficient and costly to maintain, can be replaced by a single airship.

For this mission, the HAA will serve as a geo-stationary platform for communication relay. A communications payload will be used onboard the airship to provide data relay services for the entire R-2508 airspace. A map of the R-2508 airspace, generated from "GoogleEarth", is shown in Figure 1-1. The blue line shows the border of R-2508, and the green circle illustrates the coverage area of the airship. This circle has a 110 km radius (68 miles), which assumes a 10 deg elevation angle and the airship flying at 70 kft. The radius of this coverage area doubles when a 5 deg elevation angle is assumed.

The onboard guidance, navigation and control system will work autonomously to perform station-keeping in the presence of varying winds and rising/falling atmospheric density. Both the airship and the control software must be designed to be capable of meeting the station-keeping requirements. The most basic requirement for station-keeping is an allowable position error. This can be defined as a volume, such as a box, disk or sphere, centered at the desired latitude, longitude and altitude. Additional requirements that are important for long-term operations would include a maximum excursion limit and the minimum percent time on station. The exact requirements must be derived from the operational objectives of the mission.
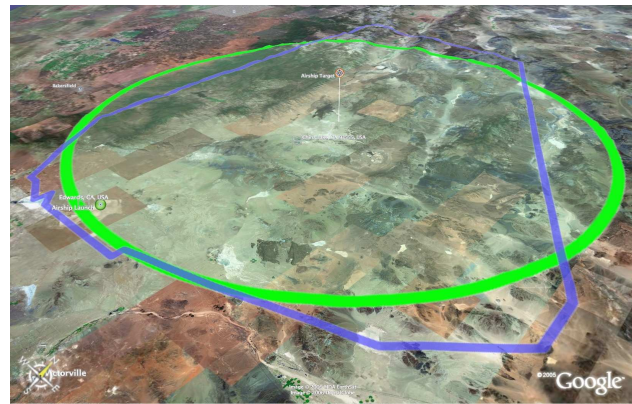

Figure 1-1. R-2508 Airspace with Airship Coverage

2   Airship Design and Analysis Tools

During previous SBIR contracts with the Missile Defense Agency and the Air Force Flight Test Center, Princeton Satellite Systems has developed a suite of useful software tools for the airship design engineer. This airship toolset has been added to our MATLAB Aircraft Control Toolbox (ACT). By itself, ACT provides a generic aircraft simulation along with a standard atmosphere model, an altitude model, a comprehensive set of coordinate transformation functions, classical controller design and analysis tools, as well as sample dynamic models for sensors, actuators, engines and aerodynamics. The additional airship toolset includes unique functionality for basic vehicle design, aerodynamic modeling, disturbance modeling, and simulation.

With the airship toolset in ACT, the engineer can quickly proceed through the fundamental steps required to develop and analyze the dynamics of a candidate airship model, and evaluate the performance of the controlled system. The tools are geared specifically towards the unique system inter-dependencies of high-altitude airships, enabling the engineer to: 1) evaluate steady-state horizontal winds as a function of altitude,

latitude, longitude and time of year, 2) size the airship hull to meet force and energy balance constraints based on average wind conditions, 3) design and visualize the geometry of the airship, including hull shape, propeller locations, and size/shape of tailfins, 4) automatically build aerodynamic models from design scripts and generate linear models at select flight conditions, 5) design and implement control software, and 6) simulate the 6 DOF motion.

A wind analysis tool enables the engineer to visualize how the wind magnitude and direction varies with altitude, latitude, longitude and day of the year. The default data set is based upon an empirical model developed by the Naval Research Laboratory. Data sets from other models may easily be interchanged. The GUI shows a 3D mesh plot of data, with sliders to show how contours change with different variables. This analysis is important in determining the average airspeeds to consider for station-keeping flight, which drives the size of the hull and the power production requirements. This tool has been used to fit approximate function models to the empirical data, for use in trajectory optimization.
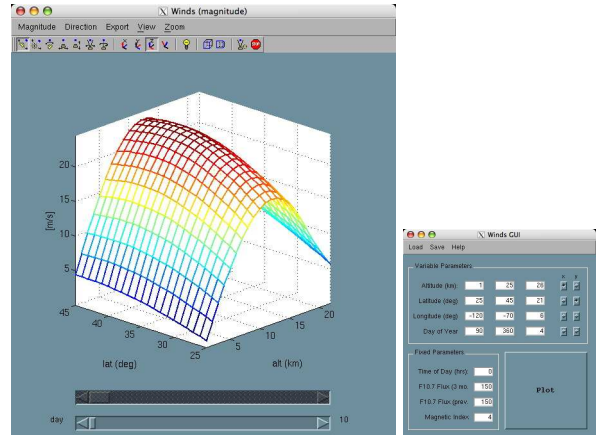

Figure 2-1. Wind Analysis Tool

Several analysis functions are available to size the hull so that it meets critical force and energy balance constraints. For example, Figure 2-2 shows the results plotted from one such function. It gives the percentage of the hull surface area that must be covered with solar cells to achieve a daily energy balance. The solid and dashed line sets correspond to two different average velocities. This and other similar plots are generated from basic geometric properties of the vehicle, allowing the user to quickly identify the feasible design space.

The airship hull is modeled as two half-ellipsoids, giving the classic "teardrop" shape, with four symmetric tail-fins and a hanging gondola that supports the payload and 1-2 pairs of electric motors with counter-rotating propellers. Geometric properties are defined in an *airship design script* in MATLAB. The script may be modified to easily create different types of configurations. The set of parameters are illustrated in Figure 2-3 on the following page, along with a CAD model of an example airship design. This 3D view is generated automatically from the function `Airship3DLayout.m` by simply passing the name of the design script. The geometric properties are used to automatically build up an aerodynamic model, which is based on a steady-state analytical model derived by Jones and DeLaurier [3, 1]. This aerodynamic force model is applied with the 6 DOF rigid body equations of motion, along with an altitude-

Figure 2-2. Solar Cell Coverage

dependent mass model, providing the full non-linear simulation of the airship. Conditions for trim flight are found automatically with a single function call. Linear models about the trim conditions are then computed automatically from the non-linear system using the central value theorem. The commands below illustrate
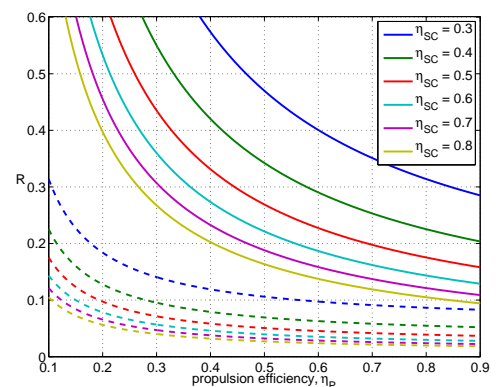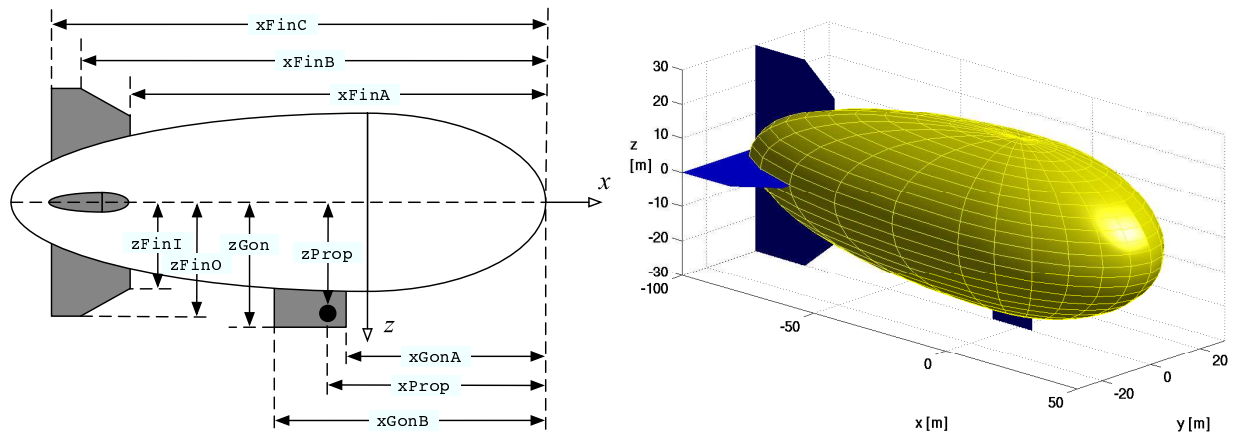
Figure 2-3. Airship Geometric Model and Baseline Design

how easy it is to initialize a model, compute trim conditions, and generate linear models.

```
>> d = BuildAirshipModel('ASM3');
>> [d,x] = AirshipInit( d, [40;-120;21], [15;0;0], [0;0;0], 1 );
>> [T,mu,dElv] = AirshipTrim(d,x);
>> g = AirshipLinMod(d,x);
>> [gLat,gLon] = AirshipStatespace(g,1);
```

3   Autonomous GN&C Design

Using the software tools described in the previous section to model and analyze airship dynamics, we have developed an autonomous GN&C system design for high-altitude airships. Our objective was to design a system that can run onboard the airship and provide practical, robust autonomous guidance and control capabilities, while enabling interactive command and control over the system from a remote operator. This goes beyond the design of feedback controllers. The complete onboard system is a comprehensive software architecture – designed to provide all of the functions necessary to perform autonomous control, and to accept and respond to a host of different commands from a remote operator.

The basic illustration of the GN&C system is shown in Figure 3-1 on the next page. Measured input data comes from GPS receivers, air data sensors, and rate gyros. These sensors provide the nominal set of state information required by the software. Additional input data comes in the form of high-level commands from a remote operator. The software is organized as three separate modules: Navigation, Guidance Law, and Control Law.

The Navigation module receives GPS measurements of the inertial position and velocity (R_{ECI}, V_{ECI}), along with measurements of airspeed velocity, angle-of-atack and sidelsip (V_T, α, β). It performs a series of coordinate transformations in order to provide position and velocity estimates to the other modules in appropriate coordinate frames. The Guidance Law receives high-level objectives from the remote operator, indicating the current desired flight objectives, and commands a smooth, wind-relative trajectory for the control law to track. The control law receives the current state information from rate gyros and air data sensors, and commands the throttle, thrust angle and surface deflections to follow the desired trajectory.

Figure 3-1. Guidance, Navigation and Control System Framework
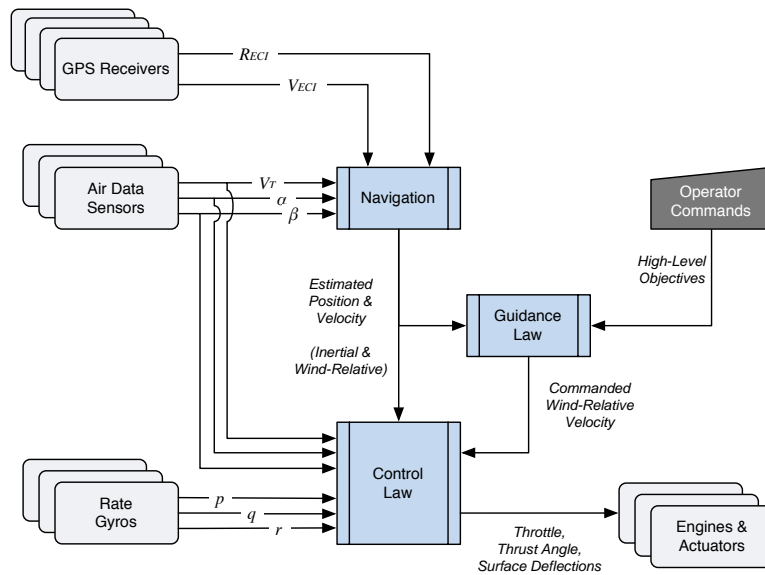
The role of the Control Law is to automatically command the throttle and adjust the control surfaces so that the desired wind-relative trajectory is maintained. These commands are computed from a state-space implementation of an $\mathcal{H}_\infty$ controller, discretized at 10 Hz. Separate controllers are designed for the longitudinal and lateral-directional modes. In addition, because the dynamics of the airship change significantly with airspeed and altitude, several different controllers are designed over a large array of flight conditions, from 0 to 20 km and from 5 to 25 m/s. The discrete state-space matrices associated with each point design are stored in memory, and a gain-scheduling algorithm is used to interpolate the matrices between the closest point designs as the flight condition changes. Each controller is designed to minimize the effects of all disturbances on the performance error signal, making it robust to appropriate levels of sensor noise and wind gusts.

The role of the Guidance Law is to command a desired trajectory for the Control Law to track, such that the airship follows the specified flight objectives. The capabilities include: Station-Keeping, Altitude-Hold, Direction-Hold, Velocity-Hold, Trajectory-Hold. Together, this menu of flight objectives can be utilized by the remote operator to easily maneuver the airship. Each command has a corresponding set of data that must be provided. For instance, the station-keeping command instructs the airship to fly within a specified horizontal and vertical distance of a specified point in space, defined by latitude, longitude and altitude. The design of the station-keeping mode of the Guidance Law is particularly important. It must continuously pilot the airship so that it maintains its desired station while using as little energy as possible. Our system has been designed with the inherent tradeoff of tracking performance and energy consumption in mind.

Figure 3-2 on the following page illustrates the results of an example simulation. Here, the airship begins its flight outside of the desired station. It is flying East at 15 m/s into the wind, at an altitude of 21 km, and with a 1.5 km error (north and east) from its target. A steady-state wind is also directed Eastward at 15 m/s, with additional random gusts in all three axes. The guidance law turns the airship and decreases the inertial velocity as it returns to the desired region. It temporarily exits the desired region before it can slow down sufficiently, then quickly achieves a steady-state position within the target zone.

Figure 3-2. Station-Keeping Simulation Results
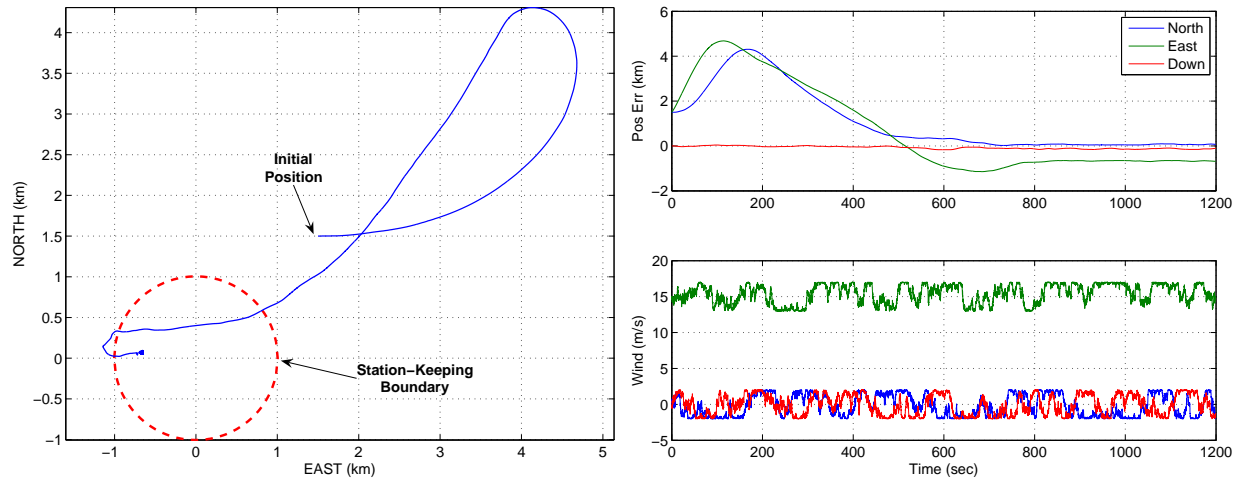

4 Building a Complete System

A complete system for real-time, autonomous airship control goes beyond the onboard software. Although designed to be autonomous for most of its life cycle, the HAA carries a host of new technologies, and therefore requires careful monitoring to ensure performance and safety. PSS is developing a complete solution for end-to-end control of high-altitude airships, one that integrates onboard software with a powerful and flexible ground-based application for telemetry and command.

The command, control and monitoring system is illustrated in Figure 4-1 on the next page. The diagram is divided into two sections – the ground station lies below the dashed line and the airship lies above it. At the ground station, the remote operator interfaces with a Flight Management System (FMS). The FMS performs two functions: 1) it enables the operator to monitor the health of the airship, and 2) it provides a remote command and control capability over the airship. Commands issued by the operator are sent from the FMS through an established uplink to the GNC system.

The GNC system provides an autopilot capability to the airship, so that its flight path meets the high-level objectives commanded by the operator. This system also gathers state and health information from itself and all other sub-systems, and transmits that data in a telemetry stream back to the ground station. When the telemetry data is received by the FMS, it is displayed to the operator via user-configurable, customized displays. This feedback loop enables the operator to monitor the overall health and performance of the vehicle, and then issue commands as necessary.

The system doubles as a virtual testbed, by connecting the FMS to a Flight Simulator on a separate workstation. The simulator includes the same software designed to run onboard the airship, along with a simulation of the airship dynamics. Interfacing the FMS with the Flight Simulator can be extremely useful. It can provide a mechanism for pre-flight validation of the GNC system with an operator or pilot in-the-loop. It also can be used as a training tool to instruct operators how to properly command and monitor the airship. Finally, it can be used before and during the mission as a prediction tool to evaluate the expected performance of the vehicle in specific scenarios.

The system is designed to be customizable. The Flight Simulator is designed to accommodate easy plug-and-play of different dynamic models. The Flight Management System provides a flexible user interface,

Figure 4-1. Comprehensive Command, Control and Monitoring System
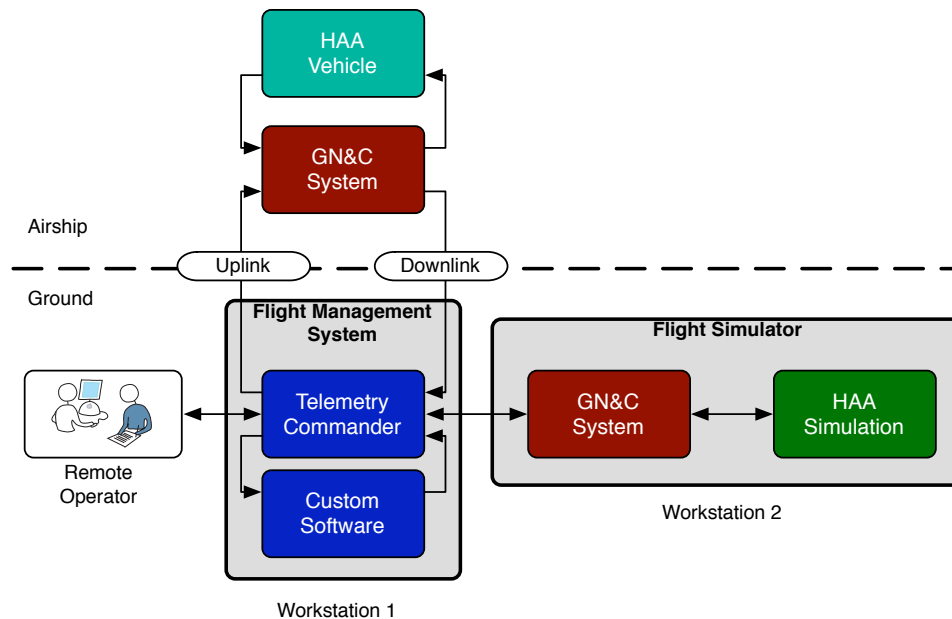
such that the operator can design and configure her own telemetry pages, and robustly interface with other 3rd party software. The GNC system is implemented in a generic, modular architecture, so that algorithms may be quickly swapped and parameters easily changed to facilitate an ongoing design. These features enable the system to be used throughout the complete mission cycle, from design to flight-test to operations.

5   Princeton Satellite Systems

Princeton Satellite Systems, Inc. (PSS) specializes in innovative, cost-effective solutions to embedded software and control system design problems and provides software and design tools to companies throughout the world. Established in 1992, PSS sells commercial software, provides consulting services, and produces custom software for industry.

Princeton Satellite Systems is an approved General Services Administration (GSA) Professional Engineering Services Contractor (Contract Number: GS-23F-0134R). Our GSA Federal Supply Schedule Contract for Professional Engineering Services (PES) consists of a 5 year base period commencing on March 15, 2005. This contract allows government contractors and government agencies contract with PSS using the pre-negotiated GSA contract at government discount rates.

In the last few years, the company has completed two Phase I SBIR contracts on the topic of autonomous control for high-altitude airships. The first contract was with the Missile Defense Agency in 2003, entitled "Long Endurance, Autonomous Control of High-Altitude Airships". The project focused on airship modeling, guidance and control design, robustness analysis, and assessing the benefits of trajectory optimization in Earth-based, high-altitude applications. The second contract was with the Air Force Flight Test Center in 2005, entitled "Autonomous Control System for High-Altitude Data Relay Stations". This project improved the airship dynamic models, extended the GN&C design, and investigated the reliability of hardware systems at high-altitude. For both contracts, Dr. Yiyuan Zhao of the University of Minnesota served as a

consultant, offering expertise in the field of trajectory optimization.

5.1   Mr. Joseph Mueller

Mr. Mueller is a senior member of the Technical Staff located in the Minneapolis, MN office. He recently served as the principal investigator for Phase I SBIR contracts with Edwards Air Force Base and the Missile Defense Agency, in which he designed guidance and control algorithms for the unmanned high-altitude airship, and examined the potential benefits of online trajectory optimization. He has also been the P.I. for Phase I and Phase II SBIR contracts with NASA Goddard, where led the development of an autonomous formation flying control system for coordinated multi-spacecraft missions.

Mr. Mueller has an M.S. and B.S. in Aerospace Engineering from University of Minnesota (1999 and 2000). For his master's thesis, he developed linear parameter-varying controllers for the F/A-18 aircraft. He is currently pursuing his Ph.D., studying the topic of distributed optimization across airborne networks.

At Princeton Satellite Systems, he has been the principal investigator for several SBIR projects, and has made significant contributions to a number of other projects. He has developed innovative guidance and control algorithms for both lighter-than-air vehicles and distributed space systems, including a decentralized guidance law for cooperative target selection in a multi-team environment, model predictive control techniques for optimal, cooperative maneuver planning, and a robust safe guidance mode for an upcoming European space mission. He is responsible for the Aircraft Control Toolbox, to which he recently added a suite of airship modeling and simulation tools, and he is currently developing a Formation Flying Design and Analysis Toolbox for MATLAB.

Selected publications include:

J. B. Mueller and S. Thomas, "Decentralized Formation Flying Control in a Multiple-Team Hierarchy", presented at the *New Trends in Astodynamics and Applications*, Princeton, NJ, June 2005, published in the *Annals of the New York Academy of Sciences*, Volume 1065: 112-138.

J. B. Mueller and G. Balas, "Implementation and Testing of LPV Controllers for the F/A-18 System Research Aircraft" AIAA Guidance, Navigation and Control Conference, Denver, CO, Aug. 2000, AIAA-2000-4446.

G. Balas, J. B. Mueller, and J. Barker, "Application of Gain-Scheduled, Multivariable Control Techniques to the F/A-18 System Research Aircraft", presented at the *AIAA Guidance, Navigation and Control Conference*, Portland, OR, Aug. 1999, AIAA-99-4206.

References

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[2] Zhao, Y., Garrard, W., and Mueller, J. B., "Bennefits of Trajectory Optimization for Airship Flights," *AIAA Unmanned Unlimited Conference*, No. AIAA-6527, AIAA, Chicago, IL, 2004.

[3] Jones, S. P. and DeLaurier, J. D., "Aerodynamic Estimation Techniques for Aerostats and Airships," *AIAA Lighter-than-Air Systems Conference*, AIAA, Annapolis, MD, 1981.