A low-cost mirror-based active perception system for effective collision free underwater robotic navigation

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Abstract

This ongoing research work presents a servo actuated mirror-based design that allows a fixed front-view visual system mounted in an underwater vehicle to extend its field of view by controlling its gaze. We are interested in the autonomous underwater exploration of coral reefs. This type of exploration must involve a cautious and collision-free navigation to avoid damaging the marine ecosystem. Generally, vision systems of underwater vehicles are carefully isolated with mechanical seals to prevent the water from entering. However, this fact causes a strictly dependence between the angle of view of the camera and the pose of the vehicle. Furthermore, the addition of a system to control camera orientation may result in a significantly reduction of useful load capacity and the movement of the vision system could carry undesirable trusting effects, especially at higher speeds. Our design of servo actuated mirror system changes the angle of view of the camera in two degrees of freedom: pan and tilt, and reaches viewing angles from the sides, bottom top and even rear views of the robot, thus enabling a more effective navigation with obstacle avoidance.

1. Introduction

Vision-based autonomous robot navigation is gaining popularity within the computer vision research community. Many of the contributions have emerged as a part of a solution to a particular navigation problem, generally for ground vehicles which may not be suitable either for aerial unmanned vehicles or even for underwater platforms. Furthermore, the robotics research community has developed many vehicle technology applications that involve visual information for navigation, such as monitoring, mapping, image acquisition and video recording, rescue and messaging, package transportation and logistic activities at indoors and open environments, increasing the computer processing power requirement. If we step back and analyze how it is that humans and even much less complex animals like insects, solve their navigation tasks, we may wonder if all this computational complexity is necessary. However, unlike many robots with an onboard vision system, we realize that humans and animals have the ability to get information from the environment without moving their body, with simple eye and/or head movements.

In many mobile robot platforms, the camera is attached to the body of the robot, restricting the possibility of varying the gaze attitude (with respect to the coordinate frame of the robot). Other mobile robots (commonly ground platforms) have active vision systems capable of tracking visual characteristics in the environment at certain time intervals, and with a wide viewing angle. This kind of systems have been used for many applications far from navigation tasks, including map-building and localization tasks, however, in the majority of the cases they cannot be incorporated in some platforms due to energy capabilities of the robot.

Any Autonomous Underwater Vehicle (AUV) carrying out an exploration task should include an effective collision avoidance strategy. This involves thinking on the type of sensors that allow for more complete coverage of the vehicle's periphery. Most of the already constructed robotic platforms have a motion of five or even six degrees of freedom. However, its sensors do not always allow for the coverage of large areas and zones in its periphery. The motion needs to be efficient in order to cover the area in the shortest time. On one hand, with the recent advances in sonar technology, a viable solution is the use of two or more Forward Looking Sonars (FLS) [10] to detect obstacles in the path [9], and to calculate a way of avoiding them. On the other hand, when ultrasonic sensors are not an option, either because of their size/weight or because of their invasiveness (in particular, we do not want to harm the fragile organisms living in a coral reef ecosystem), then visual sensors become attractive.

Typically, active vision systems are composed by a servo-actuated system to move the camera and change the view. The cumulative weight for the camera, motors and control system may represent a considerable reduction in payload capabilities of the platform, which is very critical in the development of certain applications (mainly for aerial and underwater vehicles). In addition, in order to move a camera in an underwater environment it is necessary to have different mechanisms of electrical insulation to protect the electronics of the robot and camera.

Aside from moving a camera, there is another alternative for changing the angle of view which is based on the use of mirrors. Derived from the *"Principle of Least Time"* proposed by Fermat, the law of reflection (or Snell-Descartes law) describes the relationship between the angles of incidence and refraction where the light waves change of propagation medium.

Some scanning devices and cameras are well known to use this theory to control or switch the direction of propagation of the light waves (*i.e.*, the pentaprism of SLR cameras), but recently, mirrors have also been used to develop a large variety of active vision systems for multiple applications [4], [12], [11]. Okumura *et al.* developed a high-speed gaze controller for a high-speed camera [5] based on two rotational mirrors to control pan and tilt attitudes. Motivated by the problem of the large size and weight of high-speed cameras, in that research work they constructed a fast response prototype with a response time as low as 3.5 ms, increasing the range of vision of a camera and considerably reducing the inertia of overall system. These advantages can be very useful for a robot having a vision system with fixed cameras and reduce payload capacity as in the case of drones and underwater vehicles.

The aim of this research work is to expose some of the critical physical and mathematical foundations for the design of a low-cost active perception system for an underwater vehicle to solve navigation and exploration related tasks. Particularly, we are interested in bringing out the active vision capabilities of mounting a mirror-based system to the fixed camera's configuration of the vehicle. We want also to validate the advantages of the system when applied to the exploration of coral reefs. To do so, some issues for underwater vision systems have to be considered. First, we want to emphasize that the vehicle must be able to perform smooth collision-free trajectories as it is very important to be careful with the living organisms in this type of ecosystems. To this end, the robot must be aware of the existence of objects on its periphery; more specifically, from its sides, back and even from top and bottom. Therefore, the vision system must extend the range of vision.

The outline of the paper is as follows. In Section 2, we briefly describe the pros and cons of existing vision systems with wide field of view. In Section 3, geometric considerations for mirror design are presented to extend the field of view of any existing camera configuration on a mobile platform. In Section 4 a selection criterion to determine the size of the mirrors of the system is presented, as well as preliminary results from a 3D-printed prototype on a ground mobile platform as well as images captured through mirrors in an underwater environment. Finally, the conclusions and ongoing work are presented in Section 5.

2. Background

In this section, some visual systems with wide field of view or peripheral vision are presented, as well as their main limitations when considering using them on an underwater robotic platform.

2.1. Omnidirectional Vision with Multiple Views

Omnidirectional vision has been a topic of growing interest. Many recent technologies are using multiple cameras and view-integration algorithms to achieve this omnidirectional vision. Kubota *et al.* [6] address the problem of integrating different overlapping views from a circular camera array without estimating the depth of the scene. They present a deconvolution method in simulation using synthetic images. One application that explodes the capabilities of incorporating different views is the work of Yonemoto *et al.* [13] where they proposed a vision-based motion capture system to reconstruct time-varying motion parameters of 3D multi-part objects. However, the main limitation when trying to incorporate either of these two methods lies in the characteristics of the submarine environment and the computational time for the analysis of multiple images. Furthermore, although the efficiency of both methods increases with the addition of cameras, the cost also increases significantly.

2.2. Omnidirectional Vision with Hyperbolic Catadioptric Systems

We can also obtain peripheral vision through the use of a catadioptric system, which consists in a camera, lenses and mirrors. In most cases, a catadioptric system involves a convex mirror (typically a hyperbolic mirror). Omnidirectional catadioptric systems are widely used in different applications as they allow the observation of a 360^o field of view, instantaneously. However, due to the significant distortions on the omnidirectional image, it is necessary to incorporate a specific image process (according to the camera parameters and mirror geometry) to interpret the visual information given by the mirror. Furthermore, catadioptric systems with hyperbolic mirrors have an amount of obstruction in the field of view caused by mechanical structures that hold the mirror in front of the camera. The work of Paredes *et al.* [8] outlines a methodology based on a multi-scale image inpainting algorithm with unwrapping methods to inpaint catadioptric omnidirectional images. To handle the distortions due to the geometry of the mirror, different deterministic and heuristic methods have been used. Bourgeos *et al.* [2] presented a method to unwrap catadioptric images based on total variation regularization technique, reducing the noise caused by transmission errors, and also reducing the aberrations produced by the camera lenses. On the side of the heuristic methods, Tang Zhe *et al.* [14] presented an efficient method based on artificial neural networks to reduce the catadioptric distortion, applied to localization tasks in the RoboCup. It is worth mentioning that omnidirectional catadioptric systems have been well tested in ground environments. However, for underwater environments the main challenge would be to model the geometric and color distortions originated by this type of vision systems.

2.3. Omnidirectional Vision with Planar Catadioptric Active Systems

Another approach is one where catadioptric systems use one or more flat mirrors to vary the viewing angle. By using a flat mirror instead of a hyperbolic mirror, image distortion disappears, thus it is easier to interpret visual information. In the work of Xiaodong *et al.* [12], a variable angle view system based on flat mirrors is presented to deal with the insufficient vision information for microassembly and micromanipulation approaches. This is the same idea that Okimura *et al.* used for the design of their tracking system based on mirror optics.

3. Mirror Systems Optical Theory

To start with the design of an actuated mirror system applied to a fixed camera, it is necessary to recall the image formation process. In a digital image, each pixel is given a value that comes from the photometric signal measured by the diode matrix camera sensor. These photometric values depends only on the mean wave-amplitude and frequency of the light waves that reach the sensor [1].

As mentioned above, there are several mobile robot platforms that have a camera attached to the body of the robot, restricting the possibility of varying the gaze attitude. In the mechanism of a D-SLR camera, we can see that this type of camera has a moveable mirror behind the lens which reflects an image through a pentaprism or pair of mirrors, onto the viewfinder. Thus, in an inverse approach, we could think of changing the direction of light beams from around the robot and focus them to the camera sensor with the appropriate motion of the mirror. Inspired by the form in which the humans and animals move their heads to explore their surroundings, without necessarily moving the rest of their body, it is desirable to have control in the change of view in two principal axis: pan and tilt. The change in the mirror orientation must have therefore two degrees of freedom. In the following sections we describe the details of the geometrical design and kinematics of the mirror system.

3.1. Geometrical Design

A cornerstone in the design of any mirror system is the distance between the mirror and camera. On one hand, if the mirror is placed very close to the camera, the virtual image on the mirror could present occlusions caused by the reflection of the body of the robot, dramatically reducing the useful field of view (FOV) of the device. On the other hand, if the mirror is placed too far from the camera, it would require a very large mirror in order to use most of the visual field of the camera due to the perspective. In addition, for applications involving underwater or even aerial vehicles, if we opt for a support big in lenght with a mass at the end (mirror), it could change dramatically the center of mass of the system and, therefore, it will change the dynamic parameters, which are needed for computing the controllers (*i.e.* adaptable control). To reduce the size of the mirrors, Okumura *et al.* [5] uses a set of lenses for transferring the pupil of the system, *i.e*, the geometric center is moved outside the camera body. However, for our development, this is not feasible, since one of the key goals in this research is to not drastically modify the original design of the robot. Moreover, we part from the premise that the objects or regions of interest are located at least one meter away from the vehicle, as a safety measure to develop navigation tasks. This may seem difficult to achieve once the vehicle is in motion. However, there are research groups who have developed obstacle avoidance strategies based on visual information for a cautious underwater exploration that exploits the photometric properties of underwater images thus allowing to detect when the robot is prone to a collision [7]. Thus, we assume that the platform has an infinite focal length lens and seek to place a mirror away from the robot to avoid occlusions with the body of the robot, but we also want to put the mirror closer in order to not alter the dynamics of the robot and reduce the size of the mirror. Figure 1 shows the effect of moving the mirror in the produced virtual images.

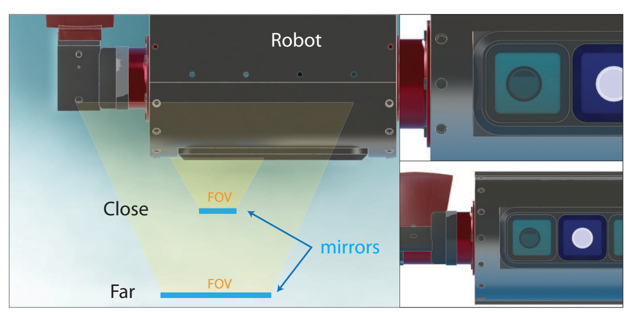

Figure 1. Effects of changing mirror-camera distance. The left image shows close and far poses of a mirror. The respective virtual camera views are shown in the right images, the upper image shows the view when the mirror is located close to the camera and the bottom image when is far.

Xiaodong *et al.* [12], consider using multiple mirrors at different stages to solve various optical problems related to the positioning of the optical system elements and image deformation caused by the lenses. Based on this approach, we propose the use of a system composed of two mirrors to address the problem of occlusions. Similarly to the pentaprism in SLR cameras, the two mirrors can change the direction of view. The objective of the first mirror is to reduce the system displacement far from the center of mass of the robot and it also produces a view of a virtual camera pointing sideways, outside the robot body. The second mirror moves in two axes and generates a second virtual camera whose view corrects image inversion caused by the first mirror and points to the desired direction of observation.

A basic scheme is shown in Figure 2, where two mirrors are interacting with the camera of the underwater vehicle and the environment.

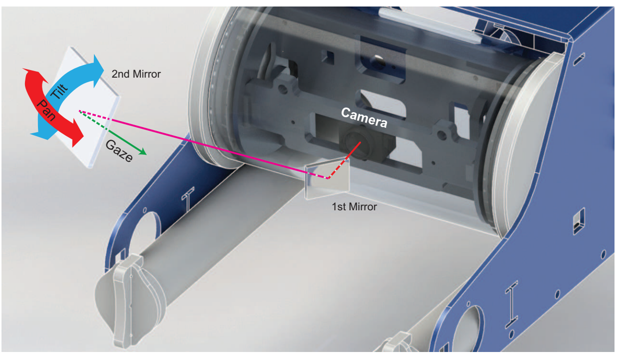

Figure 2. An illustration showing the two-mirror system interaction with the fixed camera mounted on a generic model of an AUV.

3.2. Mirror System Kinematics

Now, without loss of generality, we can describe the motion between two reference systems assigned to each of the mirrors, relative to reference frame of the camera or robot using orthogonal projections.

One of the disadvantages of including a system of two mirrors in relation to the system of a single mirror is that the mathematical model of motion of the virtual camera grows in complexity. However, with some design considerations, it is possible to simplify the motion model of the system. One of the considerations arising from the use of composite systems, is that the model can be simplified if we consider a constant translation between reference frames of each of the mirrors. Then, the first mirror can remain constant over time (or be disabled to allow the camera to see forward) and only targeting the center of the second mirror. We will work to model the system assuming that the first mirror is enabled and points directly to the second mirror. The second mirror is driven by two motors, which will be represented by the generalized coordinates $q1$ and $q2$. Considering that the axes of rotation intersect at the center of the mirror surface, the model will reduce its complexity and the rotation angle of the first mirror is fixed. A simple scheme of this is represented in Figure 3.

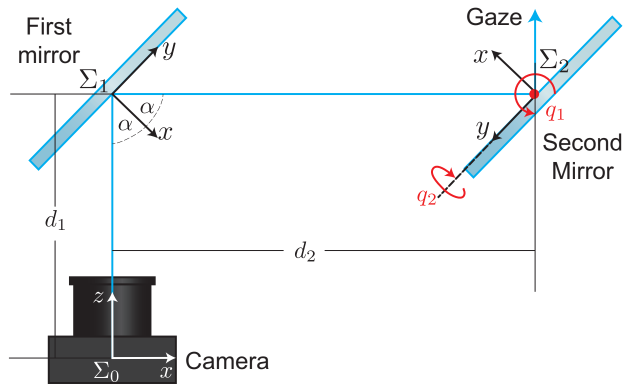

Figure 3. Reference frames of the system. Since we assume a system of fixed cameras on the robot, we consider a frame Σ_0 at the origin of the camera. The origins of the frames Σ_1 and Σ_2 are located in the center of the mirrors *1* and *2*, respectively.

The relative positions of the tilt and pan movements are described by q_1 and q_2, respectively. In this RR configuration we have that the vector of generalized coordinates $q = [q_1, q_2]^T$ that represents the values of the articular position of the mechanisms. We assume that the reference frame Σ_1, which corresponds to the first body and tilt movement, has a position displacement vector $d = d_1 + d_2$ (see Figure 3) w.r.t. the base reference frame Σ_c, Σ_c in this case corresponds to the reference frame assigned to the center of the camera. The frame Σ_1

The first transformation (rotation and displacement d_1) between both reference frames Σ_0 and Σ_1, is a constant transformation given by:

$$T_0^1 = \begin{bmatrix} \left[R_{x(-\frac{\pi}{2})} R_{z(q_1-\frac{\pi}{2})} \right] & d_1 \\ 0 & 1 \end{bmatrix} \in SO_{(4)}, \quad (1)$$

where $R_\phi(\cdot)$ is a rotation matrix over the $\phi \in \{x, y, z\}$ axis, α is the constant value of rotation to enable the mirror system, given by the orientation of the first mirror. Notice that since d_1 is only displaced in the direction of the positive $z-$ axis of the camera, we have $d_1 = [0, 0, |d_1|]^T$ .The matrix that transforms the values expressed in the Σ_2 reference frame to the Σ_1 reference frame is given by:

$$T_1^2 = \begin{bmatrix} \left[R_{x(-\frac{\pi}{2})} R_{z(q_1-\frac{\pi}{2})} R_{y(q_2-\frac{\pi}{2})} \right] & d_2 \\ 0 & 1 \end{bmatrix} \in SO_{(4)}. \quad (2)$$

As mentioned above, we consider the origin of the reference Σ_2 in the center of the second mirror. Then we have the center of the mirror is located in the vector $X_{e(2)} = [0, 0, 0]$. Note also that by placing the reference frames in the center of the mirrors and the center of rotation axis, this vector is invariant for all values of generalized coordinates vector q, then we have the vector X_e expressed in the camera frame as:

$$X_e = T_0^1 T_1^2 X_{e(2)}. \quad (3)$$

So far, we have only discussed about the description of the movement of the center of the mirror with respect to the center of the camera as a function of the joint coordinates q_1 and q_2. However, what it is in our interest is the description of the movement or pose of the virtual camera with respect to those joints. One of the optical phenomena of mirrors is the formation of a virtual image with depth equal to the actual distance of the object to the mirror (see Figure 4). We will use this property to describe the center of the virtual camera.

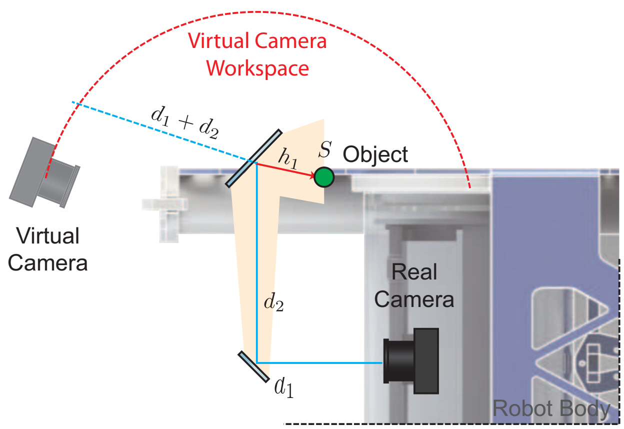

Figure 4. Virtual camera workspace. Since $d_1 + d_2$ remains constant, the locus where the camera moves is an arc of radius $r = d_1 + d_2$ for 2D projections, and the surface of an sphere for a 3D space with the same radius.

As shown in Figure 4, the position of S (representing a virtual object produced on the mirror) keeps the same displacement h_1 in the direction of the specular surface, however, the displacement h_1 on the normal axis to the mirror surface is negative. Thus, we have that the movement of the objects reflected on the mirror are symmetrical on the plane of the mirror. In a reverse approach, we can say that the movement of the virtual camera is symmetrical in the plane of the mirror relative to a static light source. To describe this movement, we simply reverse the directions of displacement $d_1 + d_2$ on the z axis, considered normal to the mirror surface. With the operator:

$$I_{-z} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}. \quad (4)$$

Since the position of the virtual camera is referenced at the center of the mirror, the position of the virtual camera relative to the frame of the robot, is given by

$$X_{\text{cam}} = X_e \begin{bmatrix} I_{3\times3} & d_2 I_{-z} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I_{3\times3} & d_1 I_{-z} \\ 0 & 1 \end{bmatrix}. \quad (5)$$

As it can be seen, the mapping of the camera's motion is nonlinear, thereby it is difficult to model an inverse relationship (there is not a unique inverse mapping) that allows us to choose a joint configuration given a desired position of the virtual camera. However, the true objective and challenge in most of the active vision systems, is to find the necessary variations for a system reconfiguration.

Different numerical and artificial intelligence methods have been tested in order to solve this inverse mapping, restricted to joint boundary and initial conditions. However, given the relationship between the motion of the virtual camera and the motion of the robot, it is necessary to incorporate the local model of displacement of the robot according to its boundaries and kinematic constraints.

4. Prototype

As mentioned above, we made the design considering the needs of an underwater vehicle for gathering visual information of its surrounding. To validate the principle of change and extend the angle of view, we developed a prototype for a ground platform available in our laboratory. Our first prototype was designed for the Pioneer P3DX robot, a differential drive robot made by Adept MobileRobots company. This platform has been widely used by the research community, since it has different tools for robot control and full integration with ROS (Robot Operating System), which make it easier to migrate the programming done on the ground platform to the underwater one. Moreover, the design of devices and controllers with ROS facilitates the integration of components that were appropriate and inexpensive to replicate a given prototype.

The actuators used to move the mirrors are standard and micro servos (Hi-Tec), which are easy to find and acquire. We used an Arduino UNO microcontroller for generating the PWM signal to control the servos, which receives the pose directives by USB from the control computer. The Arduino family is an open-source electronics platform that offers a great flexibility for prototype development and communications. In this case, we used the USB interface to connect the microcontroller to the computer, but it is also open for use in a wide variety of communication channels such as Ethernet, wifi, XBee, etc.

Now, if it is true that the approach of how to actuate the mirrors described in Section 2 is useful for any camera and works with any size of mirrors, we have not presented criteria for selecting the size of the mirrors of the system. Since the function of the first mirror is to enable the system and point directly to the second mirror to bring the center of the virtual camera outside the robot body in a more convenient location, it can be decided between a complete view of the second mirror or simply disable the system for a looking-forward mode. For this reason, we assume we are looking for covering the entire field of view with the mirror.

4.1. Mirror Size Selection

Due to the large variety of cameras and lenses, we want to extend our approach and consider the appropriate mirror size considering an infinite focal length lens and also by knowing its FOV angle.

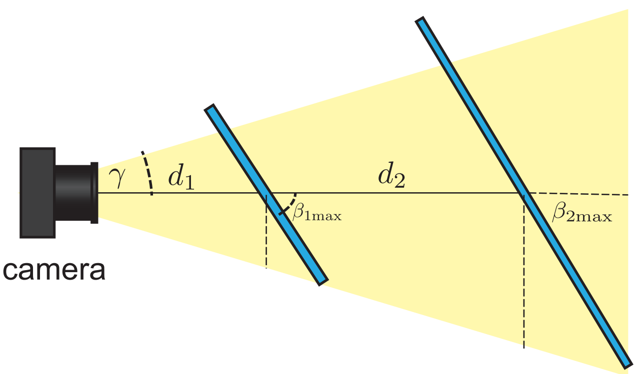

Figure 5. Geometric scheme to determine the lengths of mirrors.

Let γ be the viewing angle measured from the central axis of the camera in one of the directions (length or width) (see Figure 5). For a maximum rotation angle $\beta_{\max}$ on an axis rotation which is coincident with the optical axis, the length of each mirror is given by:

$$l_1 = 2d_1 \left(\frac{\tan(\gamma)\cos(\beta_{\max})}{\tan(\beta_{\max}) - \tan(\gamma)} \right), \quad (6)$$

$$l_2 = 2(d_1 + d_2) \left(\frac{\tan(\gamma)\cos(\beta_{\max})}{\tan(\beta_{\max}) - \tan(\gamma)} \right), \quad (7)$$

where l_1 and l_2 are the lengths of mirrors necessary to cover the entire field of view. This analysis and this calculation should be made for both the length and width dimensions, as the image format depends on the sensor (camera).

3D printing is a simple, useful and inexpensive method for prototyping. This method also offers advantages over other manufacturing methods for sharing files or complete prototype parts to replicate the results. We used a USB Firefly MV camera Point Grey Research manufacturer with a FUJINON lenses hf12.5HA. to develop our prototype (See Figure 6). The design parameters estimated for this case are shown in the Table 1.

In Table 1, one can see that the value of the angular field of view for this lenses is $29°35' \times 38°47'$. To verify the

Parameter	Value
d_1	12.5 mm
d_2	82.3 mm
γ_h	$29°35'$
γ_w	38°47'

Table 1. Ground platform prototype. Mirror parameters γ_h and γ_w are the values for width and height, respectively, of the angular field of view of the lenses

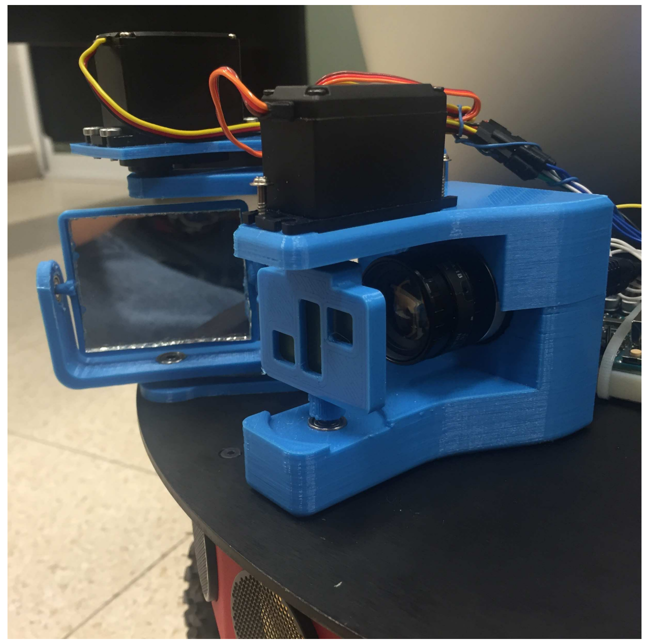

Figure 6. Prototype for ground platform. The system was mounted on the mobile robot and tried to focus on objects outside the normal angle of view of the camera

change of the direction of viewing angle we carried out a test in which the system targets outside the normal FOV. Figure 7 shows how the mirror system reaches a mark on a blackboard at the end of the room. Such visual mark is outside the normal range of vision of the camera.

The second test is to focus on an object located at the floor, *i.e.* at the bottom of the FOV. In this test we emulate an image extraction at the bottom of the ocean with an object that is outside the range of vision. In Figure 8, we can see the red object through the mirrors without presenting the effect of symmetry, because of the use of an even number of mirrors (in this case two mirrors).

4.2. Preliminar Results

One of the main aspect to take into account when working in underwater environments, is how water would affect the image seen on the mirror. First, if the image would look clear or poor in resolution, second if the optical reflexion

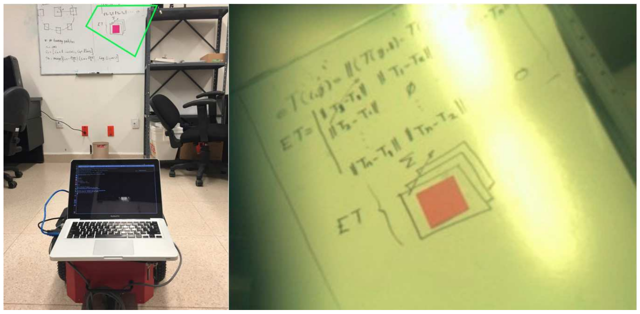

Figure 7. Focusing a visual mark above normal FOV of camera. Left: View the robot and the environment, the green area is the view area of the mirror system. Right: Camera view through the mirror system. One can see that there is no image symmetry due to the use of an even number of mirrors.

Figure 8. Focusing a visual mark under normal FOV of camera. Left: Top view of the room. Top-Right: Left side view of the robot and the object outside the range of normal view. Bottom-Right: View of the object on the floor, through mirrors.

properties and different speed of propagation of light in the environment would carry some distortions in the image.

The platform for our experiments is an amphibious robot of the AQUA family from the company Independent Robotics Inc. [3]. In water, the robot's propulsion is based on six fins that can provide motion in 5 degrees of freedom up to depths near 35 meters. AUV's medium size ($60 \times 45 \times 12$ cm) allows for easy maneuverability, which is important in the time response on the robot's control, when navigating with the purpose of closely monitoring an unstructured environment. The robot has 3 cameras on board: two on the front and one on the back. The camera in the back is mainly used to receive command codes, but the two cameras in front are used for navigation purposes. In the proposed design, we aim to use one of the front cameras, leaving the second camera to see the front at all times. Leveraging Arduino wireless communication modules, we plan to integrate the system of mirrors through a XBee protocol, in order to keep the original design and avoid dramatical modifications.

A basic diagram of the underwater platform is shown in Figure 9.

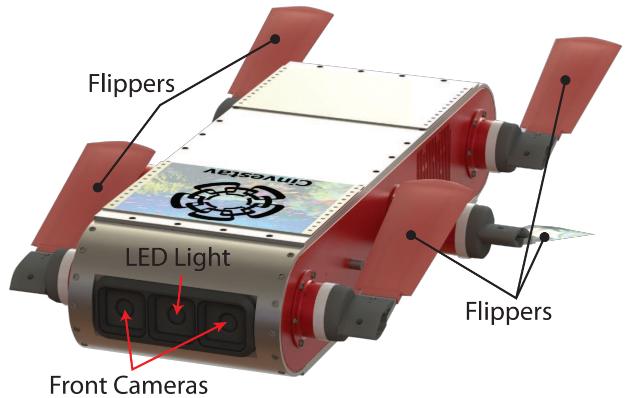

Figure 9. Dimetric view of our underwater platform.

Last year, we performed in the ocean several tests with a prototype without actuators, simply to study the interaction between the mirror and the camera of our AUV. A set of images and video sequences were taken at 10 meters depth. The captured images and photograph of the prototype are shown in Figure 10. It can be seen how the images look quite clear and do not present distortions.

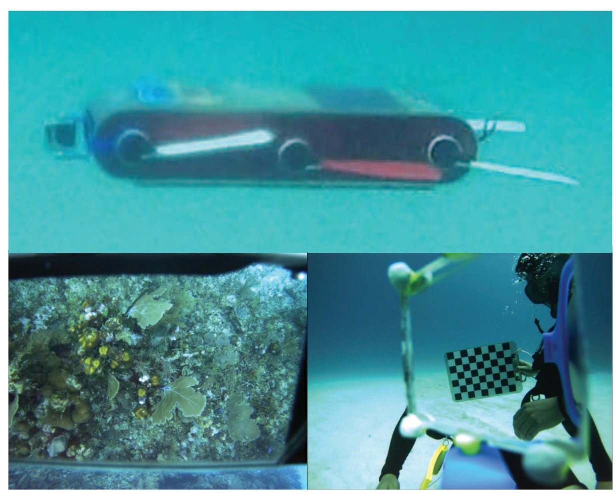

Figure 10. Photograph of our AUV using a prototype with a fixed mirror. Bottom-left: Image captured from the bottom, with a change in viewing angle of 90°. Bottom-Right: Image captured purposes of making a camera calibration through a mirror, with a change in viewing angle of 90° degrees to the left.

Two different 3D-printed prototypes with mirrors with fixed orientation (without actuators) were used to obtain the images of Figure 10. The captured images are from two different views: one from a virtual camera pointing to the bottom and the other one from a virtual camera pointing to the side of the robot. The view of the marine bottom is of great importance for collecting data of the coral reef without compromising the orientation of the AUV, which always maintained a steady pose. A lateral view of the robot is of great importance to make sharp movements, in order to avoid collisions. The bottom-right image of Figure 10 shows the captured image of a calibration pattern from a left side of the robot.

Currently, we have different designs to make a fully mechanized prototype to work on the underwater robot with most of the components using an ABS plastic material.

5. Conclusions

In this paper we have presented a design composed by two servo actuated mirrors to emulate the gathering of images when using an active vision system. Preliminary results indicate that it is possible to extend the FOV of a fixed camera and also extend its viewing angle. This mirror-based optical system represents a lower investment risk by exposing only low-cost components to the environment, without significantly modifying the platform or affecting your warranty policy. The use of a pair number of mirrors nullifies the characteristic symmetry effect presented in a reflection over a mirror. By knowing the pose of the mirror system, the camera can get useful information from the environment without compromising the stability of the robot. Our ongoing work involves complementing the navigation strategies that include obstacle avoidance by understanding the mapping between the obtained virtual images and the robot reference frames.

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References

[1] D. D. M. Bhabatosh Chanda. *Digital image processing and analysis*. PHI Learning Pvt. Ltd., Feb 2004. 4323

[2] P. Bourgeois, P. Rodríguez, and N. Ragot. Omnidirectional catadioptric image unwrapping via total variation regularization. In *Robotic and Sensors Environments (ROSE), 2011 IEEE International Symposium on*, pages 220–225, Sept 2011. 4323

[3] G. Dudek, P. Giguere, J. Zacher, E. Milios, H. Liu, P. Zhang, M. Buehler, C. Georgiades, C. Prahacs, S. Saunderson, et al. Aqua: An amphibious autonomous robot. *Computer*, (1):46–53, 2007. 4327

[4] H. Kim, C.-S. Lin, C.-B. Yoon, H.-J. Lee, and H. Son. *Progress in Pattern Recognition, Image Analysis and Applications: 9th Iberoamerican Congress on Pattern Recognition, CIARP 2004, Puebla, Mexico, October 26-29, 2004. Proceedings*, chapter A Depth Measurement System with the Active Vision of the Striped Lighting and Rotating Mirror, pages 108–115. Springer Berlin Heidelberg, Berlin, Heidelberg, 2004. 4322

[5] H. O. Kohei Okumura and M. Ishikawa. High-speed gaze controller for millisecond-order pan/tilt camera. *IEEE International Conference on Robotics and Automation*, pages 6186 – 6191, May 2011. 4322, 4323

[6] A. Kubota, K. Kodama, and Y. Hatori. Deconvolution method for view interpolation using multiple images of circular camera array. In *2006 International Conference on Image Processing*, pages 1049–1052, Oct 2006. 4322

[7] A. Maldonado-Ramirez, L. A. Torres-Mendez, and F. Rodriguez-Telles. Ethologically inspired reactive exploration of coral reefs with collision avoidance: Bridging the gap between human and robot spatial understanding of unstructured environments. In *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*, pages 4872–4879. IEEE, 2015. 4323

[8] D. Paredes, P. Rodriguez, and N. Ragot. Catadioptric omnidirectional image inpainting via a multi-scale approach and image unwrapping. In *Robotic and Sensors Environments (ROSE), 2013 IEEE International Symposium on*, pages 67–72, Oct 2013. 4322

[9] Y. Petillot, I. T. Ruiz, and D. M. Lane. Underwater vehicle obstacle avoidance and path planning using a multi-beam forward looking sonar. *IEEE Journal of Oceanic Engineering*, 26(2):240–251, Apr 2001. 4321

[10] S. L. . Z. J. . G. P. . W. Y. . Q. G. Sang Enfang. The features of two forward looking sonars for rov/uuv and their experimental results. *Underwater Technology, 2000. UT 00. Proceedings of the 2000 International Symposium on*, pages 437–441, 2000. 4321

[11] X. Tao and H. Cho. Design of variable view imaging system for active observation of micro object. *International Conference on Control, Automation and Systems*, pages 1785–1789, October 2007. 4322

[12] X. Tao, H. Cho, and F. Janabi-Sharifi. Active optical system for variable view imaging of micro objects with emphasis on kinematic analysis. *Appl. Opt.*, 47(22):4121–4132, Aug 2008. 4322, 4323, 4324

[13] S. Yonemoto, A. Matsumoto, D. Arita, and R. I. Taniguchi. A real-time motion capture system with multiple camera fusion. In *Image Analysis and Processing, 1999. Proceedings. International Conference on*, pages 600–605, 1999. 4322

[14] T. Zhe, S. H. Lian, and S. Zengqi. A neural network based localization from distorted image in omnidirectional catadioptric vision system. In *Neural Information Processing, 2002. ICONIP '02. Proceedings of the 9th International Conference on*, volume 2, pages 701–704 vol.2, Nov 2002. 4323