Pose Estimation of Autonomous Dirigibles Using Artificial Landmarks

L. S. COELHO, M. F. M. CAMPOS

Laboratrio de Robótica e Visão Computacional
Departamento de Ciência da Computação
Universidade Federal de Minas Gerais
Av. Antônio Carlos 6627 - Pampulha
31270-010, Belo Horizonte - MG, Brazil
{omni,mario}@dcc.ufmg.br

Abstract. Autonomous dirigibles - aerial robots that are a blimp controlled by computer based on information gathered by sensors - are a new and promising research field in Robotics, offering several possibilities for original research. One of them is the study of visual navigation for this kind of vehicle, which would fill an operational gap left by inertial, GPS and other kinds of well-established dead-reckoning navigation. In this paper, a simple pose estimation system based on artificial landmarks is introduced for the accomplishment of that task. The vision system is able to track artificial visual beacons - objects with known geometrical properties - and from them a geometrical methodology can extract information about orientation and position of the blimp. A simple control system uses that data to keep the dirigible on a programmed trajectory. This visual control can be done using both fixed, external cameras focusing the blimp as well as onboard cameras, thus opening a way for future research on visual cooperation between aerial and ground mobile robots. Preliminary experimental results showing the correct functioning of the system are presented and discussed.

1 Introduction

Dirigibles are aircrafts built from a lightweight envelope for buoyancy and a propelling system housed in a gondola. The envelope is filled with a lighter-than-air gaseous mix, which can be hot air, hydrogen or helium. The fact that the flight of dirigibles is based on buoyancy is one of the main advantages of this type of aircraft. Since they do not spend energy to keep themselves airborne, they are well suited for applications that demand long flight times over the same area. Also, because they can fly very close to the ground with minimal interference over the environment and can be kept aloft for extended periods of time, dirigibles fill an important gap in the spectrum of aerial vehicles for observation, supplying images with better resolution and much more acquisition flexibility than satellite or airplanes. Mapping, monitoring and surveillance of preservation or restrict access areas are examples of tasks that demand such an observational capacity.

The tasks above can be monotonous or even risky, and helium – used most of time to fill the buoyancy balloons, since it is not flammable and therefore is much safer than the other alternatives – is an expensive element. Hence, small and inexpensive aircraft would be preferable. An interesting subclass of dirigibles, considering those requisites, is that of *blimps* – dirigibles with unstructured hulls. Also, *autonomous* blimps would conform ideally to monotonous and/or dangerous missions. Autonomous blimps are aerial robots, or *unmanned aerial vehicles* (UAVs) - they are guided by computer controls produced as a feedback to the information gathered by onboard sensors. The aerial nature of dirigibles and the type of applications suited for them make visual sensors (like CCD cameras) a natural choice for their sensory apparatuses.

Visual sensors could be necessary not only to perform data acquisition as part of the mission such as taking pictures of predefined spots in an environmental surveillance mission, but they could also help on the autonomous navigation of the dirigible, supplying data to perform it in situations where more conventional, well-established aerial navigation techniques, like those using inertial, GPS and other kinds of dead-reckoning systems, are not adequate.

Among several stages that composes a mission of an autonomous aerial vehicle, taking off and landing are the most critical ones. Even though there are such vehicles that are able to perform those tasks autonomously or semi-autonomously, in general, those procedures are monitored by a human operator. Depending on the type of vehicle this phase may be heavily dependent on visual information. More specifically, in the case of dirigibles, mooring is part of both docking and undocking. It requires the correct localization of reference beacons in order to correctly position the blimp's body with respect to the docking station.

In more specific tasks like monitoring an ecological reserve somewhere in the Amazon forest, the mission of an autonomous blimp may include additional steps better performed by using vision, such navigation through control points and near-ground flight to gather samples of materials such as dirt, water, etc. Also, blimps could be used as ”aerial eyes” supporting several ground-based activities. If those activities occur in a dynamical environment, dead reckoning sensors could not be sufficient. An example of ground-based activity that could benefit from the use of an autonomous blimp with a vision system is tactical support in a battlefield. Autonomous blimps could inform the movements of the enemy, topography changes in the terrain (such as trenches and barricades) and localization of minefields. A similar actuation could be performed in urban guerrilla and law enforcement operations. There, an UAV would be able to detect and broadcast the position of individuals otherwise unseen from a ground-based point of view.

There has been important developments in the area of visual navigation in recent years. Among these efforts are those of map based, natural landmark based and artificial landmark-based. There has been fewer examples when it come to aerial vehicles. For those, usually inertial navigation systems (INS) and GPS at the heart of their navigation competence. This is clearly understood if one remembers that vision is in itself a very hard problem, and solution to some specific issues are restricted to constraints, either in the environment or in the visual system itself. Nevertheless, despite being in general a hard problem, visual navigation could be of great advantage when it comes to aerial vehicles in the aforementioned situations.

This paper presents the first steps towards the applications outlined above: a simple Computer Vision and control system designed for visual navigation of dirigibles. The vision system does tracking of artificial visual beacons, using images taken both by ground-based and onboard cameras, and accomplish simplified pose estimation of the dirigible based on those beacons. That pose data is used to control the blimp propellers in order to keep the airship on some desired trajectory. This visual and control system underwent preliminary tests for control of the position and orientation of a blimp. Results showing the efficiency of the system under pursued criteria are shown and future directions for improvement of the system and its evaluation experiments are pointed out.

The organization of this paper is done as follows. The next section presents a small survey on related work. Section 3 exposes the computer vision and control methodologies used for the autonomous navigation of the blimp. Then, preliminary experiments, implemented under the methodologies previously shown, are described and have their results discussed in Section 4. Finally, conclusions about the work presented here, as well as future possibilities, are shown in the final section.

2 Related work

Robot navigation using ultrasound sensors has been developed in a extensive and solid way [1]. There are also many works on visual navigation. Among those more successful are the ones that use navigation based on visual landmarks, for example [2]. Visual landmarks can supply full pose information, as demonstrated in [3]. Also, landmarks can be used not only for navigation, but also for cooperation among robots [4]. The vision process of *tracking* is also widely used, frequently in conjunction with landmarks [5]. In other works, more complex visual information is needed to accomplish some kinds of tasks. Those include commercial or practical applications like [6] and [7], where ranger finders are used for an accurate 3D reconstruction of the surrounding environment. Finally, sensor fusion has to be used in delicate applications like deactivation of landmines [8].

The vast majority of those works, however, deal with terrestrial mobile robots. Computer vision systems for use onboard of aircrafts include those of three-dimensional terrain mapping [9]. Other works dealing with aerial or high points of view include reconstruction of human shapes from multiple viewpoints [10].

Visual *navigation* of aerial robots is much less explored. Usually autonomous navigation of UAVs [11] relies on dead-reckoning sensors, like the inertial ones and GPS, DGPS, etc [12], which are traditional and well-established in navigation of aircraft in general. However, there is ongoing research on visual navigation of UAVs, including those using natural and artificial landmarks [13, 14]. Visual tracking of mobile terrestrial objects has also been implemented [15], as well as estimations of surface motion [16]. Although most of those works were done using airplanes and helicopters as UAVs, it has been pointed out that autonomous blimps offer an interesting set of advantages and possible applications [17].

3 Methodology

3.1 Vision

In this section, a somewhat detailed discussion about the visual beacons is firstly presented. After that, the computer vision methodologies used to solve the proposed problem are described.

3.1.1 Visual Beacons

As an introduction to the description of the visual beacons built and used in the experiments, it is first necessary to discuss about the mathematical and geometrical limitations that influenced their conceptions.

Let C be a camera with focal point F. Let M be a visual beacon with a set of 4 non-coplanar characteristic

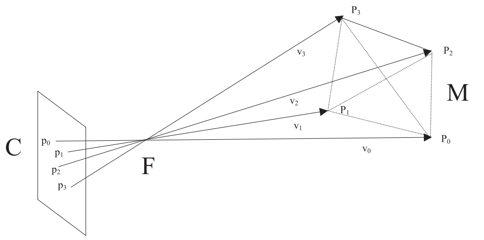

Figure 1: Image projection of the vertices of a tetrahedra beacon M over the image plane of camera C.

points $\{P_0, P_1, P_2, P_3\}$. Let $\{p_0, p_1, p_2, p_3\}$ be the coplanar points corresponding to the image projections of the characteristic points of M over the image plane of C. Le $\vec{V_i} = P_i - p_i, 0 <= i < 4$ be the light-ray-path vector [1] going from the points p_i to the corresponding P_i passin through F, and $\vec{v_i} = F - p_i, 0 <= i < 4$ the vectors i the same direction of V_i, but going just until F. Figure illustrate that geometrical construct.

Once the vectors $\vec{V_i}$ are found, the position and orientation of C can be determined. Since the distances betwee the points P_i are known and vectors $\vec{v_i}$ are determinable the points p_i are known, the following equation system can be specified:

$$\begin{cases} |\alpha_0\vec{v_0} - \alpha_1\vec{v_1}| = D_{0,1} \\ |\alpha_0\vec{v_0} - \alpha_2\vec{v_2}| = D_{0,2} \\ |\alpha_0\vec{v_0} - \alpha_3\vec{v_3}| = D_{0,3} \\ |\alpha_1\vec{v_1} - \alpha_2\vec{v_2}| = D_{1,2} \\ |\alpha_1\vec{v_1} - \alpha_3\vec{v_3}| = D_{1,3} \\ |\alpha_2\vec{v_2} - \alpha_3\vec{v_3}| = D_{2,3} \end{cases},$$

where $D_{i,j} = |P_i - P_j|, 0 <= i < j <= 3$ is the distance between points P_i and P_j. The unknowns of the system are $\alpha_0, \alpha_1, \alpha_2, \alpha_3$, and $\vec{V_i} = \alpha_i\vec{v_i}$. Expanding the modulus operations on the left side of the equations, a non-linear system with six quadratic equations and four unknowns is thus obtained. The existence of six equations guarantees one solution.

Therefore, a visual beacon with tetrahedral topology - that is, having four non-coplanar characteristic points - guarantees a unique solution to the values $\vec{V_i}$ and consequently a unique position and orientation to the camera for the point set p_i determined in an image.

However, tetrahedral - and therefore three-dimensional - beacons are more difficult to construct and reproduce than the two-dimensional ones; in particular, practical applications of autonomous dirigibles, where the distances involved could be large and thus the visual beacon, seem to favor the use of *two-dimensional* ones.

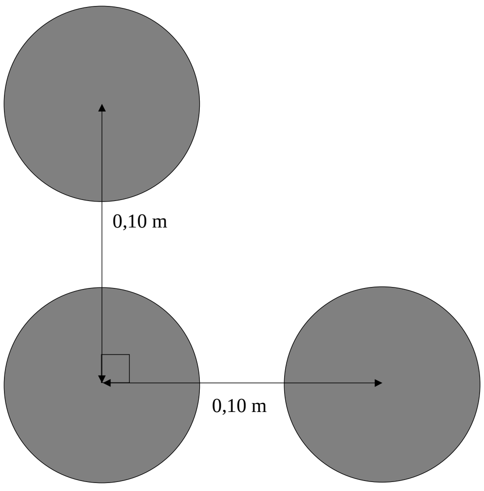

Figure 2: Diagram of artificial beacon used in the experiments

A two-dimensional beacon would have to have a minimum of three characteristic points to make possible the determination of position and orientation of the camera - since with a number of points less than three the number of solutions found for position and orientation would be infinite. Nonetheless, a *triangular* beacon would imply in an equation system with just three quadratic equations, in a way that the number of solutions for a given projection of characteristic points on the image plane would be 2 or 4, as shown in [3]. That is, for a given image of a triangular beacon, there would be two or four possible positions/orientations of the beacon with the same characteristic point projections found in the image.

However, this ambiguity can be removed in cases where it can be assumed that not all orientations are possible for the triangle. For the beacon on board of the blimp, as shown in Figure 7, the set of orientations is very restricted due to the blimp dynamics, which produces negligible pitch and roll rotations while leaving yaw free. Hence, a triangular visual beacon, an isosceles right-triangle with $0,100m$ sides, was chosen. Each vertex is assigned by a black disk with a $35mm$ radius contained in the triangle plane, with its center coinciding with the corresponding vertex. Figures 2 and 3 show an scheme of the beacon and the coordinate frame associated with it. The disks (markers) are labeled for the operation of the methodology: marker 0 is the one below at left, and 2 is the uppermost one. The strategy of using dark markers against a light background is used in order to ease the segmentation in the image acquisition phase, as described in the next section.

Once the geometrical and visual details of the beacon

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[1] Rigorously speaking, vectors and points are different geometrical entities, but along this article they will be informally treated in a similar manner - except in cases where a distinction makes itself necessary.

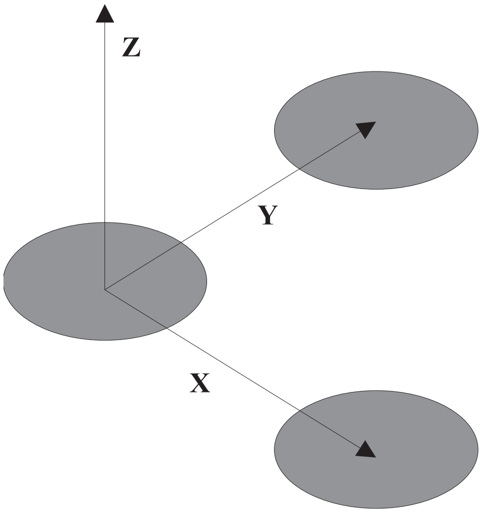

Figure 3: Coordinate system of the artificial beacon

have been described, the following sections discuss the image processing techniques used for determining the points $p_0, \ldots, p_{n-1}$ in a given image, as well as the methodologies used to determine the orientation of the beacon based on that.

3.1.2 Visual Tracking

The tracking methodology used here is of extreme simplicity. Using a graphical interface, the markers of the visual beacon are assigned through mouse clicking on a window showing the image of the blimp acquired in real time. From those start clicks, the pixels of markers are identified by means of flooding under a threshold binarization (since they are black spots against a light background). From frame to frame, the changing centroids of the markers are constantly re-determined using the centroid of the previous frame as a start search point for the marker. If this start point is not contained inside the marker, border points of the marker are search inside a *search window*, square, with a centroid coincident with the one of the previous marker. The side of each search window is initially 3 pixels and it grows by two every search iteration until a border pixel of the marker is found or the limits of the image are encountered.

3.1.3 Geometrical Approach

The application of the geometrical methodologies starts with computing the points $p_0, ..., p_{n-1}$ – considered the centroids of the markers, determined by the tracking methodology. Those points are used as input for a global search numerical method that supplies the orientation of the position and orientation of the artificial beacon. Nevertheless, to understand the framework used for orientation in this paper, this section begins with a description of the coordinate systems used.

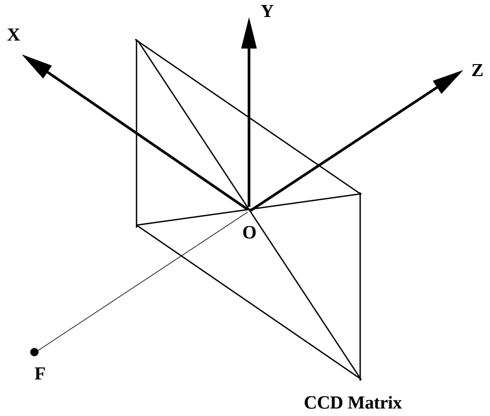

Figure 4: Scheme of the camera coordinate system.

Coordinate Systems

The *camera coordinate system* $\{\mathrm{C}\}$ is presented in first place. That system is an orthonormal basis that has as origin the CCD matrix center, X axis parallel to the CCD width, Y axis parallel to the CCD height and Z axis coincident with the camera axis (line perpendicular to image plane passing through the focal point), pointing toward the back of the camera. This arrangement, as shown in Figure 4, is adequate for visualization and verification purposes in an image acquired by the camera. Finally, for the case of the camera external to the blimp, $\{\mathrm{C}\}$ is the *world coordinate system* [18]

On the other side, $\{\mathrm{M}\}$, the beacon coordinate system - which was defined as the system used to effectively express the position and orientation of the autonomous dirigible - has as origin the point P_0, the vertex of the right angle in the triangle. The axis X is the line passing through P_0 and P_2, increasing from P_0 to P_2; the axis Y is the line passing through P_0 and P_1, increasing from P_0 to P_1; and, finally, the axis Z is perpendicular to the XY plane, passing through P_0 and pointing upwards. Figure 2 depicts this coordinate system.

Algorithms

The geometrical methodology used here for computing estimations of position and orientation of the blimp from images taken from an external camera relies on the following assumptions:

- The roll and pitch movements of the dirigible are negligible, making only the estimative of yaw worthwhile.

Yaw is intended as the angle between the X axis of the beacon frame and the X axis of the camera frame.

- The visual beacon and the camera are installed in such a way that the XZ planes of the two coordinate systems are parallel.
- The angle β between the Y axis of the beacon frame and the XZ plane of the camera frame is $0^o < \beta < 90^o$.
- The beacon is sufficiently distant to consider as orthogonal the projection of its characteristic points on the image plane.
- The camera geometry is approximated by an ideal pinhole model.

With those restrictions in mind, it can be devised a simple trigonometric methodology for estimating α, the angle between the X axis of the camera and beacon coordinate systems. Let be $\vec{a} = p_1 - p_0$ and $\vec{b} = p_2 - p_0$. The algorithm used for determining α simply searches for an α and a β that best approximates the conditions

$$\frac{\vec{a}_x}{\vec{b}} = \frac{cos\beta sin\alpha}{cos\alpha}$$

$$\frac{\vec{a}_y}{\vec{b}} = \frac{sin\beta}{cos\alpha}$$

That search is exhaustive under a chosen quantization for α and β. Finally, the sign of α is negative if $p_{1,x} > p_{0,x}$ and positive otherwise.

Since the distances between the characteristic points of the beacon and its orientation are known, it is possible to estimate its three-dimensional position. That is done by taking into account the assumption of orthogonal projection. Then, the X coordinate of the origin of $\{M\}$, for example, is given in $\{C\}$ by

$$x = \frac{D_{0,2}\cos\alpha}{|p_{2,x} - p_{0,x}|} p_{0,x}.$$

The Y coordinate can be obtained in a similar way, without any necessity of camera calibration. However, the estimation of the Z coordinate requires the knowledge of the focal distance of the camera, f. The Z coordinate is given by

$$z = -f \frac{D_{0,2}\cos\alpha}{|p_{2,x} - p_{0,x}|}$$

The methodology for controlling the position and orientation of the blimp from an onboard camera is even simpler. Since the onboard camera is assumed to be installed at the bottom of the blimp gondola, pointing downwards, and the beacon is assumed to be on the ground, with the XY plane of $\{M\}$ parallel to the image plane, the yaw orientation is straightforwardly the orientation of $\vec{a}$ or $\vec{b}$.

4 Experiments

Two experiments on visual control performed with the blimp are presented here. They are symmetrical in the sense that, while the first one controls the blimp using images taken from a fixed camera external to it, the other one closes a loop of visual control by using the onboard camera of the blimp. However, these two experiments share some common goals and experimental conditions, listed below:

- **Objectives:** Both experiments are concerned only with a simplified control of one angle of *orientation* and one dimension of *position* of the blimp. Only the tail fin and main propellers are controlled. At the present stage of this research, it would be very complex to implement a control with more degrees of freedom due to the present lack of a dynamic model for the blimp. In fact, these preliminary experiments can be used to collected data to determine the parameters of such a model.
- **Setup:** The autonomous dirigible used here is a small indoor blimp commercially obtained. It has two main propellers and two motors for driving – one tail fin propeller used for yaw control and a internal motor for vectoring of the main propellers (thus allowing pitch control). The propellers have an wireless connection with an workstation that executes the vision and control software. The blimp still has a visual beacon attached to its hull for external visual control. Finally, there is a CCD camera mounted on the blimp gondola, used for image acquisition during onboard visual control. It has a 640x480 resolution with 8 bits, gray level, per pixel. Figure 7 shows a diagram of the indoor blimp used in this work. The Computer Vision software was written in C++. Preliminary software versions, as well as its current user interface, were written in the Java programming language. The latest version was tested running on a machine with a 266 MHz Pentium MMX processor and 64 Mbytes of RAM memory, under the Windows 98 operating system.

More detailed descriptions of the two experiments are given in the following subsections.

4.1 Control from External View

The image of the dirigible was acquired by the micro-camera used for visual sensing 5. The visual beacon was attached to the uppermost part of one of the sides of the blimp, with its X axis approximately parallel to the ground. The whole experimental assembly for the blimp is shown in Figure 6. The micro-camera was attached to a wall close to blimp, with its X axis also approximately parallel to the ground.

The blimp was programmed to keep the X axis of the beacon coordinate system aligned with the X axis of the

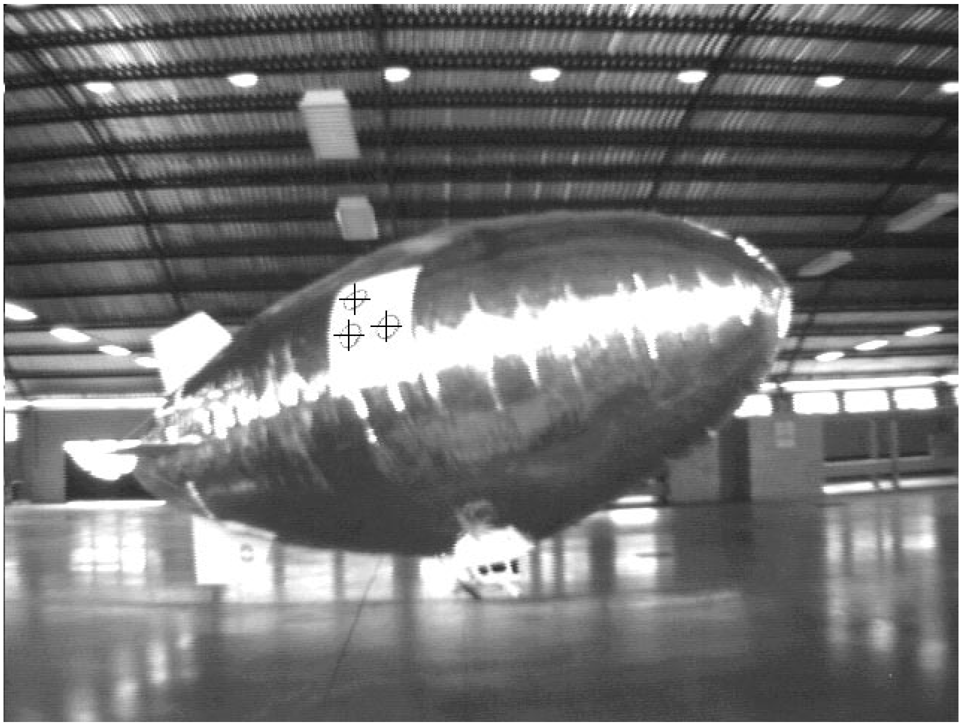

Figure 5: The blimp as seen from the image processing window with the beacon elements correctly tracked and identified.

camera coordinate system, that is, to keep its yaw angle at zero; in an informal definition, the task, in terms of orientation, is to keep the blimp length axis parallel to the wall. In terms of position, the task is to keep the X position of the blimp at zero, in the camera coordinate system.

The control of the blimp propellers in order to achieve the conditions above was set as follows. Control of orientation (yaw angle) was done using the tail fin propeller only. The activation a_t of the tail fin propeller was implemented as $a_t = A_t \sin\alpha$, where A_t is the maximum activation of the propeller. Thus, orientation control is done using a model of *proportional controller* taking $\sin\alpha$ as the error measurement.

The control of position was done using the main propellers. The activation a_m of the main propellers is $a_m = A_m \sin\alpha F_2 b = A_m \sin\alpha b p_x$, where b is a constant set in a way that bp_x lies in the range $[0, 1]$. Therefore, the activation of the main propellers is stronger when the blimp axis is aligned with X. That was done to minimize drift along the Y axis while keeping the dirigible at $p_x = 0$.

At the beginning of the experiment, the indication of the markers of the artificial beacon on the blimp was made with all the motors deactivated. After the establishment of the beacon tracking, the tail fin propeller was controlled in the way described above during approximately 40 seconds. The experimental data showing the relation between the main propellers activation and the orientation of the blimp from that point on is presented by the graphs in Figure 8.

It can be seen from the graph above that the control response in this experiment closely resembles that of a proportional controller, responding to variations of the blimp position in an almost directly proportional way. That happened because the orientation control kept the α angle close enough to zero most of time. Another observed behavior is the tendency of both position and orientation to stay at positive values, although there is also a tendency to return to zero due to control. That was due to small wind currents in the lab. Finally, it can be seen that the line representing $\sin\alpha$ and activation of the main propellers are very jagged. That is a consequence of the estimative of orientation for external views, which is done in an indirect way and thus is very sensitive to noise.

4.2 Control from Onboard View

This experiment has two fundamental differences in relation to the previous one. Images are acquired here by an onboard micro-camera connected by radio to the workstation running the system. That micro-camera is attached to the lower part of the blimp gondola pointing downwards. And the visual beacon is put on the ground below the blimp. Figure 10 shows an image of the beacon lying on the ground

Figure 6: Blimp prepared for the experiment of control from external view.

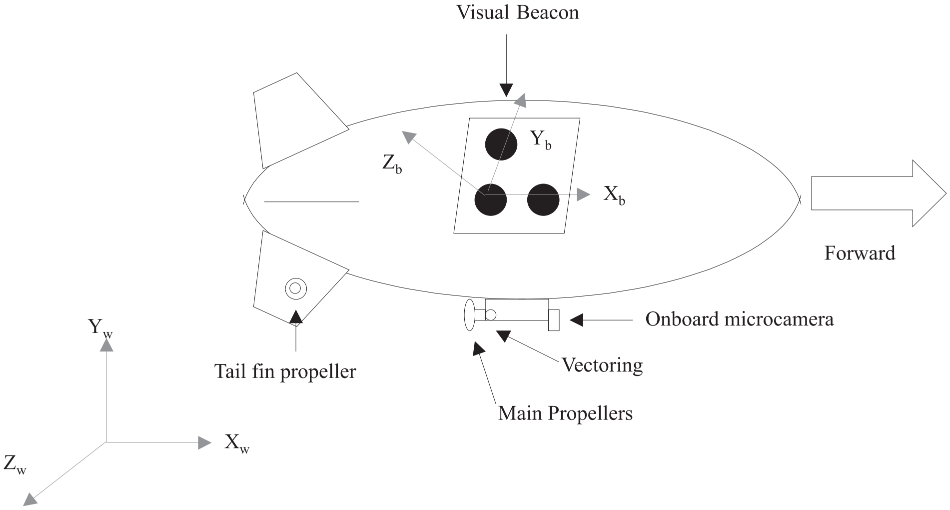

Figure 7: Reference frames for the blimp mounted beacon and for the world.

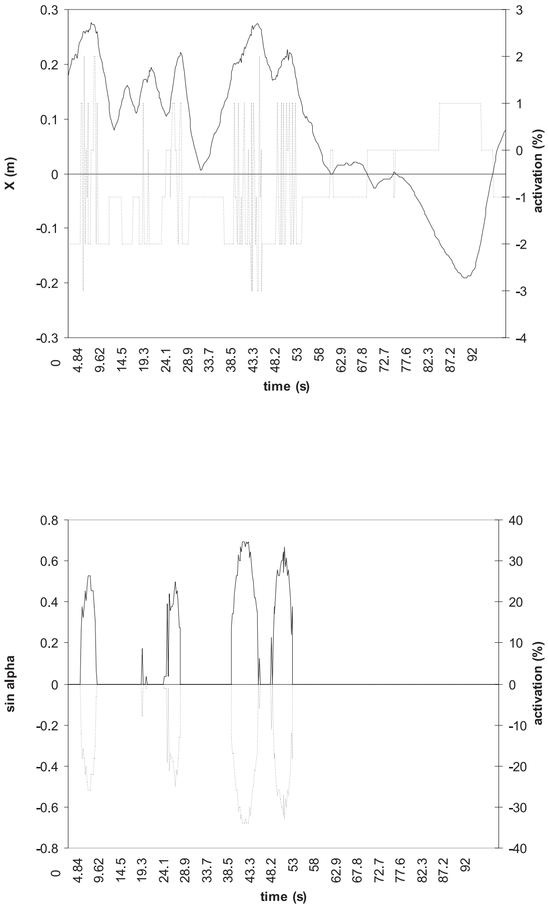

Figure 8: Control from external view. Top: Beacon position in the X axis and main propellers activation (dotted line) along time. Bottom: $\sin\alpha$ and tail fin propeller activation (dotted line) along time.

acquired and processed by the tracking system when connected to the onboard camera.

Although the experimental setup is different, the control model is quite similar to the previous one. However, the orientation goal is to keep the beacon Y axis aligned with the Y axis of the camera coordinate system and the position is controlled to set the blimp at $p_y = 0$, with all the corresponding modifications in the functions described in the previous section. Figure 9 shows the behavior of the Y position and yaw orientation of the blimp and the activation of the corresponding motors during this experiment.

It can be seen from the graph above that, in this experiment, the blimp shown a tendency for staying at positions with positive X coordinate, despite the control. That seems to have been caused by a slight wind current flowing through the lab during the experiment. That current,

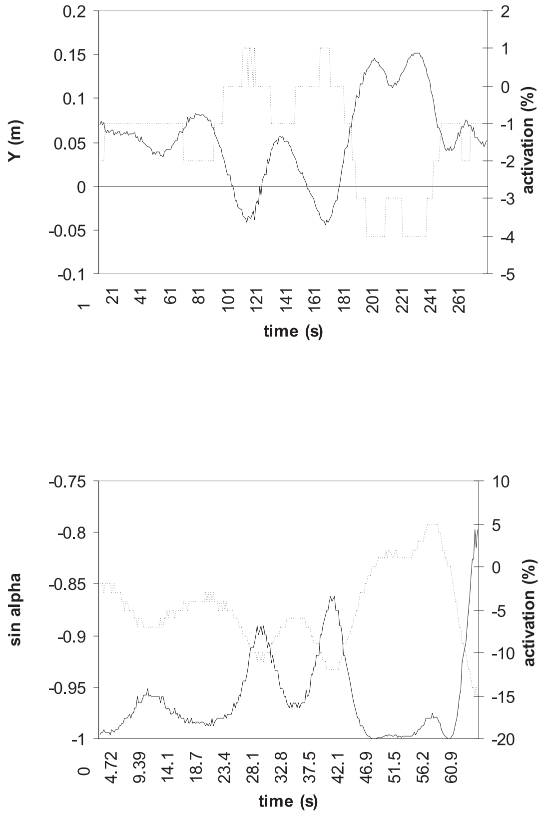

Figure 9: Control from onboard view. Top: beacon vertical position in the Y axis and main propellers activation (dotted line) along time. Bottom: $\sin\alpha$ and tail fin propeller activation (dotted line) along time.

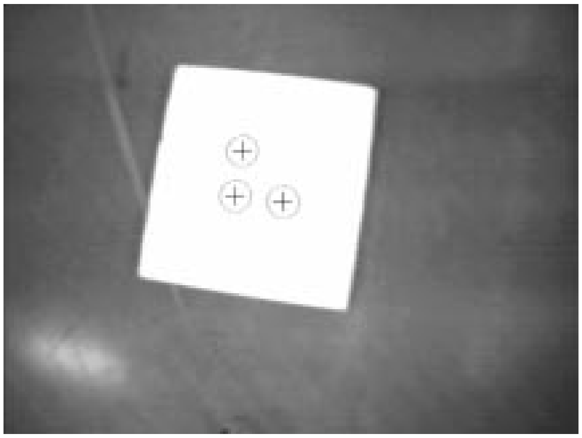

Figure 10: The markers of the artificial beacon as seen in the system graphic interface during tracking from the onboard camera.

however, did not disturb significantly the orientation of the blimp, as it can be seen from the graph of $\sin\alpha$. (In this experiment, α is the angle between the Y axis of the camera and beacon frame.) Finally, one can see that in this case the lines of orientation and activation are not jagged as in the experiment with external view. That happens due to the estimative of orientation done in its case, where orientation is directly extracted from image and thus is very robust to noise.

5 Conclusion and future work

The preliminary experimental results presented suggest that visual system under development for the blimp can achieve the desired goal of supplying data for navigation. Nevertheless, the conditions needed for the correct operation of the vision system lack robustness and have few practical value for real-world applications. In order to achieve efficient and effective visual navigation capability, the system of onboard vision should probably use *natural landmarks* – objects that already exist in the environment – instead of artificial ones. Conversely, the system of external vision should rely on the geometric and visual characteristics of the blimp itself to estimate its pose. Such improvements are currently under development.

Nevertheless, success on visually controlling the blimp from both onboard and external views opens the possibility of extending this project to encompass the unexplored issue of cooperation between UAVs and UGVs (Unmanned Ground Vehicles, or terrestrial robots). In a system already under development, the blimp will serve as an “aerial eye” to help a UGV or team of UGVs to accomplish a mission. For that purpose, the vision system has to be improved with additional features, specially at the blimp side, where terrain mapping capabilities, perhaps using structure from motion, would be desirable. The UGVs, by their turn, will visually guide the blimp to spots of interest that should be explored for the completion of the mission. The Nomad 200 robot and other smaller mobile robots at this lab will be used as UGVs for that experiment.

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