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QR-code based Localization for Indoor Mobile Robot with Validation using a 3D Optical Tracking Instrument

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Abstract— **This paper addresses effective artificial landmark based indoor localization technique for mobile robotics applications. In the proposed approach, QR-codes are strategically placed in the operating environment, attached to the ceiling; they are used as artificial landmarks for providing reference points to aid the robot localization. The vision processing, robot localization and navigation tasks are all carried out on an Android Smartphone mounted on the mobile robotic platform; by taking advantage of the computational power, the built-in sensing, and the communication capabilities of the Smartphone. The Smartphone detects and recognizes the QR-codes to calculate the approximate global location of the robot. The pixel coordinate information in the image of QR-code is also used to enhance the position estimate in the real-world environment. Furthermore, the QR-code orientation in the image view is used to calculate the mobile robot's heading direction. An NDI 3D optical tracking instrument is used for validation of the effectiveness and feasibility of the proposed method. This paper demonstrates successful implementation of the QR-code based localization strategy and the experimental evaluation of its performance in actual environment.**

I. Introduction

One of the fundamental challenges in practically all mobile robotic applications is finding a cost-effective, efficient and accurate localization tool. There is a great deal of ongoing research in mobile robotics localization and navigation in indoor environment. The position and orientation of the mobile robot must be always realized quickly and correctly for a successful autonomous navigation and task performance. The mobile robot will be able to plan a trajectory to its destination only if it is able to have precise position and orientation estimation.

Although a wide variety of range based techniques can be used for localization, including sensors such as ultrasonic sensors, infrared (IR) sensors and laser scanners [1]-[3], a vision based localization method that uses artificial landmarks and image processing generally provides a simple, cost-effective and robust solution for an accurate localization. The ultrasonic-sensor based positioning system suffers from the interferences of neighboring sensors or from external sources. The laser scanners generally produce relatively accurate estimation of the robot pose in a large space, but its high cost is a hurdle preventing it from being widely used for indoor robot applications in consumer and service sectors. Localization using relatively inexpensive sensors is important, but in many instances cheap and poor quality sensors cannot provide good performance due to measurement inaccuracies in various real-world environments.

Accordingly, the work presented in this paper is focused on visual based mobile robot localization that uses QR-codes as artificial landmarks. QR-codes can be recognized rapidly in all directions from the QR-code scanner available in a Smartphone. They are strategically placed in the operating environment and used as global reference points to aid mobile robot localization. The real-world x, y coordinates of each QR-code are stored in a database, along with their unique ID numbers, in advance. The use of the database enables users to manage a large amount of real-world coordinate information in accordance with the unique ID numbers of the respective artificial landmarks. The real-world coordinates for the mobile robot is then calculated using the stored QR-code coordinates and geometric calculations applied to the pixel position of the QR-code in the acquired image.

This paper presents the development of the QR-code based localization algorithm, using a Smartphone application. The use of Smartphone for this application is found to be suitable because of its capabilities that combine excellent computational power, with multiple internal and external sensors including high resolution camera, and communication services. Another main benefit of using Smartphone as the mobile robot control platform is its relatively light weight, low-power consumption, and small physical dimensions that make it suitable to easily mount on even smaller mobile robot platforms.

The overall system configuration is depicted in Figure 1. It is a high level representation of the major building blocks that are used for the implementation of the mobile robot localization system. The wireless connection between the Smartphone and the mobile robot is established over Bluetooth. The proposed main control application on the Smartphone for the vision processing is developed using open source libraries available from Zebra Crossing (ZXing) [23] and Open Source Computer Vision for Android SDK (OpenCV4Android) [24]. They are respectively used to implement QR-code and circle shape recognition tasks. After the application detects a QR-code, the Smartphone uses its Wi-Fi communication to retrieve the real -world coordinate information of artificial landmarks from an external database.

For evaluating the localization accuracy of the proposed system a high quality NDI 3D Investigator optical motion tracking system [25] has been utilized. This system employs an advanced motion capture technology. Smart markers, attached to target objects, emit infrared light that are tracked by the optical instrument. The optical instrument not only obtains accurate coordinate information and heading direction

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of the object, but also tracks the position of the mobile robot consistently as long as the markers stay within the fields of view of the camera system.

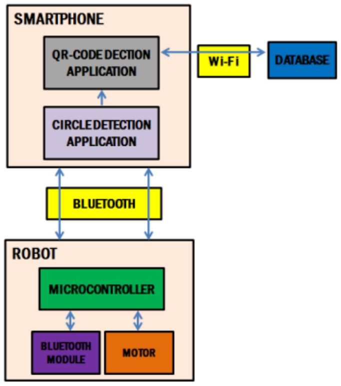

Figure 1. Block diagram illustrating the proposed localization system architecture.

The rest of this paper is organized as follows: The next section provides a brief summary of related work in the literature. Section III presents the implementation details of the proposed indoor mobile robot localization system, categorized into hardware components and the software modules. The NDI 3D Investigator optical motion tracking system used to verify performance of our localization method is introduced briefly in section IV. Experimental results are given in section V. Finally, in section VI, the paper concludes with a summary and a discussion on future extensions of this work.

II. Related Works

Localization is one of the fundamental problems of mobile robotics, and hence a great deal of works is already available in the literature. This section primarily looks at related-work in vision based localization techniques. The main task of a vision-based method is to collect and extract features from either natural or artificial landmarks. To further narrow down the scope of the literature review this section concentrates mainly in indoor localization strategies that utilize visual landmarks.

A vision system is essential for detection of landmarks that are generally defined as distinct features that could be used to aid robot localization. The natural landmark-based approach suffers limitations because it is sensitive to dynamic environmental conditions and requires high computational power for image processing, thus in general extracting features using natural landmarks are considered to be difficult tasks [5]. Alternative approaches proposed in the literature utilize artificial landmarks, such as unique and easily recognizable images, shapes, colors, and/or codes for vision based localization in a mobile robotic field [6]-[10]. Comparing with natural landmarks, artificial landmarks are found to have benefits of relatively faster and easier to be detected and recognized, although it takes relatively more effort to set them up compared to the natural landmarks.

The main concept of the proposed work by Yoon-Gu Kim et al. [11] is similar to our approach in the way it calculates real coordinates for an indoor mobile robot by combining simple artificial landmarks based image information and distance information calculated from Cricket system [12]. Cricket uses the time difference of arrival (TDOA) between radio frequency signals and ultrasonic pulses in order to estimate distance. Our work by contrast uses image information from QR-codes only to localize mobile robot without using additional infrastructure.

The Ubisense ultra-wide band (UWB) system [13]-[15] is a Real-Time Localization System (RTLS) using UWB signal. It is a successful commercial UWB localization platform that combines TDOA and angle-of-arrival (AoA) information for increased position accuracy. Lianlin Zhao et al. [16] have demonstrated experimental results and carried out comparisons on localization accuracy using the Ubisense system and the Cricket system. Both systems show excellent results for indoor localization and they conclude that the Cricket localization data is more accurate.

Papers [17]-[19] proposed mobile robot localization based on radio frequency identification (RFID) technology. Several RFID tags are attached on the floor, for providing location reference information, and they are detected and recognized by the RFID reader mounted on the robot. The accuracy and robustness of these methods depend on the distance between the tags, and the distance between the tags and the reader. To increase the localization accuracy the number of RFID tags per unit area has to be increased. Therefore, this technique may not result in economical and easily scalable solution because of the increasing number of required tags and the associated cost of their deployment.

The technique that is being proposed in this paper is low-cost, robust, and easily scalable. The QR-codes are easily created with unique identifications, such as coordinate information, and printed on a sheet of paper. QR-codes can be detected from longer distances than the detection range of passive RFID tags. Thus, QR-codes mounted on the ceiling two to three meters high can be easily detected by a Smartphone mounted on a robot within about 15 cm height above the floor.

Unlike passive RFID tags, the horizontal separation distance between consecutive QR-codes can be increased to more than two to three meters and still maintain acceptable accuracy for typical indoor applications. So with the proposed technique the user can determine the actual distance between the QR-code landmarks based on the desired accuracy.

III. Implementation Details

In this section, the hardware and software design techniques for the implementation of our proposed QR-code based localization method is described.

A. Hardware Design

Figure 2 (A) shows the proposed mobile robot platform used as the test-bed for the practical experiments. The mobile robot platform is based on iRobot create base [21] that is controlled via a serial interface with a microcontroller. It has an Open Interface protocol to allow for easy interfacing with a microcontroller that can send drive commands and receive sensor packets. The mobile robot and a Bluetooth communication module are controlled by the microcontroller. The Bluetooth communication module, HC-06 [22], is used to allow for wireless communication between the microcontroller and a Smartphone device, where most of the vision-based localization algorithm is implemented. The Smartphone camera is facing upward to recognize QR-codes and circle shapes placed on the ceiling.

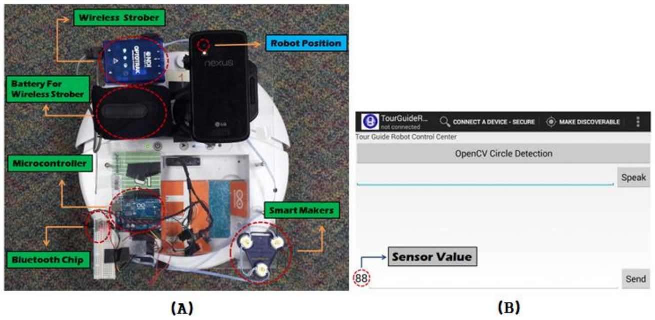

Figure 2. (A) Autonomous mobile robot platform used in this work and deployment of the hardware components: a microcontroller, a Bluetooth module, smart markers, wireless strober, battery and Smartphone placed on the robot. (B) Screenshot of the main control application on the Smartphone.

B. Software Design and QR-code Detection Method

As shown in Figure 2 (B), a mobile app is developed to demonstrate the effectiveness of the QR-code based localization technique. The app contains a main control program and task to handle the QR-code recognition, circle shape detection, reading of the Smartphone's orientation sensor, and access to a database. The detailed implementation of Smartphone app for a tour guide robot task has been fully explained in our previous paper [4]. The previous app has now been extended to provide information about the sensor value accessed from the orientation sensor of the Smartphone. The orientation measurement is based on the geomagnetic sensor in combination with the accelerometer sensor, which allows the Smartphone to calculate the azimuth value. Embedded sensor fusion of Smartphone as presented by [20] has been implemented to measure more accurate and reliable sensor data. The sensor value obtained from the orientation sensor can be used to implement the turning motion of the mobile robot within its range between 0^o and 359^o and the value updates whenever the mobile robot rotates. The main drawback of this sensor is that soft or hard iron material located near the magnetic sensor will cause unpredictable error that depends on the mutual alignment with the Earth's magnetic field.

A database is designed to manage real-world coordinate information of artificial landmarks identified by the unique ID of QR-codes strategically placed in the operating environment. Moreover, to help in the validation process, additional information such as the calculated real-world mobile robot coordinate and heading direction of the mobile robot is stored in the database whenever it recognizes each QR-code.

From experimental studies we found out that the QR-code recognition process exhibits degraded performance when the robot is moving fast. To address this challenge our proposed technique utilizes circular shapes printed on paper and attached on the ceiling surrounding the QR-code. The robot slows down as it detects the circles while approaching the QR-code. The vision system can handle more effectively the circle detection even while the robot is moving at its normal speed. This setup results in a more successful recognition of the QR-codes. Figure 4 shows a picture of the ceiling with the QR-codes surrounded by the circle shapes, in the experimental setup.

C. Mobile Robot Localization using QR-code

1) Calculation of Robot's Heading Direction

The QR-code attached to the ceiling is divided into several angular regions in the range from 0^o to 359.9^o as shown in Figure 3. When the QR-code reader detects a QR-code, it obtains the three coordinates located in the top left, top right and bottom left corners of the QR-code in the image domain. These are useful information that allows the robot to infer its own orientation in the world coordinate frame from the pixel coordinates of the QR-code in the image domain as well as the stored real-world coordinates of the recognized QR-code. Whenever a mobile robot recognizes a QR-code, it stops for a moment to determine its real-world coordinates and heading direction and to figure out how to get to its next destination marked by another QR-code.

When the robot is navigating in a given environment to execute a task, such as a tour-guide robot application, it determines its drive heading direction based on its current location and orientation and the location of the next QR-code on its path, as determined from the database. After this calculation is completed the mobile robot then executes the motion commands to move towards its next stop.

2) Calculation of Robot's Position

This section deals with how to convert a specific pixel coordinate of the QR-code into the real-world coordinates. The image coordinates of the QR-code corners are then used to determine the current coordinate of the mobile robot in the global reference frame. Figure 3 shows an illustration of how the robot detects the QR-code and the three corners that are used for the calculation of the robot location.

The conversion of distance information between the center of the QR-code and the center of the image from the image domain to the real-world domain is shown in Equation (1) below. Parameters I_D and R_D in the equation are assumed to be the diagonal distances of the QR-code in the image domain and in the real-world, respectively. *Dist_image* is considered to be the distance between the camera center coordinate and the center of the QR-code, in the image domain. *Dist_real* is the distance from the center of the QR-code to the position of the robot in the real-world domain. The calculation process of *Dist_real* and θ are represented by the following equations:

$$Dist\_real = (R_D * Dist\_image) / I_D \tag{1}$$

$$\theta = atan(Image\_height / Image\_base) \tag{2}$$

where θ is the angle between *Image_base* and *Image_height*, i.e. the base and height is x and y axis distance between the center of the image and the center of the QR-code in the image domain, respectively. *Real_base* and *Real_height* can be obtained by the following equations:

$$Real\_base = Dist\_real * cos(\theta) \tag{3}$$

$$Real\_height = Dist\_real * sin(\theta) \tag{4}$$

where *Real_base* and *Real_height* are defined as x-axis and y-axis distance, respectively between the position of the robot and the center of the QR-code in the real-world domain. The center coordinates of the QR-code in image frame of the Smartphone camera play an important role to estimate the actual x and y coordinates of the robot position. The image frame of the Smartphone camera is divided into four areas. The calculation process depends on the area where the center coordinates of the QR-code are located. If the center of the QR-code is located in Figure 3, area ①, the actual x and y coordinates of the robot position are calculated using the following equations (5) and (6), respectively:

$$X = R_X - Real\_base \quad (5)$$

$$Y = R_Y - Real\_height \quad (6)$$

where R_X and R_Y are the real-world coordinates of the QR-code stored in the database. These values are accessed in accordance with ID number of artificial landmarks using the Smartphone.

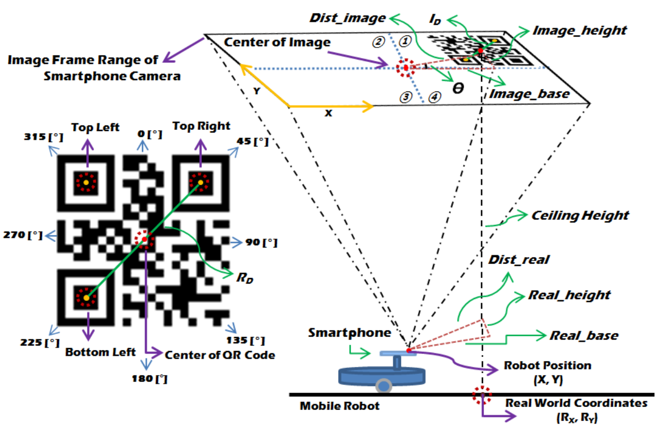

Figure 3. Indoor localization based on QR-code image information, and calculation of mobile robot heading direction from QR-code orientation. The real dimension of the QR-code used is 18.5cm x 18.5cm.

3) Testing Area in Indoor Environment

The testing environment is a classroom as shown in Figure 4. The dimensions for the robot experimental test traveling area are approximately 2.4 X 1.8 meters and the ceiling is about 2.2 meters high. The main reason for limiting the operating region to this dimension is because of the limited operating zone of the NDI 3D Investigator optical tracking instrument that we used for the evaluation of the accuracy of our proposed technique. The next section provides details of the optical tracking instrument and its setup for our experimental purpose.

A Nexus 4 Google Android Smartphone serves as the QR-code reader. Due to the ceiling height the phone requires a slightly longer time to recognize the QR-codes compared to when the phone is at a close proximity. It was also observed that the recognition rate of the QR-code reader drops when the robot is moving fast. To address this challenge, we devised a mechanism that employs circle detection method to tell the robot to slow down as it is getting close to the QR-code. With this technique the QR-code reader was able to recognize all the QR-codes deployed in the test operating area without any difficulty. The results section presents the actual calculation results of the robot location and heading information, and analyzes the errors from several experimental runs.

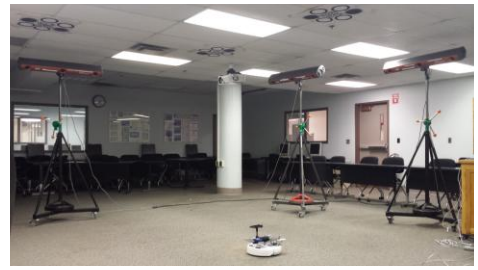

Figure 4. QR-Codes are attached on the ceiling in the actual experimental environment.

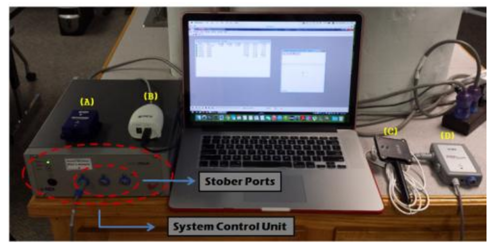

Figure 5. Essential components to use the NDI 3D Investigator Optical Tracking Instrument and Picture of collecting data from the 3D optical coordinate measuring machine, (A) Wireless transmitter, (B) USB interface, (C) 4 Maker Digitizing Probe, and (D) Tool Strober.

IV. NDI 3D OPTICAL TRACKING INSTRUMENT

The NDI 3D Investigator optical tracking instrument is used for the validation of the localization performance of the proposed method. This high quality research grade instrument is widely used for a range of applications where extremely accurate and high speed tracking of targets are desired. It has an accuracy of 0.4 mm and an update rate of 100 Hz. It employs IR based smart makers that can be configured as a rigid body in a triangular shape and attached to a mobile robot to track the translational and rotational movements of the target object by the optical tracking instrument.

A wireless strober controlled by the System Control Unit (SCU) is used to activate and deactivate the smart markers. The signals from the SCU are transmitted to the wireless strober via a wireless transmitter. The SCU is the central component of the optical tracking instrument. It processes data received from the optical instruments and communicates with the laptop computer through a USB connection to collect the data. A software application called "NDI First Principles" is provided by the manufacturer of the instrument for its configuration and real-time capture of the processed data. In Figure 2 (A), the setup of the wireless strober and the smart markers is placed on the mobile robot platform. Figure 5 shows the setup of the SCU, wireless transmitter, and the computer running the application for the data collection. A 4 Marker Digitizing Probe that comes with the NDI instrument set is used to estimate the real-world coordinates of the 4 reference QR-codes in the operating environment and to fix the relative coordinate of the mobile robot position based on smart markers. The camera lens on the Smartphone is defined as the center position of the mobile robot. Figure 5 (C) and (D) show the digitizing probe and the tool strober, respectively.

V. Experimental Results

The principal objective of the experimental setup is to determine the accuracy of the proposed localization algorithm and verify the results using the NDI 3D Investigator optical tracking instrument. For the test setup a simple indoor environment in a classroom is used. The test navigation path is clear of any obstacles.

Four QR-codes are used to define a configuration of the test path, as shown in Figure 6. The measurement unit is in cm. The mobile robot first moves to the first QR-code from its starting location. When it detects the first QR-code, the mobile robot calculates its own localization and the heading it needs to follow. In Figure 6, the estimated locations from F_1 to F_5 are computed when the mobile robot detects each QR-code for the first time. The green circles in Figure 6 represent the real locations of the robot as obtained by the NDI optical tracking equipment, while the blue triangles are the estimated locations as computed by the QR-code based localization technique.

Some of the factors contributing to the location estimation errors are explained as follows. One of the main reasons is that although the mobile robot must be stopped after a QR-code is detected so we can obtain stable location estimate, the robot is not prepared to stop until the main control application on the Smartphone sends a stop command via Bluetooth to the mobile robot after the QR-code recognition task returns to the main control application. So the actual location of the robot that the optical tracking instrument reports does not exactly correspond to what the QR-code based localization method calculates, since the QR-code localization calculation was taken before the mobile robot is actually stopped. Thus, the relatively higher errors at points F_1 to F_5, in Figure 6, are due to the time it takes for the mobile robot to stop after the QR-code detection was done.

For example, at the start of the navigation the robot heads towards the first QR-code, Q_1, but it detects Q_1 for the first time when it gets at point F_1. At this point the QR-code recognition algorithm gives the image information of QR-code to the main control application on Smartphone, and then the stop command is sent from the main control application to the robot. But it takes time, up to approximately 1.92 seconds, for the robot to actually stop. This contributes to most part of the error between the QR-code based localization and that of the true locations measured by the optical tracking instrument.

For a more realistic comparison, the QR-code based localization is repeated again after the robot is driven and completely stopped right underneath the QR-code locations. To arrive at these locations the robot calculates the distance and heading from the preceding F_i location and the next QR-code location (Q_i). It repeats this process until it covers all the four QR-codes (Q_1, Q_2, Q_3, and Q_4). Finally, from the fourth QR-code the robot returns back to the first QR-code, completing its test path. The turning motion of the mobile robot is controlled with the help of the Smartphone's orientation sensor.

The localization results calculated when the robot detects each QR-code are saved in a database, and later compared against the tracking information obtained from the NDI 3D Investigator optical instruments. For our experimental evaluation, we consider the location and heading data obtained from the optical tracking instrument to be the true coordinate and heading values.

Figure 7 shows the average errors and standard deviation in the location estimates for the x and y coordinates of the robot position at the F_i (when it detects Q_i for the first time) and Q_i (right underneath the i^{th} QR-code) locations. The errors at F_i's are relatively higher than at Q_i's, due to mainly the discrepancies explained earlier in the actual timing of the QR-based localization calculation at these separate points.

The statistics of the Smartphone's orientation sensor errors when the mobile robot implements turning motion of 45°, 90°, and 135° are presented in TABLE I. The table also includes heading errors obtained from the QR-code based localization method. In all the test cases the errors are computed with respect to the true orientation and heading values obtained from the optical tracking instrument from the 10 experiments.

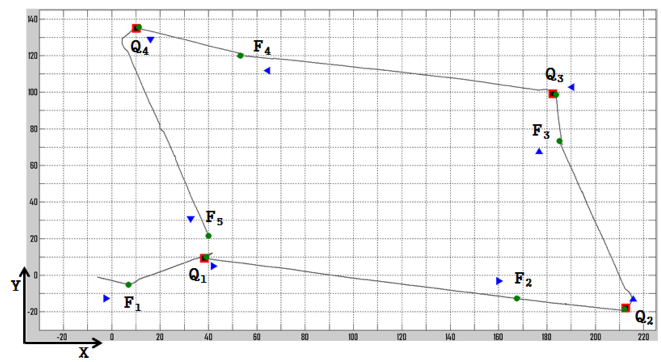

Figure 6. Experimental results and trajectory obtained from NDI 3D Investigator optical tracking instrument. (Blue triangles are estimated by the proposed localization method, green circle is real location measured by the optical instrument, and red rectangles are fixed in each QR-code location.)

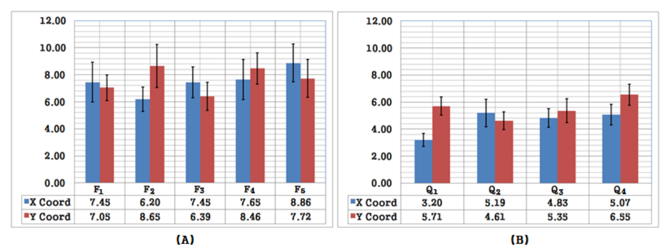

Figure 7. Average errors in cm and the standard deviations in the X & Y coordinates of the localizations obtained by the proposed QR-code based method compared to the true location obtained from the 3D NDI instrument; (A) at F_1, F_2, F_3, F_4, F_5, and (B) at the QR-code locations Q_1, Q_2, Q_3, Q_4.

TABLE I. The Average Errors in Degrees and the Standard Deviations of the Orientation Sensor of the Smartphone and the Heading Direction from QR-code Based Localization, Compared with the 3D NDI Investigator Optical Instrument.

		θ (°)	
		Average Error	**Standard Deviation**
Rotation Angle	**45°**	**0.990**	**0.36**
	90°	**1.860**	**1.24**
	135°	**3.239**	**1.41**
Headig Direction		**1.218**	**0.38**

As can be seen from the results, the localization error is not consistent. In general the error depends on a number of factors, including the actual calibration of the true locations of the

QR-codes, as well as relative position of the robot from the QR-code when it does the detection and calculation of the localization. The average errors in the orientation sensor gradually increase with the increase in the actual rotation angle. Experimental results show that the localization can be achieved with reasonably good accuracy using the proposed localization method.

To further improve the performance of the system, experiments were carried out to use color detection techniques to replace circle detection mechanism that was used to slow down the robot as it approaches a nearby QR-code. When the circle shape landmarks were used, the mobile robot could only move at maximum speed of 100 mm/s in the testing environment so it does not miss the detection of the landmarks. However, with the use of the colored QR-code, as shown above, it was possibly to increase the maximum speed of the robot up to 160 mm/s. Effective QR-code detection was achieved by using only the QR-codes, thus avoiding the use of several circle shape landmarks surrounding the QR-codes.

VI. Discussion and Conclusion

In the robotics research fields, mobile robot localization has been one of the challenging problems. Accurate position information of a mobile robot is a requirement to accomplish several tasks. This paper proposed an approach for indoor mobile robot localization using artificial landmarks made up of QR-codes mounted on the ceiling. Reference coordinates associated to the QR-codes and image processing techniques are used to calculate the location and heading of the mobile robot. From repeated experimental tests the proposed method was able to achieve average localization accuracy with errors in the range 3.2 cm to 6.55 cm at the QR-code locations, and heading errors of up to 1.218^{o}. The experimental verifications of the proposed localization technique were done using a research grade NDI 3D Investigator optical tracking instrument. The localization data collected by the optical instrument is considered as the true position and orientation values. This is used for evaluating the results of experiments of the proposed localization method. The overall results of the proposed method are found to be satisfactory for common indoor mobile robotic applications such as tour-guide robots that the authors are primarily interested in.

In future work, we plan to extend this work to further improve performance of the localization when the robot exits the view of the reference QR-codes.

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