Global Localization of a Mobile Aquatic Robot in an Indoor Environment

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***Abstract*—Localization, which is the ability of a mobile robot to estimate its position within its environment, is a key capability for autonomous operation of any mobile robot. This paper presents a system for indoor global localization of a mobile robot in a known environment based on visual and compass information. The system is based on colour detection and uses homogrphy between the image plane and the world plane to estimate the position of the robot. In this system the orientation of the robot is estimated using compass data. During localization, images of the scene are captured using the off-board cameras; Using homography and rectification, an image with frontal view of the whole pool is created. Based on the new image, the specific colour placed on the robot is detected. In this project ROS (Robot Operating System) is used to communicate with the robot. The system developed in this project was used to locate the position and orientation of a mobile aquatic robot called Kingfisher when used inside a pool. The system developed for the localization was able to successfully obtain the robot location and orientation using the mounted off-board cameras and the on-board compass.**

***Index Terms*—Mobile aquatic robot, Global localization**

I. Introduction

A. Motivations and objectives

The objective of this project is the global localization of an aquatic robot indoors which will enable it to have the capabilities of GPS outdoors. The system will be designed to be operated in an environment similar to the Tait Mackenzie Pool in York University (figure 5) and to support the Kingfisher robotic platform (figure 1).

Self-localization of a robot is a challenging and important problem for autonomous mobile robots. A successful movement of a mobile robot depends on a real-time and accurate navigation. The localization is one of the most critical building blocks of robot navigation. In outdoor environments i.e. the environments in which there is a clear view of the sky, it is possible to use GPS to address the localization of robots. In contrary, in indoor environments like built up urban centres and near mountains, GPS is not available and other localization methods need to be considered. As an example the Kingfisher robot can be considered. The Kingfisher robot is designed to operate on the surface of relatively still water. When operating normally outdoors, its onboard GPS can be used to solve robot localization. When testing the robot indoors GPS is not available and an alternative is required. This indoor system should have performance characteristics similar to that of the GPS system onboard the Kingfisher.

B. Localization methods

The localization of a robot in indoor environment is a difficult task since the robot needs to estimate its position with respect to a predefined map using specific sensors. Given the importance of robot localization, a number of different methods for localization in indoor environments have been developed using sensor technologies including vision, laser, ultrasonic, and magnetic sensors ([1], [2], [3]). Most of non-vision based systems like laser methods are expensive for low-cost applications. In addition, such methods are not accurate enough for some specific localization tasks ([4]). Vision-based approaches, on the contrary, provide simple and robust tools for accurate and economical robot localization. With the advances in the computer industry and the rapid improvements in the computational capabilities of processors as well as production of digital cameras with high resolutions, more attention has been drawn recently to vision-based localization methods like landmark-based methods ([1]).

1) Landmark-based methods with natural landmarks: The landmark-based method is one the usual approaches for vision-based robot localization. Many researchers use natural objects or special features in indoor environments as the landmarks to determine the position and orientation of the mobile robot. In this method, since the image coordinates for the landmarks are projected depending on the camera pose, the camera pose will be determined using the relation between the two-dimensional

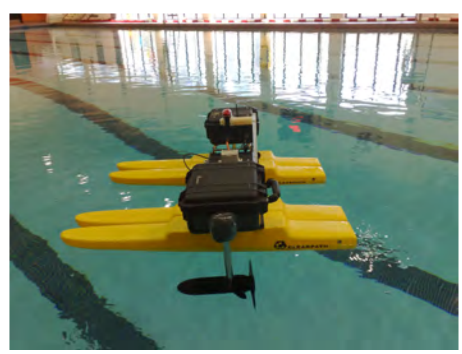


Fig. 1: Kingfisher robot

image coordinates and three-dimensional world coordinates of the landmarks. Since the camera is fixed to the robot, the camera pose is considered the same as the robot pose. In the following, different landmark-based methods used in the literature by different researchers are presented and discussed.

In [1], a vision-based localization in indoor environments is proposed which uses scale-invariant feature points (SIFT) as visual landmarks to perform a three-dimensional mobile robot localization. Since the SIFT features are invariant to scale changes, rotation, affine transformation, and the changes in illumination, they will be independent of camera viewpoint and hence are suitable for robot localization. When the system is running the SIFT features are detected and then matched with the landmarks in the database. The results of their tests show that the position error was 26cm and the orientation error was approximately 7.5 degrees.

2) Landmark-based methods with artificial landmarks: Another approach for landmark-based localization is to use artificial landmarks. The artificial landmark is a very simple and powerful tool for self-localization in indoor environment. It reduces the chances of landmark mismatching which can result in large errors of localization, by using specific artificial landmarks and placing them in a well-selected position in the environment. However, this method is not natural and designed landmarks need to be attached whenever necessary. Landmark-based visual positioning method using artificial landmarks has been used by a number of researchers like [5], [6].

In [5], a planar landmark like a poster is used as the artificial landmark. The system adopted by them is based on two loops that run at different frequencies: tracking and localization. In their method the salient objects should be extracted before using the localization techniques. In the tracking part, a 2D model is extracted for every image by matching its region with the model of the previous image. The tracking part is done in order to decompose the image of the target into two components, a 2D motion and 2D shape change due to robot displacements. The tracking is done based on partial Housdroff distance between an image and a model. In order to estimate the 3D localization, the positions of the posters are obtained based on offline explorations.

The navigation system used by [5] was based on the expression of trajectories with respect to landmarks reference frames. The robot localization was relative to a reference landmark. They further improved the landmark detection based on edge grouping by a relaxation algorithm. They also developed a new recognition method based on matching of a set of interest points using the partial Housdroff distance ([6]).

3) Ceiling-based visual positioning: Generally the image processing including feature extraction and landmark recognition is not robust enough since the activities of the objects in the environment make the indoor environments dynamic. Sometimes, the moving objects in the indoor environments may occlude the landmarks from the cameraś view that will result in failure in the feature extraction and landmark recognition. In order to address this problem the features on the ceiling are used as landmarks that are regular and are rarely occluded. The methods using such landmarks are called ceiling-based visual positioning methods . Much work has been conducted in the positioning methods based on ceiling features. A brief review on the research in this field existing in the literature is provided below.

Most of the offices have regular ceilings consisting of blocks with many parallels and corner points. These line and point features are not only available to the intrinsic parameters calibration for a camera, but also are useful for the estimation of the position and orientation of a mobile robot. A simple and convenient positioning method for an indoor mobile robot is developed by [7] based on the natural features on such regular ceilings. The same as the other ceiling-based vision methods, a camera pointing to the ceiling was mounted on top of a mobile robot . In the system used, since the position estimation depends on the estimated orientation, the errors in the orientation have strong influence on the position error. By improving the accuracy of orientation and image feature extraction, the positioning system can become more accurate. In the case of ceilings with general shape, point features on the ceiling can be used to estimate the orientation of the mobile robot. In [7], the system is tested in a room with regular ceiling consisting of blocks. The results proved the effectiveness of the proposed method.

Assuming a flat ground, the localization can be estimated by using a ceiling map that is created by a single upward camera. But in the environments with debris, the estimated location contains error since the frame of the camera will be rotated. A visual compensation system by using a forward camera is presented by [8] to reduce the error by assuming no flat ground. The system was tested in an indoor environment with debris. The maximum absolute value of the error was reduced to approximately 11% by using forward camera compensation.

4) Global vision-based methods: Global vision-based methods perform the localization of mobile robots using cameras installed in the environment and with respect to the targets mounted on the robot. The application of these methods is fairly easy and its position resolution mainly depends on the number of cameras used to cover the environment. The following paragraphs provide a brief literature review on the localization methods developed based on this approach.

A real-time method is used by [9] to determine the position and orientation of a mobile robot using an overhead fixed vision system that covered the whole view of the environment and localized the robot based on the position of the known coplanar points fixed on the robot. A single camera was used and it was assumed that the movement of the robot was planar. The used pattern was composed of infrared diodes that were easier to detect. In order to obtain the 3D location of the pattern, four matched points were used. Using the inverse perspective transformation based on calibrated cameras and the corresponding perspective projection of the extracted points on the patternś plane, it was possible to obtain the 3D location. As the pattern was attached on top of the robot, the position of the robot could be obtained by a transformation from the pattern frame to the robot frame. In [9] also proposed to use a multi-camera system to improve the accuracy of localization system. They used three cameras to cover the whole work area and a prediction system to estimate the position of the robot and select the corresponding camera.

Two systems for estimation of the position and orientation of a robot is presented in [10]. The two systems were a combination of differential odometry and gyroscope and integration of camera and compass respectively. They used camera positioning system integrated with compass to improve the estimated position and orientation of odometry combined with gyroscope. In the camera positioning system and compass, camera and compass were used to estimate the position and orientation respectively. In this system, a fixed camera capturing the work area was used.

C. Problem Statement

The development of an alternative to GPS that can be operated inside the pool requires a sensing technology that enables the robot to estimate its position and orientation without resorting to GPS signals. Given the volume of the pool area, the available space, energy and cost budgets, the most likely sensor technology that can be used to replace GPS is a combination of vision and existing compass sensor mounted on robot board. Therefore, some off-board cameras and a target located on Kingfisher will be used to identify the position and a compass on-board the robot will be used to identify the orientation of the robot.

To estimate the position of the robot using global vision, homography is used to find the perspective transformation between image plane and the world plane. To remove the distortion, images are rectified using the computed homography matrix. Furthermore, the estimation of the position of the robot is based on the colour detection.

D. Structure of the paper

In section II, some basic knowledge that are required in the method proposed in this project will be presented. In section III, the environment and the robot used in this project will be introduced and evaluated. The system overview of proposed method in this project will be presented in section IV. The test data and a discussion on the selected methods will be presented in section V. At the end, in section VI, the conclusions and the future work to improve the project will be discussed.

II. GLOBAL LOCALIZATION

A. Robot position estimation using vision

In order to estimate the position of a robot in 3D environment, a basic understanding of the methods used such as homography, and rectification is required. The following sections provide an overview of the basic concepts of these methods.

1) Calibration and homography: To find a perspective transformation between two planes (camera plane and world frame), homography matrix is computed and used. A non-singular linear transformation of the projective plane into itself is called homography. The most general homography is represented by a non-singular 3x3 matrix so that:

$$\lambda \begin{bmatrix} x'_1 \\ x'_2 \\ 1 \end{bmatrix} = \begin{bmatrix} H_{1,1} & H_{1,2} & H_{1,3} \\ H_{2,1} & H_{2,2} & H_{2,3} \\ H_{3,1} & H_{3,2} & H_{3,3} \end{bmatrix} \begin{bmatrix} x_2 \\ x_2 \\ 1 \end{bmatrix} \quad (1)$$

Points are expressed in homogenous coordinates, that is we denote 2D points in the image plane as (x_1, x_2, x_3) with $(x'_1 = x_1/x_3, x'_2 = x_2/x_3)$ being the corresponding Cartesian coordinates. The matrix H is defined up to a scale factor (it has 8 degrees of freedom). In inhomogenous coordinates:

$$\begin{cases} x'_1 = \dfrac{H_{1,1}x_1 + H_{1,2}x_2 + H_{1,3}}{H_{3,1}x_1 + H_{3,2}x_2 + H_{3,3}} \\ \\ x'_2 = \dfrac{H_{2,1}x_1 + H_{2,2}x_2 + H_{2,3}}{H_{3,1}x_1 + H_{3,2}x_2 + H_{3,3}} \end{cases} \quad (2)$$

A unique homography matrix can be computed from four points provided that no three of them are collinear (see figure 2). It is then necessary to find at least four points correspondence to define the transformation matrix uniquely.

The map between a 3D point w and its projection onto the image plane is given by a 3×4 matrix $\mathbf{P}$ (in homogeneous coordinates) such that:

$$\kappa \tilde{\mathbf{m}} = \tilde{\mathbf{P}} \tilde{\mathbf{w}} \quad (3)$$

where κ is the depth of $\mathbf{w}$.

The map between a world plane and a perespective image is an homography (a plane projective transformation). The easiest way to see it, is to choose the world coordinate system such that the plane of the points have zero z coordinate (see figure 3).

Then the perspective projection matrix $\tilde{\mathbf{P}}$ reduces to

$$\kappa \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} P_{1,1} & P_{1,2} & P_{1,3} & P_{1,4} \\ P_{2,1} & P_{2,2} & P_{2,3} & P_{2,4} \\ P_{3,1} & P_{3,2} & P_{3,3} & P_{3,4} \end{bmatrix} \begin{bmatrix} x \\ y \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} P_{1,1} & P_{1,2} & P_{1,4} \\ P_{2,1} & P_{2,2} & P_{2,4} \\ P_{3,1} & P_{3,2} & P_{3,4} \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (4)$$

which is a 3×3 matrix representing a general plane to plane projective transformation (homography).

2) Image Rectification: The projective homographies can be used to obtain a frontal view of any planar figure appearing in an image.

Figure 4a shows the original picture obtained with a pinhole camera while figure 4b shows the rectified and warped image

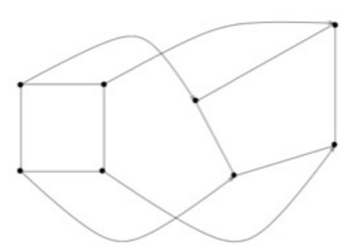


Fig. 2: Four points correspondences determine a homography

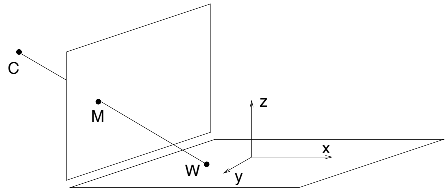
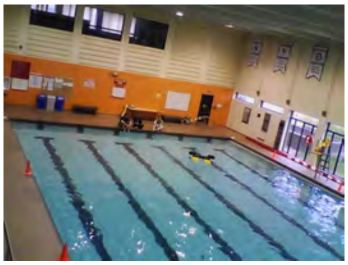
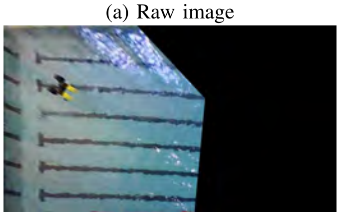


Fig. 3: The map between a world plane and a perspective image is an homography



(a) Raw image



(b) Rectified image

Fig. 4: Image Rectification of a planer image

obtained by mapping the pixels in the original image with the planar homography obtained using the obtained homography matrix.

B. Orientation estimation using electronic compass

An OS5000-US Solid State Tilt Compensated 3 Axis Digital Compass (USB & Serial) is mounted on the centre of Kingfisher. OS5000-US combines a small size with the flexibility of both an USB and RS232 Serial connection and 5V power is required for USB. The compass is connected to the system of Kingfisher via USB 2 port ([11]).

III. Evaluation of Kingfisher and Tait pool

Since the system being built within this project is designed to be operated in to the Tait Mackenzie Pool environment and to support the Kingfisher robotic platform, the Kingfisher robot and its performance within Tait pool environment must be evaluated.

The Kingfisher Robot (see Figure 1) is an unmanned surface vehicle that can locate itself with 2 cm precision in an outdoor environments using differential GPS [12]. It fits within a $1270 \times 1270 \times 520mm$ envelope. The robot is powered via two 12v NiMH Battery Packs [13] and the device consists of:

- a main frame
- a primary Thruster Module which houses a FitPC2 and GPS module
- a secondary Thruster Module which houses VIP Series wireless radio
- four pontoons
- a mobile base station provides connectivity to off-board computation and storage

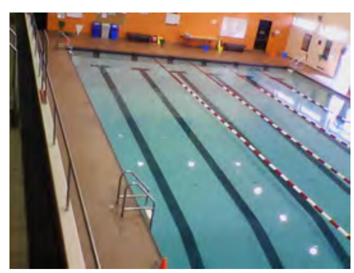
At the controller level, Kingfisher offers direct control over the PWM output to the primary and secondary propellers. Speed or position control is implemented at the PC controller level, using GPS, compass, and other sensor data to provide the necessary feedback.

The Tait Mackenzie pool is a $25 \times 14m$ swimming pool located in the northwest part of the York university campus. The Tait pool environment is complex. The pool environment has lights located at some height, a number of fixed visual landmarks, and a spectator area that can be used to mount cameras in. Unfortunately the field of view of standard focal length cameras is insufficient to enable a single camera to obtain a good view of the entire pool. Furthermore, for a reasonable camera resolution, a single camera is unlikely to provide good resolution of the surface of the water and hence at least two cameras are required. (see Figure 5).

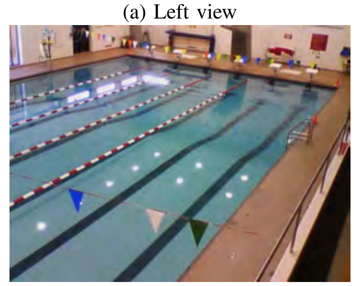
IV. System overview

This system runs on two systems: the off-board computer and the onboard FitPC2. Figure 6 shows the block diagram of the system showing the interactions between nodes.
The nodes defined and used for this project are:

- **camera node :** captures frames from IP cameras and publish the images
- **homography node :** computes H matrix
- **Rectification :** rectifying and merging
- **detection node :** target detection and provides position estimation
- **Compass node :** provides orientation estimation



(a) Left view



(b) Right view

Fig. 5: Different views of Tait Mckenzie Pool

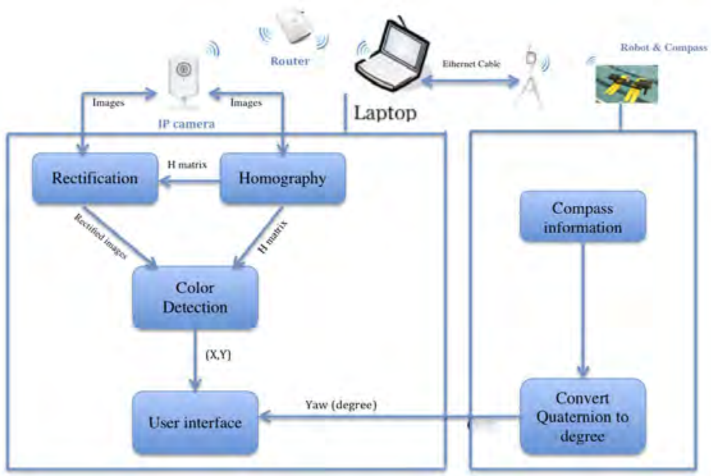


Fig. 6: Block diagram of the system showing the interactions between nodes

A. Camera

DCS-930L-DLink Wifi cameras with 1/5" CMOS sensor with 5.01 mm lens and up to 20 FPS at 640x480 resolution were used for this project ([14]): As explained before, at least two cameras are required to cover the whole field of view of the environment.These cameras communicate with the off-board computer via a router with static IP. The camera node continuously access to the IP camera and publish its image data.

B. Homography

Based on what explained in homography section, to compute homography matrix between two planes (camera plane and world plane) at least four points are required. Therefore, four points have to be selected and based on correspondence real values, the perspective matrix will be computed. Figure 7 represents the algorithm used in homography node.

C. Rectification

Using the projective homographies, a frontal view of any planar figure appearing in an image will be obtained. Rectification of an image has some advantages: First, the distortion will be removed, second, by rectifying the images and merging them to one image all reflections and lights made by other things around the pool like windows and walls will be removed. This eventually will make target detection easier. Figure 8 shows rectification and merging of the camera images.

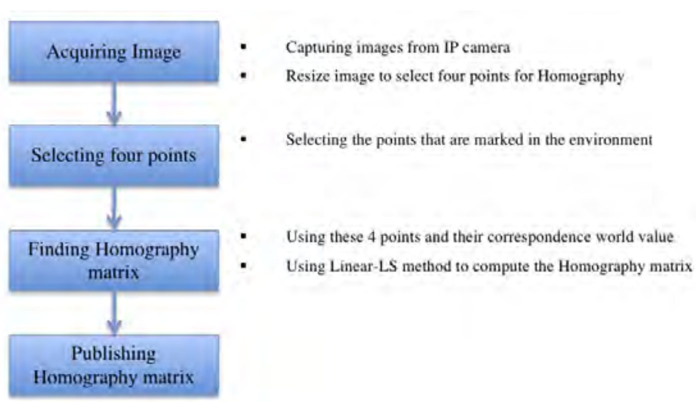
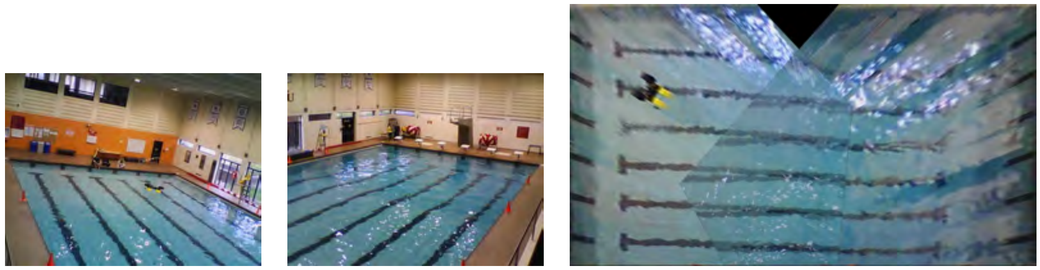


Fig. 7: Flowchart to determine homography matrix for every camera

D. Color detection

The image processing is performed using Intel Open Computer Vision (OpenCV) library. OpenCV is a library of programming functions for real time computer vision. The OpenCV library is a cross-platform middle-to-high level Application Programming Interface (API) consisting of more than 500 functions that implement image processing operations and popular image processing algorithms [15]. It has C++, C, Python interfaces. OpenCV is used as the primary vision package in ROS (Robot Operating System) ([16]). It is decided to use the Kingfisher pontoons as the target in this project. The kingfisher has four pontoons with yellow colour as shown in figure 1. The software algorithm of the detection node is described in Figure 9. The first step of the node is subscribing to the rectified and merged image (2500 by 1400 pixel which is the size of the Tait pool- for every one centimeter one pixel) created by rectified algorithm explained in previous paragraphs. The images are sent continuously from the IP cameras to computer via wireless network and after rectification and merging are sent to this node.The second step is to perform a colour threshold to identify the pontoon colour (yellow) of the Kingfisher. The subscribed images are converted from RGB to HSV. The result is an image consisting of binary pixels. The third step is to create region of interest (yellow colour) by removing noise and fill true region (Dilate and Erode) and creating bounding box around the object. The fourth step is to determine parameters of the centre of bounding box. The fifth step is to find the correspondence camera by multiplying the detected centre point to inverse of homography matrices. If $-1 < u < 640$ and $-1 < v < 480$ is satisfied, the robot



(a) Camera 1 image (b) Camera 2 image (c) Rectified and merged image

Fig. 8: Rectification and merging of the camera images

is captured via the correspondence camera.The last step is to publish all resulting data to user interface.

Figure 10 shows detection of pontoons in the merged rectified image. In figure 10b the red and green circles around the detection point show detection of the target by the right and left camera respectively.

E. Compass

The compass node is running on the onboard FitPC2 and using an IP and Ethernet cable will communicate to the off-board computer. The OS5000 compass is connected to the onboard computer via USB and it works with the 19200 baud rate.

V. Experimental results

The test data for these experiments consisted of the position results and orientation results. The positions were estimated using cameras mounted in the environment to monitor the environment and the orientation was estimated using onboard compass connected to the robot.

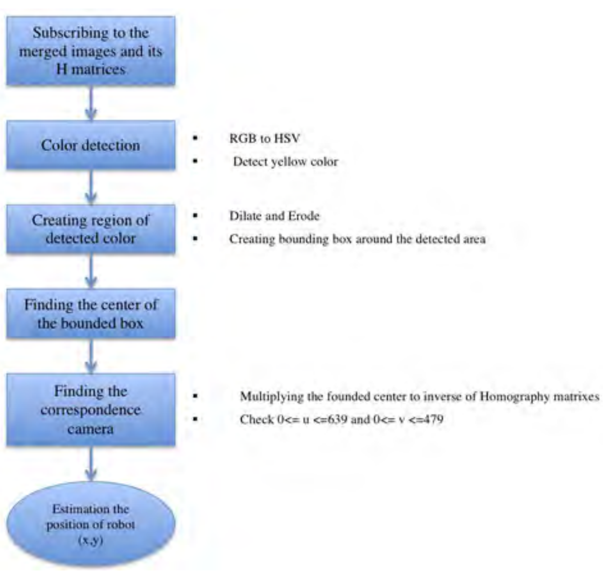


Fig. 9: Flowchart to detect the Kingfishers pontoons (yellow colour) and determined the position of the robot

A. Position results

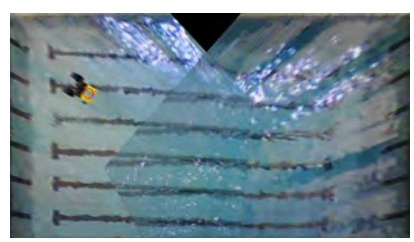
Test data for this part is the centre of detected area as the position of the robot in each frame. These also consisted of JPEG images, which were rectified, merged and marked as the detected point of the images taken from the test environment using the off-board cameras of the robot. Each image had a resolution of 2500 by 1400 (one pixel for one centimetre).

In the experiments, three cameras were used to monitor the pool environment which were mounted in the right, left, and middle of the spectator area of the Tait pool. During the experiments a problem was observed with the homography of middle camera which caused the failure of the rectification of the middle camera images. Fortunately, only a very small portion of the pool was covered only by the middle camera (see figure 8c) and the aforementioned problem did not cause any significant problem for the localization of the robot.

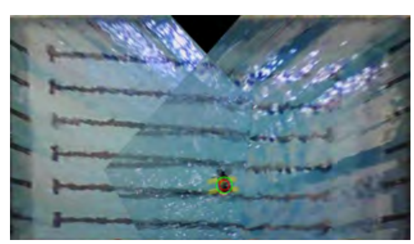
B. Compass results

The compass data consist of Euler angle (roll, pith and yaw). But the useful compass data in this project is the yaw data (the rotation around the vertical axis).

Simultaneous position and orientation results at specific locations of the robot captured by the system are depicted



(a) Pontoons detected by one camera



(b) Pontoons detected by two cameras

Fig. 10: Detection of pontoons in the merged rectified image

in figure 11. In this figure the numbers shown for each point are x coordinate (cm), y coordinate (cm), and rotation (degree) respectively. The rotation is measured with respect to the north direction and is positive towards east.

C. Failure in homography of middle camera

Figure 12 shows an image from the middle camera. As can be observed from this figure since the rectifying of the middle camera is not correctly performed, it is not matched with the result of the other cameras correctly and two robots are detected at the same time. The reasons of this mismatching and wrong warping can be:

- Error in computation of the Homography matrix that means there was some mistake in the measurement of the marked points
- The two marked points of four points are close to each other, it can causes some mistake in the computation of the perspective matrix

D. Discussion on the selection of target

As a first try for the selection of a target, an active emitter (LED) was chosen as target and mounted on the centre of the Kingfisher at an specific height (see figure 13). The detection algorithm for detecting the LED was based on colour and motion detection. An advantage of this method was that it allowed to detect exactly the centre of robot as the LED was installed at the centre of the robot. The following are disadvantages of this method based on the experimental results:

- Since the cameras are mounted far away from the robot, a big target is required for the proper detection
- The speed of capturing of the frames was not fast enough to detect the motion (on and off) of the LED.
- The reflection of environment colours and the motion of the water create the same situation as the Led flashing.
- Since the target was mounted at an specific height on the robot, unexpected waves in the pool can cause the frame of Kingfisher and camera to rotate which can cause errors in the estimated location, therefore it should be compensated using the compass data (roll and pitch).

In order to solve the problems of using LED as a target, the target and its algorithm to detect it was changed. In the new algorithm the aim was to detect the pontoons of the Kingfisher as explained in section IV-D. The kingfisher has four pontoons with yellow colour. The advantages of the new algorithm are:

- The target is big enough to detected
- The yellow colour is more unique in the pool
- It does not the height from the centre of the robot, therefore, it can be possible to neglect the error created by the unexpected wave in the water

The drawbacks of the new algorithm is that in the situation that camera can see only one side of the Kingfisher, the detected region is not the centre region of the four pontoons. This causes some errors when one camera is monitoring the robot. In the areas that two or three camera are monitoring the robot, this problem is solved.

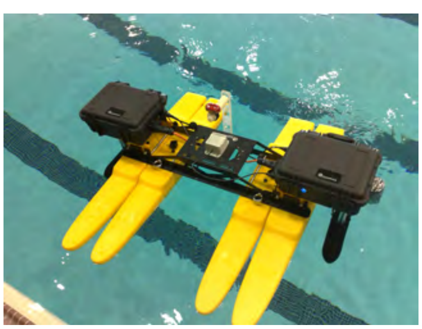


Fig. 13: The LED mounted at an specific height on the Kingfisher used as the first target

VI. Conclusions and future work

The aim of this project was to localize a mobile aquatic robot in indoor environment where the GPS in unable to perform. There are several methods for vision global localization in indoor environment. Base on the volume of the area of the pool environment considered in this project, the available space, energy and cost budgets, the proposed method to estimate the robot pose is using off-board cameras to monitor the environment with a target attached to the robot and compass mounted on-board to estimate the orientation.

In order to estimate the position of the robot, the perspective transformation between image plane and world plane is found by using homography. To compute the homography matrix, at least four points are required. After computing the homography matrix that represent the transformation between image plane and world plane, images are rectified. Rectification process corrects image distortion by transforming the image into a standard coordinate system using the computed homography matrix. The rectified image of each camera monitoring some part of the environment was merged in an image in order to use for target detection. The target detection method proposed is based on Kingfisher's pontoons that have yellow colour.

The system developed was able to successfully locate the position of the Kingfisher robot in the pool. However, some problems were observed during the tests like the failure of the homography of the middle camera.

The accuracy of the proposed method depends on accurate measurements for homography and target detection. The real position of the robot is measured manually. During the experiment in the pool, as explained before, the homography of the middle camera had some problem and hence the real position of the robot in the pool was not recorded for the purpose of localization error computation.

The algorithms presented in the project needs some improvement. The improvements suggested by the auther can be summarized as follows:

- Debugging the error in homography of middle camera and test the system again in the pool to measure the real position of the robot in order to identify the accuracy of this system.

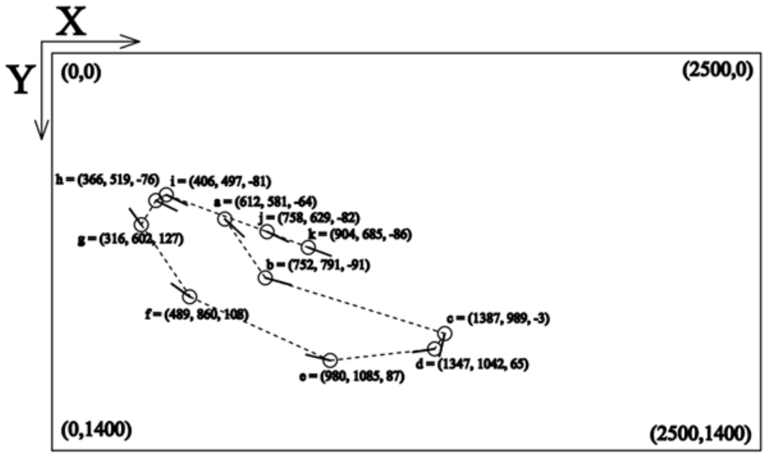
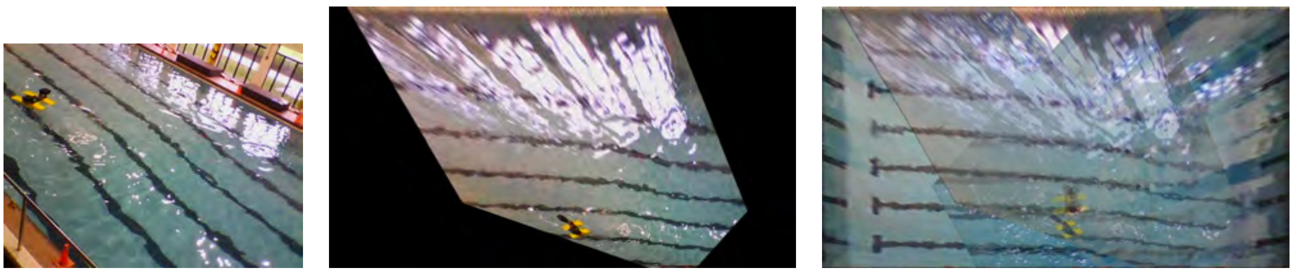


Fig. 11: Simultaneous position and orientation results at specific locations of the robot shown on the plan view of the pool. The numbers shown for each point are x coordinate (cm), y coordinate (cm), and rotation (degree) respectively



(a) Raw image (b) Rectified image (c) Merged rectified image

Fig. 12: Middle camera images

- Improving the target detection when only one side of the robot is detected.
- Synchronizing the position data and compass data. In ROS, the nodes have two primary methods of communication between one another: asynchronous topic-posting and synchronous request/response. The method that was used in this project was asynchronous based on *topics* that are publishing and subscribing between all the nodes and all the time that code is running. ROS, however, also provides a request/response, synchronous communication scheme known as *services*.
- Providing the codes for point-to-point navigation of the robot: after the system is synchronized and its accurate is verified, the system can be used to control the robot between some defined positions.

VII. ACKNOWLEDGMENT

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