Autonomous Robots 14, 147–164, 2003

Robotic Airships for Exploration of Planetary Bodies with an Atmosphere: Autonomy Challenges

ALBERTO ELFES
Jet Propulsion Laboratory (JPL), NASA/California Institute of Technology, Pasadena, CA 91109, USA
elfes@jpl.nasa.gov

SAMUEL S. BUENO, MARCEL BERGERMAN, ELY C. DE PAIVA AND JOSUÉ G. RAMOS, JR.
CenPRA/LRVC, Campinas, SP, Brazil
samuel.bueno@cenpra.gov.br
marcel.bergerman@cenpra.gov.br
ely.paiva@cenpra.gov.br
josue.ramos@cenpra.gov.br

JOSÉ R. AZINHEIRA
IST/IDMEC, Lisbon, Portugal
jraz@dem.ist.utl.pt

Abstract. Robotic unmanned aerial vehicles have great potential as surveying and instrument deployment platforms in the exploration of planets and moons with an atmosphere. Among the various types of planetary aerovehicles proposed, lighter-than-atmosphere (LTA) systems are of particular interest because of their extended mission duration and long traverse capabilities. In this paper, we argue that the unique characteristics of robotic airships make them ideal candidates for exploration of planetary bodies with an atmosphere. Robotic airships extend the capabilities of balloons through their flight controllability, allowing (1) precise flight path execution for surveying purposes, (2) long-range as well as close-up ground observations, (3) station-keeping for long-term monitoring of high science value sites, (4) transportation and deployment of scientific instruments and in situ laboratory facilities across vast distances, and (5) opportunistic flight path replanning in response to the detection of relevant sensor signatures. Implementation of these capabilities requires achieving a high degree of vehicle autonomy across a broad spectrum of operational scenarios. The paper outlines some of the core autonomy technologies required to implement the capabilities listed above, drawing on work and results obtained in the context of AURORA (Autonomous Unmanned Remote Monitoring Robotic Airship), a research effort that focuses on the development of the technologies required for substantially autonomous robotic airships. We discuss airship modeling and control, autonomous navigation, and sensor-based flight control. We also outline an approach to airborne perception and monitoring which includes mission-specific target acquisition, discrimination and identification, and present experimental results obtained with AURORA.

Keywords: robotic airship, autonomy architectures, UAV, planetary exploration, atmospheric vehicles, aerobot, flight path control, UAV perception

1. Introduction

Exploration of the planets and moons of the Solar System has so far been done through remote sensing from Earth, fly-by probes, orbiters, landers and rovers. Remote sensing systems, probes and orbiters can only provide non-contact, low- to medium-resolution imagery across various spectral bands; landers provide high-resolution imagery and in situ data collection and analysis capabilities, but only for a single site; while rovers allow imagery collection and in situ science across their path. The crucial drawback of ground-based systems is their limited coverage: in past or planned exploration missions, the rover range has varied from approximately 130 m (for the 1997 Sojourner mission) to 1 km (projected for the 2003 Mars Exploration Rovers), to tens of kilometers (for the Lunokhod rovers), and to possibly a few hundreds of kilometers (according to some of the scenarios considered for the 2009 Mars Science Laboratory (MSL) mission).

While the data collected through these various approaches has been invaluable, there is a strategic gap in current exploration technologies for systems that would combine extensive coverage with high-resolution data collection and in situ science capabilities. For planetary and planet-like bodies that are endowed with an atmosphere, this gap can be addressed by aerial vehicles. In our Solar System, in addition to Earth, the planets Venus and Mars, the gas giants (Jupiter, Saturn, Uranus and Neptune) and the Saturn moon Titan have significant atmospheres (Fig. 1). Aerial vehicles that have been considered for planetary exploration include

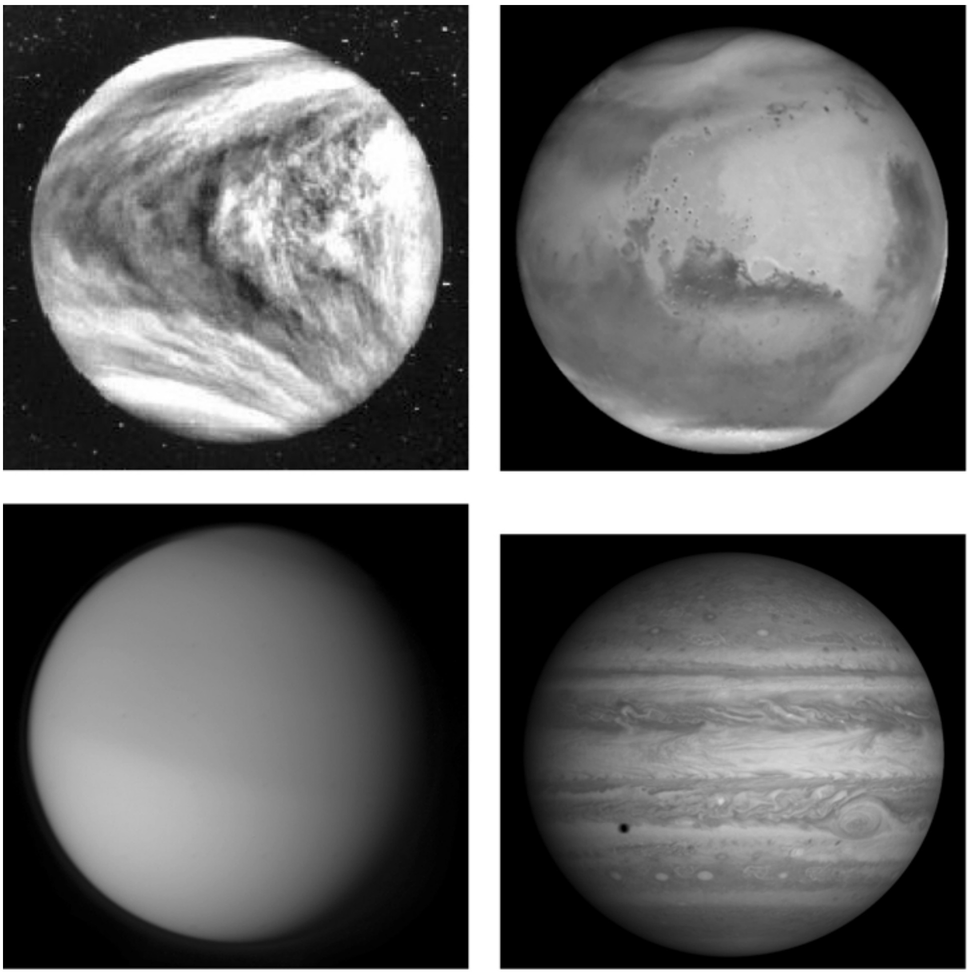


Figure 1. Some Solar System bodies with an atmosphere: Venus (upper left), Mars (upper right), Titan (lower left) and Jupiter (lower right). *Source*: Jet Propulsion Laboratory.

airplanes and gliders, helicopters, balloons and airships. Flight time for gliders depends heavily on wind and updraft patterns, which in turn constrain their surface coverage, while airplanes and helicopters expend significant energy resources simply staying airborne (Elfes et al., 2001). These considerations point towards the use of lighter-than-atmosphere (LTA) systems for planetary exploration due to their potential for extended mission duration, long traverses, and extensive surface coverage capabilities.

Until recently, interest in LTA systems has been primarily focused on passive systems or balloons. NASA's Jet Propulsion Laboratory (JPL), for example, has a Planetary Aerobot Program (Jet Propulsion Lab, 2000) which has conducted preliminary studies on balloons (also called aerovers or aerobots) (Heun et al., 1998) and ballutes (Hall, 2000). The latter are inflatable drag devices whose purpose is to assist in planetary aerocapture and aeroentry, and are not further discussed here.

In this paper, we argue that robotic airships have unique capabilities that make them ideal candidates for airborne planetary exploration. Airships combine the long-term airborne capability of balloons with the maneuverability of airplanes or helicopters. Their controllability allows precise flight path execution for surveying purposes, long-range as well as close-up ground observations, station-keeping for long-term monitoring of high-value science sites, transportation and deployment of scientific instruments and in situ laboratory facilities across vast distances to key science sites, and opportunistic flight path replanning in response to the detection of relevant sensor signatures. Furthermore, robotic airships provide the ability to conduct extensive surveys over both solid regions and liquid-covered areas, and to reconnoîter sites that are inaccessible to ground vehicles. Implementation of these capabilities will require, of course, achieving a high degree of vehicle autonomy across a broad spectrum of operational scenarios.

While the use of robotic airships for planetary exploration is only starting to be addressed, interest in unmanned aerial vehicles (UAVs) is burgeoning in other application areas. In addition to their increasing use as military intelligence gathering and surveillance platforms, UAVs have enormous potential in civilian and scientific contexts. Civilian applications include traffic monitoring and urban planning, inspection of large-scale man-made structures (such as power transmission lines, pipelines, roads and dams), agricultural and livestock surveys, crop yield prediction, land use studies, planning of harvesting, logging and fishing operations, law enforcement, humanitarian demining efforts, disaster relief support, telecommunications, and many others. Scientific applications cover areas such as mineral and archaeological site prospecting, satellite mimicry for ground truth/remote sensor calibration, and environmental, biodiversity, and climate research and monitoring studies.

Elsewhere (Elfes et al., 2001), we have argued that robotic airships represent the alternative of choice for many of these applications. Satellite imagery available for civilian applications is limited in terms of the spatial (pixel) resolution and the spectral bands available, as well as in terms of the geographical and temporal swaths provided by the satellite. Manned aerophotogrammetric or aerial inspection surveys are very costly in terms of aircraft deployment, crew and maintenance time, etc., and their systematic use is therefore beyond the financial scope of many governments and international agencies. These limitations can be addressed through the development of unmanned, substantially autonomous robotic airships that will ultimately allow the airborne acquisition of information in highly flexible, cost-effective, and affordable ways.

The increasing deployment of UAV systems brings with it the development of technologies that have direct applicability to robotic airships for planetary exploration. We ourselves have been engaged since 1997 in a pioneering project in robotic airships, known as Project AURORA (Autonomous Unmanned Remote Monitoring Robotic Airship). In this work, conducted at the Automation Institute (now CenPRA) in Brazil, we have been developing the core control, perception, and reasoning technologies for substantially autonomous airborne vehicle operation (Elfes et al., 2001, Bueno et al., 2002). These include the ability to perform mission, navigation, and sensor deployment planning and execution, flight planning and execution, failure diagnosis and recovery, and adaptive replanning of mission tasks based on real-time evaluation of sensor information and constraints on the airborne system and its surroundings. Our driving applications have been environmental, biodiversity, and climate research and monitoring (Elfes et al., 2000), for which we have selected airships as the technology of choice.

In the sequence of this paper, we address in more detail the use of airships in planetary exploration, and discuss some of the core autonomy technologies required for robotic airships for planetary exploration. We draw on research done in AURORA on airship modeling and control, autonomous navigation, and sensor-based flight control. We also outline initial steps towards an approach to airborne perception and monitoring, and present illustrative experimental results obtained from AURORA.

2. The Potential of Airships for Planetary Exploration

Planetary exploration to date has been primarily performed by fly-by or orbital probes (such as the Voyager, Galileo, Cassini and Odyssey spacecrafts). These are able to quickly and efficiently provide global, albeit limited-resolution surveys of planetary bodies. Additionally, severily restricted surface exploration has been performed by stationary landers (such as the Viking probes) or mobile robots (such as the Sojourner rover). The strategic gap between orbital and ground systems can be bridged through robotic airships that provide low speed, low altitude sensing platforms for high resolution, wide area, controllable data acquisition and monitoring over any type of terrain and geographical site.

The capabilities and features of robotic airships that make them ideal platforms for planetary exploration include:

- The potential for extended mission durations, spanning weeks, months and potentially years. This is due to the fact that airships do not require energy to remain aloft, but only for active maneuvering.
- Excellent payload to weight ratio, particularly as the payload weight increases.
- High stability. The intrinsic aerodynamic characteristics of airships make them resilient, stable and low vibration aerial platforms. Flight control is highly robust, while the low levels of atmospheric turbulence generated only minimally disturb the environment that is being monitored. Reduced levels of high-frequency platform vibration also minimize sensor noise and hardware malfunctions.
- Very long traverse capability. By employing a combination of wind-powered long-distance passive flight with self-powered active local maneuvering, airships can cover enormous distances, enabling them to survey large portions of the surface of a planetary body, far beyond what current or planned surface mobility systems could cover. Additionally, autonomous large-scale atmosphere and weather characterization are possible.
- The capability to survey planetary areas beyond the reach of current ground systems, such as heavily accidented areas, canyons, mountain ranges, volcanoes, shore lines, and liquid bodies (such as the oceans that probably exist on Titan).
- Flight controllability, allowing precise flight path control for systematic surveying, height control for long-range and close-up ground observations, and station-keeping for long-term monitoring of sites of high scientific value.
- Transportation of scientific instruments and onboard laboratory facilities across vast distances, as well as soft landing, deployment and recovery of sensor pods and in situ laboratories at key science sites. Deployment/recovery is facilitated by the vertical take-off and landing capabilities of airships, precluding the need for runways.
- Opportunistic flight path replanning in response to dynamically acquired, scientifically relevant sensor data.
- Finally, airships can be deployed after planetary entry, with inflation and flight initiation happening either during descent or on the ground. Additionally, if lift is produced by heating local atmospheric gases in the envelope, transportation of the lifting gas becomes unnecessary. As a result, airships can achieve the limited weight and size requirements of payloads being transported by spacecraft to a planetary body.

Many of the aspects discussed above are summarized in Table 1, which compares the performance of airplanes,

Table 1. Comparison of aerial vehicle technologies for airborne sensing and monitoring applications. High compliance with each requirement is indicated by three marks (+++), medium by two marks (++), and low or no compliance by one mark (+).

Requirement	Airplane	Helicopter	Airship
Low speed, low altitude flight	+	+++	+++
Station-keeping capability	+	+++	+++
Long endurance	++	+	+++
Vertical take-off/landing	+	+++	+++
Maneuverability	++	+++	++
Payload to weight ratio	++	+	+++
Safe operation	++	+	+++
Low noise and turbulence	+	+	+++
Low vibration	++	+	+++
Low operational cost	++	+	+++
Control simplicity	++	+	+++

helicopters, and airships. Balloons are not considered here because they are not maneuverable. It should be noted that, among UAV aircraft used today, by far the most commonly employed are reduced-scale fixed-wing vehicles (airplanes), followed by rotary-wing (helicopter) aircraft. Airships are only recently becoming a focus of interest in the UAV world (Boschma, 1993), although their advantages are recognized in other areas (Mowforth, 1991; Netherclift 1993).

As can be inferred from Table 1, airships are, on most accounts, better suited to airborne monitoring tasks than airplanes or helicopters. Fundamentally, this is due to two reasons. Firstly, airships derive the largest part of their lift from aerostatic, rather than aerodynamic, forces. Therefore, an airship is not required to spend significant amounts of energy to float in the air, but only to move between locations or to counteract the drift caused by wind. Consequently, airships need smaller engines than airplanes and helicopters for propulsion, which in turn produce less noise, vibration, and turbulence, and consume less energy. Secondly, airships have a dynamic behaviour that is intrinsically of higher stability than other airborne vehicles, making them ideally suited as low-vibration observation platforms. It must be noted, however, that these conclusions depend on the wind characteristics of the atmosphere, as high winds may require greater energy output from airships.

Planetary exploration through aerovehicles brings with it, of course, a number of additional challenges that vary substantially depending on the deployment scenario. The Martian atmosphere is composed mostly of carbon dioxide, and is very thin and cold (0.0006 bar, -73°C), while Venus has a carbon dioxide atmosphere that is very dense and hot at the surface (92 bar, 460°C) and also contains highly corrosive components such as sulfuric acid. Titan, a moon of Saturn, also has a dense atmosphere (four times the density at the Earth's surface, with a surface pressure of 1.5 bar, a gravity of 1/7 that of Earth, and a surface temperature of -180°C), and presents a very exciting scenario for airship deployment (Hall et al., 2002, Lorenz, 2000). The atmospheres of the gas giants (Jupiter, Saturn, Uranus, Neptune) are characterized by pressures and dynamics of such magnitudes that at currently only travel in the upper reaches of the atmosphere is in the realm of the conceivable. While the environmental conditions of these scenarios present significant challenges for balloons or airships, preliminary studies for balloons (Jet Propulsion Lab, 2000) and for HALE (high altitude, long endurance) stratospheric airships (Rehmet et al., 2000; Kueke et al., 2000; Jones and Daly, 2000) have shown the potential of current and emerging technologies to cope with these extreme conditions.

An additional challenge that occurs in planetary exploration is the power source for the airship engines. Preliminary energy requirement studies in the context of HALE airships again provide useful insights (Rehmet et al., 2000; Kueke et al., 2000). Current unmanned airships typically use batteries and/or chemical fuel; the Lotte airship (Kroeplin, 2002) adds a cover of solar cells on the upper part of the envelope to increase mission range. Power is, of course, a pervasive problem in space exploration, and standard solutions include solar power, chemical fuel, and radioisotope thermoelectric generators (RTGs). Beyond Mars orbit, the use of solar power becomes unrealistic, and the most viable alternative is RTGs. Recent political developments seem to indicate that NASA will again be allowed to consider the use of RTGs for planetary exploration; this entails an additional incentive for the use of robotic airships, as RTG-provided energy could be used both for propulsion and for controlled heating of the lift gas, facilitating altitude control of the airship. To minimize energy consumption and maximize the range of robotic airships, an optimal flight planning approach would entail combining both the opportunistic use of prevailing wind patterns and altitude control mechanisms (such as suggested for aerobots (Jet Propulsion Lab, 2000)), and active flight control using the onboard propulsion system.

An autonomous airship will need a basic set of operational capabilities to be able to perform successfully during different flight phases. These phases can be summarized as consisting of deployment or takeoff, ascent, cruise, surveying, cruise, descent, and potentially anchoring for probe deployment. These phases, in varying order, would be repeated over the lifetime of a planetary mission. Figure 2 relates the flight phases to a core set of operational autonomy capabilities. In Fig. 3, the main components of a high-level robotic airship architecture are shown. In what follows, we will discuss our work on several components of this architecture.

3. Towards Autonomous Robotic Airships

Project AURORA (Autonomous Unmanned Remote Monitoring Robotic Airship), started by the authors in 1997, focuses on the development of the technologies required for substantially autonomous airship

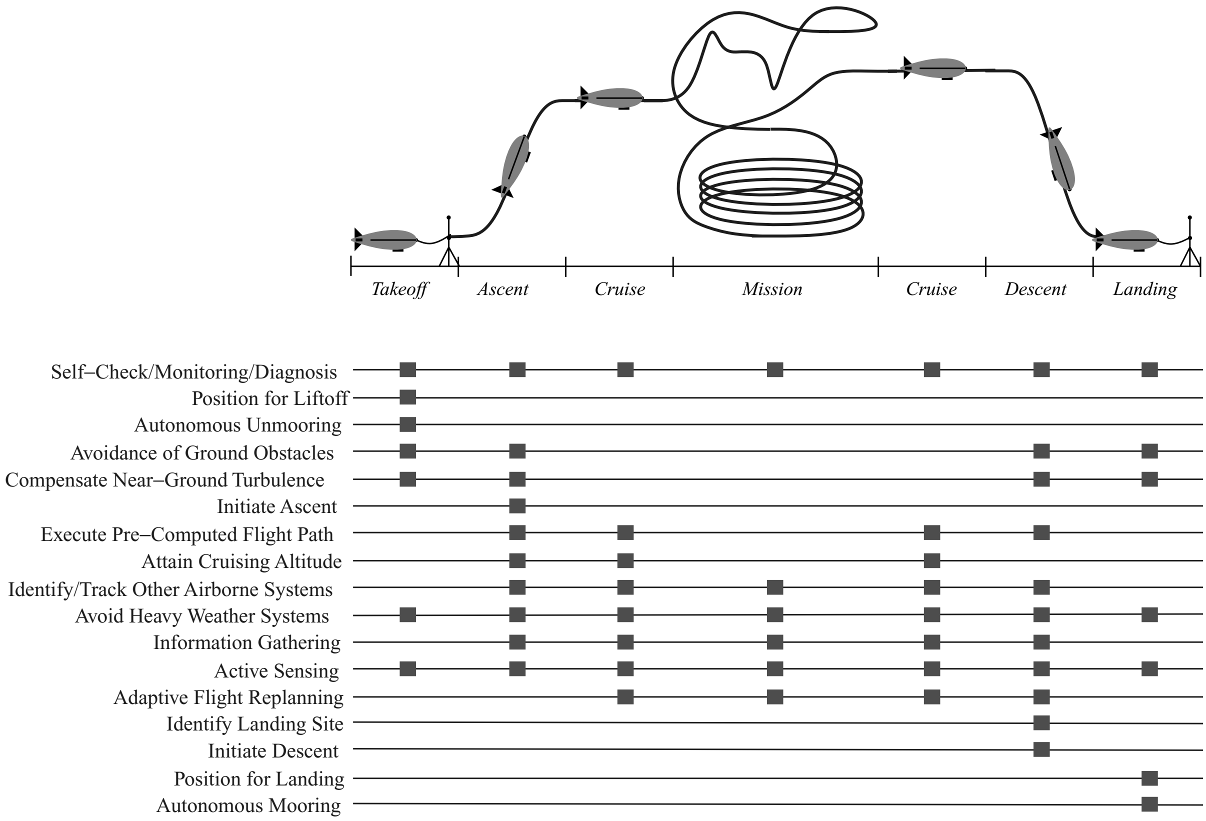


Figure 2. Flight phases for an autonomous robotic airship. The table shows the major tasks to be addressed at each flight phase.

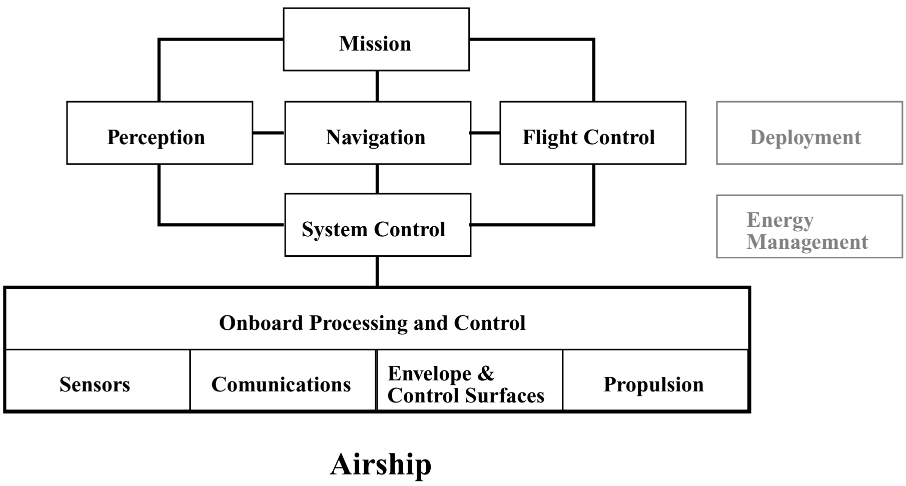


Figure 3. Major components of an autonomous robotic airship architecture.

operation. Our driving applications have been largely related to environmental, biodiversity, and climate research and monitoring. The project builds on previous research done by the authors on remotely piloted helicopters (Ramos and Neves, 1995). Details on various parts of the project can be found in Elfes et al. (1998), De Paiva et al. (1999), Paiva et al. (1999a), Azinheira et al. (2000a), Elfes et al. (2000, 2001).

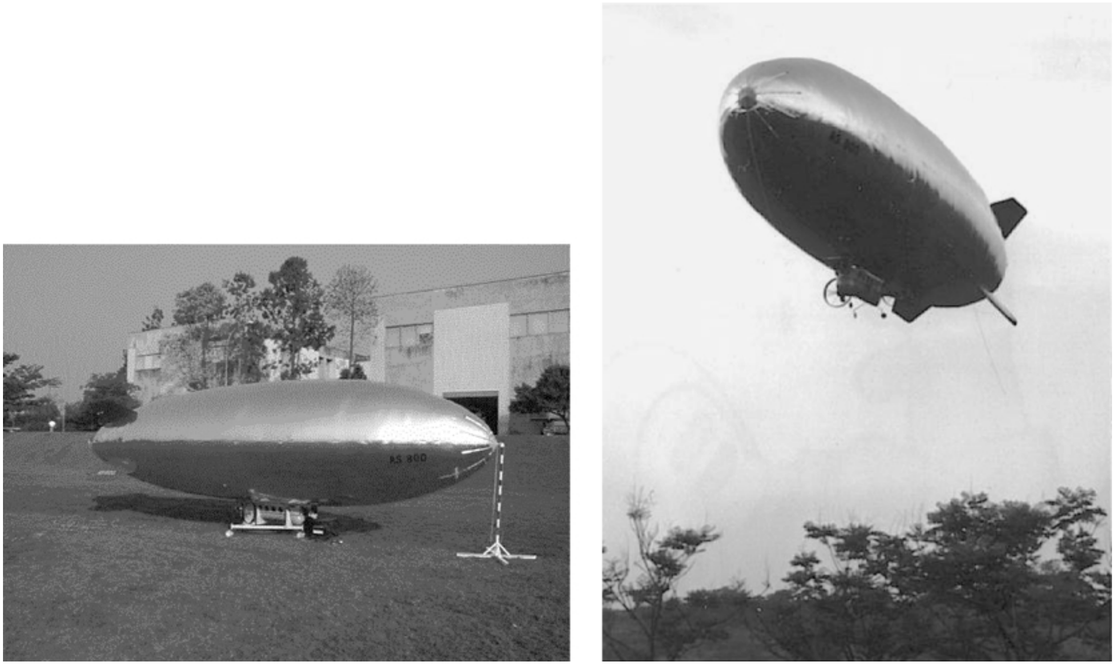


Figure 4. The AURORA I Robotic Airship. The airship, shown moored on the left and in flight on the right, is 9 m long, has a diameter of 2.25 m, and a volume of 24 m^3.

Recent developments and results are presented in Bueno et al. (2002).

Our first prototype, AURORA I, is shown in Fig. 4. The major physical subsystems of AURORA I include: the airship; the onboard control and navigation subsystems, including the internal sensors, hardware, and software; the communications subsystem; the mission sensors; and a base station. By internal sensors we understand those atmospheric, inertial, positioning, and imaging sensors required by the vehicle to accomplish its autonomous navigation tasks. Mission sensors are those selected for specific aerial data-gathering needs, and are not addressed here. The other subsystems are described in the sequence.

3.1. The Airship

AURORA I is conceived as a proof-of-concept system, to be used in low-speed, low-altitude applications. The LTA platform is the AS800 by Airspeed Airships (1998) and Wells (1995). The vehicle is a non-rigid airship (blimp). It has a length of 9 m, a diameter of 2.25 m, and a volume of 24 m^3 (Fig. 4). It is equipped with two vectorable engines on the sides of the sensor and communications pod, and has four control surfaces at the stern, arranged in an "×" configuration. The payload capacity of the airship is 10 kg at sea level, and its maximum speed is 60 km/h. Onboard sensors include DGPS, INS and relative wind speed systems for flight control, and video cameras for navigation and monitoring.

The onboard subsystems include a CPU, sensors, actuators, and a communication subsystem. A compass, inclinometer, and GPS receiver are directly connected, via serial ports, to a PC 104 computer. All other control, navigation, and diagnosis sensors (engine speed, altitude, control surface position, wind speed, accelerometers, fuel and battery level, and engine temperature) and actuators (engines and control surfaces) are connected to a microcontroller.

The ground station is composed of a processor, a differential GPS receiver, and a microcontroller board connected to a remote control unit (RCU). For safety purposes we developed a backup command system which allows the ground operator to teleoperate the airship in case of a software or hardware failure.

Communication between the ground station and the airship occurs over two radio links. One of them operates in analog mode to transmit video imagery from the airship to the ground station. The other operates in digital mode to transmit sensor and command data between the ground and onboard stations. The range for direct line-of-sight data transmission is 30 km. An error detection scheme utilizing CRC and packet retransmission insures data integrity.

A human-machine interface (HMI) provides the communication and visualization mechanism between the operator and the navigation system onboard the airship. Telemetry data visualization, particularly of GPS and inertial sensor data, both for simulated and actual flights, is available to the operator. Additionally, a physical model-based virtual reality airship simulator was developed (Ramos et al., 1999). The simulator is based on a very accurate dynamic model of the airship, outlined in Section 4.1, and incorporates real-world topographical information of selected regions. The simulator is used to validate control strategies and navigation methods, for pilot training, and for mission planning and pre-evaluation.

The software architecture is built as a 3-layer structure, combined with a high-level data flow programming method and system development environment. As the underlying operating system for the AURORA project we have chosen to use RT-Linux. It is known to be reliable and robust, can be used under real-time requirements, and requires relatively little memory and disk space. As airships have relatively large time constants, this allows us to run the individual control and navigation modules as processes under RT-Linux. Processes running on the onboard system read and send sensor data to the ground station and execute the autonomous flight control strategies, sending commands to the actuators. These tasks are executed at a 100 ms rate. This sampling interval was selected based on simulated flights and corroborated as sufficient in actual experimental flights.

The ground station sends commands and mission paths to the onboard control system. It also receives sensor data from the airship, displaying them in real time during simulated and actual flights. The ground system records all data received from the airship for post-flight analysis and visualization. For pilot training and airship teleoperation the remote control unit is used, connected to one of the serial ports of the ground station through a microcontroller. The complexity of the system being developed led to the implementation of a deliberative-reactive intermediate-level process control and communications architecture, where different subsystems can run independently and as separate threads, while able to exchange information and activate or inhibit each other.

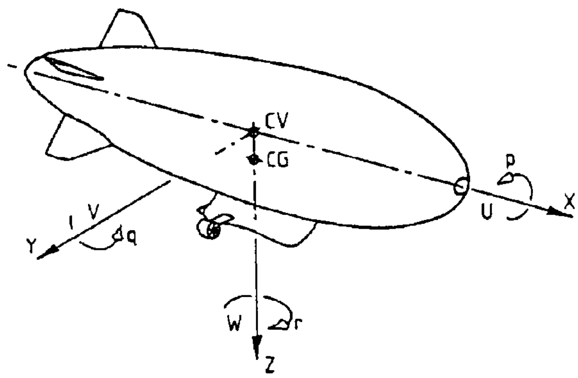


Figure 5. Local reference frame for the airship (Mowforth, 1991).

4. Airship Control

4.1. Dynamic Modeling and Control System

As the basis for the development of the control and navigation strategies, we have developed a 6-DOF physical model of the airship that includes the nonlinear flight dynamics of the system. We briefly review the model here, while a more detailed presentation is found in Gomes and Ramos (1998).

The dynamic model assumes that motion is referenced to a system of orthogonal body axes fixed relative to the airship, with the origin at the Center of Volume (CV), assumed to coincide with the gross Center of Buoyancy (CB) (Fig. 5).

The orientation of this body-fixed frame (X, Y, Z) with respect to an Earth-fixed frame (X_E, Y_E, Z_E) is obtained through the Euler angles (Φ, Θ, Ψ). The airship linear and angular velocities are given by (U, V, W) and (P, Q, R), respectively. Angular velocities (P, Q, R) are also referred to as the roll, pitch and yaw rates.

While developing an accurate mathematical model of airship flight dynamics, the following aspects were taken into account:

- The airship displaces a large volume of air and consequently its virtual mass and inertia properties are substantial when compared with those associated with the vehicle itself. The model incorporates the mass and inertia of the vehicle, the mass and inertia of the buoyancy volume (the air displaced by the total volume of the airship), and the virtual mass and inertia of the air surrounding the airship that is displaced by the relative motion of the airship in the atmosphere.

- The airship mass may change in flight due to ballonet deflation or inflation. For purposes of the dynamic model, we have assumed that the airship mass varies slowly, and the associated time derivatives are zero.
- To accommodate the constant change of the position of the Center of Gravity (CG), the airship motion has to be referenced to a system of orthogonal axes fixed relative to the vehicle with the origin at the Center of Volume (CV) (Fig. 5).
- The airship is assumed to be a rigid body, so that aeroelastic effects are ignored.
- The airframe is assumed to be symmetric about its vertical (XZ) plane, so that both the CV and the CG lie in the symmetry plane.

Taking into account the considerations given above, we have developed a dynamic model that is expressed as:

$$M \frac{dx_A}{dt} = F_d(x_A) + F_a(x_A) + P + G \qquad (1)$$

where M is the 6×6 mass matrix and includes both the actual inertia of the airship as well as the virtual inertia elements associated with the dynamics of buoyant vehicles; $x_A = [U, V, W, P, Q, R]$ is the vector of airship state variables; F_d is the 6×1 dynamics vector containing the Coriolis and centrifugal terms; F_a is the 6×1 vector of aerodynamic forces and moments; P is the 6×1 vector of propulsion forces and moments, and G is the 6×1 gravity vector, which is a function of the difference between the weight and buoyancy forces.

The aerodynamic model used extends the seminal work presented in Gomes (1990), and takes advantage of information from a wind tunnel database built to model the Westinghouse YEZ-2A airship (Gomes, 1990). The adaptation was possible due to the same length/diameter ratio (4 : 1) of both airships. The aerodynamic coefficients available in the database are a function of the aerodynamic incidence angles (angle of attack and sideslip angle varying in the range of $[-25^\circ, +25^\circ]$), and of the three deflections of the tail surfaces (elevator, rudder and aileron, also varying in the range of $[-25^\circ, +25^\circ]$).

Using this 6-DOF non-linear model, a SIMULINK-based control system development environment was built to allow the design and validation of flight control and trajectory following strategies (Paiva et al., 1999b).

As control actuators, the AS800 has deflection surfaces and thrusters. The "×"-arranged deflection surfaces generate the equivalent rudder and elevator commands of the classical "+" tail, with allowable deflections in the range of $\pm 25^\circ$. The engines can be vectored from -30° to $+120^\circ$ up. The rudder and elevator are responsible for directional control (left and right, up and down) and their effect is due to aerodynamic forces produced at medium to high speeds. The thrusters are responsible for generating the necessary forces for controlled airship motion. Their vectoring is used for vertical load compensation and for control of vertical displacements at low speeds. It is important to note that for large airships operating under the critical airspeed of 5 m/s, the control surfaces are considered to be ineffective (Gomes and Ramos, 1998; Gomes, 1990). For the AS800, control is still possible at low airspeeds due to the flow generated by the main thrusters, which increases the efficiency of the deflection surfaces. The airship also has a stern thruster used mainly during hover. Different arrangements of actuators and thrusters can provide easier hover and slow-speed maneuvering capabilities.

Using both the model outlined above and analyses of airship motion, we have identified three important control challenges: non-minimum phase behavior and oscillatory modes at low speeds, time-varying behavior due to altitude variations and fuel burning, and variable efficiency of the actuators depending on airship speed. All of these issues were taken into account in the design of the control system.

The airship control system is designed as a 3-layer control system (Paiva et al., 1999b). At the bottom level, the actuators described above provide the means for maneuvering the airship along its course. At the intermediate level, two main control algorithms with different structures are available to command the actuators based on the mission profile. These two control algorithms implement longitudinal and lateral control. The longitudinal control algorithm is based on a feedforward/feedback structure, and controls the propulsion, vectoring and elevator deflection for take-off, cruise, hover, and landing maneuvering operations. The lateral control algorithm, discussed in more detail below, controls rudder deflection and the tail thruster for turning maneuvers. Finally, the top level of the control architecture is implemented as a supervisory layer that is responsible for failure detection and mission replanning in the presence of unexpected events.

4.2. Path Tracking

An important airborne vehicle autonomy problem is following a pre-computed flight path, defined by a set of points given by their coordinates (latitude and longitude), with given speed and altitude profiles. In this section we introduce the trajectory following problem and outline the approaches investigated in AURORA, as well as the trajectory error metrics.

We posit trajectory following as an optimal control problem, where we compute a command input that minimizes the path tracking error for a given flight path. Allowable flight paths are defined as sequences of straight line segments joining waypoints. The heading change at each waypoint (between consecutive segments) may vary in the $\pm 180^\circ$ range, and the distance between the actual airship position and the precomputed trajectory path is to be continuously minimized. The longitudinal motion is maintained at a constant altitude and airspeed, and is considered decoupled from the lateral motion; this is a common assumption in aerial vehicle control (Kaempf and Well, 1995).

We start by presenting the airship lateral dynamics model. The dynamics of the airship in the horizontal plane is given by the fourth order linear state space system:

$$\dot{x} = Ax + Bu \quad (2)$$

where the state x includes the sideslip angle β, yaw rate R, roll rate P and roll angle Φ. The control input u is the rudder deflection ζ.

The path tracking error metric is defined in terms of the distance error δ to the desired path, the angular error ϵ, and the ground speed V (Fig. 6). Assuming the airship ground speed to be constant and the angular error ϵ to be small, the following linearized path tracking model results:

$$\begin{cases} \dot{\delta} = V \sin\epsilon = V_0\, \epsilon \\ \dot{\epsilon} = R \end{cases} \quad (3)$$

where V_0 is the reference ground speed considered for design purposes.

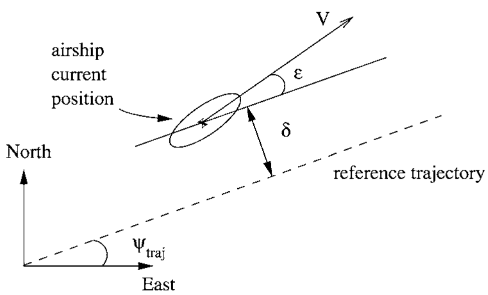


Figure 6. Definition of path tracking error.

In order to accommodate both the distance and angular errors in a single equation, a look-ahead error δ_a may be estimated at a time Δt ahead of the actual position:

$$\delta_a \approx \delta + V_0 \Delta t \epsilon \quad (4)$$

This strategy has already been successfully used for the guidance of both unmanned aircraft [30] and ground mobile robots (Botto et al., 1999).

It is important to note that the ground speed V will be kept constant only in the absence of wind (as the longitudinal controller maintains a constant airspeed). Therefore, the tracking controllers should present robustness properties in order to assure good tracking under wind incidence. This is the case for the control strategies discussed below, whose robustness was verified through simulated examples and actual flight experiments.

The first approach we developed for the nonlinear control problem presented above uses the linearized path tracking error dynamics (Eq. (3)) around a trim condition for a constant fixed airspeed. A robust H_∞ design is used next to assure that a previously defined operation envelope is covered, taking into account the simplified model and unmodeled uncertainties.

The control problem may then be expressed as the search for a regulator F of the output y, where the error e is expressed in terms of the look-ahead track error δ_a (Fig. 7). The system G to be controlled is obtained as the series of the lateral airship model (Eq. (2)) and the linearized path tracking model (Eq. (3)). The lateral dynamic model of the airship used in the design is an approximation of Eq. (2), where only the second order horizontal motion (with states β and R) is considered. Here the control signal is fed directly to the rudder without the need for any lower level controller.

For the correct shaping of the controller, a mixed sensitivity H_∞ technique is used (Doyle et al., 1992), allowing us to specify the characteristics of the closed loop in the frequency domain. Three weighting functions (W_1, W_2, W_3) are used, respectively, for the sensitivity function S_1 (performance), for the actuation sensitivity function S_2 and for the complementary sensitivity function S_3 (stability robustness). The look-ahead distance used for the controller design is

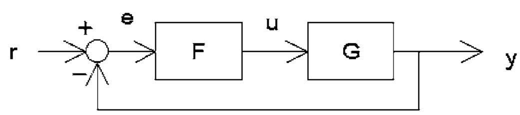


Figure 7. H_∞ control block diagram.

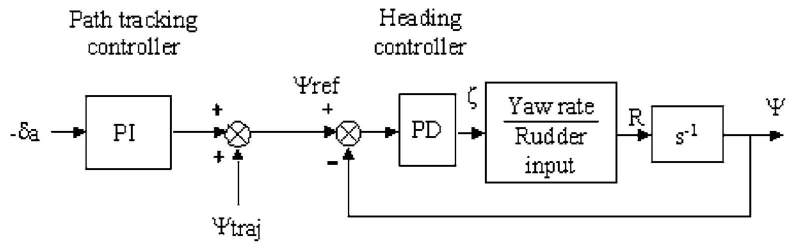


Figure 8. PI control block diagram.

chosen with a reference speed of 10 m/s and time of 2.5 s, so that $e = \delta_a \approx \delta + 25\epsilon$.

The sensitivity weighting function W_1 is chosen to permit good tracking at low frequencies. The complementary sensitivity weighting function W_3 is used for high frequency noise rejection. Finally, the actuation sensitivity weighting W_2 reduces the use of actuators for higher frequencies. The closed-loop behavior of the linearized system can be expressed in terms of the performance sensitivity function, and shows excellent agreement with the frequency shaping: good command following at low frequencies (low error), and disturbance rejection at higher frequencies. The controller is designed for continuous time, reduced to a fifth order controller and finally put in discrete form with a 10 Hz sampling rate. A detailed discussion of this approach is found in Paiva et al. (1999a, 1999b), Ramos et al. (2000), and Azinheira et al. (2000b).

The second approach investigated is based on a classical PI approach, with a heading control inner loop and a path-tracking outer loop (Fig. 8). The heading controller is based on a proportional-derivative (PD) controller. The path-tracking controller is a proportional-integral (PI) controller whose output, added to the

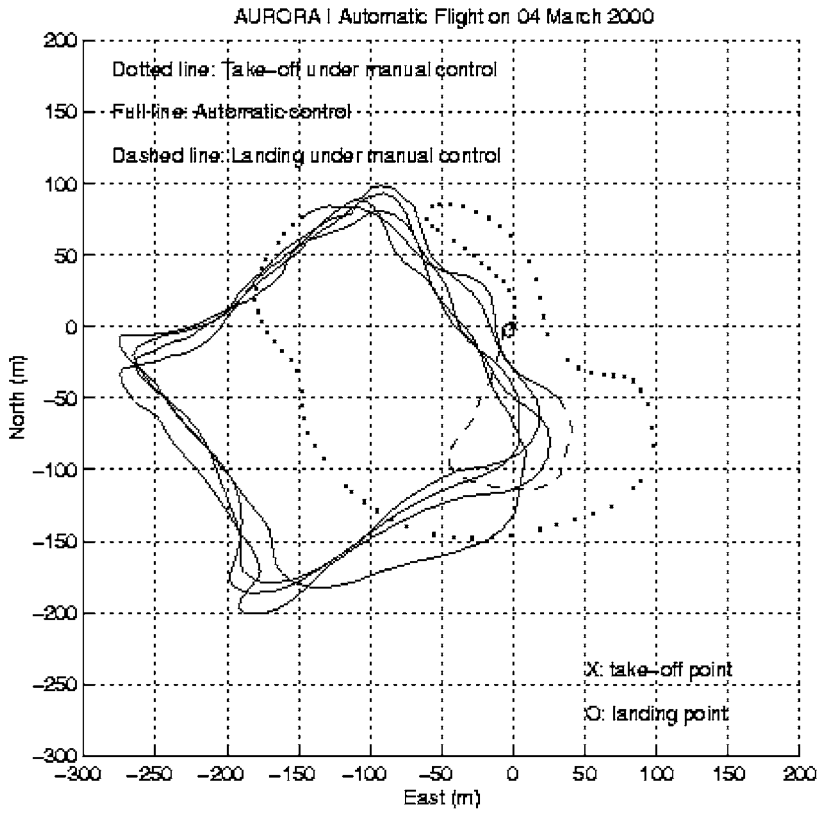


Figure 9. Autonomous flight of the AURORA I airship, following a predefined mission trajectory.

trajectory heading angle Ψ_{traj}, yields the reference signal Ψ_{ref} for the heading controller. The PI controller input is the look-ahead path tracking error δ_a, given in equation Eq. (4). The PI controller uses the tracking error δ_a to correct the reference signal for the heading controller, with the necessary correction forcing the tracking error to decrease. It is interesting to note from this control structure that, in the absence of wind, the reference heading angle will be the same heading angle Ψ_{ref} of the trajectory. In the presence of wind, however, to compensate for the lateral forces, the airship heading angle will assume the value necessary to minimize the look-ahead tracking error δ_a, and the airship will consequently fly "sideways" under such conditions. The proportional and integral gains of the controller are obtained by trial and error, and the PI controller uses an anti-wind up strategy to avoid saturation of the integral term.

The lateral dynamic model used is the fourth order transfer function from the yaw angle Ψ to the rudder deflection ζ, obtained from Eq. (2). This single controller presents good robustness properties for different dynamic models, covering a wide range of airspeeds and heavinesses (heaviness is the difference between the airship weight and the buoyancy forces). Again, details are found in Paiva et al. (1999a, 1999b), Ramos et al. (2000), and Azinheira et al. (2000b).

Simulations and experimental work have shown that the PI and H_∞ approaches follow the reference flight path well, with little influence from the presence of wind. In most situations, the H_∞ controller is more ambitious and makes the control signal saturate for longer periods of time. At higher airspeeds, this may cause the control actuator signal to oscillate slightly due to higher controller gain. Despite this, the variances of the control signals are very close for the PI and H_∞ approaches. However, the H_∞ controller shows a remarkable advantage over the PI controller when the airship is subjected to step disturbances (Azinheira et al., 2000b).

Overall, it can be said that the trajectory error minimization strategy leads to PI and H_∞ approaches exhibiting similar path tracking behavior and robustness characteristics, while the H_∞ controller presents superior performance under wind disturbances.

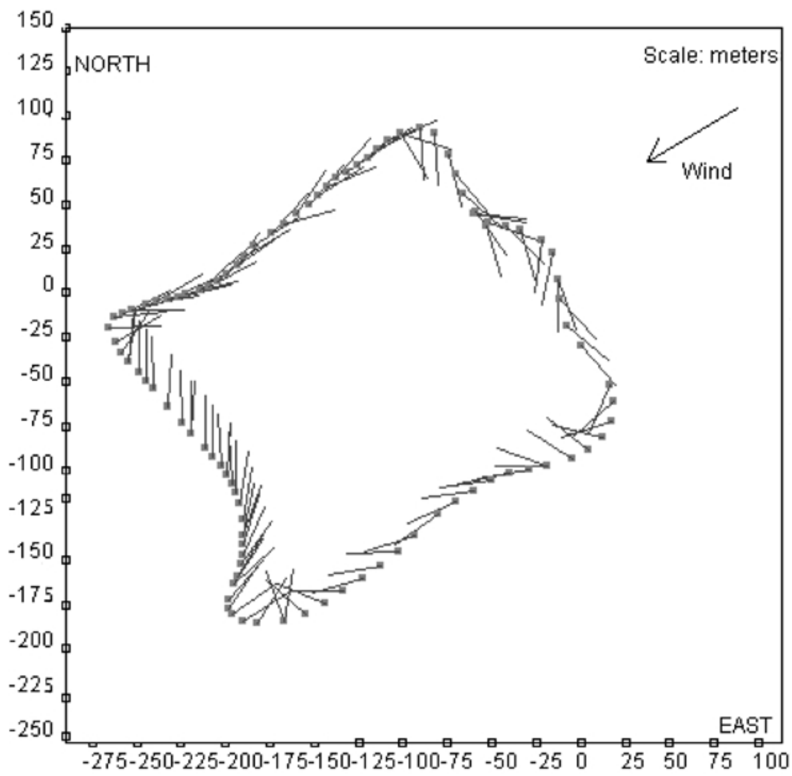


Figure 10. AURORA I position and heading along a loop.

5. Autonomous Flight Trajectory Following

Initial experimental validation of the modeling and control work presented above was done by testing the PI guidance control method. The PI approach was chosen for the first test flight experiments due to the simplicity of the control structure and its implementation. The H_∞ approach has been implemented and is currently undergoing testing. Airship position and heading were obtained from DGPS and compass data.

Results from one of our first flights are shown in Figs. 9 and 10. In this flight, take-off and landing of the airship were done manually. The mission path, flown autonomously by the airship, was defined as a square with sides of 200 m length. Wind speed during the experiment stayed in the range of 0 to 10 km/h, blowing approximately from the northeast. Airship path following was controlled automatically by the onboard system, while altitude was controlled manually by the ground pilot (Ramos et al., 2000, 2001).

In Fig. 9, the dotted line represents the airship motion under teleoperation from take-off until hand-over to autonomous control. The continuous line represents the airship motion under PI trajectory tracking control. Finally, the dashed line shows the motion of the airship after hand-back to teleoperation for the final landing approach. The plot clearly shows the adherence of the airship trajectory to the mission path, as well as overshoots due to the disturbing winds when the airship turns from southwest to northwest.

Figure 10 presents one of the loops performed by the airship around the square. The dots represent the airship position and the lines represent its heading. As remarked before, the control method composed by the tracking and heading controllers automatically adjusts the airship heading to compensate for wind disturbances; for example, in the lower left part of the square loop, the airship navigates "sideways", while in the upper left it navigates mostly aligned with the trajectory.

6. Perception

Sensor-based adaptive navigation of a robotic aircraft requires several perceptual competencies. Our work in perception-based navigation and control for the AURORA airship is still in an initial phase. It is

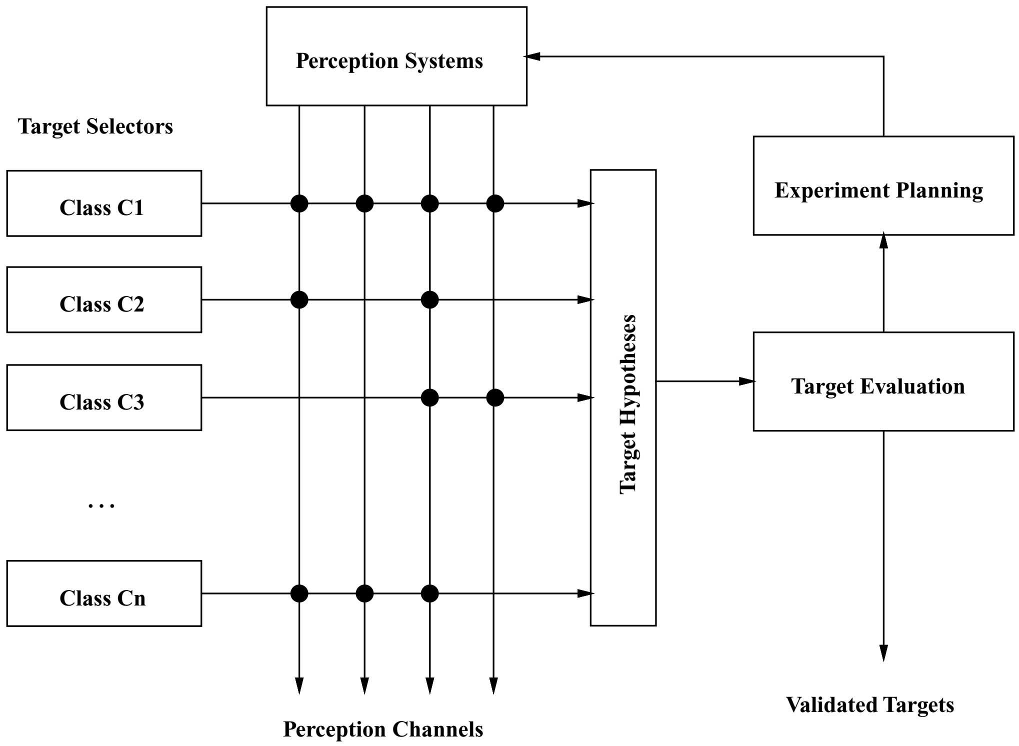


Figure 11. System architecture for dynamic target identification: a target selection, validation and classification cycle is implemented.

currently focused on two sets of issues: visual-based servoing for autonomous take-off, hovering, tracking, and landing purposes; and autonomous target recognition and tracking mechanisms for finding and identifying man-made structures (such as roads or pipelines), geographical structures (such as rivers), air and water pollution sources, and biological targets of interest.

Our approach to dynamic target recognition is based on a cycle of hypothesis formulation, experiment planning for hypothesis validation, experiment execution, and hypothesis evaluation (Fig. 11).

6.1. Adaptive Target Identification

As a representational framework, we encode sensor observations using stochastic visual lattice models (Kämpke and Elfes, 1999) that draw on our previous work on the use of Markov Random Field (MRF) models (Winkler, 1995) in robot perception and control (Elfes, 1991, 1992, 1996).

For target identification and classification we use a classical hypothesis testing approach (Fukunaga, 1990). For a c-class classification problem, with classes $\omega_1, \ldots, \omega_c$, we assign the observation X to class k if the posterior distribution for k is the largest of all posterior distributions. The Bayes classification error depends fundamentally on the conditional density functions $p_i[X|\omega_i]$. We affect the shape of these functions by explicitly controlling the position of the robot vehicle and its sensor parameters, thereby improving the classification error (Elfes et al., 2000).

In the architecture for adaptive target recognition that we are developing, target selectors, which determine what classes of targets are being sought, are switched on or off depending on the type of mission being executed.

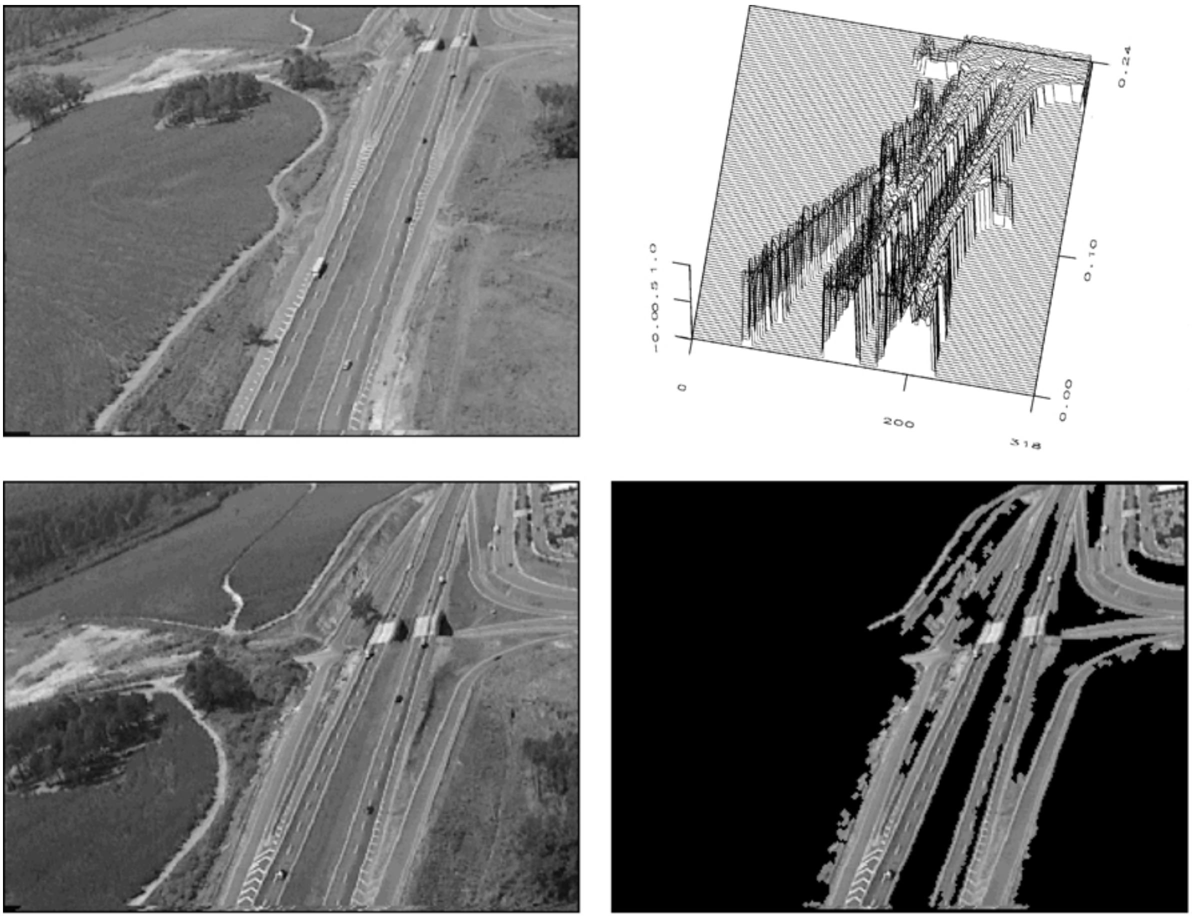


Figure 12. Identification and tracking of a paved road using an airborne camera. The road classification probabilities for the upper left image are shown on the upper right, while for the lower left image the segmented image is shown on the lower right.

The selectors, in turn, are used to identify candidate target hypotheses for further evaluation. This may lead to an outright rejection or validation of the targets, or to controlled acquisition of additional imagery to increase the discriminatory capability of the system.

6.2. *Optimal Design of Experiments*

To control the acquisition of new data in an optimal way, we use an approach derived from the theory of optimal design of experiments (Fedorov, 1972) to discriminate hypotheses based on the entropy measure. For c classes, we have a set of prior probabilities, $p_0[H_j]$, $j = 1, \ldots, c$, that correspond to the hypotheses of the target belonging to the classes $\omega_1, \ldots, \omega_c$. Assuming that a new experiment $\mathcal{E}$ has been conducted in the form of a sensor observation, we obtain the posterior probabilities $p[H_j]$. We compute the increase in information obtained from the observation, ΔI, using a mutual information measure. For a finite-horizon problem and a finite set of sensing options (obtained from the tesselation of the representational space and a discretization of the sensor pose and parameter alternatives, see Elfes (1996)), we can compute the expected value of ΔI with respect to the results of the observations. The sequence of observations (experiment) that maximizes the expected mean increment of information $E[\Delta I(\mathcal{E})]$ will be an optimal experiment.

6.3. *Target Identification and Tracking Using Aerial Imagery*

Figure 12 shows results from paved road identification and tracking. Identification and segmentation of the roads in the images was done using probabilistic measures based on the spectral characteristics of the targets in the visible RGB bands. Atmospheric conditions and sensor limitations lead to a higher correct classification rate for road portions closer to the airborne camera, while some parts of the imagery that are further away from the airship are misclassified. As the airborne vehicle comes closer to the new target regions, the change in the distributions of the observations leads to a correct reclassification.

7. Conclusions

In this paper, we have suggested that robotic airships provide a strategic alternative for planetary exploration, and outlined the advantages of airships vis-a-vis other aerial vehicles. We discussed the autonomy requirements of planetary exploration airships, and presented an overview of some of the autonomy technologies undergoing development in AURORA. These include autonomous flight control, trajectory following, and preliminary work towards autonomous perception-based flight planning and execution. The positive results obtained from our autonomy technology development serve to support our argument that robotic airships represent a strategic alternative for exploration of planetary bodies with an atmosphere.

Acknowledgments

The authors wish to thank Sergio B.V. Gomes for contributing to Project AURORA his unique knowledge on airship modeling and operation; Gregg Podnar, from Carnegie-Mellon University, and Mario F.M. Campos, from DCC/UFMG, for fruitful discussions on applications of airships; and our students for their effort and help implementing parts of the project.

The work presented in this paper was partially supported by the Information Technology Institute (formerly called the Automation Institute) of the Brazilian Ministry of Science and Technology, and partially by the Brazilian funding agencies FAPESP and CNPq. A. Elfes was supported during the period 2000/2001 by a Mercator Professorship of the German Research Foundation (DFG), and by the Research Institute for Applied Knowledge Processing (FAW), in Ulm, Germany. He has been at the Jet Propulsion Laboratory since May/2001.

Dr. J.R. Azinheira was supported by the Portuguese Operational Science Program (POCT I), co-financed by the European FEDER Program.

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the sponsoring organizations or of the organizations the authors have been or are currently affiliated with.

References

Airspeed Airships. 1998. *The AS800 Airship*. http://airship.demon.co.uk/airspeed.html.

Azinheira, J.R., de Paiva, E.C., Ramos, J.J.G., and Bueno, S.S. 2000a. Mission path following for an autonomous unmanned airship.

In *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, Detroit, MI, IEEE.

Azinheira, J.R., Paiva, E.C., Ramos, J.J.G., and Bueno, S.S. 2000b. Mission path following for an autonomous unmanned airship. In *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, San Francisco, USA, IEEE.

Boschma, J.H. 1993. The development progress of the U.S. Army's SAA LITE Unmanned Robot Airship. In *Proceedings of the AIAA Lighter-Than-Air Systems Technology Conference*, AIAA.

Botto, A., Azinheira, J.R., and Costa, J.S. 1999. A comparison between robust and predictive autonomous guidance controllers. In *Proceedings of the Eighteenth IASTED International Conference*, Innsbruck, Austria, IASTED.

Bueno, S.S., Azinheira, J.R., Ramos, J.J.G., Paiva, E.C., Rives, P., Elfes, A., Carvalho, J.R.H., and Silveira, G.F. 2002. Project aurora: Towards an autonomous robotic airship. In *Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2002)*, Lausanne, Switzerland, IEEE/RSJ.

De Paiva, E.C., Bueno, S.S., Gomes, S.B.V., and Bergerman, M. 1999. A control system development environment for the aurora semi-autonomous robotic airship. In *Proceedings of the 1999 IEEE International Conference on Robotics and Automation*, Detroit, MI, IEEE.

Doyle, J.C., Francis, B., and Tannenbaum, A. 1992. *Feedback Control Theory*, Macmillan: New York.

Elfes, A. 1991. Dynamic control of robot perception using stochastic spatial models. In *Information Processing in Mobile Robots*, G. Schmidt, (Ed.), Springer-Verlag: Berlin.

Elfes, A., 1992. Multi-source spatial fusion using bayesian reasoning. In *Data Fusion in Robotics and Machine Intelligence*, M.A. Abidi, and R.C. Gonzalez (Eds.), Academic Press: San Diego, CA.

Elfes, A. 1996. Robot navigation: Integrating perception, environment constraints and task execution within a probabilistic framework. In *Reasoning With Uncertainty in Robotics*, vol. 1093 of *Lecture Notes in Artificial Intelligence*, L. Dorst, M.van Lambalgen, and F. Voorbraak (Eds.), Springer-Verlag: Berlin, Germany.

Elfes, A., Bergerman, M., Bueno, S.S., and Carvalho, J.R.H. 2001. Modelling, control and perception for an autonomous robotic airship. In *Modelling of Sensor-Based Intelligent Robot Systems*, H. Bunke, H.I. Christensen, G. Hager, and R. Klein (Eds.), Springer-Verlag: New York.

Elfes, A., Bergerman, M., and Carvalho, J.R.H. 2000. Towards dynamic target identification using optimal design of experiments. In *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, San Francisco, CA, IEEE.

Elfes, A., Bueno, S.S., Bergerman, M., and Ramos, J.J.G. 1998. A semi-autonomous robotic airship for environmental monitoring missions. In *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, Leuven, Belgium, IEEE.

Elfes, A., Campos, M.F.M., Bergerman, M., Bueno, S.S., and Podnar, G.W. 2000. A robotic unmanned aerial vehicle for environmental research and monitoring. In *Proceedings of the First Scientific Conference on the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)*, Belém, Pará, Brazil, LBA Central Office, CPTEC/INPE, Rod. Presidente Dutra, km 40, 12630-000 Cachoeira Paulista, SP, Brazil.

Fedorov, V.V. 1972. *Theory of Optimal Experiments*, Academic Press: New York.

Fukunaga, K. 1990. *Introduction to Statistical Pattern Recognition*, 2nd edn., Academic Press: New York.

Gomes, S.B.V. 1990. *An Investigation of the Flight Dynamics of Airships with Application to the YEZ-2A*. Ph.D. Thesis, College of Aeronautics, Cranfield University.

Gomes, S.B.V. and Ramos, J.J.G. 1998. Airship dynamic modeling for autonomous operation. In *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, Leuven, Belgium, IEEE.

Hall, J.L. 2000. A review of ballute technology for planetary aerocapture. In *Proceedings of the 4th IAA Conference on Low Cost Planetary Missions*, Laurel, MD, IAA.

Hall, J.L., Kerzhanovich, V.V., Jones, J.A., Cutts, J.A., Yavrouian, A.A., Colozza, A., and Lorenz, R.D. 2002. Titan Airship Explorer. In *Proceedings of the 2002 IEEE Aerospace Conference*, Big Sky, Montana, USA, IEEE.

Heun, M.K., Jones, J.A., and Neck, K. 1998. Solar/Infrared Aerobots for Exploring Several Planets. Jpl new technology report npo-20264, Jet Propulsion Lab (JPL), Pasadena, CA.

Jet Propulsion Lab. 2000. *Planetary Aerovehicles*. http://www.jpl.nasa.gov/adv_tech/balloons/ summary.htm.

Jones, J.G.L. and Daly, N. 2000. Remote piloted airships for the development of stratospheric communication and control systems. In *Proceedings of the 3rd International Airship Convention and Exhibition (IACE 2000)*, Friedrichshafen, Germany, The Airship Association, UK.

Kaempf, B.G. and Well, K.H. 1995. Attitude control system for a remotely-controlled airship. In *Proceedings of the 11th AIAA Lighter-Than-Air Systems Technology Conference*, Clearwater, USA, AIAA.

Kämpke, T. and Elfes, A. 1999. Markov sensing and superresolution images. In *Proceedings of the 10th INFORMS Applied Probability Conference (AP99)*, Ulm, Germany.

Kroeplin, B. 2002. Solar Airship LOTTE. In Technical Report, Institute for Statics and Dynamics of Aerospace Structures, University of Stuttgart, Germany.

Kueke, R., Lindstrand, P., Groepper, P., and Schaefer, I. 2000. High altitude long endurance aerostatic platforms: The European approach. In *Proceedings of the 3rd International Airship Convention and Exhibition (IACE 2000)*, Friedrichshafen, Germany, The Airship Association, UK.

Lorenz, R.D. 2000. Post-Cassini exploration of titan: Science rationale and mission concepts. *Journal of the British Interplanetary Society*, 53.

Lourtie, P., Azinheira, J.R., Rente, J.P., and Felício, P. 1995. ARMOR project—Autonomous flight capability. In *Proceedings of the AGARD FVP95 Specialist Meeting: Design and Operation of Unmanned Air Vehicles*, Turkey, AGARD.

Mowforth, E. 1991. *An Introduction to the Airship*, The Airship Association Ltd.: UK.

Netherclift, O.J. 1993. *Airships Today and Tomorrow*, The Airship Association Ltd.: UK.

Paiva, E.C., Bueno, S.S., Gomes, S.B.V., Ramos, J.J.G., and Bergerman, M. 1999b. Control system development environment for AURORA's semi-autonomous robotic airship. In *Proceedings of the 1999 IEEE International Conference on Robotics and Automation*, Detroit, USA, IEEE.

Paiva, E.C., Elfes, A., and Bergerman, M. 1999a. Robust control of an unmanned airship for cooperative robotic applications. In *Proceedings of the 1999 International Workshop on Dynamic Problems in Mechanics and Mechatronics (EURODINAME '99)*, Schloß Reisensburg, Ulm, Germany, Springer-Verlag: Berlin.

Ramos, J.J.G., Maeta, S.S., Bergerman, M., Bueno, S.S., Bruciapaglia, A., and Mirisola, L.G.B. 1999. Development of a VRML/JAVA unmaned airship simulation environment. In *Proceedings of the 1999 International Conference on Intelligent Robots and Systems (IROS'99)*, Kyongju, South Korea, IEEE/RSJ.

Ramos, J.J.G. and Neves, O. 1995. Environment for unmanned helicopter control system development: Application examples. In *Proceedings of the 4th IEEE Conference on Control Applications*, Albany, NY, IEEE.

Ramos, J.J.G., Paiva, E.C., Azinheira, J.R., Bueno, S.S., Maeta, S.M., Mirisola, L.G.B., Bergerman, M., Faria, B.G., and Elfes, A. 2001. Flight experiment with an autonomous unmanned robotic airship. In *Proceedings of the 2001 International Conference on Field and Service Robotics (FSR 2001)*, Helsinki, Finland, IEEE.

Ramos, J.J.G., Paiva, E.C., Maeta, S.M., Mirisola, L.G.B., Azinheira, J.R., Faria, B.G., Bueno, S.S., Bergerman, M., Pereira, C.S., Fujiwara, C.T., Batistela, J.P., Frazzato, R.R., Peixoto, R.P., Martins, G.C., and Elfes, A. 2000. Project aurora: A status report. In *Proceedings of the 3rd International Airship Convention and Exhibition (IACE 2000)*, Friedrichshafen, Germany, The Airship Association: UK.

Rehmet, M.A., Kroeplin, B.-H., Epperlein, F., Kornmann, R., and Schubert, R. 2000. Recent developments on high altitude platforms. In *Proceedings of the 3rd International Airship Convention and Exhibition (IACE 2000)*, Friedrichshafen, Germany, The Airship Association: UK.

Wells, N. 1995. Practical operation of remotely piloted airships. In *Proceedings of the 11th AIAA Lighter-than-Air Systems Technology Conference*, Clearwater Beach, FL, AIAA.

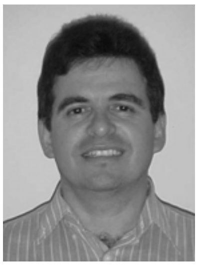
Winkler, G. 1995. *Image Analysis, Random Fields and Dynamic Monte Carlo Methods*, Springer-Verlag: Berlin.

Alberto Elfes received the E.Eng. degree in Electronics Engineering in 1975 and the M.Sc. degree in Computer Science in 1980, both from the Aeronautics Institute of Technology (ITA), Brazil. He obtained the Ph.D. degree in Electrical and Computer Engineering from Carnegie-Mellon University (CMU), USA, in 1989. From 1989 to 1993 he was a research scientist at the Department of Computer Sciences, IBM T. J. Watson Research Center, NY. In 1993 he was invited by the United Nations Development Program (UNDP) to join a pilot project in strategic information technologies, where he was responsible for advanced research and training programs. From 1994 to 2000 he was director of the Automation Institute, Brazil. After a sabbatical at the FAW research institute in Germany, he became a principal scientist at the Jet Propulsion Laboratory in 2001. He has worked extensively in stochastic models for robot perception, navigation and control, and developed the Occupancy Grid and Inference Grid frameworks. His recent and current research work includes robotic airships for environmental research and planetary exploration, and new approaches to complex system risk analysis and design optimization for space missions.

Samuel Siqueira Bueno received the B.S. degree from the Catholic University of Minas Gerais in July 1981, the M.Sc. degree from the University of Campinas in July 1989, and the Ph.D. degree from the University of Nice-Sophia Antipolis (Laboratoire I3S-CNRS), France, in December 1993. Since 1983 he is a research scientist at the CenPRA Research Center in Campinas, Brazil. Since 1996 he is the coordinator of the Robotics and Computer Vision Laboratory (LRVC). His interest areas include identification and control of industrial processes and aerial robotics.

Marcel Bergerman received his B.S. and M.Sc. degrees from the University of São Paulo, Brazil, respectively on December, 1990 and on July, 1992. He received the Ph.D. degree from Carnegie Mellon University, Pittsburgh, USA, in December, 1996. From 1997 to 2000 he was the coordinator of the Robotics and Computer Vision Laboratory at the Information Technology Institute in Campinas, Brazil, where he managed or co-managed projects involving Internet-accessible laboratories, autonomous robotic airships for aerial inspection, and control of underactuated manipulators. He currently works at the Genius Institute of Technology in Manaus, Brazil, as a project leader in the technology group. At GIT Dr. Bergerman is responsible for technology prospection and assessment through product and technology feasibility studies, for establishing technological partnerships with universities and other research institutes, and for securing the investments needed for the realization of technology innovation projects.

Ely Carneiro de Paiva received his B.S. from the Universidade Federal de Uberlîndia on December 1989, and the M.Sc. and Ph.D. degrees from the University of Campinas (Unicamp), Brazil, in May 1993 and April 1997, respectively. Since 1997, Dr. de Paiva has worked as a research scientist at the Robotics and Computer Vision Laboratory (LRVC) of the CenPRA Research Center (formerly the Automation Institute) in Campinas, Brazil. His research areas include modeling, identification, control and navigation of autonomous robotic systems, with special focus on the AURORA project.



Josué J.G. Ramos received the B.S. degree from the Federal University of Santa Catarina, in December, 1979, and the M.Sc. degree from the University of Campinas, Brazil, in July, 1986. He obtained a Ph.D. degree from the Federal University of Santa Catarina, in March, 2002. Since 1983 he has been a researcher at the CenPRA Research Center, where he has worked on robotic manipulators, unmanned helicopters, and autonomous airships.

José R. Azinheira received his Ph.D. from l'Ecole Centrale de Paris in 1986. He is currently working in the Control Group of the Mechanical Engineering Department of Instituto Superior Tecnico, from the Technical University of Lisbon, where he has been involved in the aerial robotic projects ARMOR and AURORA, working in the areas of modeling, simulation, control and instrumentation.