Distance and angle measurement using monocular vision

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***Abstract*— Accurate localization is a fundamental challenge and one of the essential tasks in mobile robot applications. In this paper, we proposed an image-based method to measure parameters of an object by a visual camera/monocular vision. If the sizes of the object are unknown, based on information extracted from two images at two different positions of the camera on the optical axis, these sizes can be calculated accurately. Furthermore, the distance and direction (angle) of the object can also be determined. If the dimensions of the object are known, just one image is enough to determine distance and direction (angle) of the object. Unlike other existing methods, the proposed method does not require the object to be perpendicular to the optical axis of the camera.**

***Keywords*— distance measurement; angle measurement; monocular vision; visual camera; optical axis.**

I. Introduction

Accurate localization of static and moving objects is a fundamental challenge and one of the most important tasks in mobile cooperative robot applications. Many sensors, techniques, operating principles and systems for determining the location of mobile robots or objects of interest have been developed such as laser, ultrasonic sensors, Bluetooth, infrared, radar systems, GPS, optical/optical-mechanical sensors using different methods (time of flight, triangulation, structured light, odometry…) [1], [2], [3], and [4]. However, each technique has its advantages and disadvantages over others. The different constraints of them force us to consider the benefits and costs of available sensory systems such as size, weight, durability, accuracy, cost…. For example, the significant disadvantage of laser or ultrasonic sensors is that the reflection of the signal is dependent highly on the object surface's material and the orientation. GPS is not appropriate for robots that operate mostly indoors due to its large size, limited accuracy, and satellite visibility requirements. Although using radio communications for relative localization without any external fixed beacon can be achieved, it is necessary to use a high-frequency system combined with the use of directional antennas to accomplish the same resolution as with ultrasonic or infrared. This implementation results in a too big and expensive solution for being implemented in small size boards.

Recently, image-based techniques have been of interest to many researchers because of their advantages: they are difficult to disturb, good balance among cost, reliability, and usability; and a relatively wide range of measured distances. Related works can be divided into the stereo vision and monocular vision. Stereo vision is highly accurate, but it needs time to process many images and quite expensive because of requiring two cameras [5], [6] and [7] while monocular vision is somewhat accurate but cheaper and easier to handle because of using only one camera [8]-[14]. This work is focused on the problem of measuring the parameters of the object such as size, position (distance, angle) can be determined indirectly using monocular sensor systems (single camera).

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II. Distance and angle measurement of a known-sizes object

The model of the object which is used in this work has the shape of a rectangle (Fig. 1). We will begin with the case in which the sizes (width w and height h) of the object are known. Our work is to find the distance d from the camera to the object and angle α of rotation of the object. To measure these parameters, we use a single camera to capture a photo of the object. The sizes of the object in the image plane of the camera vary when the distance and the angle of the object to the camera change. Based on information of these sizes extracted from the image, the known real sizes of the object and given focal length f of the camera, we can estimate the distance and angle of the object accurately.

A. Distance measurement

Assume that the camera's image plane and the object plane both are vertical. If the object does not rotate around its vertical axis, the object plane is parallel to the camera's image plane, meaning that the angle $\alpha = 0$ (Fig. 2), we can calculate the distance d from the object to the camera based on either the width w or the height h as following [15], [16]:

$$d = \frac{wf}{w'} = \frac{hf}{h'} \tag{1}$$

where w' is the size of the width w of the object in the image, h' is the size of the height h of the object in the image.

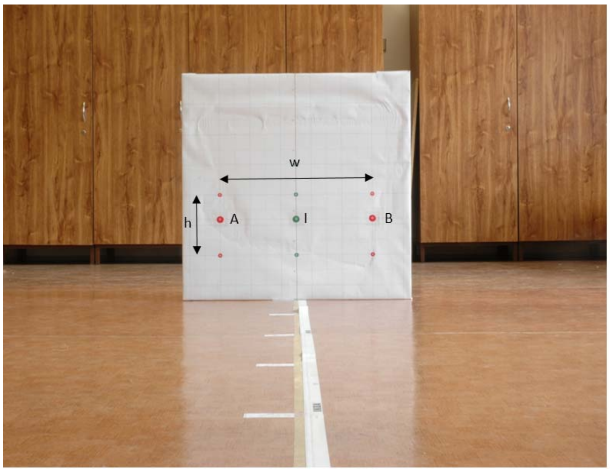

Fig. 1. Model of the object to be measured.

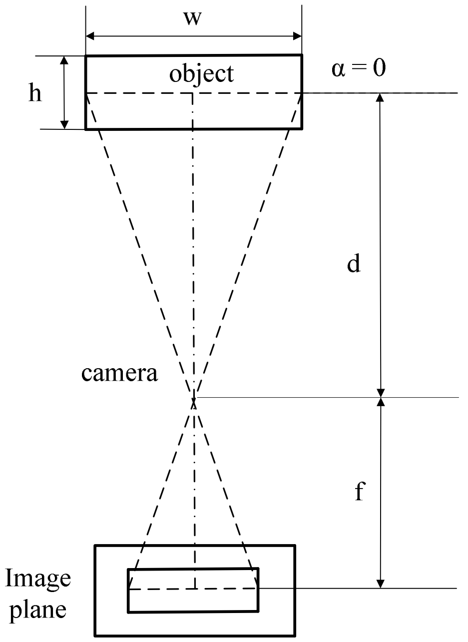

Fig. 2. The camera's image plane and the object plane are parallel.

Note that all the elements in (1) must be in the same unit of length, for example, in millimeters. Based on the dimension and resolution of the camera's CCD sensor, we can convert the size of the object in the image from pixels to millimeters easily. For example, our camera used in the experiment has these parameters (Fig. 3):

Resolution: 3008x2000 [pixels] ~ X×Y [pixels]

CCD sensor's size: 23.7x15.6 [mm] ~ $A \times B$ [mm]

One pixel in the horizontal direction has a size of 23.7/3008 [mm] and in the vertical direction has a size of 15.6/2000 [mm].

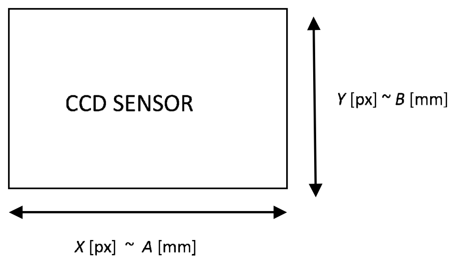

Fig. 3. CCD sensor's size.

If the object rotates around its vertical axis, the object plane is not parallel to the camera's image plane anymore. In this case, there is an angle α between the camera's image plane and the object plane (Fig. 4).

Then point B is further from the camera, in contrary, point A is closer to the camera. In the image, the sizes in width of the object decrease while the height of the object at the point I does not. Then we can still calculate the distance d from the object to the camera based on the height h as follows:

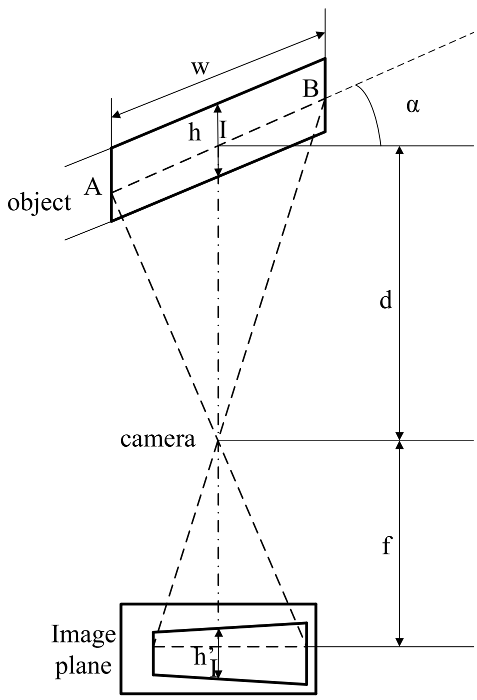

Fig. 4. The object rotates around its vertical axis.

$$d = \frac{hf}{h_I^{'}} \tag{2}$$

where $h_I^{'}$ is the size of the object's height at the point I in the image.

B. *Angle measurement*

Assume that the object rotates an angle α around its vertical axis. The schematic diagram of angle measurement is shown in Fig. 5.

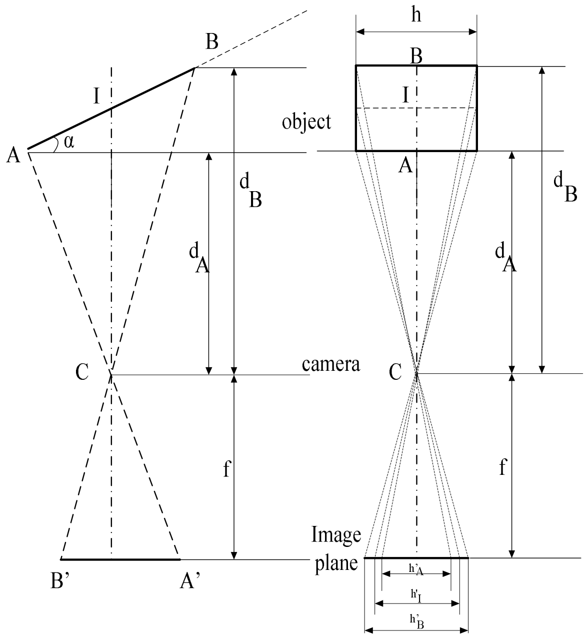

Fig. 5. Schematic diagram of angle measurement.

From the figure, the incline angle α can be obtained as:

$$\sin\alpha = \frac{d_B - d_A}{w} \tag{3}$$

where d_A, d_B - distances from point A and point B, respectively, to the camera plane.

Based on the relationship of similar triangles, we have:

$$\frac{d_A}{f} = \frac{CA}{CA'} = \frac{h_A}{h'_A} \tag{4}$$

$$\frac{d_B}{f} = \frac{CB}{CB'} = \frac{h_B}{h'_B} \tag{5}$$

where h_A, h_B – the heights of the object at point A and B, (and h_A=h_B=h_I=h)

h'_A, h'_B – the sizes of the object's height at point A and B in the image.

From (3), (4) and (5), the angle α can be expressed as the following equation:

$$\alpha = \arcsin\left[\frac{fh}{w}\left(\frac{1}{h'_B} - \frac{1}{h'_A}\right)\right] \tag{6}$$

The equations above to calculate the angle α are also valid for the case α = 0, in which the object does not rotate, then d_A=d_B, h_A=h_B, and h'_A=h'_B.

As a result of that, by the information extracted from only one image, we can estimate the distance and angle of a known-sizes object to the camera.

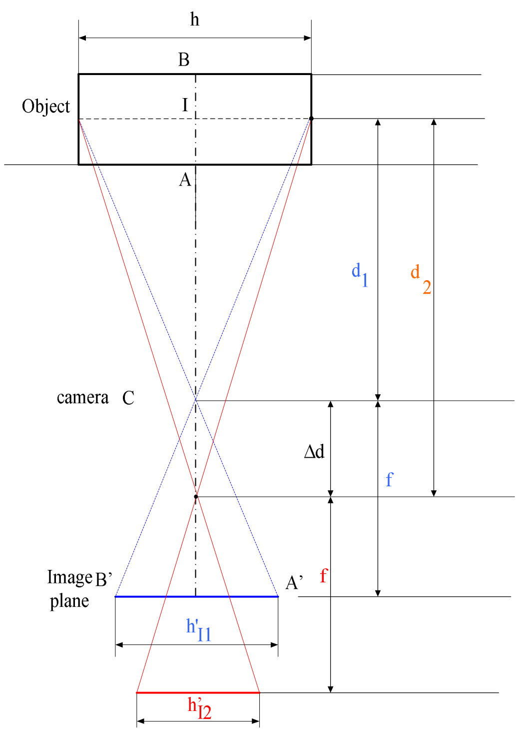

Fig. 6. Schematic diagram of using a single camera to measure the height and the distance of the unknown-sizes object.

III. Sizes, Distance and Angle Measurement of an Unknown-Sizes Object

In many cases, the information of the object's sizes is not available. So how to measure the distance and angle of the object still using a single camera? The equations above are not valid for the unknown-sizes object. Thus we have to find another solution to this problem.

We see that when the camera moves forward or backward along its optical axis which does not change, the distances from the points A and B to the optical axis and the angle α between the camera's image plane and the object plane are still unchanged. From this point, we propose a method to measure the parameters of the object based on the displacement of the camera along its optical axis.

The schematic diagram of the proposed method is illustrated in Fig. 6. The camera captures two images of the object at different position 1 and 2, the displacement between two positions is Δd is known. Based on the relationship of similar triangles, we have:

$$\frac{h}{h'_{I1}} = \frac{d_1}{f}; \tag{7}$$

$$\frac{h}{h'_{I2}} = \frac{d_2}{f} = \frac{d_1 + \Delta d}{f} \tag{8}$$

where h'_{I1}, h'_{I2} - the size of the object's height at the point I in the image at position 1 and 2, respectively.

Then the height of the object can be obtained as:

$$h = \frac{h'_{I1} h'_{I2} \Delta d}{(h'_{I1} - h'_{I2}) f} \tag{9}$$

Also, the distance from the object to the camera can be calculated as follows:

$$d_1 = \frac{h'_{I2}\Delta d}{h'_{I1} - h'_{I2}}; \quad d_2 = d_1 + \Delta d \tag{10}$$

We will find the width of the object similar to the above and then the angle of rotation of the object. From Fig. 7, we have:

$$\frac{w_A}{w'_{A1}} = \frac{d_{A1}}{f}; \frac{w_B}{w'_{B1}} = \frac{d_{B1}}{f} \tag{11}$$

$$\frac{w_A}{w'_{A2}} = \frac{d_{A2}}{f} = \frac{d_{A1} + \Delta d}{f}; \frac{w_B}{w'_{B2}} = \frac{d_{B2}}{f} = \frac{d_{B1} + \Delta d}{f} \tag{12}$$

where w_A, w_B – the sizes of the projections of the segments AI and BI on the vertical plane that passes through point A and B, respectively and parallel to the image plane, respectively.

w'_{A1}, w'_{A2}, w'_{B1}, w'_{B2} – the sizes of AI and BI on the image at position 1 and 2, respectively.

d_{A1}, d_{A2}, d_{B1}, d_{B2} – the distances from point A and point B at position 1 and 2, respectively, to the camera plane.

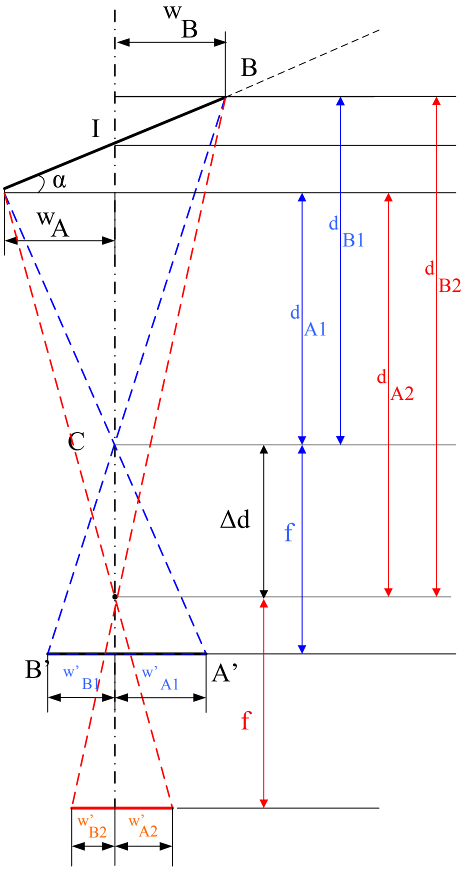

Fig. 7. Schematic diagram of using a single camera to measure the width and the angle of rotation of the unknown-sizes object.

From (11) and (12), we have:

$$d_{A1} = \frac{w'_{A2}\Delta d}{w'_{A1} - w'_{A2}}\,;\, d_{B1} = \frac{w'_{B2}\Delta d}{w'_{B1} - w'_{B2}} \tag{13}$$

$$w_A = \frac{w'_{A1}w'_{A2}\Delta d}{(w'_{A1} - w'_{A2})f}\,;\, w_B = \frac{w'_{B1}w'_{B2}\Delta d}{(w'_{B1} - w'_{B2})f} \tag{14}$$

Then the angle of rotation of the object can be derived as follows:

$$\alpha = \arctan\left[\frac{d_{B1} - d_{A1}}{w_A + w_B}\right] \tag{15}$$

Also, the width of the object can be obtained as:

$$w = \frac{w_A + w_B}{\cos\alpha} \tag{16}$$

IV. Experiments Results

In this section, we present the experiment results of the proposed method to measure the parameters of the object using a single camera (Fig. 8). The experiment aimed to assess the applicability of the proposed method. The camera plane and object plane are vertical. The object has real sizes of width and height are: $w = 500$ [mm], $h = 200$ [mm]. The object was placed at a distance from 1 to 5 m to the camera. The focal length f of the camera is 35 [mm] and kept to be constant through the process of experiments. No zoom or auto-focus was applied so that the focal length did not change its value. These settings made the image sharp in all the ranges of the experiments.

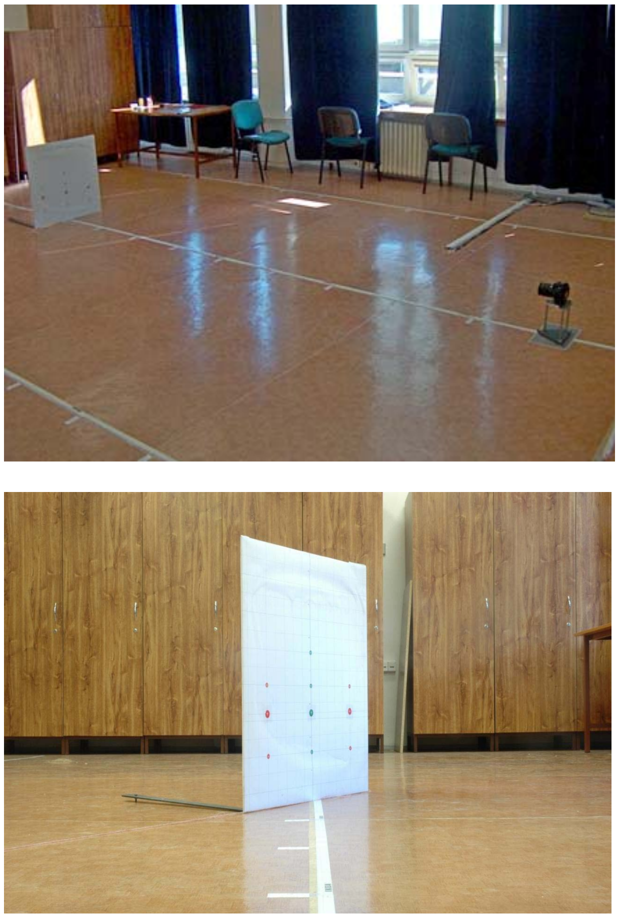

Fig. 8. Experiments to measure the parameters of an object using a single camera.

TABLE I. Known-sizes object with no rotation

Real distance	Measured distance	Distance error	Measured angle	Angle error
[mm]	[mm]	[%]	[°]	[%]
1002	986	-1.58	-0.87	-0.48
2003	2021	0.91	-0.78	-0.44
3004	3063	1.95	-0.01	0.00
4002	4098	2.39	-0.01	-0.01
5003	5128	2.50	-0.01	-0.01

TABLE II. Known-sizes object with an angle of rotation 45°

Real distance	Measured distance	Distance error	Measured angle	Angle error
[mm]	[mm]	[%]	[°]	[%]
1002	973	-2.87	45.38	0.90
2003	2019	0.79	45.45	1.07
3004	3063	1.95	44.78	-0.43
4002	4088	2.16	45.23	0.61
5003	5113	2.20	44.09	-1.89

The images after capture were analyzed by the software GIMP 2.8.18 to extract the necessary information. The sizes in pixels converted into millimeters for the next calculations. The results of experiments are shown in Table I in which the sizes of the object are known (the object did not rotate around its vertical axis, i.e angle of rotation α = 0°) and Table II (angle of rotation α = 45°). As it is illustrated in the tables, the distance error tends to increase proportional to the distance, from -1.58 to 2.50 % in Table I and from -2.87 to 2.20 % in Table II, i.e., the further the distance is, the bigger the distance error is. This result is consistent with the results of previous studies [15], [16], and [17].

In distance measurement, there are some problems when the surface of the object to be measured, and the axis of the measuring device is not perpendicular. In general, the results are not inaccurate, or even unmeasurable. The advantages of the proposed method are shown in cases where the object plane is not perpendicular to the optical axis of the measuring device – camera, it is possible to estimate not only the distance to the object but also the angle of rotation.

Note that the proposed method does not require a camera calibration, which needs to capture multiple images of a checkerboard pattern at a distance roughly equal to the distance from the camera to the target. The camera calibration increases the accuracy of the results, however, has a set of requirements and takes much time, in some cases is not easy to implement. The proposed method used only one image captured when the sizes of the target are known. As a result, data processing and computation work are reduced compared to the use of multiple images.

Moreover, this method can determine the sizes of the unknown-size object and use this as the basis for subsequent calculations. It offers many other benefits, especially for positioning and localization problems.

The results of experiments in which the sizes of the object are unknown are shown in Table III (angle of rotation α = 0°) and Table IV (angle of rotation α = 45°), respectively. As shown in the tables, the distance and angle of rotation of the object are estimated relatively accurate with a small number of errors. The errors can occur because some reasons such as inaccuracy in the preparation phase (the object plane and camera plane were not perfectly vertical, the object plane was not completely flat). Errors may also appear from lens distortion, inaccuracy in determination of the parameter's values (such as focal length, camera's sensor size, object's sizes) or inaccuracy in image processing and also the distance from the camera to the object. The evaluation and the analysis of the influence of these factors on the measurement results will be the future work.

TABLE III. UNKNOWN-SIZES OBJECT WITH NO ROTATION

Real distance	**Measured distance**	**Distance error**	**Measured angle**	**Angle error**	**Measured width**	**Width error**	**Measured height**	**Height error**
[mm]	[mm]	[%]	[°]	[%]	[mm]	[%]	[mm]	[%]
1002	954	-4.82	-0.38	-0.21	487	-2.62	193	-3.29
2003	1943	-3.01	0.29	0.16	487	-2.56	192	-3.89
3004	2953	-1.69	-1.15	-0.64	486	-2.86	193	-3.58
4002	3981	-0.52	2.86	1.59	484	-3.11	194	-2.84

TABLE IV. UNKNOWN-SIZES OBJECT WITH AN ANGLE OF ROTATION 45°

Real distance	**Measured distance**	**Distance error**	**Measured angle**	**Angle error**	**Measured width**	**Width error**	**Measured height**	**Height error**
[mm]	[mm]	[%]	[°]	[%]	[mm]	[%]	[mm]	[%]
1002	932	-7.00	45.35	0.85	489	-2.23	191	-4.26
2003	1936	-3.35	46.34	3.04	478	-4.47	192	-4.11
3004	2980	-0.81	44.36	-1.36	493	-1.33	195	-2.70
4002	3993	-0.22	47.98	6.73	496	-0.90	195	-2.33

V. CONCLUSION

This paper proposed a method to measure the parameters of an object using a single camera. If the sizes of the object are known, the distance from the object to the camera and the angle of rotation of the object can be determined by only one image. In the cases where the object's sizes are unknown, based on the information extracted from two images at the different position of the camera on its optical axis, not only the distance and angle of rotation of the object but also its sizes are possible determined accurately. Experimental results with small errors indicate the applicability of the method to practical applications. Nevertheless, more research is needed to evaluate the effect of the factors on the measurement results such as parameters of the camera (focal length, sensor's size, resolution of the camera), parameters of the object (sizes, distance, angle). Also, this work can be further developed for the case where the object is not on the optical axis of the camera.

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