# The Potential of Robotic Airships for Planetary Exploration

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## Abstract

*There is a growing interest in the use of aerial vehicles to support the exploration of planetary bodies that have an atmosphere. Among the various types of planetary aerovehicles proposed, balloons are of particular interest because of their potential for extended mission duration, allowing scientific instruments to be carried across vast distances or to be soft landed on key observation sites. In this paper, we suggest the use of robotic airships as a complementary technology for planetary exploration. Robotic airships have an enormous potential as observation and data-gathering platforms. They extend the capabilities of balloons through their higher controllability, allowing precise flight path execution for surveying purposes, hovering for long-term monitoring of specific sites, and opportunistic flight replanning in response to sensory information. We outline the basic technologies required for autonomous airships, and discuss the airship modelling and control, autonomous navigation, and sensor-based flight control technologies being developed in the context of Project AURORA (Autonomous Unmanned Remote Monitoring Robotic Airship). We also present the hardware and software architectures developed for the airship. Additionally, we outline our current research in airborne perception and monitoring, including mission-specific target acquisition, discrimination and identification tasks. Experimental results from this research are presented.*

## 1 Introduction

Strategies for unmanned exploration of the solar system increasingly include the use of aerial vehicles to support the exploration of planetary bodies that have an atmosphere. These include Venus, Mars, the Saturn moon Titan, and the outer planets (Jupiter, Saturn, Uranus and Neptune).

Among the various types of planetary aerovehicles proposed, passive airborne systems such as balloons are of great interest because of their potential for extended mission duration, allowing scientific instruments to be carried across vast distances or to be soft landed on key observation sites. NASA, for example, has a Planetary Aerobot Program [21], which focusses on the development of ballons [17] and ballutes [16]. The latter are inflatable drag devices whose purpose is to assist in planetary aerocapture and aeroentry, and are not discussed here.

In this paper, we suggest the use of robotic airships as a alternative technology for planetary exploration. Robotic airships have an enormous potential as observation and data-gathering platforms. They extend the capabilities of balloons through their higher controllability, allowing precise flight path execution for surveying purposes, hovering for long-term monitoring of specific sites, and opportunistic flight replanning in response to sensory information.

In the context of Project AURORA (Autonomous Unmanned Remote Monitoring Robotic Airship), we have been developing the underlying technologies for substantially autonomous airborne vehicle operation [8]. 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 current driving applications involve environmental, biodiversity, and climate research and monitoring [11], for which we have chosen airships as the technology of choice.

In this paper, we provide an overall view of the component systems already developed or currently being researched in the context of AURORA, and suggest that many of the underlying approaches can be of use in the deployment of planetary exploration airships. We discuss airship modelling and control, autonomous navigation, and sensor-based flight control. We also present the hardware and software architectures developed for the airship. Additionally, we outline our current research in airborne perception and monitoring, including mission-specific target acquisition, discrimination and identification tasks. Experimental results from our work are also presented.

## 2 The Potential of Airships for Planetary Exploration

On Earth, unmanned aerial vehicles (UAVs) have a wide spectrum of potential applications that is only beginning to be addressed. In addition to their use as military intelligence gathering and surveillance platforms, UAVs have enormous potential in civilian and scientific applications. 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 surveys, planning of harvesting, logging and fishing operations, law enforcement, humanitarian demining efforts, disaster relief support, and telecommunications relay, among 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 [8], 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 time, maintenance time, etc., and their regular use is therefore beyond the financial scope of many governments and international agencies. In contrast, we have suggested that the development of unmanned, substantially autonomous robotic aerial vehicles will ultimately allow the airborne acquisition of information in a highly flexible cost-effective, and affordable way.

Many of the data gathering applications mentioned above have mission profiles that require low speed, low-altitude airborne sensing platforms. Other important capabilities include: hovering ability; extended airborne capability for long duration studies; low noise and turbulence generation, so as not to disturb the environment that is being measured and monitored; very low vibration, so as to reduce sensor noise and hardware malfunction; vertical take-off and landing capability, to preclude the need for runways and allow monitoring of remote, difficult to access regions with limited logistics support; good maneuverability; have a large payload to weight ratio; and have a low operational cost. When evaluated along these requirements, airships are shown to be better suited, for many applications, than airplanes or helicopters.

Planetary exploration through aerovehicles brings with it, of course, a number of additional challenges. The Martian atmosphere is composed mostly of carbon dioxide, and is very thin and cold ($-73°$ C, 0.0006 bar), while Venus has a carbon dioxide atmosphere that is very dense and hot at the surface (460° C, 92 bar) and also contains highly corrosive components such as sulfuric acid. Titan, a moon of Saturn, also has a very dense atmosphere (four times the density at the Earth's surface, with surface pressure of 1.5 bar and surface temperature of $-180°$ C). The atmospheres of the gas giants (Jupiter, Saturn, Uranus, Neptune) are characterized by pressures and dynamics of such magnitudes that at the present only travel in the upper atmosphere is in the realm of the possible. While these environments present significant challenges for balloons or airships, preliminary studies for balloons [21] and for HALE (high altitude, long endurance) stratospheric airships [27, 20, 18] have shown the potential of existing technologies to cope with these extreme conditions.

An additional challenge that occurs in planetary exploration is the obtention of power for running the engines on an airship. This, of course, is a pervasive problem in all approaches to planetary exploration. Solutions include solar power, chemical fuel, and radioisotope thermoelectric generators (RTGs). The appropriate solution depends on the planetary body where the robotic airship will be deployed, and is an open research issue, although preliminary studies in the context of HALE airships provide useful insights [27, 20]. To maximize the range of robotic airships, the best approach would entail combining both the opportunistic use of prevailing wind patterns and altitude control mechanisms (such as suggested for aerobots [21]), and active flight plan execution using the onboard propulsion system.

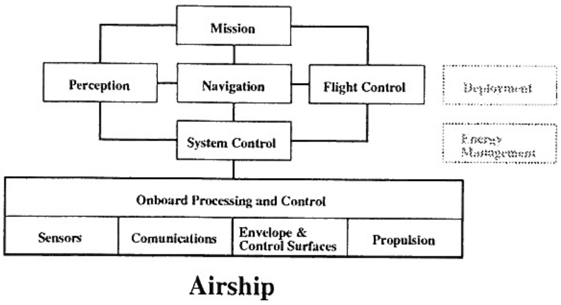

Figure 1: Major components of an autonomous robotic airship. Deployment and energy management are key issues in planetary exploration using robotic airships, but are not addressed in this paper.

In Fig.1, the main components of a robotic airship are shown. In what follows, we will discuss our work on implementing several of these components.

## 3 Towards Robotic Airships

Project AURORA (Autonomous Unmanned Remote Monitoring Robotic Airship) focusses on the development of the technologies required for substantially autonomous airborne vehicle operation. The main tasks involved in autonomous flight are summarized for the various flight phases in Fig. 2. Details on various parts of the project can be found in [10, 4, 23, 2, 9, 8].

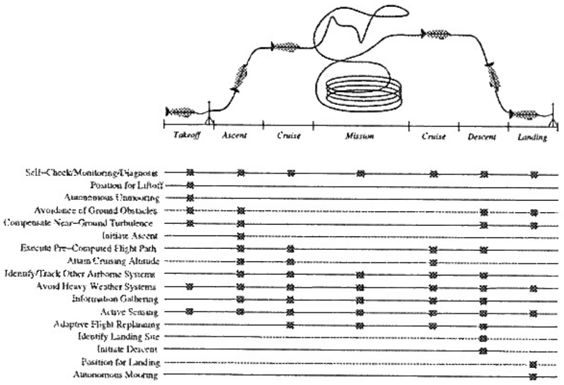

Figure 2: Flight phases for an autonomous robotic airship. The table shows the major tasks to be addressed at each flight phase.

### 3.1 The AURORA I Vehicle

Our first prototype, AURORA I, is shown in Fig. 3. 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 discussed in detail. The other subsystems are described in the sequence.

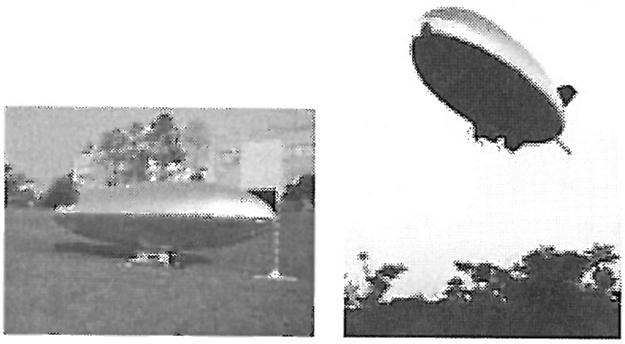

Figure 3: The AURORA I Robotic Airship. The airship, shown moored on the left and in flight on the right, is 9 m long, has a diameter of 2.25 m, and a volume of 24 m$^3$.

### 3.2 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 [28, 1]. The vehicle is a non-rigid airship (blimp). It has a length of 9 m long, a diameter of 2.25 m, and a volume of 24 m$^3$ (Fig. 3). 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 50 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 microprocessor.

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 take over control of the airship in case of a software or hardware failure.

Communication between the ground station and the airship occurs over two radio links. The first one operates in analog mode to transmit video imagery from the airship to the ground station. The second one 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 [24]. 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. In future work we plan to enhance the HMI, interfacing it to a geographical information system (GIS).

# 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 [15]. The aerodynamic model we developed is based on the seminal work presented in [14], and takes advantage of information from a wind tunnel database built to model the Westinghouse YEZ-2A airship [14]. The adaptation was possible due to the same length/diameter ratio (4:1) of both airships.

The dynamic model assumes that motion is referenced to a system of orthogonal body axes fixed in the airship, with the origin at the Center of Volume (CV), assumed to coincide with the gross Center of Buoyancy (CB). 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 $(\Phi, \Theta, \Psi)$. 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.

A physically-based and accurate dynamic model of an airship differs from the usual aircraft model in a number of ways. In particular, a lighter-than-air vehicle displaces a very large volume of air and its virtual mass and inertia properties are significant. The dynamic model can be stated as:

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

where $M$ is the $6 \times 6$ 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 $6 \times 1$ dynamics vector containing the Coriolis and centrifugal terms; $F_a$ is the $6 \times 1$ vector of aerodynamic forces and moments; $P$ is the $6 \times 1$ vector of propulsion forces and moments, and $G$ is the $6 \times 1$ gravity vector, which is a function of the difference between the weight and buoyancy forces [22].

## 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. 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. The dynamics of the airship in the horizontal plane is given by the fourth order linear state space system:

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

where the state $x$ includes the sideslip angle $\beta$, yaw rate $R$, roll rate $P$ and yaw angle $\Psi$. The control input $u$ is the rudder deflection $\zeta$.

The path tracking error metric is defined in terms of the distance error $\delta$ to the desired path, the angular error $\epsilon$, and the ground speed $V$. In order to accommodate both the distance and angular errors in a single equation, a look-ahead error $\delta_a$ may be estimated some time ahead of the actual position:

$$\delta_a \approx \delta + V_0 \; \Delta t \; \epsilon \qquad (3)$$

where $V_0$ is the reference ground speed considered for design purposes. This approach was implemented using both $\mathrm{H}_\infty$ and PI control approaches [22, 23, 26, 3, 8].

## 5 Autonomous Flight Trajectory Following

Initial experimental validation of the modelling and control work presented above was done by testing the PI guidance control method. Airship position and heading were obtained from DGPS and compass data.

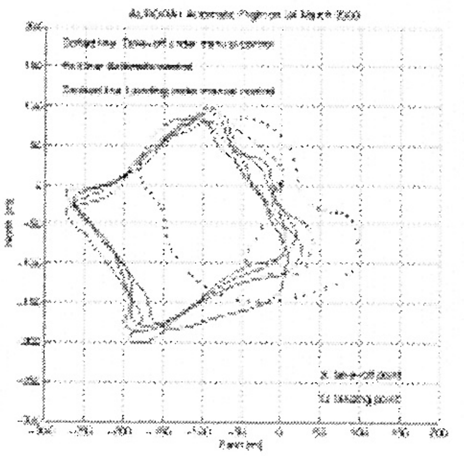

Figure 4: Autonomous flight of the AURORA I airship, following a predefined mission trajectory.

Figs. 4 and 5 show the results from an autonomous flight. The AURORA airship was flown over the CIACOM military field outside of the city of Campinas, Brazil. 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 150 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 [26, 25]. In Fig. 4, the dotted line represents the airship motion under manual control 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 manual control 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.

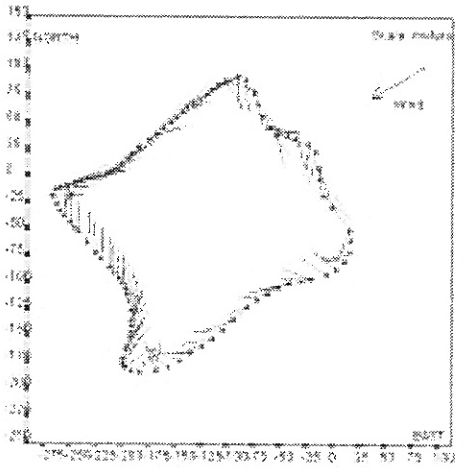

Figure 5: AURORA I position and heading along a loop.

Fig. 5 presents one of the loops performed by the airship around the square. The dots represent the airship position and the lines represent its heading. It should be noted that 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 facing towards 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 currently focussed 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.

### 6.1 Adaptive Target Identification

As a representational framework, we encode sensor observations using stochastic visual lattice models [19] that draw on our previous work on the use of Markov Random Field (MRF) models [29] in robot perception and control [6, 5, 7].

For target identification and classification we use a classical hypothesis testing approach [13]. For a $c$-class classification problem, 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 [9].

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. 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 [12] 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 information obtained from the observation using a mutual information measure $\Delta I$. 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 [7]), we can compute the expected value of $\Delta I$ 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

Fig. 6 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.

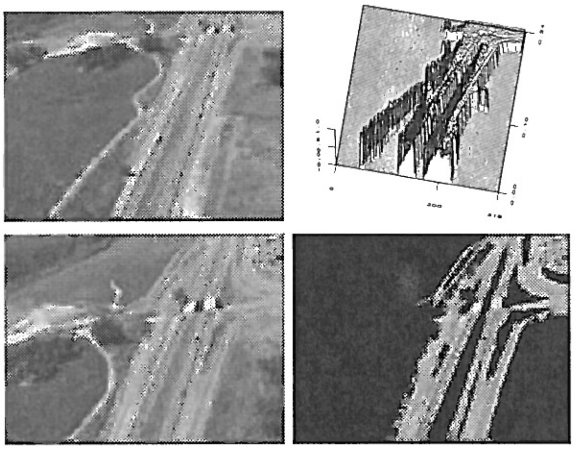

Figure 6: Identification and tracking of a paved road using an airborne camera. The road classification probabilities for the upper left image are shown on the upper right, while for the lower left image the segmented image is shown on the lower right.

## 7 Conclusions

In this paper, we have suggested that robotic airships provide an interesting alternative for planetary exploration. We have presented an overview of Project AURORA, including the physically-based dynamic model developed for the system, the control approach used, and the hardware and software architectures. We also discussed our results in autonomous flight control, and preliminary work towards autonomous perception-based flight planning and execution. The technologies presented, although tested only on Earth, suggest that robotic airships can be used for the exploration of planetary bodies with atmospheres.

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