Development of Aerobots for Satellite Emulation, Architecture and Art

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Abstract In this paper, we present two unique aerobots: a spherical blimp used for satellite emulation and a cubic blimp developed for use in floating architecture and visual art. The blimp designs bear a number of similarities, in particular, their construction with an exoskeleton, full actuation to enable six-dof motion and requirement for autonomous localization. Experimental results are presented to demonstrate the closed-loop control for station-keeping, as well as the selected performance statistics such as maximum speeds attained and time the aerobots can remain afloat. Additional qualitative results are presented from the experiments with satellite capture and artistic performances and common challenges with further use in the intended and new applications will be outlined.

1. Introduction

The concept of aerobot, i.e., an autonomous flying robot, has been around for several decades. The use of balloons or airships as aerobots has been explored in-depth in the context of planetary exploration [1]. Indoor applications of such systems, beyond their use for educational purposes, are rare. In this paper, we would like to present two aerobots developed for two very different purposes, yet with a design and features which have much in common. The first platform, developed in the Aerospace Mechatronics Laboratory at McGill (AML) is a spherical airship, the design of which was motivated by one of the authors' research on the problem of robotic grasping of objects in space. In particular, the airship represents a novel concept for emulating gravity-free conditions in a laboratory setting and has been used to develop autonomous algorithms for satellite capture in the context of satellite rescue and on-orbit servicing operation. The second platform was designed and constructed at the NXI Gestatio Design Laboratory of the University of Quebec in Montreal originates from an architectural myth studied by its creator, professor Reeves, architect and artist. Reeves envisioned more than 10 years ago the possibility of developing flying objects whose shape would be in strong contradiction with the idea of flying or hovering. Such hovering structures as well as the paradox they represent (see Fig. 1) would constitute an architectural statement by themselves: they somewhat materialize the old and mythical dream of an architecture freed from the law of gravity --- an image that can be found along the whole history of architecture, in many civilizations [2]. The cubic shape, chosen for the [Voiles|SAILS] aerobot prototypes (see Fig. 1), makes them conceptually similar to bricks, the basic unit of construction, and gives them the potential to assemble into bigger structures. From that conceptual starting point, the first prototypes developed to date show a high potential for visual art installations, as well as for hybrid theatrical performances where aerobots interact with human actors. The cubic aerobot described in this paper, called Tryphon, evolved into a research-creation platform bringing the disciplines of engineering, performing art, architecture and visual art together.

Fig. 1 [Voiles|SAILS] Concept: a) Krutikov flying cities and b) Simulation of interactively assembled Tryphons.

1.1 Related Work

The description of related work will be presented in relation to the two applications for which the aerobots were designed. Starting with the application of satellite emulation in the laboratory setting, previously developed experimental facilities for satellite emulation are usually built by using a spherical air bearing [3]. Experimental test-beds for space robotics research typically use one of the following concepts to emulate weightless environment of space on earth: (a) the robot moves on a flat horizontal surface; (b) a neutral buoyancy water tank; (c) complicated gravity compensation systems and (d) a free-fall tower.

To the best of our knowledge, no other aerobot has been used to date for architectural research and exploration. The closest systems somewhat comparable to the concepts used in the [Voiles|SAILS] program for architectural research are the rapid prototyping printers. From a computer generated, or a computer assisted design, the architect can get a small scale version to better visualize the 3D presence of the building. In terms of robots and art, many examples may be found since the Norman White installation “Facing Out Laying Low” in 1977 [4]. Robotic art is a field of media art that is increasingly explored by contemporary artists; this helped by the development of easy to use systems such as the Arduino open-source computing platform [5]. Hybrid performances are still very rare, but among the most known are the “Grace State Machines” of Bill Vorn (University of Concordia) or the “Hexapod” of Stelarc (University of Western Sydney) [6].

This manuscript describes the design, development and experiments conducted with the two aerobots. Where appropriate, similarities between the two aerobot platforms are highlighted and commonality of issues related to the development of autonomous capabilities and autonomous operations are discussed. Results are presented which demonstrate the performance of the two aerobots for each of their intended applications. In particular, for the spherical airship, we showcase its capability to produce general rotational motion and the free-floating nature of its response as a result of interaction with a robotic arm during capture. For the Tryphon robot, we focus on the high reliability and reproducibility of generated interactions with a human, as well as its long lasting autonomy for standalone installations. The geometry is also mandatory to describe as it is key to floating architecture explorations.

2. Aerobots Design, Construction and Control

2.1 Design

The balloon employed for satellite emulation is a custom design spherical airship equipped with six propellers, accompanying control electronics, onboard power, and sensors for pose estimation. The design (see Fig. 2a) was motivated by three principal requirements: 1) the balloon must closely emulate a free-floating object which requires it to be neutrally buoyant and balanced; 2) it must carry a grapple fixture, initially, a simple design and ultimately more sophisticated designs; 3) it has to be capable of a range of motions including rotation about a fixed axis and tumbling to emulate, for example, a spin-stabilized satellite or a spacecraft out of control. Moreover, these motions need to be generated in a controlled manner to allow multiple experimental tests under the same conditions. After several design iterations over a period 2003-2007, the current design, shown in Figure 2 incorporates the following main components:

1) A light 6-ft diameter spherical bladder bag, made of 2.5 mil thick polyurethane for a maximum net lift of 3.34 kg.
2) A rigid frame (Fig. 2), designed and manufactured in-house, made up of three carbon-fiber hoops with light-weight honey-comb cores arranged normal to each other. Each ring is made up of quarter-length arcs interconnected at small carbon-fibre extensions (see Figure 2b). The frame allows for easy and reliable balloon assembly and to eliminate the inaccuracies introduced by the deformable blimp bag on the airship dynamics and control. The balloon bag is inflated inside this structure and supports it through a friction fit.
3) Six identical propellers mounted in ducted fans, consisting of DC motors driving 48 mm diameter propellers within 35 mm long plastic cylinders (see Figure 3a). At a nominal voltage of 8.4 VDC, each thruster is capable of producing up to 0.45 N thrust in its primary direction or up to 0.25 N in its reverse direction. The propellers are mounted in custom-made supports, in a symmetrical arrangement on the sphere. With the chosen arrangement of the propellers the balloon is fully actuated and in theory, is capable of producing decoupled motions in all three translations and rotations.
4) Six speed controls for the propellers. The ducted fan speed control electronics perform two main functions: signal conditioning and amplification of the control signal. The incoming standard PWM signal is converted to a bipolar PWM signal zeroed around 50% duty cycle, allowing for forward and reverse thrusting of the ducted fans.
5) The sensor suite on the airship includes two types of sensors: an Inertial Measurement Unit (IMU) Microstrain GX1 and a laser rangefinder (Hokuyo URG-04LX). The sensors communicate wirelessly with the ground station via two pairs of Bluetooth transceivers.
6) The battery used on the balloon to power the propellers and the speed control electronics is an 8.4 VDC, 4000 mAh lithium-polymer battery. A second battery powers the IMU, the laser rangefinder and the Bluetooth transceivers.
7) A composite-material grapple fixture affixed to the structure for experiments in capture of the airship by the robotic arm.

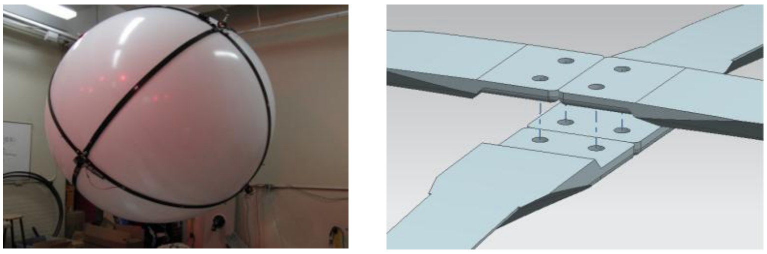

Fig. 2 Helium airship for satellite emulation: a) Current airship configuration; b) Joint of two hoops of the rigidizing structure

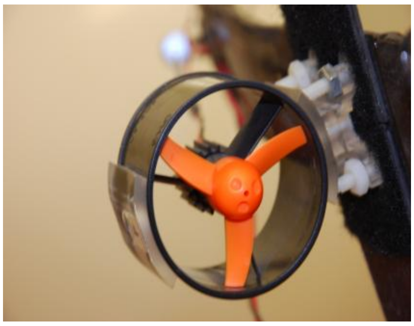

Fig. 3 Balloon propellers in the mount on the structure and Vicon marker cluster around one of the propellers

In order for the airship to closely emulate a free-floating object in space it must be both neutrally buoyant and balanced, thereby eliminating the effects of gravity. With these conditions met, the unactuated airship freely floats in air and has no preferred orientation. An additional desirable property is for the airship to have a diagonal inertia matrix in the body-fixed frame, the axes of which are aligned with the three orthogonal propeller thrusts. To meet these requirements, the locations of components which can be placed freely on the ring structure were determined to achieve the center of mass close to the geometric center of the 6-ft sphere and a nearly diagonal inertia matrix. The airship is also equipped with 6 posts affixed to the propeller mounts on which balancing masses can be easily placed to aid with the balancing procedure. The final balancing is carried out manually by the operator, again with the aid of balancing masses.

The Tryphon robot flies thanks to an inflatable cubic blimp, 2.05 metres on the side, and similarly to the spherical blimp, it is filled with helium. The material used for the blimp is 3.5 mil thick polyurethane, which weighs 3.5 oz per square yard (0.12kg/m^2). The blimp itself is made of six square faces welded together. As with any other balloon shape, the faces become convex when the balloon is inflated and more pressure tends to make it more spherical. To maintain a cubic shape, the blimp has to be constrained by a rigid structure --- an exoskeleton. Therefore, unlike the case of the spherical blimp, where the exoskeleton is primarily used for mounting equipment on the blimp, the structure confining Tryphon is there to maintain its cubic shape. The structure is made of carbon fiber tubes, strips and rods (see Fig. 4a). Each edge is a triangular truss of 2.25 metres length and the whole structure weighs approximately 1 kg. Assembly of the cube, including filling it with helium, can be completed in less than two hours by two people.

Similarly to the spherical airship, the structure of Tryphon also supports all the electronics as well as the propulsion system. The actuators consist of small ducted fans, with ducts and propellers made of carbon fiber. Four are located at the midpoint of each bottom edge and oriented in the x and y positive directions. Another four motors are similarly placed along the vertical edges (see Fig.4b). Positioning the motors this way allows an independent control of the translations of the robot along the x, y and z axes. Since there is no motor on the top trusses, and since most of the batteries are fixed to the bottom trusses, the global centre of mass of the system lies about 20 cm below the centroid of the cube. Thus, the robot cannot turn upside down and its roll and pitch angles are thus stabilized in a passive way.

To fix the body reference frame, for both the spherical airship and the cubic blimp, the origin of the frame is located at the blimp centroid. This choice is made to simplify the formulation of the dynamics equations since the centre of mass can easily change, depending on the equipment mounted on the robot. For example, the use of textiles to hide the edges of Tryphon, or a change in the sensors' configuration, will modify the mass distribution.

In the current prototype of the cubic blimps, the bladder used is made of thicker material, which allows the blimp to maintain nearly perfect equilibrium for several days: usually 3 to 6 days, depending on the room temperature variations. The 8 batteries allow a soft control of the oscillation when stabilizing, installation known as the “Paradoxal Sleep”, for about 6 to 8 hours in optimal room conditions (no ventilation, and constant temperature). In harsh environment, like a building hall, or with heavy interaction, like in hybrid performances, the airship can operate for approximately 2 to 3 hours with its current set of batteries. Table 1 presents a comparison of the design of the two blimps.

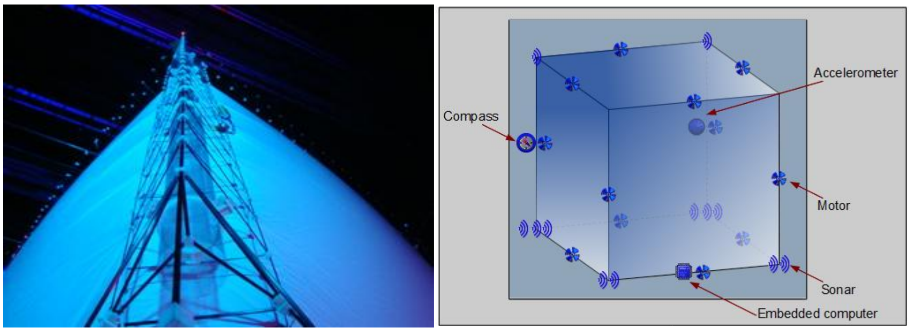

Fig. 4 Tryphon design: a) Structure of one carbon fiber truss and its polycarbonate ducts; b) Layout of actuators and sensors

2.2 Control of Aerobots

The spherical airship is controlled from a ground-station PC that transmits commands to the airship wirelessly over a Futaba radio. The ground-station PC performs all computations for the controller. The controller resides in the Simulink environment with the QuaRC toolbox and soft real-time target developed by Quanser. Initially [7], a PD controller was implemented on the airship with gains adjusted through simulation and by a trial and error process. The state feedback for the controller in [7] was obtained from the measurements by the Vicon motion-capture system, which is a set of six infrared cameras mounted along the periphery of the lab. They track retro-reflective markers affixed to the spherical airship (see Figure 2b). The system therefore provides position and orientation data for the blimp; velocities were calculated by taking finite differences of the previous 10 samples. Recently [8], we have implemented optimal LQR and LQG controllers on the airship and improved the state estimation from Vicon measurements by using the Unscented Kalman filter with angular velocity measurements from the onboard IMU.

Table 1: Design comparison of two blimps

	Satellite emulator	**Tryphon**
Structure	Molded carbon fiber rings	Assembled carbon fiber rods, tubes and strips in 12 triangular sections trusses
Balloon	Spherical white bladder, 2.5mil polyurethane.	Truncated white cube bladder, 3.5mil polyurethane.
Motors	6 GWS fans	8 to 12 Alfa carbon fiber propellers and duct mount on Mega brushless motors
Sensors	IMU, Laser range finder, MoCap external system	16 sonars, 8 light sensors, compass, accelerometer
Batteries	8.4 VDC, 4000 mAh LiPo 8.4 VDC, 850 mAh	8 LiPo 2500mAh
Brain	Computer off board	Gumstix onboard computation
Other		20 hubs to allow different sensor configurations

The control architecture of the [Voiles|SAILS] aerobots evolved over the course of many performances and installations created by actors, visual artists and other artists involved in the project [9]. In 2006, the first autonomous control was reactive to the physical attributes of the space. Compass and sonars were the only sensor inputs used to stabilize the aerobots relatively to a fixed setup. A simple distributed PID controller (one by sensor, one by motor and one by robot state) was sufficient for these needs at that time. Since then, an accelerometer and a gyroscope were added to provide the aerobots with more information on its state. Light sensors and microphones were also implemented for human interactions. A study of different controller approaches led to the use of a fuzzy controller in completely autonomous and stand-alone installations (without human interaction) while the performances with actors or dancers rely on a PID controller onboard and a trajectory planning algorithm used in parallel with the fuzzy controller.

The development focus was set on embedding the hardware and control in the robot, with only a laptop running a custom designed java interface to allow the technician operating the aerobots in their installations to monitor its battery and mechatronic states. For research and creation purposes, the team is currently exploring the potential of external motion capture systems, such as the Vicon system used for the AML spherical blimp. Such a system could be used to detect visitors, to enhance the interactions as well as to control the motion of the blimp and to better understand the dynamics of its unique shape.

3. Closed-Loop Control Experiments with Aerobots

In this section, we present a sampling of experimental results obtained for the aerobots to demonstrate the hovering performance of the two blimps under the PD control. As mentioned earlier, the Tryphon usually relies on its onboard computer and sensors for control. For the experimental results presented here, however, experiments were conducted in a large room equipped with a Vicon tracking system in order to understand the aerobot dynamics and to evaluate the controller performance. Specifically, a PD controller combined with a Kalman filter of Vicon pose measurements was implemented in Matlab for off-board closed-loop control.

The relevant experimental response statistics of the controllers are stated in Table 2 in addition to “application” related statistics, such as the time that the aerobots can remain afloat and the maximum translational and rotational speeds achieved in our laboratory environments. Fig. 5 displays the hovering performance (position response) of the spherical and Tryphon blimps under PD control, with pose feedback provided by the Vicon motion capture system. The corresponding results for attitude response are shown in Fig. 6. Fig. 7 presents the response of the spherical blimp to light translational and rotational disturbances, demonstrating the rise times of approximately 5 seconds, settling times of 15 seconds, and overshoot of approximately 10%, although the latter is rather difficult to determine because of the poorly defined steady state. Analogously, in Fig. 8, we include the step position response of the Tryphon aerobot, showing the rise time of 15 seconds, settling time of approximately 50 seconds and overshoot of around 25%.

From the results in Table 2, we observe that the station-keeping control of the spherical blimp is better than of Tryphon. In particular, the RMS errors for position regulation of the two blimps are 0.028 m and 0.101 m respectively, while the corresponding errors for attitude regulation are 0.017 rad and 0.122 rad. On the other hand, Tryphon can maintain neutral buoyancy for a significantly longer time period, nearly one day. Tryphon is also able to reach a higher translational speed, although the results obtained for the AML spherical blimp were quite limited by the size of the laboratory at McGill. At the same time, the spherical blimp can reach a higher rotational speed, because of better aerodynamic characteristics.

Table 2: Experimental performance comparison of two blimps

	Satellite emulator	Tryphon
Regulation position error (RMS)	0.028 m	0.101 m
Regulation attitude error (RMS)	0.017 rad	0.122 rad
Neutral buoyancy time	~1 hour	~24 hours
Max. translational speed	0.3 m/s	0.75 m/s
Max. rotational speed	2.3 rad/s	1.6 rad/s

4. Applications of Aerobots

4.1 Satellite Emulation Experiments and Potential Applications

A number of experiments have been carried out with the spherical airship employed as a free-floating target for capture by the seven-dof robotic arm housed in the laboratory. Snapshots of the satellite capture experiments are shown in Fig. 8 for a successful capture of the slowly translating airship by its grapple fixture. The fiducial three-dot mark on the airship is employed for visual servoing of the robot when its end-effector is sufficiently close to the grapple fixture. The capture also involves the planning of the optimal interception trajectory, as per the algorithm described in [10]. Currently, we are working on probabilistic path planning methods to allow capture of the spherical blimp under uncertainty in its state, and for arbitrary motions, including tumbling and motion on a collision course with the robot itself.

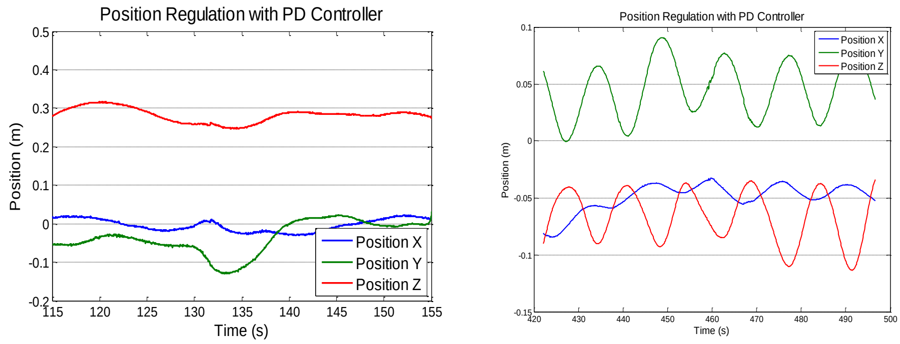

Fig. 5 Position regulation of the AML spherical (left) and Tryphon (right) blimps.

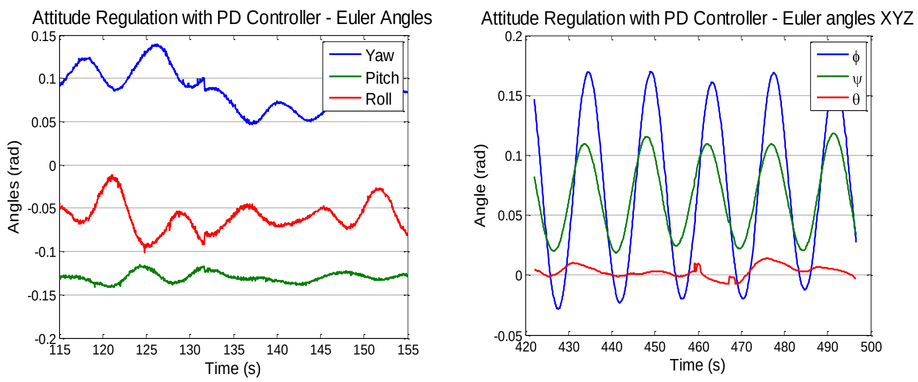

Fig. 6 Attitude regulation of the AML spherical (left) and Tryphon (right) blimps.

Fig. 7 Recovery from position disturbance (left) and attitude disturbance (right) of the AML spherical blimp.

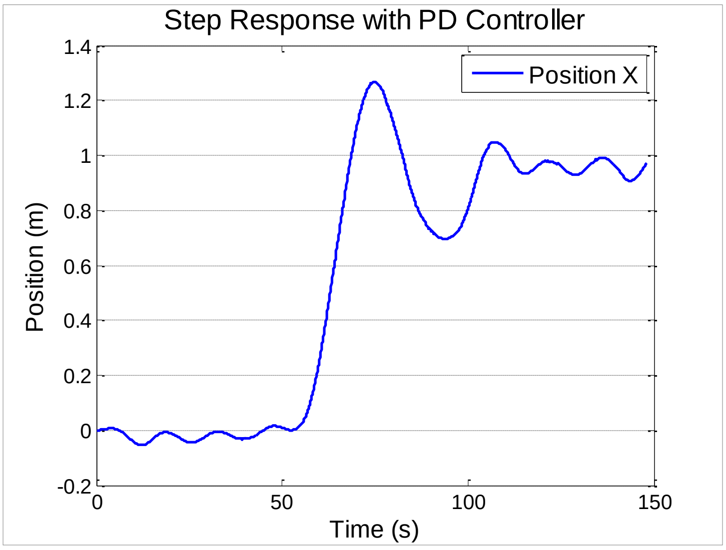

Fig. 8 Step response in *X*-position of Tryphon.

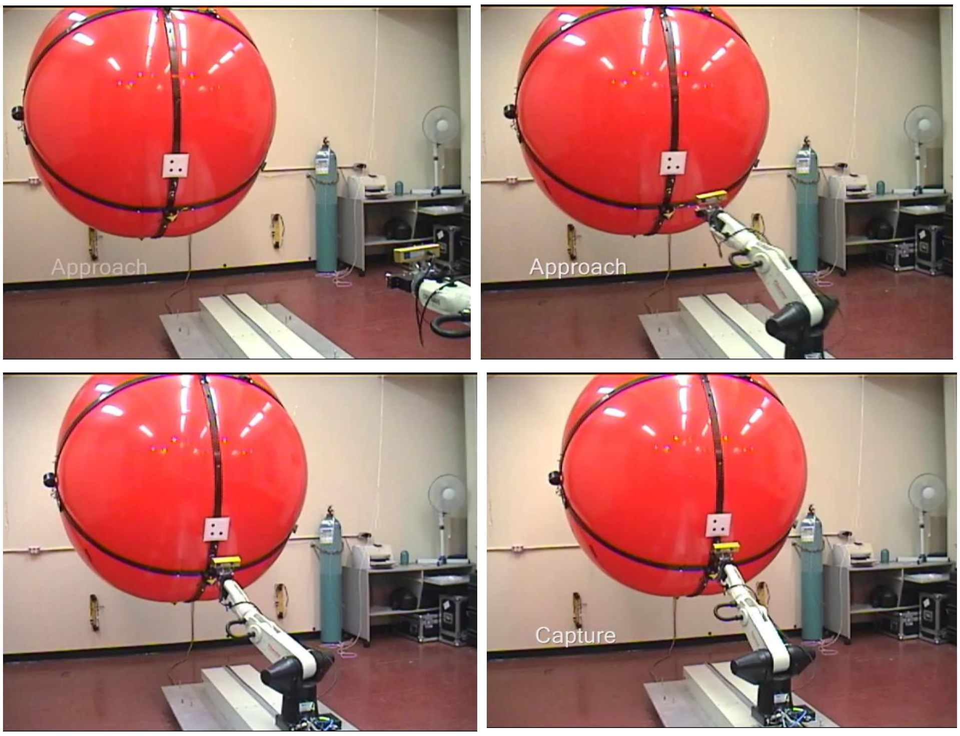

Fig. 9 Snapshots of airship capture maneuver with seven-dof robotic arm.

Another potential application of the spherical blimp that has been explored in AML is as an autonomous aerial vehicle for safety and security missions. Possible scenarios envisioned are where the airship is deployed in a large facility, in the event of an accident, for instance. The airship would fly inside the facility and take measurements and/or video of the scene. Note that the size of the spherical blimp would also permit it to negotiate a wide staircase. In this type of scenario, the airship has to be able to navigate its environment autonomously, and hence it must be equipped with sensors for autonomous localization-not a trivial task given the blimps limited payload. Some efforts to solve the localization problem by using optical flow and Monte Carlo Localization with a laser range finder have been made and we are continuing further research in this direction.

The airship has been recently used as an aerial platform for partial testing of state estimation and localization algorithms that we have developed for an entirely different unmanned aerial vehicle: a quadrotor platform [11]. Indeed, because of its inherent safety and user-friendliness, the airship represents an ideal platform for testing and evaluation of path planning, localization and some aspects of control of unmanned rotary vehicles.

4.2 Tryphon Performance Experiments and Potential Applications

Since the development of the robotized version of the [Voiles|SAILS] prototypes, numerous performances and installations have been achieved. In Figs. 10 and 11, we include pictures of three performances conducted since 2006 in a variety of venues. The first picture on the left shows an event at the Montreal Science Center in 2008, based on the idea to introduce robots to children. Actress Veronique Daudelin is shown explaining the functionalities of Nestor, the smallest brother of Tryphon. During the performance, she triggered different scripted actions by using various stimuli: a quick movement in front of sonar initiated a rotation of the aerobot, a powerful beam of light on a light sensor attracted the aerobot to the middle of the space. Children were also invited to start such interactions with Nestor.

Fig. 11a shows a picture of the first performance of the [Voiles|SAILS] aerobots, in 2006 at the Museum of Civilization in Quebec City. Three early blimp versions with a linden structure, called Mascarillons, were hovering in a large room in the dark. When a visitor approached, a real-time projection of an actress' eyes illuminated the closest aerobot's sides and the visitor could start a discussion with a "peculiar intelligence," simulated by an actress hidden behind the scene.

Finally, over the period from 2009 to 2010, numerous workshops were conducted with actors from a theater company, the "Théâtre des 4 coins". During each workshop, lasting for two weeks, the actors visited a room with one or more Tryphons to develop movements, choreography, scenarios and interactions with the blimps (see Fig. 11b). The first public demonstration based on these workshops will be held in Sao Paulo FILE festival in July 2012. The show will be based on a partially improvised choreography and the aerobot will be controlled by the dancer's movements and singing.

Fig. 10 Interactive Performance in Montreal Science Center. Actress: Véronique Daudelin.

Fig. 11 Left: discussion with an aerobot at the Quebec Museum of Civilization, 2006; right: art residency with the Theatre des Quatre Coins at Laval University, Quebec, 2010.

The above example events illustrate the specific constraints that determined the design of the Tryphons, which are quite different from those that defined the AML spherical aerobot. The Tryphons were planned from the very beginning with artistic/performance objectives in mind. Thus, their abilities and functionalities were to be used for the sake of conveying expressions and emotions through combinations of translations, rotations, states and behaviours; they were seen as embedding notions of *personality* and *identity*. While the first installations involved only reactions from visitors, the cubes were designed to interact with humans (audience or performers) through a variety of sensors. Scripted interactions with actors have been possible for the past three years, and many relevant observations were made prior to that from the visitors' reactions to the cubes. These observations allowed us to refine the aerobot's sensing abilities in order to create full interactive performances, in which performers and aerobots interact through real hybrid choreographies. In particular, they influenced the number and positioning of sonar sensors on the cube's periphery, and led us to use information from different sensor modalities, in order to compensate for the imprecisions inherent to any kind of sensing device.

Interactions with humans can lead to applications in the fields of museology or event design. The cubes "have been invited" to fashion design shows; with a proper sensor configuration, they could be used as individual or group guides for exhibitions or historical places. In addition to the possibility for them to speak through sound transducers, they could display written information on their faces thanks to micro video projectors inserted in the helium bladder.

Similarly to the AML spherical blimp, the cubes can also be used for engineering applications. Profiting from their cubic shape, which allows assembly of Tryphons into structures, several horizontal or vertically connected cubes can lift multi-kilogram payloads, like flying cranes. In indoor large spaces, they could be used to carry objects or pieces with excellent degree of precision. The cubes can become test-beds for the development of control algorithms for six-dof objects in zero-gravity environment. In this case though, their particular geometry imposes certain limits: because of the cubic shape, their moments of inertia depend on their rotation axis. However, that very same shape allows for implementation and testing of autonomous assembly algorithms for applications to space structure assembly and other space missions.

5 Conclusions and Future Work

We have summarized the development and experiments conducted with two unique indoor aerobots: the spherical blimp developed at McGill and the square Tryphon blimp developed at UQAM. The aerobots represent a significant departure from conventional lighter-than-air vehicles, both in their design and intended applications. Future work holds many more challenges with respect to developing motion planning, state estimation and control strategies for fully autonomous operation of the blimps for the intended applications: accurate trajectory tracking for satellite emulation and for indoor navigation, docking of airships for recharging, self-assembly of Tryphons into free-floating structures and autonomous behaviours in response to artists' commands for hybrid performances.

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