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Visual localization of mobile robot using artificial markers

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Abstract

The paper presents localization method for mobile robots with use of artificial markers deployed to an environment. A specialty of the markers is that the position and rotation of the camera relative to the marker can be determined from only one marker. Further in the paper, some experiments are described. The results prove that this system can be reliably employed in visual localization of mobile robots.

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1. Introduction

Forasmuch as a mobile robot should perform meaningful activity, it is necessary that the robot knows what its position is. Therefore it has to have some kind of localization method implemented. These methods depend on a robot type, on a type of robot's sensors, on a type of coordinate system or on a type of environment where the robot operates. In a field of mobile robot localization, trigonometric methods, inertial navigation methods, methods for GNSS systems or mathematically complicated probabilistic method prove their worth.

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Nomenclature

x	position of a marker relative to the optical centre of the camera
z	distance between a camera and a plane which is perpendicular to the optical axis of a camera and is intersecting the centre of the marker
θ	orientation of a robot relative to marker
x_w	global coordinate of a robot position
y_w	global coordinate of a robot position
θ_w	global orientation of a robot
W	the first element of a quaternion provided by the functions of ArUco library
X	the second element of a quaternion provided by the functions of ArUco library
Y	the third element of a quaternion provided by the functions of ArUco library
Z	the fourth element of a quaternion provided by the functions of ArUco library
θ_R	orientation of a robot relative to marker
θ_Z	global orientation of a marker
x_z	global coordinate of a marker position
y_z	global coordinate of a marker position

Currently, almost every newly developed mobile robot has built-in camera system [1]. Therefore it is convenient to utilize it for determining a robot's position in an environment. A visual localization belongs to the set of trigonometric methods. The visual system can include one or two cameras and should detect some markers in the environment by use of computer vision tools [2,3,4,5]. These markers may be artificial or natural (inclusive of characteristic properties of the environment that can be obtained using various algorithms). If the visual system consists of only one camera the robot's position relative to the mark is calculated from two snapshots of the environment in which one marker at various locations in the image is during the motion of the robot. If we want the robot to be able to determine its coordinates without movement, it is necessary that at least two different markers with known positions are present in the image.

But there is also the possibility to determine the relative position of the static robot to a single marker. It is when a special type of 2D marker is used. If we know the calibration parameters [6] of the camera lens we can get the translation and rotation of the marker towards the image plane [7]. Many types of 2D marker systems such as ARStudio, ARToolkit and ARTag (Fig. 1.) were primarily developed for the purpose of augmented reality [8]. In order to clearly identify the marker, a system for visual localization using 2D markers consists of a set of plane patterns and algorithms that recognize these patterns [8]. Moreover, it must be ensured that the pattern encoding the unique marker identifier cannot be created by rotation of another pattern used in the environment [6]. These requirements are fulfilled in the system of markers called ArUco that is based on the ARTag and comes with library of functions for detection and localization of the markers.

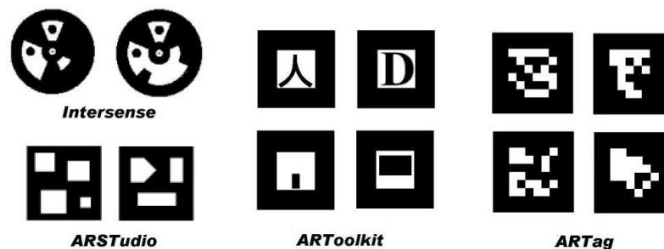


Fig. 1. Examples of 2D marker systems [8].

Further in the paper the ArUco system is introduced and results of experimentation with the system focused on mobile robot localization are presented. As a part of visual system, there have been used two types of cameras during the experiments: webcam integrated in Dell Vostro V131 laptop (1MP resolution) and network HDR (High Dynamic Range) camera IDS UI-5120SE-M (0.44MP resolution) [9] (Fig. 2.) with zoomable lens. An advantage of using the webcam is higher resolution but the advantage of HDR camera is higher dynamic range, i.e. the ability to separately adjust the gain of each pixel of a special CMOS chip. The aim of the experiments was not only to verify that the ArUco system can be used for mobile robot localization, but also to choose a suitable type of camera system for this purpose.



Fig. 2. Network HDR camera [10].

2. The system of markers ArUco

The markers in the system ArUco are defined as 7×7 squares array. Each of squares is either black or white but the outer two rows and columns are black (Fig. 3.). The system comes with algorithms that are implemented in functions for recognition of these patterns. Thanks to the use of digital coding theory system reaches a low level of confusion or false marker detection. For successful detection of the marker the system assumes the marker size and calibration parameters of the camera are known.

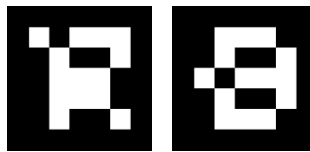


Fig. 3. Patterns of artificial markers ArUco.

An internal binary code of the marker is defined by five words, each of which contains five bits. To encode the identifier a slight modification of Hamming code is used. Therefore, out of the five bits of the word only the two are carriers of useful information. Thus the number of unique markers is equal to 1024 [7].

After successful detection of the marker, functions of ArUco library provide position information relative to optical center of the camera. For the rotation the system ArUco provides standard transformation matrix or quaternion. For the purposes of locating this data must be transformed into Euler angles. In terms of mobile robot localization, it is necessary to determine the rotation about the z axis:

$$\theta = \arctan \left[2.(X.Y - W.Z), W^2 - X^2 - Y^2 + Z^2 \right] \quad (1)$$

Where W , X , Y and Z are the elements describing the quaternion provided by the functions of ArUco library. Robot position relative to the marker is given by:

$$\begin{aligned}
 x_w &= x \cdot \cos(\theta) - z \cdot \sin(\theta) \\
 y_w &= z \cdot \cos(\theta) - x \cdot \sin(\theta) \\
 \theta_w &= \theta
 \end{aligned}
 \tag{2}$$

Where x is a position of the marker relative to the optical center of the camera along the x -axis, z is a distance between the camera and plane perpendicular to the optical axis of the camera and is intersecting the center of the marker and θ is angle between the camera and the marker (Fig. 4.).

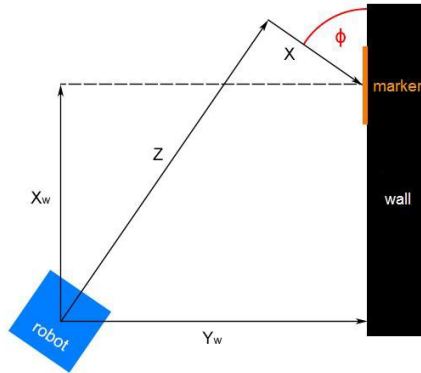


Fig. 4. Determining of the robot’s position relative to the marker.

The global position of the robot x_w, y_w and θ_w according to the Fig. 5. is then given by:

$$\begin{aligned}
 x_w &= x \cdot \cos(\theta_r + \theta_z) - z \cdot \sin(\theta_r + \theta_z) + x_z \\
 y_w &= z \cdot \cos(\theta_r + \theta_z) - x \cdot \sin(\theta_r + \theta_z) + y_z \\
 \theta_w &= \theta_r + \theta_z
 \end{aligned}
 \tag{3}$$

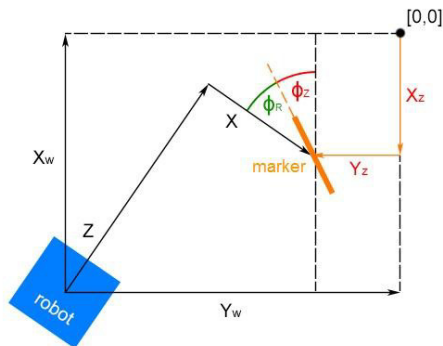


Fig. 5. Determining of the robot’s global position using the marker position.

The detection system of ArUco is able to find more than one marker in a given image. Then it is possible to calculate the position of the robot based on a position of each marker. To refine the resulting position, the average of

the obtained data can be used. If the system finds a marker that is not included in the set of known markers (with known positions) it will not consider the marker in calculation of the robot position.

In order to verify the localization system based on ArUco, several experiments have been performed.

3. Experiments

First of all, it is necessary to verify whether the system is able to correctly detect identifier and also the position of the marker relative to camera. The marker was placed in front of the camera that had been calibrated using a calibration grid beforehand. Through the use of functions of ArUco library, it was possible to recognize the marker in the image and to write the number of the identifier and to depict 3D cube upon the marker inside the image (Fig. 6.). This simple experiment proves correct settings of the system.

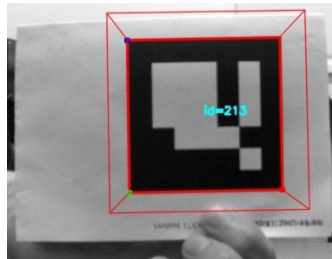


Fig. 6. A successful recognition of the ArUco marker.

In the next experiment, the marker was manually placed in sequence to certain positions and each relative position of the robot with camera against the marker was determined. A size of the edge of used marker was 10cm. For this experiment both camera types have been employed and two settings of focal length for HDR camera lens were used (normal and wide-angle). The sequence of the positions was in a range from 20 to 150cm along the z-axis using a 10cm steps. The resulting relation between error of measurement and the distance of the marker from the robot can be seen in Fig. 7. for both cameras and both settings of the focal length of HDR camera lens.

The results prove that the accuracy of determining the position is good enough up to the distance of 100cm for both cameras and all settings. In case of wide-angle focal length of HDR camera, the increase of the error above the distance of 100cm is due to shrinkage of the markers in the image. The markers look smaller and for the algorithm it is hard to correctly determine the position. A better performance of webcam beside the HDR camera with normal focal length is due to a better resolution.

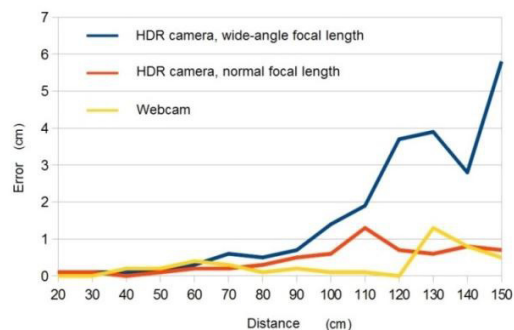


Fig. 7. A relation between an error of measurement and the distance of the marker from the robot.

Further experiment is oriented on an effect of strong backlight that is common problem of visual systems. Overexposure of the pixels in ordinary camera systems at area of strong light causes depression of gain for whole image and consequently loose of visual information near the area of strong light [11]. In the experiment the strong backlight is caused by daylight entering the room through a window. Using the standard webcam the system ArUco was not able to detect any pattern neither a marker because the area around the window was too dark. Contrariwise, the HDR camera has no problem to depress the gain only for the pixels which are overexposed by strong light. Therefore, other areas of the image can preserve details and may be readable for the ArUco system. The comparison of the conditions can be seen in Fig. 8.

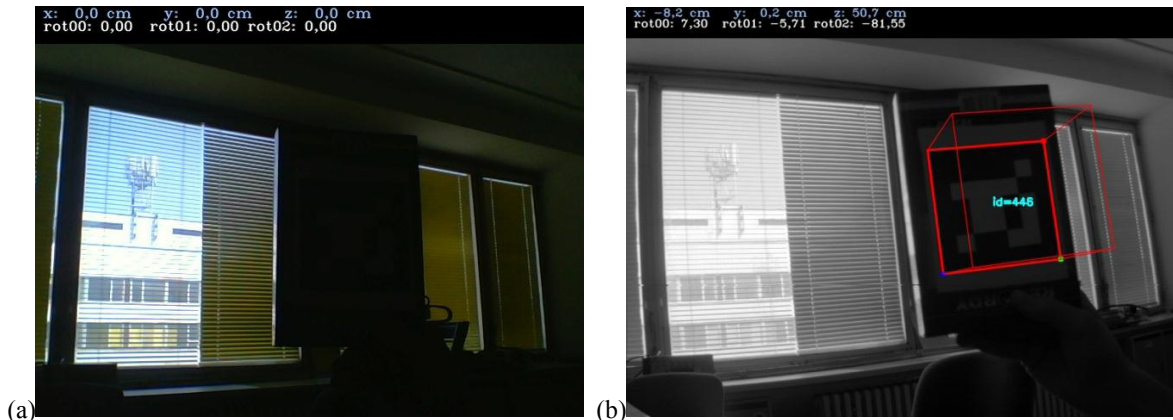


Fig. 8. A marker detection in the image with strong light using (a) Webcam and (b) HDR camera.

As the system ArUco is able to detect more markers at the same time, it was prepared an experiment that compares accuracy of determining the position of the robot in case of sensing one and two markers. The size of the marker's edge was 6cm. The setting of the experiment when two markers are used is depicted in Fig. 9. where the distance between markers is 20cm. The sequence of the positions was again in a range from 20 to 150cm along the z-axis using a 10cm steps. During the test, only HDR camera had been used.

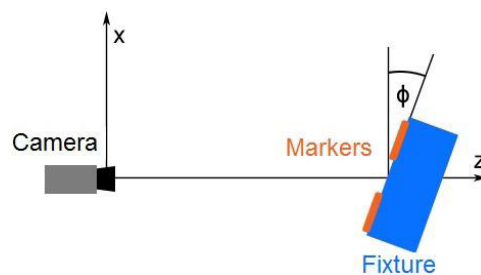


Fig. 9. The setting of the experiment when two markers are used.

From the results in Fig.10., it is obvious that determination of the robot's position is more accurate when using more markers. However, ArUco system is limited by total of 1024 markers. That means the robot is not able to operate in very large area and we have to reduce the area if we want to get more accurate results by using denser presence of the markers.

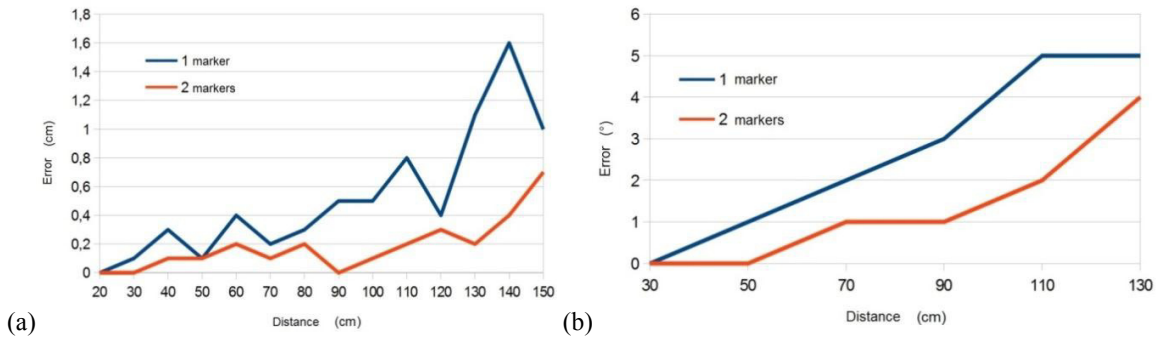


Fig. 10. A relation between an error of measurement ((a) in position, (b) in direction) and the distance of one and two markers from the robot.

A final experiment is focused on repeatability. An assumption is that a localization system returns the same results when the same inputs are given. In the experiment, an environment contained three markers placed on the wall at the same height from the floor. Two of them were on the same wall and one was placed on a perpendicular wall. Localization was performed in three different known robot positions. In fourth position, which was the same as the first, the ArUco system should return the same position (Fig. 11.). Again, only the HDR camera was used. The experiment was done for two different sizes of the markers. In the first case, the edge of the marker was 16cm long and 10cm in the second case.

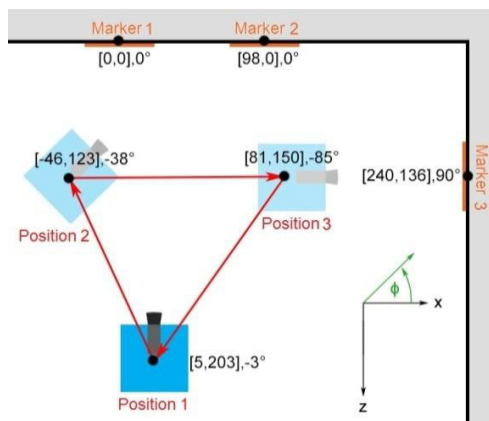


Fig. 11. An overview of the experiment of repeatability of the localization using ArUco system.

The results in Fig. 12. show that in first case the first and fourth position were determined correctly and the triangle of robot's movement is closed. In second case the first and fourth computed positions are different. In Fig. 13., we can see that the maximum error was higher for the smaller marker. For the localization purpose at least the 16cm marker square is required.

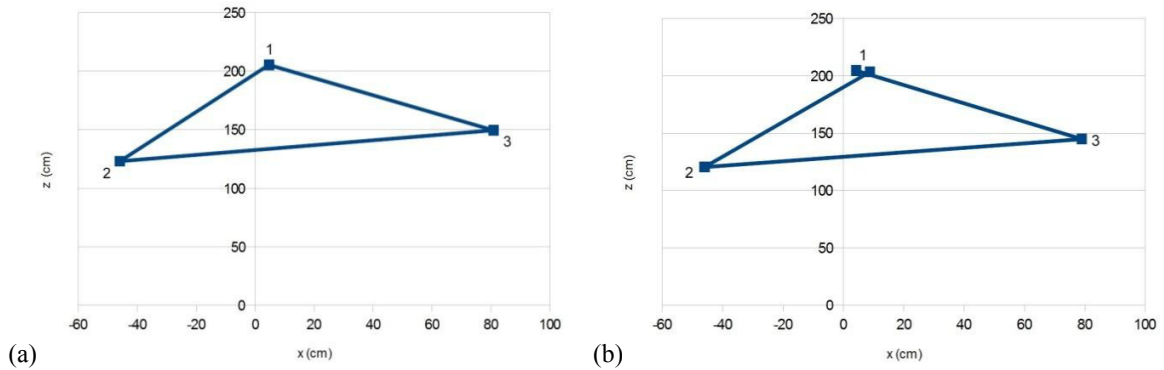


Fig. 12. Accuracy of localizing the robot in its 3 positions (marker edge size: (a) 16 cm, (b) 10 cm).

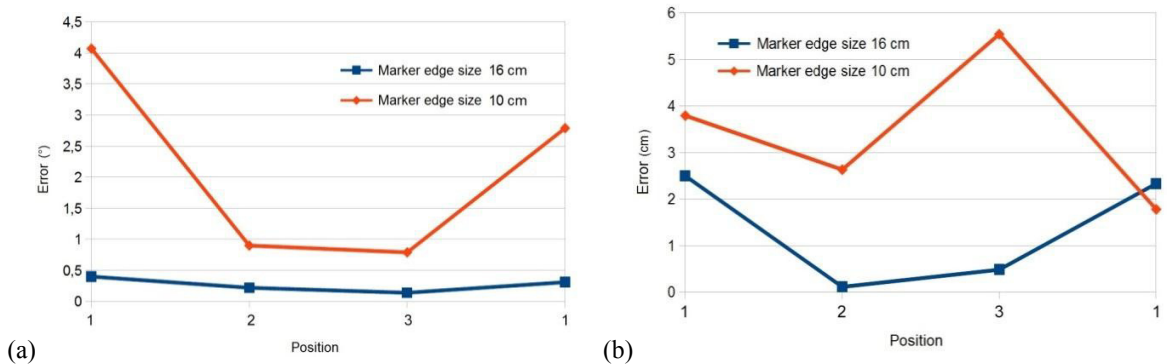


Fig. 13. An error of measurement ((a) in a direction, (b) in a position) during a test of repeatability.

4. Conclusion

In the paper, the markers developed for augmented reality was used for localization of mobile robot. Some experiments were done and they prove that system ArUco can be used in visual localization. The results show that the accuracy in localization is affected by a size and amount of visible markers, also by a distance between robot and marker, and by the type of the camera which is used in the system. If we do not expect strong backlight the webcam is good choice mainly because of low purchase cost and good resolution. Special HDR camera does not have such a good resolution but excels in difficult situations when strong light is present in a part of the image. To conclude the paper, we can say that the ArUco markers can be used in small areas of robot operation where a sufficient density of markers can be easily ensured. The marker size have to be at least 16cm square when it is read by the camera (with normal focal length) from the distance about 2m. This localization may be used as a supplementary navigation to other approaches because it does not suffer with cumulative offset. The error in position determination depends only on conditions that ensure good readability of the marker by a visual system and is independent of time.

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