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Localization and navigation using QR code for mobile robot in indoor environment

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***Abstract*—Localization and navigation are fundamental issues to mobile robotics. An approach for localization and navigation for a mobile robot in indoor environment is proposed in this paper. In this approach, QR codes are used as landmarks to provide global pose references. Label and location information is stored in QR codes which are strategically placed in the operating environment. The mobile robot is equipped with an industrial camera pointing to the ceiling to read QR codes at high speed. The pose of the robot is estimated according to the positional relationship between QR codes and the robot. For the purpose of collision-free navigation, a laser range finder (LRF) is applied to build a map in unknown environment and detect obstacles. Dijkstra algorithm and Dynamic Window Approach (DWA) are applied in path planning based on a 2D grid map. Experimental results show that this approach has good feasibility and effectiveness.**

I. INTRODUCTION

Localization and navigation are essential problems in mobile robotics, which have been studied by many researchers in this area [1-3]. Moreover, the accuracy of localization have a direct influence on the accuracy of navigation, so a mobile robot which can perform assigned task quickly and rightly is based on high accuracy of localization. Generally, indoor localization methods are mainly classified as relative localization and absolute localization. Relative localization technology usually uses Dead reckoning (DR) and inertial navigation for the robot pose calculation. DR methods are used to estimate the total distance travelled from a starting point [4-6], however, the estimation error will be accumulated over time. To improve the accuracy of localization, many approaches have been considered to combine with kinds of external sensors, such as sonar, beacon, cameras, odometry, laser range finders and GPS etc. [7]. With the coming of new type sensors, researchers tried to use those sensors to solve localization problem, and one attractive way is to make use of them for absolute localization.

In recent research, landmarks are wildly used in indoor mobile robot localization. There are two kinds of landmarks, natural landmarks and artificial landmarks. The benefit for natural landmarks is that they do not need to change environment, but how to discriminate natural landmarks in real environment it quite hard. Thus to recognize natural landmarks, Alves et al. [8] used the light fixtures as natural landmarks to implement a localization and navigation system in office-like environments.

As a typical landmark in absolute localization methods, Quick Response (QR) code is applied in indoor mobile robots, mainly because of storing large amounts of information. In addition, QR code is small, low cost, easy to make and simple implementation. By means of the sensor of camera, this paper utilized QR codes as landmarks for accurate absolute localization.

Reference [9] addressed the application of QR codes as landmarks for mobile robot navigation, but this method of displaying big QR code on every box is not widely used. Besides, fast detection is caused because of the mobile robot moving fast [10], so some positioning error still exists in the landmark system.

Combing smartphone with mobile robot, QR codes were provided for location references and ultrasonic range sensors were useful to avoid obstacles in [11]. Unfortunately, the robot has to slow down when getting close to QR codes, because it is difficult for smartphone camera to detect QR codes if robot moves fast at most 1m/s. Additionally, QR codes were intended for increasing the precision in determining the position of the robot [12], not for real-time absolute localization. As a result, it can be found that one of the problems of using QR codes is that the recognition rate will be reduced when the size of QR codes is small in the camera's field of view or the robot moves fast. Another is that the processing resources are worth considering in real-time critical situations.

In our method, an industrial camera with suitable exposure time is mounted on a mobile robot pointed to the ceiling, which makes QR able to be detected easily. At the same time, QR codes are strategically displaced on the ceiling which can provide global location information. In addition, a recognition algorithm proposed in this method not only improves the recognition rate but also reduces the computation time. Therefore, the current time location of the mobile robot can be quickly estimated and used as input data for further robot navigation. In order to reduce localization error, camera calibration is carried on. Besides, we use this method for robot navigation. A laser range finder is placed for 2D map building and object detection. In the process of constructing a map, a grid map is built with Rao-Blackwellized particle filer (RBPF) [13] using the absolute localization. Furthermore, Dijkstra algorithm [14] and DWA [15] are used for global and local path planning to verity this method.

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The remainder of the paper is organized as follows. In Section II, a vision system based on QR codes is presented. The localization method using QR codes are addressed in details in Section III. Section IV discusses the experimental results. Finally, Section V summarizes the paper and provides future work.

II. QR Code Vision System

The vision system in this approach is based on an industrial camera mounted on top of a mobile robot to recognize QR codes, as shown in Fig. 1. The main purpose of the vision system is to gain information from QR codes, including decoded information and orientation information. To do that, the whole process can be divided into three steps. The first step is camera calibration to obtain the camera parameters. The second step is QR code encoding. Then QR code is generated by a kind of code generation software and placed at the ceiling in the distribution like grid pattern. The final step is QR decoding. After that, decoded information and orientation information contained in QR codes is used as the references for absolute localization of the mobile robot.

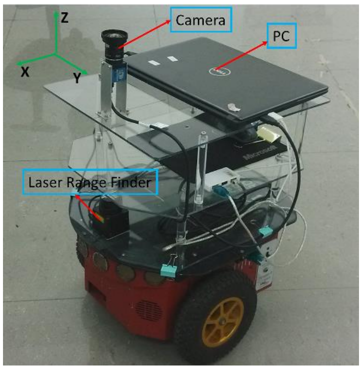

Fig. 1. Illustration of the mobile robot

A. *Camera and Calibration*

1) *Camera*

In the vision system, the reason why an industrial camera is chosen is mainly because the exposure time of an industrial camera is adjustable compared with a web camera. When the robot moves at high speed, it is difficult to recognize QR codes from the blurred image (as shown in Fig. 2) acquired by the web camera. Hence in real environment, it is more suitable using an industrial camera for mobile robot localization than a web camera.

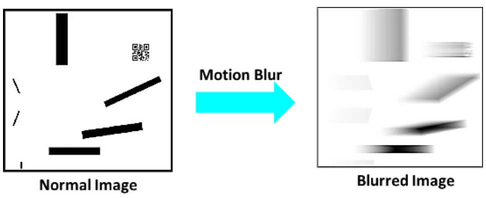

Fig. 2. Motion blur

The camera in our vision system is a Mercury series camera made by Daheng IMAVISION (Fig. 3), which the frame rate is 120fps, the pixel size is 5.6um × 5.6um, the focal length is 3.5mm and the exposure time is also adjustable. When installing the camera, we make the camera perpendicular to the ceiling as much as possible. In this case, QR codes can be recognized when the speed of robot is 2.5 m/s.

(a) (b)

Fig. 3 (a) MER-030-120UM and (b) Computar H0514-MP2

2) *Calibration*

To obtain camera parameters in a given distance, camera calibration needs to be done. For calibration, at first, we need to understand the relationship between the four plane coordinate systems of camera model, namely the pixel plane coordinate system (u,v), the image plane coordinate system (x,y), the camera coordinate system (X_c,Y_c,Z_c) and the world coordinate system (X_w,Y_w,Z_w) in Fig. 4.

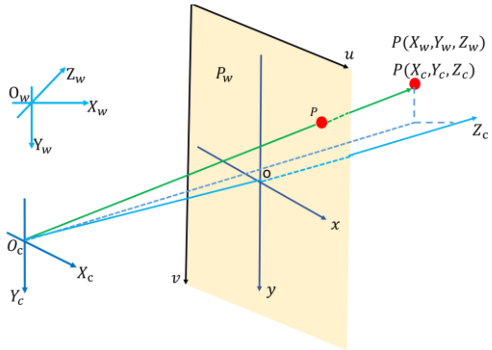

Fig. 4. Four coordinate systems

The pinhole camera model is described as

$$Z_c\begin{pmatrix}u\\v\\1\end{pmatrix}=\begin{pmatrix}1/dx & 0 & u_0\\0 & 1/dy & v_0\\0 & 0 & 1\end{pmatrix}\begin{pmatrix}f & 0 & 0 & 0\\0 & f & 0 & 0\\0 & 0 & 1 & 0\end{pmatrix}\begin{pmatrix}R & t\\0^T & 1\end{pmatrix}$$
$$=\begin{pmatrix}f_x & 0 & u_0 & 0\\0 & f_y & 0 & 0\\0 & 0 & 1 & v_0\end{pmatrix}\begin{pmatrix}R & t\\0^T & 1\end{pmatrix}\begin{pmatrix}X_w\\Y_w\\Z_w\\1\end{pmatrix}=M_1M_2X_w=MX_w \tag{1}$$

In this linear model, $f_x=f/dx$, $f_y=f/dy$, which dx and dy are representing for the physical size of each pixel on the X axis and Y axis direction, and f is the focal length; M is a 3×4 projection matrix; M_1 known as the camera internal parameters is totally determined by f_x,f_y,u_0,v_0, which are only related to the camera internal structure; M_2 known as the camera external parameters is completely determined by the position of camera relative to the world coordinate system.

There are many different approaches to calculate the intrinsic and extrinsic parameters for a specific camera setup. In our approach, the camera parameters are obtained by a software Halcon [16] which is the comprehensive standard software for machine vision with an integrated development environment developed by the German MVtec. In the process of calibration, a calibration target is made according to the standard calibration target provided by Halcon, and then some images containing the calibration target are collected. Next, the position of calibration dot on calibration target can be determined and the corresponding relationship between 3D coordinates and image coordinates can be got, in the end, internal and external parameters of camera are obtained by calculation. As the precision of calibration result is closely related to the accuracy of localization result, so camera calibration is very important in the vision system.

B. QR Code and Distribution Pattern

QR code in Fig. 5 is generated by a code generation software named Barcode Generator QR Code. Label and location information is encoded in each QR code. We set the direction of the QR code as the red lines indicate. Since the label and location information is different in each code, as a result, it will not be confused with each other when QR code is decoded.

In this method, those QR codes are placed at the ceiling in like grid pattern, which belongs to the regular distribution. In case of this regular distribution, the camera can detect at least one QR code in the camera's field of view, then the robot can find at least one QR code at any location, as a result, it is easy to estimate the position of the robot than using the random distribution.

In General, one of QR codes is selected specially, which its location is as the reference origin of the absolute coordinate system. Thus relative to the reference location, the actual location of the other codes in this absolute coordination system is able to be determined.

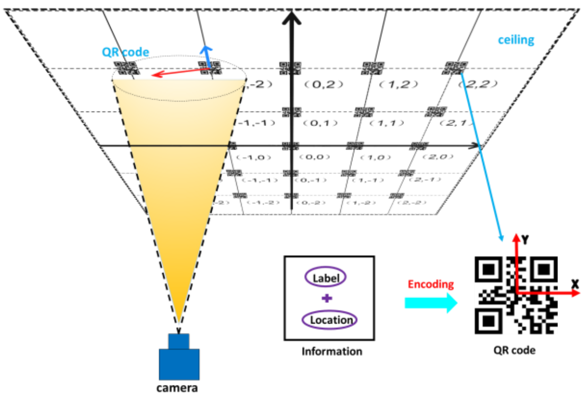

Fig. 5. QR code and Grid-like pattern

C. QR Code Recognition

A fast recognition algorithm is presented in this section. We make use of library ZBar [17] and Open Source Computer Vision (OpenCV) [18] in decoding process. ZBar is an open source software for reading bar codes from various sources, and OpenCV is an open source computer vision library that implement many common algorithms for image processing and computer vision.

Under different lighting conditions, in order to get a clear image, the camera's exposure time needs to be adjusted to maintain an average pixels. After images are acquired by the camera and transmitted to PC, they are converted to the gray scale images for processing so as to reduce the computation resources. After that, feature extraction in the gray scale image is performed to detect the contour of QR code. There are some constraints to ensure that the right codes will be found such as the type of codes and the size of QR codes. In figure. 6, QR codes which have been recognized are tagged with a red rectangular box as an example. Next, after QR codes being detected, the information which is stored in QR codes will be decoded. And the decoding process can be completed using libraries of Zbar and OpenCV.

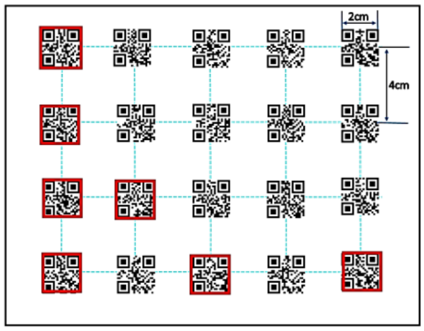

Fig. 6. QR codes recognition

However, it is not enough for us to detect QR codes, we also need to determine the direction of QR code in the image so that it is able to provide orientation information for robot localization. The whole process of finding the direction of QR code is illustrated in Fig. 7, which red arrows indicate the positive direction of the QR code. Consequently, the location and orientation information is available for further mobile robot localization.

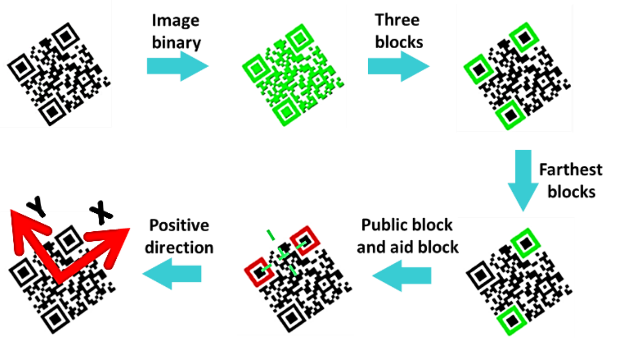

Fig. 7. Positive direction

III. LOCALIZATION USING QR CODE SYSTEM

Localization plays an important role in the navigation of a mobile robot. We aim to calculate the pose of the mobile robot according to the positional relationship between camera and QR codes when QR codes are able to be recognized.

Decoded information and orientation information of QR codes are used for absolute localization. Let us assume that the location of QR code i in the world coordinate system is as (x_i, y_i), then this QR code can be represented by (i, x_i, y_i), which the information i, x_i and y_i in the QR code can be obtained by decoding by previous. We define an absolute coordinate system and the origin of coordinate system is $O(x_0, y_0)$. What is more, we can see that there is some QR codes in the camera's field of view as the camera is mounted on the mobile robot. Accordingly, we can clearly see the positional relationship between the mobile robot and QR codes, as shown in Fig. 8.

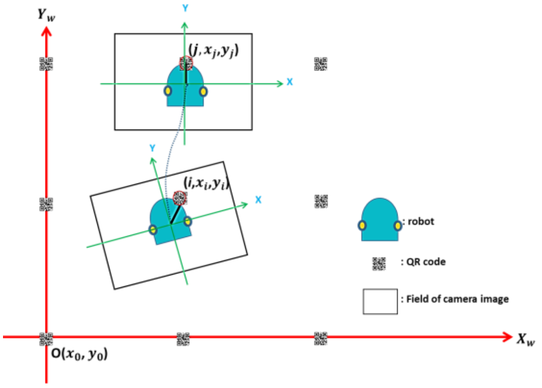

Fig. 8. Camera's field of view

According to Fig. 9 and Fig. 10, in the image plane, the distance between QR code and the image center is as L with unit pixel, and $\vec{a}$ is the vector from QR code to the image center. Define that the angle between the vector $\vec{a}$ and y axis of QR code is α_1 and the angle between the positive direction of QR code and the y axis of the image plane is α_3. Obviously, the relation between α_2 and α_1 is $\alpha_2 = \pi - \alpha_1$, where α_1 and α_3 can be calculated from orientation information. In addition, L' component on the x axis and y axis of QR code are $diff_x$ and $diff_y$ respectively.

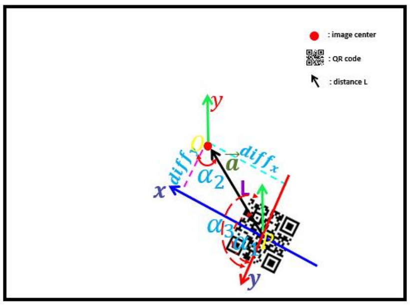

Fig. 9. Image plane relationship

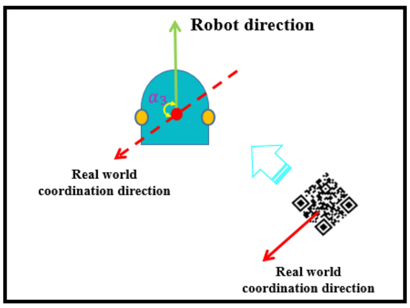

Fig. 10. Real world coordination

The robot's pose $(robo_x, robo_y, robo_\theta)$ can be calculated by (2).

$$\begin{pmatrix} robo_x \\ robo_y \\ robo_\theta \end{pmatrix} = \begin{pmatrix} qr_x \\ qr_y \\ \alpha_3 \end{pmatrix} + \begin{pmatrix} L \times \cos\alpha_2 \\ L \times \sin\alpha_2 \\ 0 \end{pmatrix} \begin{pmatrix} unit_x \\ unit_y \\ 0 \end{pmatrix}^T \quad (2)$$

Where the location of QR code as (qr_x, qr_y) in absolute coordinate system is obtained by location information, and the physical distance of each pixel in real world on x axis and y axis are $unit_x$ and $unit_y$, which $unit_x$ and $unit_y$ can be confirmed by camera calibration.

In some cases, we will encounter this situation that there is more than one QR codes which are recognized in the same image. With the purpose of reducing computation and time consumption, although the information from each code can be used to calculate the robot current pose, only one code will be randomly selected for pose calculation.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

In order to evaluate the feasibility and effectiveness of the proposed method for mobile robot localization and navigation, experiments have been conducted in the laboratory corridor of Ningbo Institute of Materials Technology and Engineering, CAS, as shown in Fig. 11. Robot Operating System (ROS) development environment from Willow Garage is applied in the experiment, which provides many libraries and tool for mobile robotics.

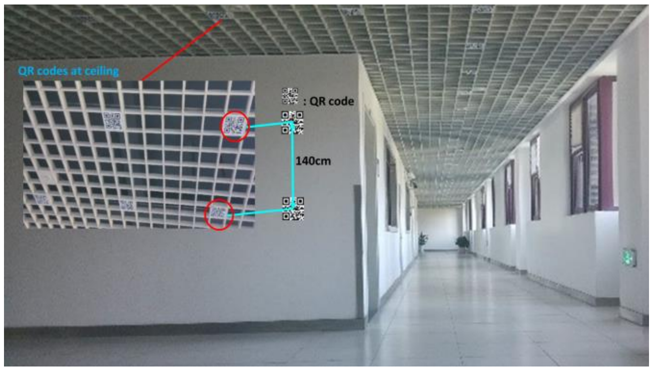

Fig. 11. Photographic image of the laboratory corridor

A. Localization

In the image, QR code will fail to be detected when the size of QR code is too small, so we need to choose the appropriate size of QR code. In our approach, the proportion of the size of QR code in the image is greater than 0.06. Thus the dimensions of QR codes which are placed on the ceiling are all $0.12m \times 0.12m$. Besides, the height of ceiling is $2.45m$, and the height of camera from the ground is $0.60m$, and the camera's field of view is about $1.90m(w) \times 1.46m(h)$. Given the camera's field of view, the interval between two QR codes is $1.40m$ so that there is more than one QR code that can be seen in the camera's field of view. We calculate the pose of the mobile robot according to above configuration parameters.

The proposed method could estimate the absolute localization of robot more accurately, at the same time, in real-time. The calculation time of localization is about $20ms$ to $30ms$ once a time, so it is quite suitable for real-time task. Additionally, Table I illustrates localization error between the method in [12] and our proposed method. In Table I, localization error in the proposed method has $6.02cm$ in the average at $X-Y$ coordinates and $13.0cm$ at maximum, while method in [12] has $6.29cm$ at $X-Y$ coordinates in the average and 32.9cm at maximum. So it shows that our method is effective in mobile robot localization.

TABLEI. LOCALIZATION ERROR

Localization Error			
Method used	***X-axis[cm]***	***Y-axis[cm]***	***Maximum[cm]***
Method in [12]	*6.29*	*6.29*	*32.9*
Our Proposed Method	*6.02*	*6.02*	*13.0*

B. Mapping

Simultaneous localization and mapping (SLAM) is the process by which a mobile robot can build a map of the environment and, at the same time use this map to compute its location [20]. SLAM is divided into two main parts, which one is the localization and the other one is mapping. A 2D occupancy grid map was built by using the ROS package called gmapping, which is a highly efficient Rao-Blackwellized particle filer (RBPF) to learn grid maps.

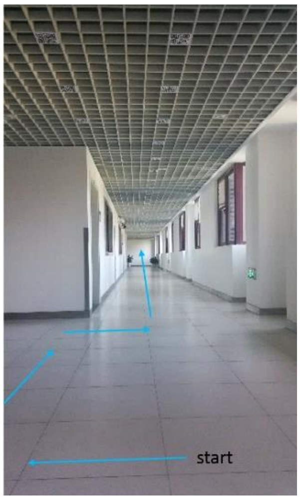

Fig. 12. Testing environment

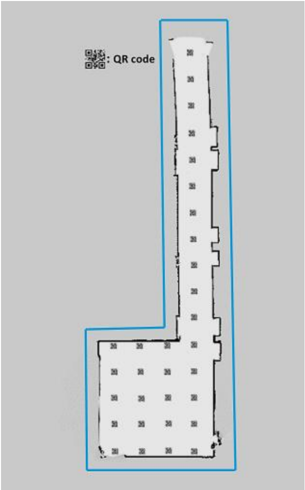

Fig. 13. Mapping result

In order to build a map, two kinds of data are required as input, which are usually the observation data of sensor and the movement data of the mobile robot. We provide global pose data based on QR codes and laser range finder data as inputs. As the global pose is quite accurate, so it makes a more accurate map. The testing environment and the mapping result are shown in Fig. 12 and Fig. 13, respectively. In Fig. 12, blue arrow shows the moving path of the mobile robot. In Fig. 13, it can be clearly seen that the rectangle shape of the testing environment. Moreover, QR codes are displayed in the 2D grid map, which shows the location of the QR codes in the environment.

C. Path Planning

When an autonomous robot moves from a point to a target point in its given environment, it is necessary to plan an optimal or feasible path avoiding obstacles in its way. In order to verify the effectiveness and reliability of our proposed method, the path planning algorithm adopts Dijkstra algorithm in global path planning and DWA in local path planning, which is based on the package Navigation provided by ROS. This process is mainly to decide which way to go if it exists and what the execution speed is. It takes in information from laser range finder streams, map and a goal pose and outputs safe velocity commands that are sent to a mobile base.

The laser range finder is applied to detect the object in front of robot, and any object on the height will considered into the path. The cost map uses sensor data and information from the static map to store and update information about obstacles in the world, it maintains information about where the robot should navigate in the form of an occupancy grid. During the process of navigating the path, when an obstacle is detected on the path ahead or close to it by the laser range finder, its position is associated with the cost map, the robot will adjust its trajectory according to some characteristics, such as proximity to obstacles, the goal, the global path and speed.

In Fig. 14, the mobile robot tried to move from the starting goal to the target goal. Blue line shows a global path of the mobile robot when there is not any obstacle on its way. Then we set some obstacles (such as boxes) on the way for the mobile robot to move from the starting goal to the target goal, shown as the yellow blocks. Green line shows the real trajectory when there are some obstacles which should be avoid by the mobile robot. Firstly, the laser range finder detects the obstacle (a) in predefined distance threshold, then the robot moves to the left and ran forward. Secondly, when the obstacle (b) is detected, the robot keeps going far away from the obstacle (b). Thirdly, the robot changes its' route to avoid collision with the obstacle (c), then it moves to the right and ran forward. Finally, when obstacle is out of the predefined range, the robot would continue its way until reaching the target goal. It shows that this method has good effectiveness and reliability.

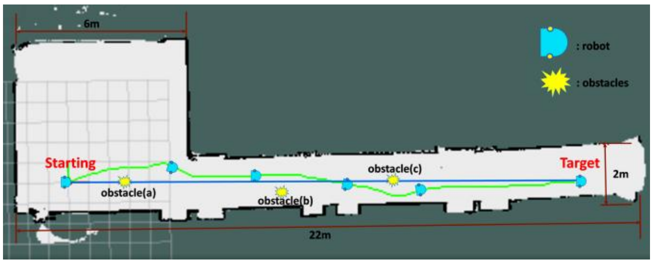

Fig. 14 Global path and obstacle avoidance

D. Discussion

In our approach, the QR codes as landmarks are needed to be placed on the ceiling, so it is suitable for indoor environment which has a ceiling and is easy to set landmarks. Also, for the distribution of QR codes, according to actual environment it can make some adjustment slightly if at least one QR codes in the camera's field of view are always detected. In addition, the camera exposure time is adjusted to better adapt to the lighting conditions, but in a completely dark environment, the recognition of QR codes is failed. Therefore, proper light conditions are also needed in the environment. Furthermore, in order to make the localization more accurate, calibration should be done at first. Consequently, the proposed approach is used generally for indoor robots.

There is some uncertainty for localization using QR codes due to ambient light or sheltering obstacles. In this case, we cannot get any localization and orientation information from QR codes. Some researchers have utilized external sensors or other methods, such as Dead Reckoning. For this reason, when QR code is missing in the camera's field of view, odometry data can be used for compensation to reduce localization error. Odometry data is not so accurate in localization for a long time due to error accumulation, however, within a short time it is a reliable way to exploit the position provided by odometry to reduce the localization error when QR code cannot be recognized.

V. CONCLUSION

In this paper, an approach based on QR codes as landmarks for mobile robot localization and navigation have been proposed. By using an industrial camera and a fast recognition algorithm, the vision system recognizes QR codes accurately and rapidly which allows the robot to move at high speed. Moreover, to make robot localization more accurate, camera calibration is performed at first. For the purpose of verifying the feasibility and effectiveness of this method, a grid map is built by using Rao-Blackwellized particle filters and Dijkstra algorithm and DWA are used in path planning based on ROS packages. From the experimental results, it shows that our method is feasible and effective in indoor environment. In future work, more robust localization and navigation system of the mobile robot will be studied. Meanwhile, we plan to reduce the number of QR codes and provide more information for localization and navigation. Consequently, our approach would be adequate for use in indoor environment.

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