Omni-directional vision with a multi-part mirror

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Abstract. This paper deals with an omni-directional sensor based on a camera and a mirror generated with a surface of revolution. The requirements the device must fulfill result from its use as the main perception system for the autonomous mobile robots used in F2000 RoboCup competitions. The more relevant requirements which have been pursued are 1) range sensing in a quite wide region centered around the robot, with good accuracy; 2) sensing around the robot in a given vertical sector, in order to recognize team-mates and adversaries (all robots have a colored marker above a given height); 3) range sensing in a region very close around the robot, with the highest accuracy, to locate and kick the ball. Such requirements have been fulfilled by the design of a mirror built up of three different parts. Each part is devoted to the fulfillment of one requirement. Concerning the first requirement the approach developed is based on the design of a mirror's profile capable to optically compensate the image distortion provided by the mirror profiles commonly used in previous literature. This approach resulted to be similar to a previous work by Hicks and Bajcsy, although independently developed by the authors.

Introduction

This work has been accomplished in the framework of the Italian participation to RoboCup [5]. For a more detailed introduction to RoboCup see [6]. A robot capable to compete in a F2000 RoboCup match (F2000 is the so called "middle-size" league, i.e. robots with a dimension of about 0.5 m per side) should be able to observe what happens on the playground in order to recognize and localize objects of interest for the game; e.g. robots, ball and goals. For the above-mentioned aims, an omni-directional vision sensor [1] seems appropriate (Fig. 1); actually this kind of sensing has been chosen by many teams participating to previous RoboCup competitions (e.g. [3][7]). An omni-directional vision sensor should satisfy the following constraints:

1. it must be able to observe around the robot, in the horizontal plane;
2. it must be able to observe the markers, which allow to distinguish team-mates from adversaries, independently from the robots position in the playground; this results in a constraint on the observed angular sector, in the vertical plane;
3. it should be able to perceive colors, because the objects can be distinguished by their colors (with the current rules all the relevant objects have quite different

colors);

4. it must be able to locate the ball (direction and distance) with enough accuracy as follows:
    - 4.1 when the ball is in contact or very near to the robot: very good accuracy, in order to properly control the kicking;
    - 4.2 when the ball is within few meters from the robot: good accuracy and constancy of the accuracy in the range in order to control the motion to properly approach the ball itself;
    - 4.3 when the ball is quite far: good accuracy for the direction, in order to be able to head toward the ball, some inaccuracy may be allowed for the distance;
5. it must allow localization of the relevant objects (players, goals, and other relevant features of the playground);
6. it must allow the self-localization of the robot with respect to the playground.

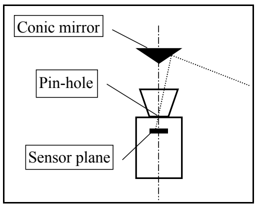


Fig. 1. Sketch of the COPIS sensor (camera plus mirror configuration)

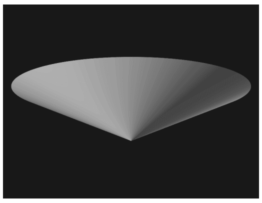


Fig. 2. Conic mirror

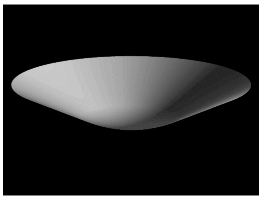
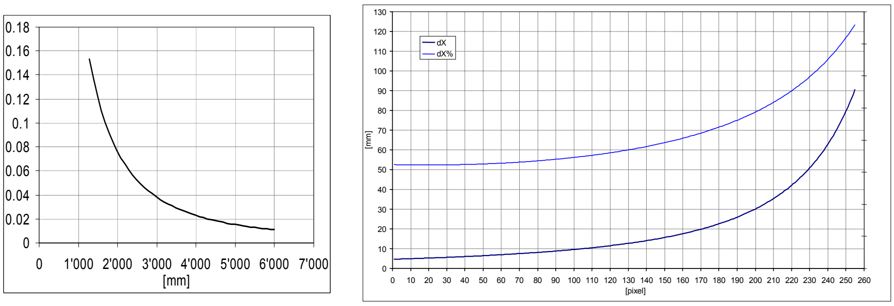


Fig. 3. Conic-spherical mirror

In literature different mirror geometries have been proposed and even in RoboCup some teams already used mirrors other than the original conic one (Fig. 2). For instance in [3], a conic mirror with a "spherical vertex" (Fig. 3) has been motivated by the need of getting a higher resolution in the area close to the robot (the spherical part magnifies the scene). Such mirrors introduce large distortions on image distances of objects at the playground level. It should be noted that such distortion grows with the distance of the object from the observer (Fig. 4b).

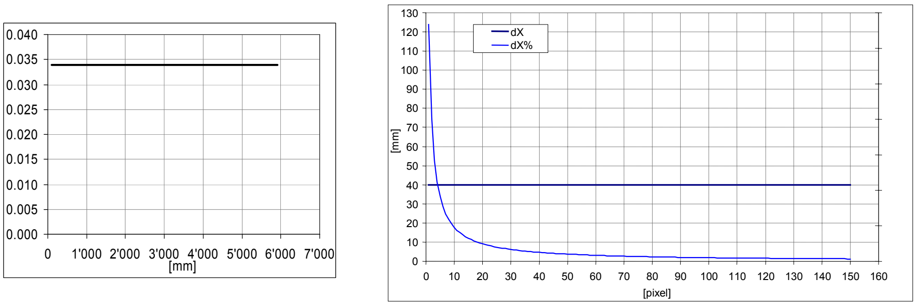
On one hand, it is quite obvious that the "nominal" value of the estimate can be easily corrected exploiting the known profile of the mirror; on the other hand, the accuracy of the measure is corrupted without the possibility to compensate for such degradation.

Therefore, one of the objectives of this work was to develop an optical compensation of the above-described distortion, working directly on the mirror profile in such a way that the absolute localization error remains constant with the object distance. Both the idea of an optical compensation and the analytical set up for the determination of the compensating mirror profile turned out to be indistinguishable from a previous work, by Hicks and Bajcsy [4]. Such work does not detail some implementation aspects, which are presented here instead. Moreover, it should be mentioned that the approach here taken, which aims at the defintion of a complete solution to a set of real requirements, involves more than the optical compensation just described, which provides a solution to one requirement only. Such global approach implies the integration of the different proposed solutions to each requirement. Due to the fact that each solution is the design of a part of a mirror, the overall outcome of this work is one single mirror, built up of different parts.



a) b)

Fig. 4. Conic mirror: a) the image dimension of a given object vs. its distance from the observer; b) absolute (dx) and relative (dx%) error affecting the localization due to the spatial sampling of the radial distance from the center of the image



a) b)

Fig. 5. Isometric mirror: a) the image dimension of a given object vs. its distance from the observer; b) absolute (dx) and relative (dx%) error affecting the localization due to the spatial sampling of the radial distance from the center of the image

Concerning the optical compensation, it should be observed that, by keeping constant the pixel density, a constant absolute error, with respect to the distance, can be attained as well as a decreasing relative error. This allows for a better accuracy in locating objects, with respect to what can be attained with commonly used mirrors (compare Fig. 4b and 5b). We called “isometric” this kind of mirror because of its capabilities to map scene distances, in any direction, in proportional image distances within the whole range covered by the mirror (Fig. 4a and 5a). With a conventional (e.g. conic) mirror, the image size of an object is maximum when the object is in contact, is minimum when the object is at the greatest distance.

It should now be clear that the effect of the distortion due to conventional mirrors represent a degradation. This is true not only under the point of view of the localization accuracy, but also under the point of view of the detection of relevant features (e.g. the ball). The smaller the ideal image size, the higher the probability of a detection failure of the feature. A failure can happen when the image formation will not take place under ideal conditions. Non-ideal conditions are due to shadows, non-uniform lightening, electronic noise in the hardware, etc.

Mirror design

In this section the procedures followed to design the proposed mirror are introduced. To completely satisfy the requirements, the mirror design has been split in three parts: isometric, constant curvature and planar.

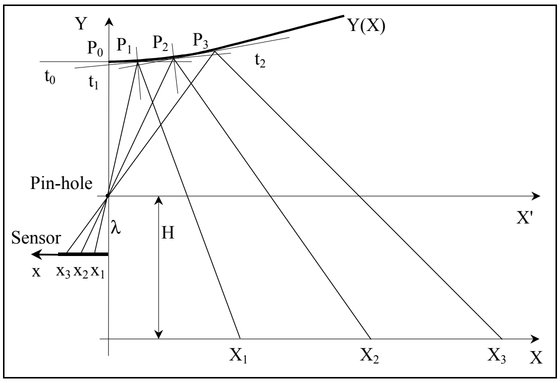


Fig. 6. Sketch for inferring the differential equation generating the isometric part of the mirror

Isometric mirror part

The first requirement implies the design of a mirror capable to compensate the distortion, introduced by the linear profile of a conic mirror, by means of a non-constant curvature of the profile. This is the idea that turned out to be the same as the one proposed in [4]. This design problem has been modeled by the following differential equation (1), which can be inferred by applying the laws of the Linear Optics (Fig. 6).

$$\frac{\frac{X}{Y}+\frac{2Y'}{1-Y'^2}}{1-\frac{X}{Y}\frac{2Y'}{1-Y'^2}}=\frac{\eta Y-X^2}{X(Y+H)};\quad \begin{cases} Y(0)=Y_0 \\ Y'(0)=0 \end{cases} \qquad \mathbf{(1)}$$

where: $Y' = dY / dX$, $\eta = k\lambda$, λ = focal length, k = proportionality constant from X' to x, H = Pin-hole height from the playground.

This equation has been written in a reference frame XY centered in the Pin-hole of the camera. Refer to [4] to find a different formulation obtained under similar conditions. Although we independently obtained this formulation, the approach is quite similar to the one taken in [4] and the results are identical. Differently from [4], we developed a "geometrically" based integration of equation (1). Our approach bases on a local first order approximation of the profile: at each point the profile has been approximate by its tangent. The higher the considered number of points on the profile, the better the approximation. The mirror profile should compensate for the radial distortion of the lengths, so that to a given length on the image plane should correspond a proportional length on the scene plane, independently from the position in the scene/image. Referring to Fig. 6, this means that we want to obtain:

$$\frac{X_1}{x_1} = \frac{X_2}{x_2} = \ldots = \frac{X_n}{x_n} = k \qquad \textbf{(2)}$$

In our approach, the sensor plane is scanned at constant steps (Δx, as small as possible), consequently the scene plane is scanned at steps $\Delta X = k\, \Delta x$. Applying the Optics laws on a Pin-hole model of the camera, the path from the image points to the scene points can be determined. In particular, taking the mirror point P_1, the path to X_1 is known as well. The line passing through the Pin-hole and reaching the sensor in x_1 is also known, and the tangent t_1 to the mirror in P_1 can be determined too. Choosing a Δx very small the mirror profile can be well approximated by its tangent; the next point P_2 can be determined by intersecting the tangent in P_1 with the line defined by x_2 and the Pin-hole. The Optics gives now the line from P_2 to X_2. The tangent t_2 in P_2 can now be computed, and then the next point P_3. By iterating such a procedure the sequence of points that gives the approximation of the mirror profile can be calculated.

The initialization of the procedure is as follows:

1. the first point $x = 0$ corresponds to the scene point $X = 0$;
2. the first mirror point is $P_0 = (0, Y_0)$;
3. the tangent in P_0 is horizontal.

The resulting profile looks quite similar to the one obtained in [4]. It is convex into its first half, i.e. the part that goes from axis of symmetry toward the outside of the mirror. It then has an inflection point and then gets slightly concave. Fig. 7 shows a scene, used in the rest of the paper; the observer robot is the one at the center of the playground. The image observed through the mirror in such a configuration is presented in Fig. 8. The transformation between the two 2D Euclidean spaces, i.e. from the playground to the sensor plane, keeps angles unchanged and changes lengths by the multiplication with a constant. This transformation, being linear, changes its metric Euclidean tensor to the same metric Euclidean tensor, neglecting the constant. Hence lengths remain unchanged, apart the constant, angles remain unchanged, and parallel lines remain parallel. As an example, a chessboard on the playground is transformed in a scaled chessboard in the image. This is true disregarding the aspect ratio, i.e. the different sampling frequencies on the sensor plane.

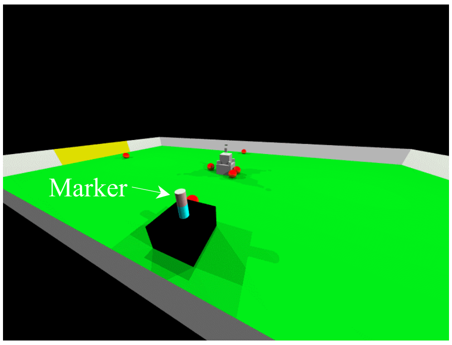


Fig. 7. Perspective view of the scene

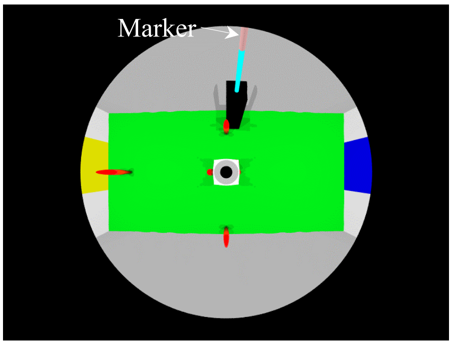


Fig. 8. The same scene as in Fig. 7, as seen by the robot through an isometric mirror

Constant Curvature mirror part

The mirror design described above does not satisfies all the requirements because it observes an angle which heads too low, in such a way that it cannot observe the higher part of the scene. The information needed to distinguish the robots of the two teams can be found instead at a quite high height. Therefore we decided to devote part of the image and of the mirror to this aim. This part of the mirror satisfies a different design criterion with respect to the isometric one. As already mentioned, the process for identifying each robot as a team-mate is based on the marker color and not on its shape. Therefore, it has been possible to release the no-distortion requirement, which was convenient for the isometric part. On the other hand, the continuity between the two portions of the image should be preserved, to be able to associate the marker to the body of the robot. The robot body is underneath the marker, i.e. nearer to the image center, along the same radius. Moreover, when the bottom of the robot is observed through the isometric part of the mirror, which is a very likely case, it will be possible to measure its distance with a quite good accuracy. The image continuity can be granted by imposing the continuity on the junction between the isometric and the new part of the mirror (point A in Fig. 9). Another condition comes from fixing the point $B = (X_B, Y_B)$ and setting height h_{max} so that it can be observed at distance d_{max}. This constraint gives the tangent to the profile in point B.

$$\begin{aligned} \tan(\tau) &= (h_{max} - Y_B) / (d_{max} - X_B) \\ \tan(\beta) &= X_B / \lambda \\ \tan(\gamma) &= \tan((\beta + \tau - \pi) / 2) \end{aligned} \qquad \textbf{(3)}$$

where: λ = focal length.

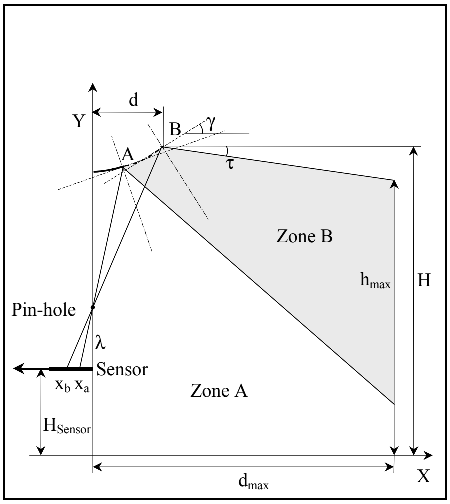


Fig. 9. Sketch for the design of the "constant curvature" part of the mirror

Because there is no other constraint, this portion of the mirror can be designed, e.g., by imposing a constant variation of the tangent between the two endpoints. Hence the name “constant curvature” given to this part of the design. In this condition the mirror will cover completely the highest part of the scene (Zone B). On the other hand, when the robots are quite near, they will be observed by the first part of the mirror (Zone A).

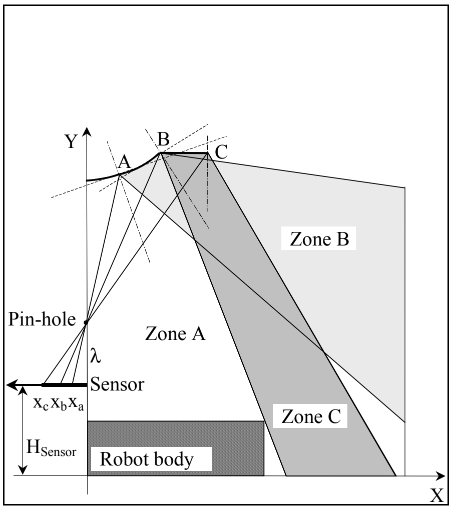


Fig. 10. Sketch for the design of the "planar" part of the mirror

Planar mirror part

The overall mirror still does not satisfy the requirements: due to the robot body occlusion (Fig. 10), it is not possible to observe the scene in its neighborhood. More specifically, when the ball is in contact or very near to the robot, it is not observable. Moreover, the isometric part of the mirror produces a too small image of the ball when it is in the kicking range, i.e. where the highest accuracy should be needed in order to control accurately the kicking contact. To solve this problem a third part of mirror has been introduced, aiming at observing an area very close to the robot body. This part of the mirror should be the outmost part of it, although it looks nearer than the other parts do. The reason for this is the need to have the least occlusion from the robot body. The simplest solution to this problem is a planar mirror, specifically a circular crown, lying on a plane perpendicular to the rotational axis. The height of this part has to be as low as possible, with respect to the camera, in order to give out the largest images of the ball. On the other hand this part of mirror should not be on the line sight of other parts of mirror. Hence the choice is to have the circular crown at the same height of the last point of the constant curvature part of the mirror (point B in Fig. 10). The radial dimension (point C) is set as follows:

$$\begin{aligned} X_C / (Y_C - \lambda - h_{Sensor}) &= x_c / \lambda \\ Y_C &= Y_B \end{aligned} \qquad \textbf{(4)}$$

where h_{Sensor} = height of sensor plane, λ = focal length.

The area observed by this part of the mirror at the playground level (zone C) is observed by the isometric part of the mirror too. The image produced by the circular crown, on the other hand, is much larger (Fig. 13), hence allowing a more reliable detection and a more accurate localization of the ball when near to the robot. This configuration produces a discontinuity in the image, which is not a problem.

The resulting mirror

The mirror profile resulting from the design described before is shown in Fig. 11. The mirror (Fig. 12) is capable to observe up to 6 m far away without image distortion at the playground level; thanks to its constant curvature part it can observe up to the maximum height, 600 mm, at the maximum distance allowed in the playground (11.2 m). Its outer part allows the observation of objects from 0.39 m to 0.51 m. Fig. 13 shows the image that can be obtained using such mirror on the scene of Fig. 7. The magenta cylinder is the marker. By comparing the third part of the mirror with the first, one can see that the third part allows an easier detection and localization of the ball.

In Fig. 14 the robot has been moved in front of the blue goal. The effect of the optical compensation lasts up to 6 m, but, thanks to the continuity with the second part, it is still possible to detect the yellow goal and the other robot marker, although they are distorted by the constant curvature part of the mirror. The distorsion is due to the fact that the body of the objects, i.e. the balls and the robot, are over the playground whilst the isometric compensation holds only at the playground level.

However, their distances from the observer, measured at the contact point with the playground, can still be recovered with the limited error provided by the isometric design.

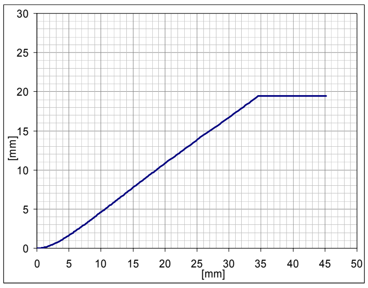


Fig. 11. Profile of the overall mirror

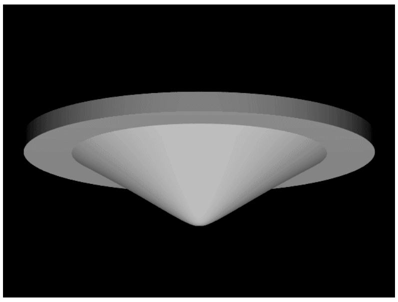


Fig. 12. The proposed mirror

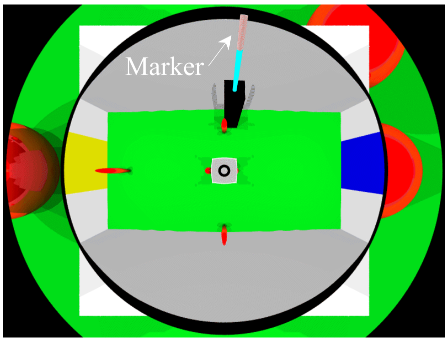


Fig. 13. Image taken when the robot is in the center of the playground

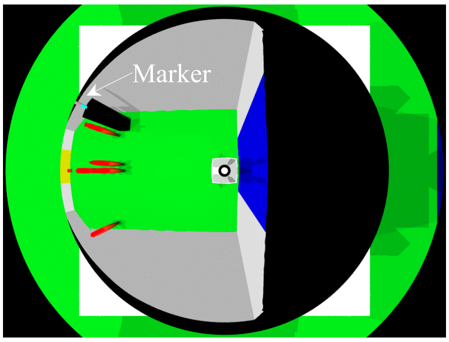


Fig. 14. Image taken when the robot is in front of the blue goal

Conclusions

The paper stems from the definition of some requirements for the sensor system of a robot for F2000 RoboCup competitions. The proposed solution is based on the design of a mirror of an omni-directional system, differently from approaches trying to compensate in software the shortcomings of conventional mirror design. The proposed design resulted in a three-part mirror, each part being devoted to fulfill one of the requisites. The first part aims at an un-warped image of the playground; this development resulted nearly identical to a precedent work [4]. Details on the integration of the differential equation governing this part of the design are presented. The second part allows to recognize team-mates and adversaries observing colored markers over them. The third part allows to precisely localize the ball when very close to the robot. At the moment of writing the mirror is under construction and we hope to be able to install the mirror on the Italian National Representative robots in RoboCup F2000 championships.

Acknowledgements

This work exists thanks to the contribution of Prof. Andrea Bonarini, Dipartimento di Elettronica e Informazione, Politecnico di Milano. His contribution has been fundamental for our effective introduction to the field of RoboCup competitions. Without his experience the setting up of the requirements would have not been possible. Moreover, we are grateful for the very fruitful conversations, which took place during the development of the work.

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