Real-time Omni-directional Distance Measurement with Active Panoramic Vision*

Sooyeong Yi**, **Byoungwook Choi**, **and Narendra Ahuja**

Abstract: Autonomous navigation of mobile robot requires a ranging system for measurement of distance to environmental objects. It is obvious that the wider and the faster distance measurement gives a mobile robot more freedom in trajectory planning and control. The active omni-directional ranging system proposed in this paper is capable of obtaining the distance for all 3600 directions in real-time because of the omni-directional mirror and the structured light. Distance computation including the sensitivity analysis and the experiments on the omni-directional ranging are presented to verify the effectiveness of the proposed system.

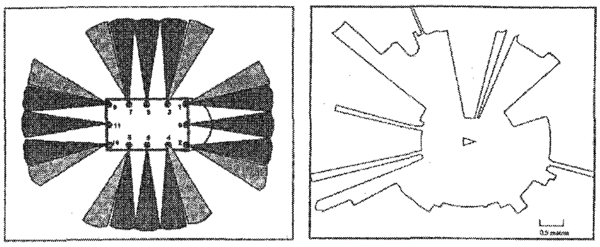
Keywords: Active vision, mobile robot, omni-directional mirror, panoramic vision, structured light.

1. INTRODUCTION

A ranging system is one of primary concerns for autonomous navigation of mobile robot since the localization and the map construction can be realized on the basis of the range information [1]. There are many kinds of ranging sensors such as the ultrasonic sensors, laser sensors, and stereo camera sensors etc. Among those kinds of sensors available, the stereo camera sensors are the most versatile and widely used since they acquire comparatively rich information with the others. However, there are several practical problems in the conventional stereo camera sensors: (1) narrow FOV (Field-Of-View), (2) computational burden for matching a point in stereo images, so called the correspondence problem, and (3) vulnerability to illumination noise.

The wider angle for distance measurement is desirable in practical application of the ranging system since it implies the richer information for robot. A simple way to get the wide angle is rotating scan with a ranging sensor or ring structure with multiple ranging sensors. However, the rotating scan requires the motorized moving parts and the time-consuming information processing, which imposes a limitation on the real-time application of the ranging system. The omni-directional ranging system with the ring structure can be exemplified by the array of ultrasonic sensors (Fig. 1) proposed in [1], which demands costly multitude of the range sensors.

For camera sensor, a novel approach to get the wide FOV is to use a curved mirror such as conic, parabolic, or hyperbolic mirror [2,3]. It is possible to get 360^o omni-directional image by an ordinary camera with the curved mirror in one shot without any rotating scan. Gluckman *et al.* proposed a stereo omni-directional camera system by using two parabolic mirrors with two cameras [4] and Lin *et al.* adopted a conic mirror and beam splitter to get the omni-directional distance information [5]. For a cost-effective omni-directional raging system, Yi *et al.* proposed a single camera stereo approach by using a concave lens and a hyperbolic mirror [6]. It is well known that the major hindrance of the conventional stereo camera system in the practical real-time



(a) (b)

Fig. 1. A ranging system by using the ring array of ultrasonic sensors [1]: (a) A ring array of the ultrasonic sensors on mobile robot, (b) The corresponding distance map.

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application is the correspondence problem as well as the illumination noise. The aforementioned omni-directional stereo camera approaches are also suffering from those problems of course.

On the other hand, in order to overcome the problems in the stereo camera systems, a single camera approach with structured light, known as active vision system has been developed [7]. The active vision system replaces a camera in the stereo camera system with an artificial structured light source such as laser light, which provides distinguishable features in image plane, hence it is easy to discriminate the points of interest and the time-consuming matching problem is avoidable.

With the advantages of the individual omni-directional vision and the active vision, it is expected that the combined approach give an efficient solution for the real-time distance measurement in all direction. Joung *et al.* designed an active omni-directional range sensor by using a conic mirror [8] and recently, a similar scheme was proposed by R. Orghidan et. al [9,10]. Basically, the omni-directional active vision system consists of two major parts: the projection of the structured light and the image acquisition. For the light projection in all directions, a rotational scan of a point laser was used in [8], which requires moving parts with restriction on the real-time application. The approach in [9,10] adopted a circular laser onto an additional omni-directional mirror for the projection, which demands burdensome alignment of the laser source with the mirror as well as an extra cost for the mirror.

In this paper, it is aimed to propose an omni-directional ranging system to get the distance map in all direction similar to that in Fig. 1(b). An active omni-directional vision approach is used for the proposed ranging system, which removes the motorized moving parts and the additional projection mirror. With this configuration, a real-time and cost-effective omni-directional ranging system is expected for application on mobile robot.

Organization of this paper is as follows: The overview of the proposed omni-directional ranging system and distance computation including the sensitivity analysis are presented in Section 2 and Section 3 respectively. In Section 4, some experiments are carried out to verify the effectiveness of the system. Finally concluding remarks are described in Section 5.

2. THE PROPOSED OMNI-DIRECTIONAL RANGING SYSTEM

The omni-directional ranging system in this paper applies 360° stripe laser structured light and observes the distortion of the structured light through an omni-directional mirror as illustrated in Fig. 2. Owing to the omni-directional mirror, it is possible to obtain 360° scene in one shot by an ordinary camera. The observed image contains the distortion as determined by the distance and the orientation of object surfaces on which the laser stripe is applied. Combining 2D information in the image plane together with 1D information of the artificial structured light gives 3D data including distance of the objects.

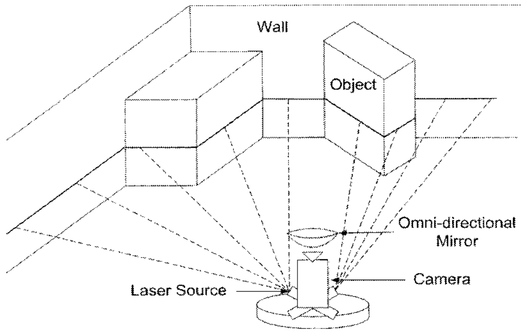


Fig. 2. Illustration of the omni-directional ranging system.

Two sources of advantages of the ranging system are as follows: (1) the omni-directional vision for fast acquisition of all directional information in one shot, (2) the active vision based on the structured light to avoid the burdensome correspondence problem and to get the robustness against the illumination noise. As well as those advantages, the proposed system is cost-effective and appropriate for real-time application since it adopts the stripe type structured light instead of the rotational scan with moving parts and an additional projection mirror.

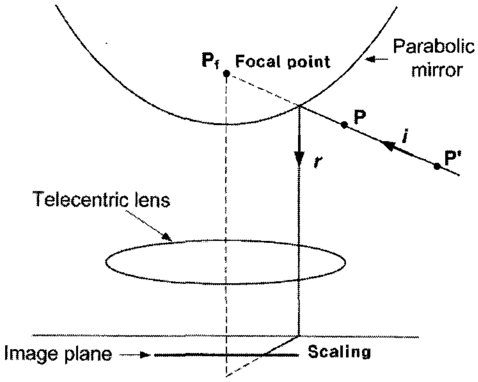
There are several types of omni-directional mirrors such as conic, hyperbolic, and parabolic mirrors [11]. Among them, the ranging system proposed in this paper adopts the parabolic mirror since it is relatively tractable in mathematical relationship between the object and the image point and easy in calibration [12].

3. DISTANCE COMPUTATION

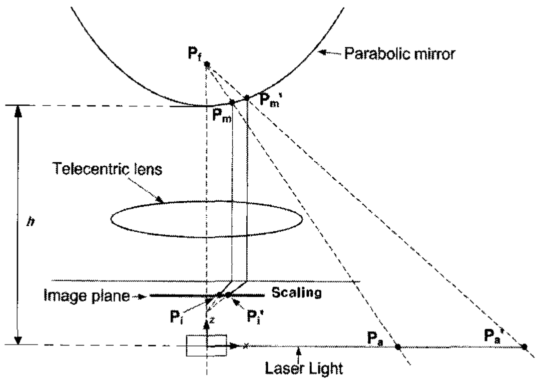
Fig. 3(a) shows the cross-section of the ranging system and the property of the parabolic mirror in $x-z$ plane. As illustrated in the figure, the ray of light, i incident toward the focal point of the parabolic mirror will be reflected in parallel with the vertical axis of the mirror. This requires an orthographic system rather than the perspective graphic to obtain the reflected image, which can be implemented by a telecentric lens with long focal length [13]. As a property of parabolic curve (1a), the focal length from the vertex is given as (1b).

$$z = \alpha x^2 \tag{1a}$$

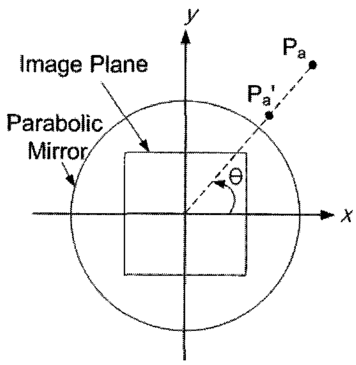
$$f = \frac{1}{4\alpha} \tag{1b}$$



(a) The parabolic mirror with orthographic imaging.



(b) The parabolic mirror with structured light.



(c) Top view.

Fig. 3. The omni-directional ranging system with a parabolic mirror.

3.1. Distance computation

As described in Fig. 3(b), two points of object, $\mathbf{P}_a(x_a, z_a)$ and $\mathbf{P}'_a(x'_a, z'_a)$ are reflected at two different points $\mathbf{P}_m(x_m, z_m)$ and $\mathbf{P}'_m(x'_m, z'_m)$ on mirror surface and correspond to $\mathbf{P}_i(x_i, z_i)$ and $\mathbf{P}'_i(x'_i, z'_i)$ respectively on the image plane after being scaled. That is, the object points with the same height, z_c, have different images according to their distances in the parabolic vision system. Thus, with the additional height information provided by the artificial structured light, it is possible to get distance to an object point.

The equation for distance computation from the omni-directional image with the structured light can be described as follows. At first, the reference coordinate system is assigned at the structured light source as shown in Fig. 3(b), so that the height of the object point projected by the structured light is $z_c = 0$ without loss of generality. The surface equation of the parabolic mirror in the cross section can be described as follows:

$$z = \alpha x^2 + h, \tag{2}$$

where α and h determine the shape and the height of the mirror respectively. With (1b), the focal point of the mirror in the reference coordinate is given as

$$\mathbf{P}_f(x_f, z_f) = \left(0, \quad h + \frac{1}{4\alpha}\right). \tag{3}$$

The line equation passing through $\mathbf{P}_f(x_f, z_f)$ and $\mathbf{P}_a(x_a, z_a)$ projected by the structured light is described as

$$z = -\frac{z_f}{x_a} x + z_f. \tag{4}$$

Combining (2) with (4) gives a relationship between the distance x_a of the object point and x_m on the mirror surface as

$$x_a = \frac{z_f x_m}{z_f - h - \alpha x_m{}^2}. \tag{5}$$

From the orthographic imaging of the system, x_i on the image plane is simply proportional to x_m on the mirror surface as $x_m = k x_i$ with a scaling factor k. As a consequence, the relationship between the observed image, x_i and the real distance, x_a becomes

$$x_a = \frac{k z_f x_i}{z_f - h - \alpha k^2 x_i^2}. \tag{6}$$

Since the omni-directional image preserves the directional angle θ of the object points about z axis as in Fig. 3(c), the distance equation, (6) holds in all 360° directions for the desired omni-directional distance map with a single image.

3.2. Sensitivity

As defined by $S = \Delta x_a / \Delta x_i$, the sensitivity implies the magnitude of error in the distance measurement according to the pixel error observed on the image plane. In general, constant sensitivity is desirable for the uniform accuracy in the distance measurement.

Differentiating (6) with respect to x_i and inserting (3) and (6) give the sensitivity as

$$S = k \cdot (h + \frac{1}{4\alpha}) \cdot \frac{\frac{1}{4\alpha} + \alpha k^2 x_i^2}{(\frac{1}{4\alpha} - \alpha k^2 x_i^2)^2}. \quad (7)$$

Here, the parameters, α and k are determined by the shape of the mirror and the scale of the image. The design parameter, h, can be chosen for the appropriate sensitivity of the ranging system.

An exemplar curve of the sensitivity are depicted in Fig. 4 where the parameters are $\alpha = 1/66.8$, k=0.196, and $h = 1{,}191$mm respectively. Those parameters are from the actual ranging system designed in this paper. In the figure, the sensitivity is small constant in rough sense within $x_i < 100$, which corresponds to actual distance, $x_a < 2{,}162$mm from (6) and the possible error in the distance measurement according to the observed pixel error is relatively uniform in the region. However, the sensitivity increases largely in $x_i > 100$, in which the pixel error on the image plane causes large and non-uniform error in the distance measurement. This is because of the curvature of the curved mirror, which makes the image dense around the center, $x_i = 0$ and coarser as x_i increases as depicted in Fig. 5(a).

One way to improve the sensitivity in the ranging system is to increase the height of the mirror, h, so that to gather the image points around the center as illustrated in Fig. 5(b). This dependency of the sensitivity on h can be explained by (8), which is a rearrangement of (7) with (6).

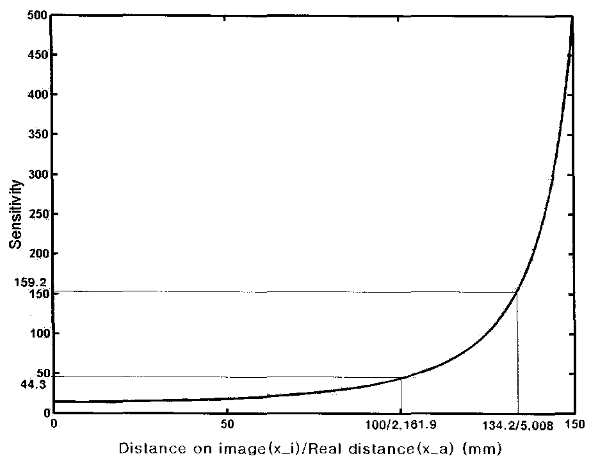
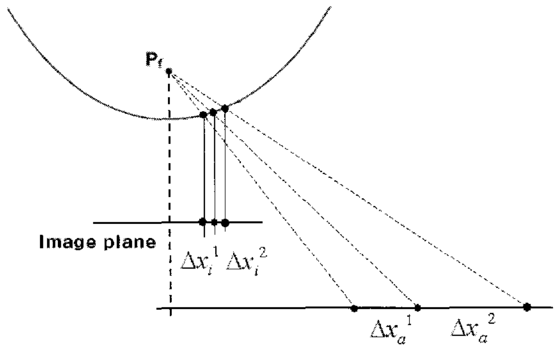
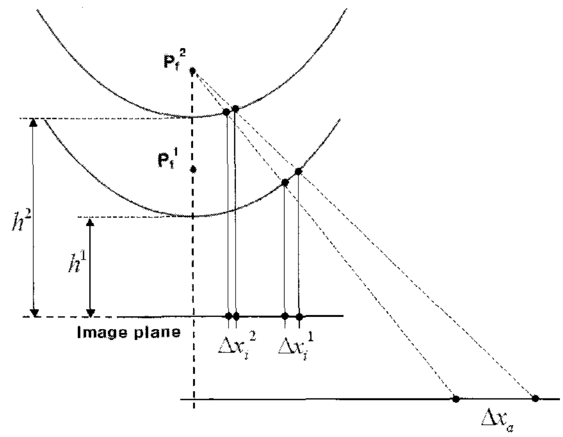


Fig. 4. Sensitivity curve: At $x_i \approx 100$ $S \approx 44.3$ and at $x_i \approx 134$ ($x_a \approx 5{,}008$), $S \approx 159.2$, which is the maximum distance of experiments in the later Section 4.



(a) According to x_i: For the same $\Delta x_i^1 = \Delta x_i^2$ $\Delta x_m^1 = \Delta x_m^2$, Δx_a is increasing, i.e., $\Delta x_a^2 = \Delta x_a^1$ as $x_i^2 > x_i^1$.



(b) According to h: For given Δx_a, Δx_i is decreasing, i.e., $\Delta x_i^2 = \Delta x_i^1$ as $h^2 > h^1$.

Fig. 5. Sensitivity, $S = \Delta x_a / \Delta x_i$.

$$S = \frac{\alpha k x_a^2}{h + \frac{1}{4\alpha}} \cdot \left[1 + \frac{x_a^2}{\left\{ (h + \frac{1}{4\alpha}) - \sqrt{(h + \frac{1}{4\alpha})^2 + x_a^2} \right\}^2} \right] \quad (8)$$

Equation (8) implies that the sensitivity is inversely proportional to h with given x_a, hence it can be improved by increasing h, which requires tradeoff with the size of the ranging system of course.

4. EXPERIMENTS AND DISCUSSION

The omni-directional ranging system in Fig. 6 is implemented with a parabolic mirror from Remote Reality Inc [14], which has $\alpha = 1/66.8$. As the structured light, four stripe laser sources with 90° width of projection each are assembled to cover the whole 360° directions. The height of the mirror from

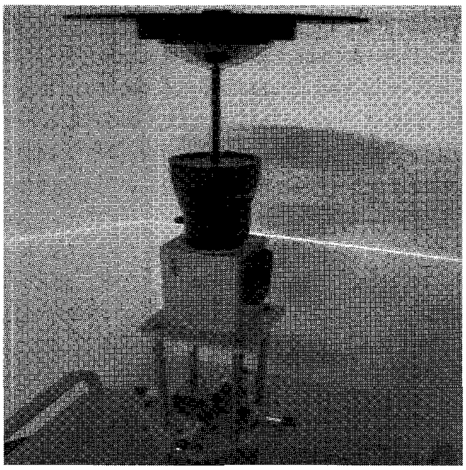


Fig. 6. The omni-directional ranging system.

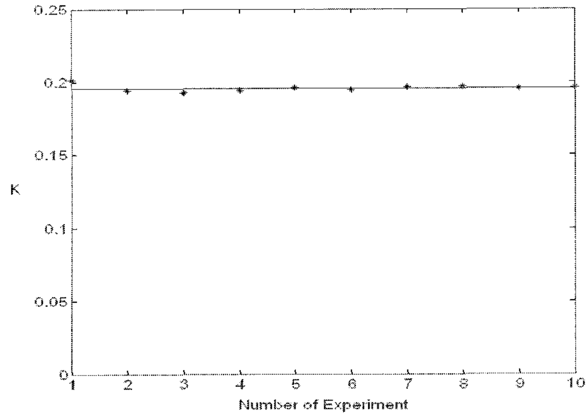


Fig. 7. Result of calibration for k.

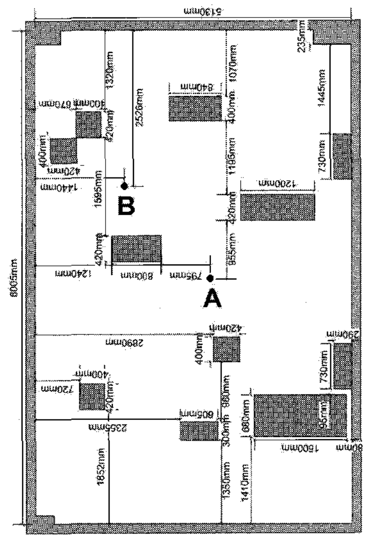


Fig. 8. The object layout in the workspace.

the laser source is designed as $h = 1{,}191\text{mm}$, which gives the focal points as $\mathbf{P}_f(x_f, z_f) = (0, 1207.7)$ from (3).

4.1. Calibration

The parameters of the ranging system consist of the scaling factor, k, the mirror shape, α, and the mirror height, h as well as the intrinsic parameters of the ordinary camera adopted in this paper. By using the unifying theory of the central panoramic vision, a simultaneous calibration is possible for the parameters altogether [10]. However since α, and h are given from specification of the mirror and the ranging system in general, the parameters to be calibrated through an experiment are the remaining intrinsic parameters of the camera and the scaling factor. In order to take advantage of the well-developed calibration package for an ordinary camera, a two-step calibration procedure is proposed in this paper:

Step 1: Calibration for the intrinsic parameters of an ordinary camera by using the Matlab toolbox [15].

Step 2: Calibration for the scaling factor.

Step 1 is not described here since it is well known in [15]. Once Step 1 is completed, the calibration for the scaling factor, Step 2, is relatively simple since it contains only one variable, k as presented below.

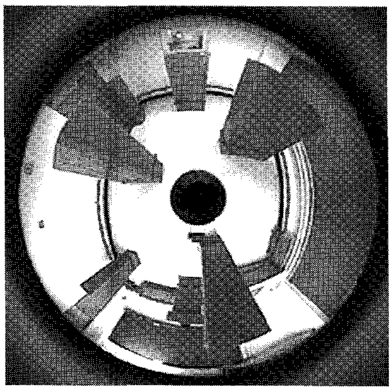
Equation (6) gives the following (9) for k with respect to x_i and x_a:

$$k = \frac{-(h + \frac{1}{4\alpha}) + \sqrt{(h + \frac{1}{4\alpha})^2 + x_a^{\,2}}}{2\alpha\, x_a\, x_i}. \tag{9}$$

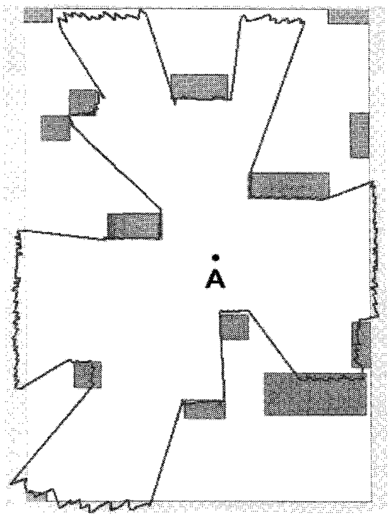
It should be noted that, based on *a priori* known layout of environmental objects shown in Fig. 8, it is possible to get the referential distance, $x_{a,ref}$ in every direction at arbitrary given position in workspace. For calibration of k, an omni-directional structured light image is obtained by the ranging system consisting of the ordinary camera, the parabolic mirror, and the telecentric lens for the orthographic imaging at a position in the workspace and the distortion of the image is rectified by the intrinsic parameters of the camera from Step 1. Then, a set of 72 data pairs, $(x_i, x_{a,ref})$, is prepared where x_i is sampled data by 5° interval from the omni-directional image and $x_{a,ref}$ is the referential distance in the corresponding direction of each x_i. From the set of data, it is possible to get the least-square value for k using (9) with known α and h. The mean value and the standard deviation of k from the repeated experiments at the several different positions are as follows: $k_{mean} = 0.196$, $k_{std} = 0.002$.

4.2. Experiments for distance measurement

By using the parameters obtained above, experiments are conducted to verify the performance of the ranging system. The image taken at position A in the

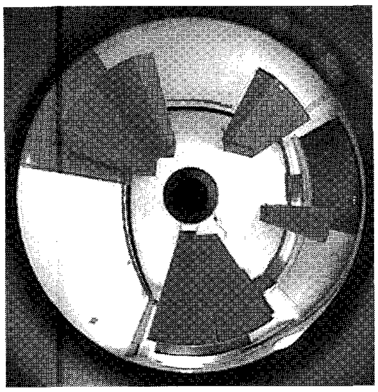


(a) The omni-directional image.

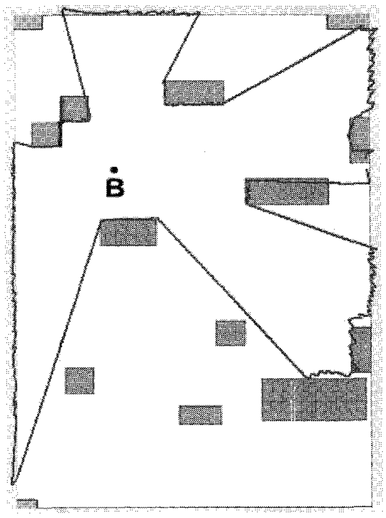


(b) Distance map.

Fig. 9. The omni-directional image taken at the position A and the corresponding distance map.



(a) The omni-directional image.



(b) Distance map.

Fig. 10. The omni-directional image taken at B and the corresponding distance map.

workspace is shown in Fig. 9(a). The bold line in the figure represents the stripe laser structured light. The corresponding omni-directional distance map from (6) is presented in Fig. 9(b), in which the distance map is overlaid onto the object layout. Fig. 10 shows the image captured at a different position B and the corresponding omni-directional distance map.

In order to evaluate the accuracy of the distance measurement, 144 pairs of data, $(x_a, x_{a,ref})$, are arranged from the distance maps obtained at A and B and the corresponding referential distances. The following Fig. 11 is the data set, which shows relatively small error in $x_a < 2{,}000$mm and large error in $x_a > 2{,}000$mm as discussed in Sec. 3.2. It should be noted that the sensitivity at $x_a \approx 5{,}000$mm is $S \approx 159$ which is around 3.6 times of $S \approx 44$ at $x_a \approx 2{,}000$mm as in Fig. 4. The maximum error in the distance measurement is 300mm in the whole region of $x_a < 5{,}000$mm.

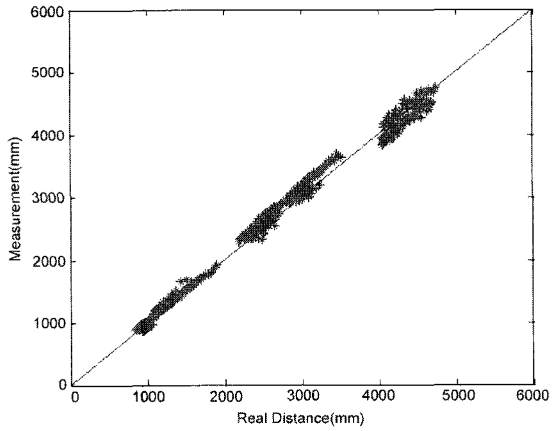


Fig. 11. Accuracy of the distance measurement.

Since a mobile robot moves continuously in the workspace, a real-time capability in the distance measurement is the most important as a ranging system of the mobile robot. For example, the ring array with 12 ultrasonic transducers mentioned in Sec. 1 takes around 50ms per a ultrasonic module and total

50ms×12=600ms for 12 directional distance information. The ultrasonic ring array is frequently used as a ranging system for a mobile robot, however the total processing time is too long in terms of the general speed level of a mobile robot. In an extreme case, the mobile robot should stop moving momentarily to get the distance map. On the contrary, the ranging system in this paper requires around 50ms for 360° omni-directional distances including the image acquisition and the distance computation, which is appropriate for real-time application. The rate of the image acquisition depends on the H/W adopted in the ranging system of course.

5. CONCLUSIONS

An effective omni-directional ranging system and the algorithm for distance computation are presented in this paper, which is based on the omni-directional active vision using a curved mirror and the laser structured light. The distance computation is a simple and explicit closed-form, thus the calibration of the parameter is relatively easy.

With the ranging system, a mobile robot would be able to get 360° all directional distances to environmental objects in real-time for autonomous navigation. More specifically, it takes around 50ms to get the omni-directional range map, which is fast enough considering the general speed level of a mobile robot. The sources of the real-time capability of the proposed system are summarized as follows: (1) omni-directional vision to get all directional information in one image, (2) structured light based active vision to avoid the burdensome correspondence problem in the image processing, and (3) elimination of the motorized moving parts for rotational scan of the structured light.

As a result of the experiments on the distance measurement, the ranging system gives the maximum error of 300mm within $x_a < 5{,}000$mm. The sensitivity analysis for the accuracy of the distance measurement is also given in this paper, showing that the accuracy depends on the range and the height of the mirror.

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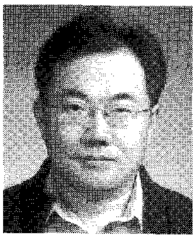

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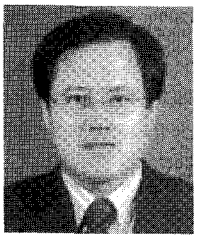

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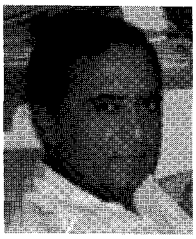

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