Real-time Sensing of Textured Range Images for Localization and Mapping

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Abstract This paper describes a real-time sensing system of range images with registered color images. One of the important applications of this system is localization and mapping for mobile robots. The proposed system consists of a commercially available laser projector and two CCD cameras. The number of pixels of a range image is 361 and the measurement range is 800-2000mm. Experimental results show 40Hz sensing of textured range images. The effectiveness of the proposed system is verified by experiments. As a major conclusion, the constructed sensing system obtains real-time textured range images which are considered as effective data for localization and mapping of mobile robots.

1 Introduction

It is easy for human beings to recognize objects and interpret scenes from visual information. For example, we can understand our location by looking surroundings. For this recognition, we do various processing, for example, sensor fusion. Many studies have been done about this recognition [1]. In this paper, we focus on this recognition in the field of robot vision and computer vision. One of the studies about this recognition is localization and mapping for mobile robots. For localization and mapping, sensor information is very important. Especially, range images are necessary and sensing speed is required to be real-time. Many methods to acquire range images have been studied in the field of computer vision, robot vision, optics etc. Several sensors are commercially available [2, 3, 4].

There are many studies about acquiring range images in real-time. Stereo vision is the most studied range sensing, and a real-time stereo camera is commercially available [5]. Kanade et al. proposed multi-baseline stereo to increase robustness of stereo vision [6]. These sensors systems are a passive methods. On the other hand, several active methods have been proposed. Sato [7] and Kanade [8] developed a special imaging detector and realized real-time imaging by scanning a laser slit with the detector. Some sensors realized scanless range image measurement by projecting multi-spots [9, 10]. In [9], special spot pattern that is made with a mask and a halogen lamp is projected and video rate range imaging was realized by developing a special hardware.

Resently, a method for range imaging based on the time-of-flight is appearing, and some sensors are commercially available [11, 12]. In the sensors, modulated light is projected by LEDs and the measurement is done at each pixel of a special time-of-flight image sensor. The measurement time of the sensor is very short from the principle. The robustness would be increased by optics technology such as an optical filter. For these reasons, the time-of-flight method is considered as an effective method to acquire range images in real-time. It is applied in many studies. However, these sensors frame rate is almost video rate. More high-speed range image sensor such as 10ms order of measurement time is required for localization and mapping of mobile robots. We have constructed a 200Hz small high-speed range image sensor [13]. However, only in the use of the range image of this sensor, it is difficult to do a localization and mapping. For example, the measurement of a smooth floor range images. It is not possible to register them correctly, because there are not corresponding points and features on the range images. We consider that range images with registered color images are required for registration. The textured range image has features on the range image, and solves the problem of the corresponding points. Aiming at the construction of the autonomous mobile robot, the purpose of this paper is to construct the sensor system for acquisition of real-time textured range images. In the following sections, we explain about constructed sensor system.

2 Method to Acquire Textured Range Images

In this section, we discrive a method to acquire textured range images. The explanation of this method is separated into 2 steps: acquisition of range images, registration for color images.

2.1 Acquisition of range images

We have constructed a 200Hz high-speed range image sensor [13]. We use the same measurement principle as this. Fig.1 illustrates the structure of the sensor. Multiple laser spots are projected by a laser projector, and a scene with projected multi-spots are observed by a CCD camera. A disparity is measured by the position of the spot in the image of the CCD camera and distance is calculated by the triangulation.

From the structure of the camera and the projector, each spot can be assumed to move on the image horizontally. Therefore, the disparity can be obtained easily. The distance is obtained by the following equations.

$$z = \frac{\alpha}{k}, \qquad \alpha = \frac{b \cdot f}{d} \tag{1}$$

where

b: baseline length (distance between the projection center and the lens center)

f: focal length of the lens of the CCD camera

d: width of each pixel of the image

k: disparity for infinite distance

To measure the distance with (1), it is not necessary to give b, f, d independently; only α is necessary. In general, α differs for each spot. α is obtained respectively. Note that the unit of k is pixel.

z_i be the distance between the camera and the spot position. k_i be the spot on the image at z_i. k_∞ be the spot at infinite distance, the disparity is expressed to be $(k_i - k_\infty)$.

An acquisition of α and k_∞. Acquiring k_i, z_i, the linear least-squares solution of k_∞ and α are given by the following equation.

$$\begin{bmatrix} k_\infty \\ \alpha \end{bmatrix} = \frac{1}{D} \begin{bmatrix} n \sum z_i^2 k_i - \sum z_i \sum z_i^2 k_i \\ \sum z_i^2 \sum z_i k_i - \sum z_i \sum z_i^2 k_i \end{bmatrix} \tag{2}$$

where $D = n \sum z_i^2 - (\sum z_i)^2$, n be the number of simultaneous equation.

2.2 Registration for color images

In section 2.1, 3D position of the spot can be obtained. For registration of color images, it is necessary to acquire the color image coordinates corresponding to the spot position. There are many methods for this problem. We adopted one of the simplest methods that the linear least-squares solution. In this paper, we express perspective projection matrix P be as follows.

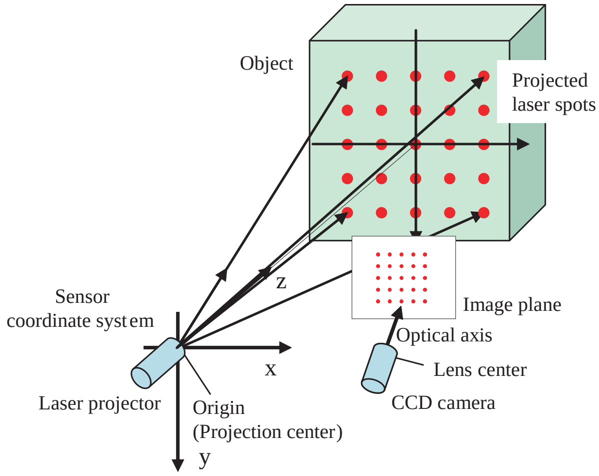

Fig. 1: Structure of the range image sensor using a multi-spot projector

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & p_{1,3} & p_{1,4} \\ p_{2,1} & p_{2,2} & p_{2,3} & p_{2,4} \\ p_{3,1} & p_{3,2} & p_{3,3} & p_{3,4} \end{bmatrix} \tag{3}$$

The relation between a position of 3D space $\tilde{X}_w$ and coordinates of color camera images $\tilde{m}$ can be given as follows.

$$\tilde{m} = P\tilde{X}_w \tag{4}$$

To reduce the influence of the error of measurement, many known $\tilde{X}_w$ and $\tilde{m}$ are used for setting up simultaneous equations. The linear least-squares solution of P is given by

$$p = (B^T B)^{-1} B^T q \tag{5}$$

where

$$\begin{aligned} p &= \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{21} & \cdots & p_{33} \end{bmatrix}^T, \\ B &= \left(C \mid D \mid E \right), \\ C &= \begin{bmatrix} X_{w1} & Y_{w1} & Z_{w1} & 1 \\ 0 & 0 & 0 & 0 \\ X_{w2} & Y_{w2} & Z_{w2} & 1 \\ 0 & 0 & 0 & 0 \\ & \vdots & & \end{bmatrix}, \\ D &= \begin{bmatrix} 0 & 0 & 0 & 0 \\ X_{w1} & Y_{w1} & Z_{w1} & 1 \\ 0 & 0 & 0 & 0 \\ X_{w2} & Y_{w2} & Z_{w2} & 1 \\ & \vdots & & \end{bmatrix}, \end{aligned}$$

$$E = \begin{bmatrix} -u_1 X_{w1} & -u_1 Y_{w1} & -u_1 Z_{w1} \\ -v_1 X_{w1} & -v_1 Y_{w1} & -v_1 Z_{w1} \\ -u_2 X_{w2} & -u_2 Y_{w2} & -u_2 Z_{w2} \\ -v_2 X_{w2} & -v_2 Y_{w2} & -v_2 Z_{w2} \\ & \vdots & \end{bmatrix},$$

$$q = \begin{bmatrix} u_1 & v_1 & u_2 & v_2 & \cdots \end{bmatrix}^T.$$

The coordinates $\tilde{m}$ is obtained from (4).

3 Sensor Hardware

Fig.2 shows the constructed sensor. The laser projector is StockerYale Mini-519X [14]. The wavelength of the laser is 785nm (near infrared) and its power is 35mW. It projects 19×19, totally 361 spots using a diffraction grating attached at the tip of the laser projector. The angle between adjacent spots is 0.90°. The monochrome CCD camera and color the CCD camera are Point Grey Research Dragonfly Express. Their maximum frame rates are 200fps and 60fps respectively, which is achieved by using fast interface to PC IEEE1394b Express Card. The number of pixels is 640×480, and the size of the pixels is $7.4\mu m^2$. A lens with f=8mm is used, and a Hoya R72 optical filter is attached to the lens of monochrome camera. Light with a wavelength less than 720nm is cut by the filter, and thus the effect of disturbance light is reduced. The laser projector and the monochrome CCD camera are set parallel with the baseline length 47.5mm. The color camera is set parallel to get same scene of monochrome camera with the baseline length 173.5mm. The sensor's size is small enough to use for many applications such as a sensor of a mobile robot.

The rotation of the projector is $\arctan(1/4) = 14.0°$, which makes magnification of the number of assigned pixels $\sqrt{17}$ times [13]. The number of pixels assigned to each spot becomes 70. With this angle, the distance between epipolar lines of two adjacent spots is 4.1pixels.

In the system, the computer is a TOSHIBA dynabook TX/68F laptop PC with Core2 Duo T8100 2.1GHz and memory 2GB.

4 Textured Range Image Measurement

We performed an experiments of textured range image measurement. Fig.3 shows measurement objects: a textured magazine(192mm×276mm), a colorful ball of 100mm diameter and a wooden board as background. The measurement distance to the magazine is about 1000mm. Fig.3 was captured by a color CCD camera other than the sensor. Fig.4(a) shows the obtained range image of measurement objects shown in Fig.3 as point cloud. The distance becomes longer, the color of point becomes more blue. Although the range image is sparse with only 361 points, rough 3D shape is obtained. Fig.4(b) shows the wireframe model created by Delaunay triangulation [15]. Fig.4(c) shows the range image with registered color images. The processing time of calculating a range image is about 1.6ms, which is fast enough for 200fps measurement. The processing time to acquire textured range images with this PC is about 25.2ms, i.e. about 40fps measurement. It spent much processing time on Delaunay triangulation for creation of surfaces. We are going to achieve a more high-speed range image measurement by the improvement of the processing time.

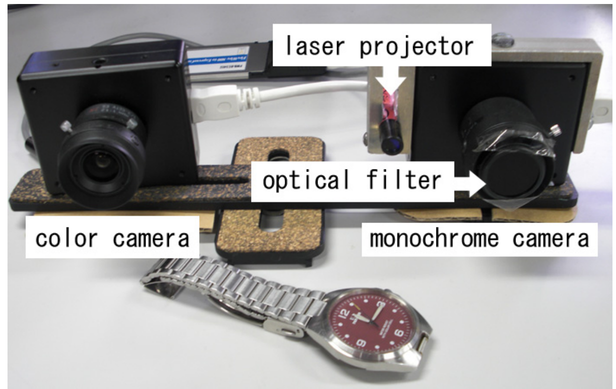

Fig. 2: Constructed textured range image sensor (left: color camera, center: laser projector, right: monochrome camera. size: 270mm×70mm×100mm, including the frame)

Fig. 3: Measurement objects (left: textured magazine, right: colorful ball, back: wooden board)

5 Conclusion

In this paper, we have constructed a real-time textured range image sensor, and showed measurement example by experiments. It consists of a high-speed monochrome CCD camera, a color camera and a laser projector that proects multiple spots. Distances to projected spots are measured by triangulation. The speed of capturing the range image is 200Hz, and the speed of capturing the textured range image is 40Hz. For localization and mapping, it is necessary to register textured range images. In this process, it is necessary to extract the features on the range images. In the constructed sensor system, the textured range image can be observed from various viewing location. The system also can put this 2D image into the effective image data processings which have been invented. We have shown the effectiveness of the constructed sensor from the sensing speed and accuracy of the range image [13]. Textured range images obtained by the constructed sensor are considered as effective data for localization and mapping of mobile robots.

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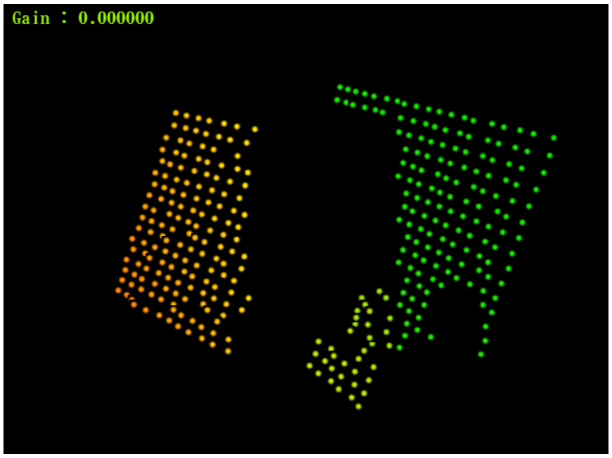
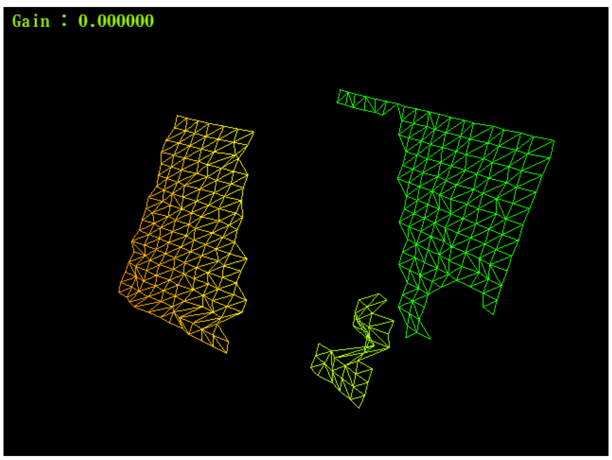
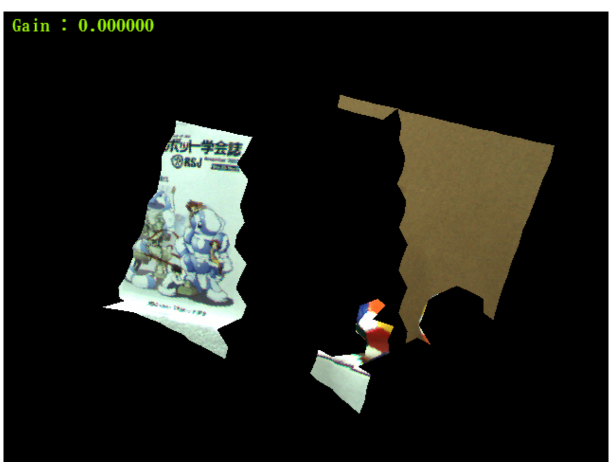


(a)Obtained range image



(b)Delaunay triangulation



(c)textured range image

Fig. 4: Range image of magazine and ball