Efficient omni-directional ranging system for mobile robot using panoramic vision with structured light

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ABSTRACT

A ranging system for a mobile robot was designed to obtain relative distances to surrounding objects and to construct a local object map, so that the robot can orient its own position and design a course on the global map. An omni-directional ranging system using a panoramic vision with structured light was presented in this paper. Due to the adoption of the panoramic mirror and the laser structured light in the proposed system, it is possible to measure the distance for the 360° omni-directional object in a very efficient manner. The effectiveness of the proposed system was verified through experiments.

1. INTRODUCTION

The “intelligent robot” concept, popularly demonstrated by the personal home-service robot implementation, has been gathering attention in recent years. The intelligent robot has the distinctive feature of mobility from the conventional fixed-body industrial robot. The mobility implies the infinite expansion of the work space of the intelligent robot. Autonomous navigation of a mobile robot in the work space requires the local object map around the robot, which can be constructed based on the on-line relative distances from the surrounding objects [1].

There are many kinds of ranging sensors built-in to measure various distances, such as the ultrasonic sensors, laser sensors, and camera vision sensors etc. Among the several kinds of sensors available, the camera vision sensors are the most widely used since it acquires relatively rich information and can be used in many applications. One of the difficult problems of the stereo vision ranging system is experienced when trying to resolve the challenge of correspondence, as well as the illumination noise. In order to overcome the problems and to measure the distance with a single camera, an active vision system with structured light has been developed [2].

An obvious method to get omni-directional distances by using a ranging sensor is the rotating scan. However, the rotating scan method requires the extra cost of motorized driving mechanism and control and the time-consuming information processing for the omni-directional signals [3]. As an exemplary ultrasonic sensor system, the ring array of ultrasonic transducers is proposed to measure the omni-directional distances as shown in Fig. 1, (a) which eliminates the motorized mechanism. The omni-directional distance map obtained by the ring array of the ultrasonic transducers is shown in Fig. 1 (b) for reference.

Since the mobile robot moves continuously in the workspace, it is desirable to have the fast omni-directional distance measurements. For the above example of the ring array system with 12 ultrasonic transducers, the distance measurement for a ultrasonic transducer takes around $50\text{ms}$ and the total measurement time for the 12 directional distances is approximately $50\text{ms} \times 12 = 600\text{ms}$, which is too long when considering the medium level mobile robot speed. Thus, in an extreme case, the mobile robot should stop moving momentarily to get the omni-directional distances.

On the other hand, an omni-directional active vision ranging sensor is proposed for fast acquisition of the omni-directional distances [4]. Owing to the conical panoramic mirror and the laser structured light adopted in the ranging sensor, it is possible to get 360° omni-directional distances with a single camera by one shot. However, the ranging system in [4] still has the problem of a motorized driving mechanism for the laser-structured light and relatively narrow viewing angle in the conical mirror.
In this paper, a new omni-directional ranging system for a mobile robot that combines panoramic vision and laser-structured light is proposed. The proposed system removes the extra motorized driving mechanism by the stripe laser-structured light instead of the dot laser, and has a wide viewing angle and simple distance computation due to the parabolic mirror. This paper is organized as follows: The main concept of the proposed omni-directional ranging system consisting of the parabolic mirror and the laser structured light is presented in Sec. 2. In Sec. 3, some experimental results are carried out to verify the effectiveness of the proposed system. Finally concluding remarks are given in Sec. 4.

2. OMNI-DIRECTIONAL VISION WITH STRUCTURED LIGHT

The omni-directional ranging system in this paper applies 360° laser stripe-structured light and observes the distortion of the structured light through a panoramic mirror as illustrated in Fig. 2. The observed image contains the distortion as determined by the distance and the orientation of object surfaces on which the laser stripe is projected. With the panoramic mirror, it is possible to observe the 360° omni-directional scene by one shot of a single camera. And by combining the 2-dimensional vision image together with 1-dimensional information of the artificial structured light, it is also possible to obtain a 3-dimensional distance to the object. Furthermore, the laser structured light makes the imaging system robust against the illumination noise.

There are several types of panoramic mirror such as conic, spherical, hyperbolic, and parabolic mirrors. Among them, the hyperbolic and the parabolic mirrors are generally used because of the wide view angle and the simple relation between the object and the image. The omni-directional ranging system described in this paper adopts the parabolic mirror as shown in Fig. 3 (a). The figure shows the cross-section in \( x - z \) plane of the ranging system. As illustrated in the same 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 vision system below the mirror to obtain the reflected image, which can be implemented by the telecentric lens with long focal length.
As shown in Fig. 3 (a), the set of points on a line of sight, e.g., \( \mathbf{P} \) and \( \mathbf{P}' \) in the 3-dimensional space drops into the same point, \( \mathbf{p} \), on the image plane. Thus, it is almost impossible to get the distance to \( \mathbf{P} \) and \( \mathbf{P}' \) with a single image as like in the conventional single vision system.

![The parabolic mirror with the orthographic image](image1)

![The parabolic mirror with the laser structure light](image2)

![Top view](image3)

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

On the contrary as described in Fig. 3 (b), two points \( \mathbf{P}_a(x_a, z_a) \) 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 the mirror surface and correspond to the different \( \mathbf{P}_r(x_r, z_r) \) and \( \mathbf{P}'_r(x'_r, z'_r) \) on the image plane. That is, the object points with the same height \( z \) have different images according to their distances in the parabolic vision system. Thus, with the additional height information provided by the artificial laser structured light, it is possible to compute the 3-dimensional distance to the object points.

The distance equation from the structured light image can be described as follows. At first, the reference coordinate system is set up 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 \( z = 0 \). The surface equation of the parabolic mirror in the cross section can be described as follows:

\[
z = \alpha x^2 + h
\]

where \( \alpha \) and \( h \) are known in advance. The focal length from the vertex of the parabolic mirror is given as

\[
f = \frac{1}{4\alpha}
\]

Thus the focal point of the mirror in the reference coordinate is

\[
\mathbf{P}_f(x_f, z_f) = \left(0, \ h + \frac{1}{4\alpha}\right)
\]
The line equation on the focal point $P_f(x_f, z_f)$ and the object point $P_a(x_a, z_a)$ projected by the structured light is described as

$$z = -\frac{x_f}{x_a}x + x_f$$  \hspace{1cm} (4)

Combining (1) with (4) gives a relation between the distance $x_a$ of the object point and $x_a$ on the mirror surface as

$$x_a = \frac{x_f x_m}{x_f - h - \alpha x_m^2}$$  \hspace{1cm} (5)

The image point $x_i$ is simply proportional to the source point $x_m$ as $x_a = k x_i$ with constant $k$. As a consequence, the relation between the observed $x_i$ and the real $x_a$ becomes

$$x_a = \frac{k x_f x_i}{x_f - h - \alpha k^2 x_i^2}$$  \hspace{1cm} (6)

Since the panoramic image preserves the orientation angle $\theta$ of the object points as in Fig. 3 (c), applying the above (6) to all $360^\circ$ directions gives the desired omni-directional distance map with a single image.

### 3. EXPERIMENTS AND DISCUSSION

Some experiments are carried out to verify the performance of the proposed omni-directional ranging system. Implementation of the ranging system uses a stripe laser with 658nm wavelength as the structured light and a RemoteReality Corp. parabolic mirror for omni-directional imaging system. Coefficients in (1) of the mirror are given as $\alpha = \frac{\sqrt{}}{66.8}$ and $h = 1191$. Thus, the focal point is $P_f(x_f, z_f) = (0, 1207.7)$ as in (3). Here, the length is described in mm.

The complete relationship between the observed $x_i$ and the real $x_a$ requires the value of $k$ in (6). In order to get the value, some preliminary experiments for the camera calibration should be conducted. On the calibration stage, the laser structured light is projected to an object point at a known position. Then, the inverse function of (6) for $k$ gives the value from the observed $x_i$ and the known $x_a$. The mean value and the standard deviation for $k$ from the repeated calibration experiment to the several different object points shown in Fig. 4 are as follows:

$$k_{\text{avg}} = 0.196, \quad k_{\text{std}} = 0.002$$  \hspace{1cm} (7)

The following Fig. 5 shows the object layout in the workspace and the image obtained by the proposed omni-directional ranging system at position $A$. The bold line in Fig. 5 denotes the stripe laser structured light. The corresponding omni-directional distance map from (6) is presented in Fig. 6, which shows the overlaid object layout by the distance map for ease of comprehension.
As implied in Fig. 3 (b), actual length corresponding to unit pixel in the omni-directional image is dependant on its distance, which means that the measurement error sensitivity by pixel error is increasing according to the distance. As a result, the maximum of the distance measurement error is within 6% in 5m.

![Object layout and omni-directional image](image)

**Fig 5**: The object layout in the workspace and the omni-directional image with the laser structured light

![Omni-directional distance map](image)

**Fig 6**: The omni-directional distance map from the image in Fig. 5 (b)

### 4. CONCLUSION

For autonomous navigation, a mobile robot should be able to determine its own position and orientation in the workspace, which is referred to as self-localization. To accomplish this process, the mobile robot should measure the relative distances between surrounding objects and build a local object map. Conventional ranging sensors measure a directional distance and the rotating scan is necessary to get the distance of all directions. The rotating scan method imposes the restriction on the robot motion due to the time-consuming signal processing.
In this paper, an effective omni-directional ranging system for mobile robot is presented, which consists of the panoramic vision system with the parabolic mirror and the stripe laser structured light. The panoramic vision obtains the 360° omni-directional information in a single image and the laser structured light provides an additional 1-dimensional information, in order to make it possible to compute the complete 3-dimensional distance for all directions. It takes less than 50ms to obtain the omni-directional distance map by the proposed system with a general image processing board spending 30 ms processing time per image. The parabolic mirror gives the simple distance computation, while the costly motorized mechanism and control are eliminated by the stripe laser in the proposed system.

REFERENCES


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