Construction of a coaxial textured range image sensing system

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***Abstract*—In this paper, construction of a coaxial textured range image sensing system that can measure a range image and a color image from the same viewpoint is reported. The measurement speed is 200fps. The resolution of the range image is 19×19: totally 361 points. The system consists of only commercially available products: a monochrome CCD camera, a color CCD camera, an IR laser projector, an optical filter and a cold mirror. The mechanism and calibration of the system are shown. Examples of measurement are shown to evaluate the system.**

I. Introduction

There has been an increasing requirement for range images in a wide range of application fields. In particular, approaches using vision are useful because of their contactless nature and flexibility. On the other hand, there are demands for improvement of performance such as accuracy, measurement range, time, cost and so on. In robotics, real-time measurement is particularly important.

Many real-time range image sensors have been studied [1]. Stereo vision is very common and commercial sensors are available [2]. However, it has an essential problem, *i.e.*, the stereo correspondence problem [3]. In [4], a 3D map is reconstructed using stereo vision and a humanoid walks through a room full of objects to reach its goal. However, the stereo correspondence problem is avoided by placing artificial patterns on most of the obstacles.

On the other hand, active sensors can obtain 3D information of an environment more robustly without the correspondence problem. Beraldin *et al.* achieved video-rate range imaging by scanning a laser spot using a synchronized laser scan technique [5]. A SwissRanger SR4000 can obtain range images at 50fps [6]. Nakazawa and Suzuki [7] constructed a sensor without scanning by projecting multi-spots. The spot pattern was generated using fiber grating and a laser. Watanabe *et al.* [8] achieved 955fps shape measurement using a newly constructed high-speed vision system. However, this system is unsuitable in some applications, for example, in mobile robots, because it is too large. For the same reason, a high-speed sensor [9] is unsuitable for applications in mobile robots. Microsoft Kinect [10], which is a range image sensor based on active stereo, is versatile but its frame rate is limited to 30fps. Tateishi constructed a small high-speed range image sensor using an IR laser for mobile robots [11]. The sensor obtains a range image using the method by Nakazawa *et al.* [7]. Because a high-speed camera is used, the size of the sensor is larger than Nakazawa's sensor. The size is still small as a high-speed sensor. The disadvantage of the sensor is sparseness of the range image. Sparse range images are unsuitable for robot vision tasks, such as 3D mapping. Ishiyama improved the Tateishi sensor for 3D mapping using sparse range images [12]. The sensor can measure not only range images but also color images at 100fps. An advantage of the sensor is that it can be used to measure range and color images at high speed. The size of the sensor is bigger than [11] because it is necessary to add a color camera.

[5], [6], [7], [8] cannot measure a color image. [2], [10] can measure color images but the measurement speed is 30fps.

Based on this backgrounds, the Ishiyama sensor [12] is more suitable than others for robots and for the measurement of moving objects because of its capacity for high-speed measurement. However, one problem with the sensor remains to be solved. The sensor is not a coaxial optical system, and one aspect of the monochrome camera differs from that of a color camera. If the difference between the viewpoints of the monochrome camera and the color camera is reduced, the accuracy of texture mapping is improved.

In this paper, we improve the Ishiyama sensor and construct a sensor that measures a range image and a color image without any deviation in the texture mapping. The deviation problem can be solved using a cold mirror. The mirror reflects the visible light and passes an infrared light. Because a laser, which is an infrared light, is passed and a visible light is reflected, the viewpoint of the monochrome camera matches that of a color camera. Therefore, a color camera can be used

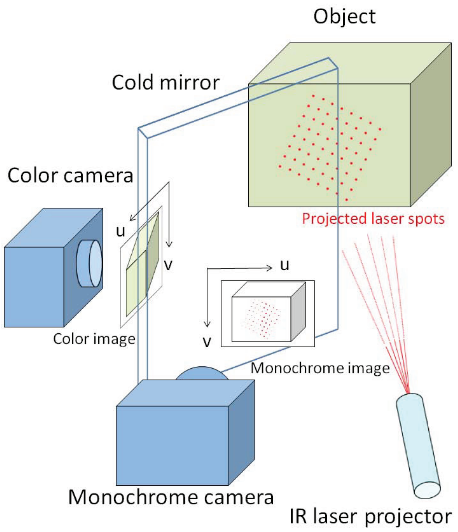


Fig. 1: Structure of the coaxial textured range image sensor

to observe a scene identical to that of a monochrome camera. In addition, an increase in speed from 100fps to 200fps is achieved.

This paper is organized as follows. First, the construction of the sensor is described; the experimental results are then shown; and, finally, the conclusion is presented.

II. Construction of the Sensor

Figure1 shows the structure of the sensor. The sensor consists of a CCD monochrome camera, a CCD color camera, an IR laser projector, and a cold mirror. Range images are obtained using a CCD monochrome camera and an IR laser projector. The cold mirror can pass an infrared light and reflect a visible light. The CCD color camera captures the same scene as the CCD because of the mirror.

A. Range image measurement

Multi-spot infrared lights are projected by a laser projector, and a scene with projected multi spots are is captured by a CCD monochrome camera. According to the configuration of the projector and the camera, these spots move horizontally on the image captured by the camera depending on the distance from the object being photographed. The distance of each laser spot from the lens center is calculated by triangulation. FigureII-A illustrates the measurement principle and related sensor parameters. The distance Z is calculated by the following equation.

$$Z = \frac{\alpha}{d}, \quad \alpha = \frac{b \cdot f}{p} \tag{1}$$

p [mm/pixel]: width of each pixel of the image

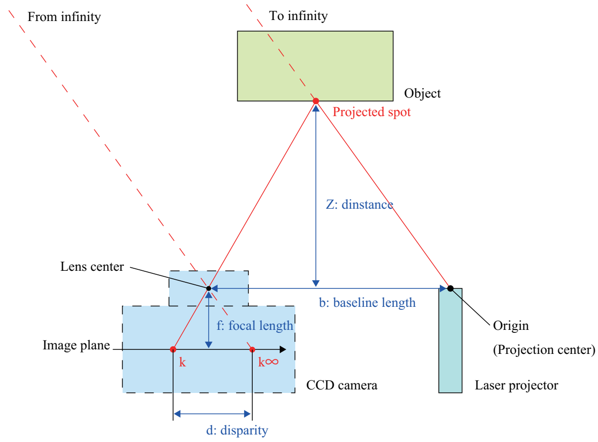


Fig. 2: Range image measurement

d [pixel]: disparity between k_∞ and k (See Fig.II-A)

In Eq. (1), because $b, f, and p$ are constants of hardware, they are put together to one constant α.

B. Sensor Calibration

In addition to the detection of the spot position on the camera image, it is necessary to obtain the constant α and k_∞ for the calculation of the distance Z by Eq. (1). From the detection of the spot position k corresponding to different distances Z_1 and Z_2, α and k_∞ are obtained as a solution of the following simultaneous equations.

$$\begin{cases} Z_1(k_1 - k_\infty) = \alpha \\ Z_2(k_2 - k_\infty) = \alpha \end{cases} \tag{2}$$

To improve the precision of calculation, α and k_∞ are obtained with a linear least-squares solution by the following equation.

$$\begin{bmatrix} k_\infty \\ \alpha \end{bmatrix} = \frac{1}{D} \begin{bmatrix} n\sum Z_i^2 k_i - \sum Z_i \sum Z_i^2 k_i \\ \sum Z_i^2 \sum Z_i k_i - \sum Z_i \sum Z_i^2 k_i \end{bmatrix} \tag{3}$$

where $D = n\sum Z_i^2 - (\sum Z_i)^2$ and n is the total number of equations. The range image can then be acquired by detection of each spot image position k from one input image.

C. Coaxial optical system

The cold mirror reflects a visible light and passes an infrared light (Fig.3) [15]. When the mirror is placed at an angle of 45 degrees to the CCD monochrome camera and the CCD color camera as shown in Fig.4, multi-spot infrared light projected by the laser projector passes through the mirror into the CCD monochrome camera, and a visible light reflected by the mirror is observed by the CCD color camera. Thus, the CCD color camera can be used to obtain an image identical to that captured with a CCD monochrome camera. A color image is flipped when it is reflected by the mirror. Therefore, a process to flip the color image is necessary.

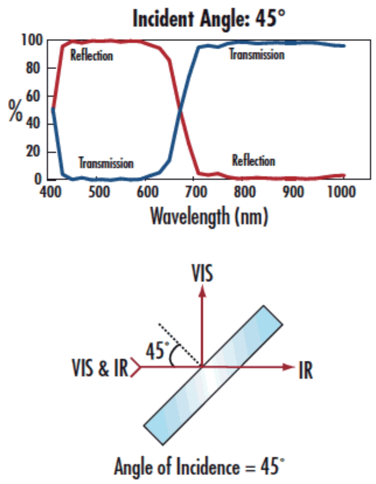


Fig. 3: Characteristics of the cold mirror [14]

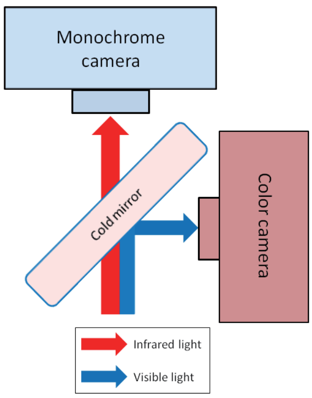


Fig. 4: Arrangement of the sensor

D. Measurement speed

This section describes the performance of the proposed system on the measurement speed. Figure5 shows the processing time of the sensor. The software system we constructed consists of two threads. The first thread is to capture a color image and a monochrome image. The second thread is to flip the color image and calculate the range image. Monochrome images and color images are captured at 200fps and all processing takes 4.8ms. This means that our system could achieve measurement with a throughput of 200 fps and a latency of 4.8ms. The processing speed of the Ishiyama sensor was 100fps. The speed of the sensor was limited by the IEEE1394b PCI Express Card (single bus version) for connecting to a PC. When this card was changed to a new card with a larger transfer bandwidth (dual bus version) than that of the Ishiyama sensor, throughput of 200fps was achieved.

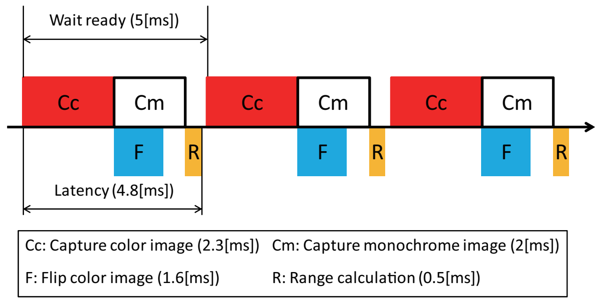


Fig. 5: Processing time

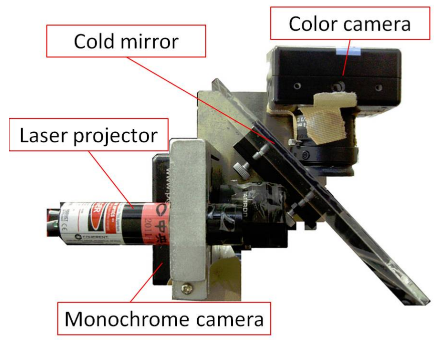


Fig. 6: Constructed sensor

E. Sensor hardware

Figure6 shows the constructed sensor. The laser projector is StockerYale Mini-519X [14]. Its wavelength is 830nm (infrared), and its power is 100mW. The laser projector can project 19×19 for a total of 361 spots using a diffraction grating attached at its tip. The angle between adjacent spots is 0.90°. The monochrome CCD and the color CCD cameras are Point Grey Research Dragonfly Express [2]. The resolution of the CCD camera is 640×480(VGA), and the size of the pixel is $7.4 \times 7.4 \mu m^2$. Their maximum frame rate is 200fps, and the cameras are attached to a PC by an IEEE1394b PCI Express Card (dual bus version). The mirror is the Edmund optics TECHSPEC cold mirror [15]. The mirror reflects 95% of visible light and passes a 90% of infrared light. The lens is TAMRON 13FM08IR and its focal length is 8mm. The optical low-pass filter HOYA R72 is attached to the top of the monochrome CCD camera lens. The optical band-pass 830nm filter produced by Edmund Optics Co. is attached behind the lens of the monochrome CCD camera. Light with wavelength out of 830nm is cut by these two filters, and the effect of disturbance is reduced. The baseline length is 52.2mm. The computer is a DELL XPS XPS720 OS: Windows Vista Ultimate desktop PC with Intel(R) Core2 Extreme CPU Q6850 @ 3.00GHz DRAM 2.00GB.

III. Experiments

A. Examples of measurement

We show the measurement results for four different types of objects: a white cylinder (Fig.7), a cube with texture (Fig.8),

Fig. 7: Target scene: cylinder

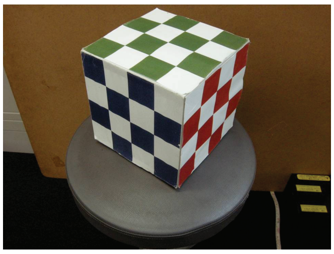


Fig. 8: Target scene: cube

Fig. 9: Target scene: human hand

Fig. 10: Target scene: various objects

a human hand (Fig.9) and various objects (Fig.10).

The results are given in Fig.11, 12, 13 and 14 respectively. Figure7 and Fig.8 show that the sensor can measure a plane and a curved surface. Although the human hand does not reflect laser spots much relative to the cylinder and the cube, the sensor can measure the hand, as shown in Fig.9. When the measurement target has a complex shape such as Fig.10, it is difficult to recognize what is measured from a range image only because of its sparseness. On the other hand, a measured object can be recognized from a textured range image. This shows that it is useful to obtain both range and color images because it is possible to compensate for the sparseness of the range image by capturing a high-resolution color image. The reasons that there are regions where range data is missing are that a laser spot does not come back because of occlusion or reflection and a reflected laser spot is weak when it hits the edge of the object.

B. Evaluation of measurement accuracy

The measurement accuracy at each distance was evaluated. When a range image of a plate that is attached vertically to the sensor's optical axis is measured, the distance of each point of the range image from the fitted plane can be considered to be the measurement error. We obtained the standard deviation of the error at each measured distance. Figure15 shows the standard deviation at each measurement distance. Using the law of propagation of errors, Eq. (1) can be transformed to

$$\sigma_z = \frac{1}{\alpha} z^2 \sigma_k. \tag{4}$$

σ_z is the accuracy of the measured distance, and σ_k is the accuracy of the spot detection. The measurement accuracy σ_z is proportional to the square of the distance assuming that σ_k is constant to the distance. As α is calibrated to be 56432mm·pixel in the constructed system, σ_k becomes about 0.078pixel. This shows that the spot position is measured with high accuracy.

C. Evaluation of coaxial optical system

To verify the reduction of the difference of the view points between the CCD monochrome and the CCD color cameras, we evaluated the disparity between the CCD monochrome camera and the CCD color camera. Figure16 shows the experimental setup. The experimental procedures are as follows. First, we obtain monochrome and color images of a target (Fig.16), which is a wooden plate with a sheet of newspaper on it, using the proposed sensor and the Ishiyama sensor. Next, the disparity between the monochrome and color images is calculated. Finally, the disparity in the proposed sensor is compared with that in the Ishiyama sensor. The measurement distance is from 800mm to 2000mm.

The results are shown in Fig.17 and Fig.18. It is verified that The proposed sensor has fewer horizontal and vertical disparities than the Ishiyama sensor. The fact that the disparity between the monochrome image and the color image is close to zero means that the sensor is almost a coaxial optical system. Consequently, the coaxial textured range image sensor is constructed appropriately. Figure19 is a comparison of the measurement results of the proposed sensor and the Ishiyama sensor. The results show that the Ishiyama sensor produces a deviation between range and color images but the proposed sensor does not.

IV. Comparison with other sensors

The characteristics of the proposed sensor are its compactness and capacity for high-speed measurement. We compared the sensor with other representative range image sensors. In

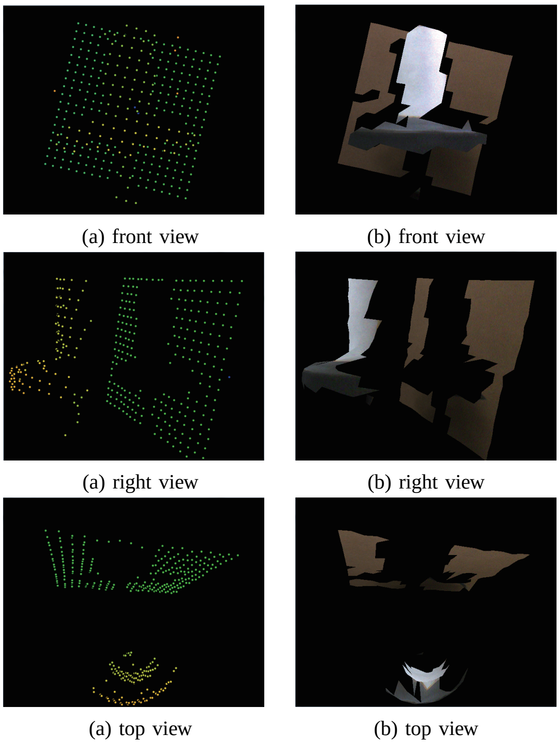


Fig. 11: Measurement results for Fig.7 (left: range image only, right: range image with color texture)

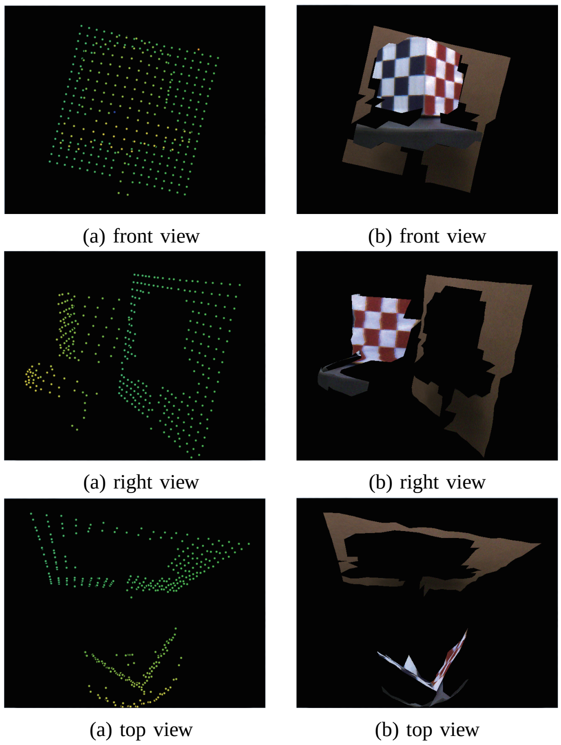


Fig. 12: Measurement results for Fig.8 (left: range image only, right: range image with color texture)

this comparison, we considered only active sensors, since we think that robust and high-speed measurement using an active method is necessary for mobile robot applications. We selected a MESA SR4000 [6], which is a typical Time-of-flight (TOF) range image sensor and Microsoft Kinect [10], which is widely used these days. Figure20 shows the compared sensors and Table 1 is a comparison of the results.

From the results, the size of the proposed sensor is smaller than that of the Kinect and larger than that of the SR4000. The sensor is the heaviest of the three, but not too heavy for mobile robots. The proposed sensor has the fastest frame rate of the three. The color image resolution of the proposed sensor is the same as that of the Kinect. The SR4000 cannot obtain color images but only reflectance images. The measurement range of the proposed sensor is at the middle of that by Kinect and SR4000, though narrower than that. In addition, the proposed sensor is the only one that can be used in the sunlight.

Each sensor has its own advantages and disadvantages. However, because of its high-speed measurement and capability of outdoor measurement, the proposed sensor is suitable for mobile robot applications.

On the other hand, the range image resolution of the proposed sensor is the lowest. This is an issue that must be improved in the future.

V. Conclusion

In this study, we developed a sensor that can obtain range and color images with a coaxial optical system and evaluated it experimentally. The sensor consists of a high-speed CCD monochrome camera, a CCD color camera, a laser projector and a cold mirror. Distances to projected spots are measured by triangulation. We demonstrated throughput of 200fps and latency of 4.8ms. Experimental results for four kinds of objects showed that they were measured correctly.

The high frame rate improves the accuracy of object tracking and matching because the movement of an object in the sampling time becomes small. The millisecond-order latency improves the reaction of the system control. The proposed sensor can be used indoors and outdoors. For these reasons, the proposed sensor is more useful in mobile robot applications than representative video rate sensors, such as the Kinect. As a next step, we should develop applications and improve the resolution of the range image measurement.

References

[1] F. Blais, "A review of 20 years of range sensor development," Videometrics VII, Proc. of SPIE-IS&T Electronic Imaging, SPIE Volume 5013, pp.62-76, 2003.

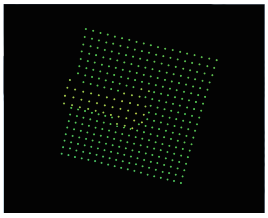
[2] Point Grey Research Inc., http://www.ptgrey.com

[3] T. Kanade, "Development of a video-rate stereo machine," Proc. of the 1994 ARPA Image Understanding Workshop (IUW'94), pp. 549-558, Nov., 1994.

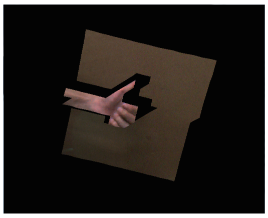
[4] R. Ozawa, Y. Takaoka, Y. Kida, K. Nishiwaki, J. Chestnutt, J. Kuffner, J. Kagami, H. Mizoguch, and H. Inoue, "Using Visual Odometry to Create 3D Maps for Online Footstep Planning," Proc. of IEEE International Conference on Systems, Man and Cybernetics (SMC2005), Hawaii, USA, pp. 2643-2648, Oct., 2005.

TABLE I: Comparison with other active range image sensors

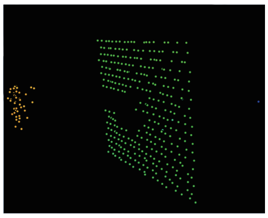
	Proposed sensor	SR4000	Kinect
Frame rate [fps]	200	50	30
Size [mm]	150×120×120	65×65×68	65×280×70
Weight [g]	830	470	600
Resolution of range image	19×19	176×144	640×480
Measurement distance [mm]	900-2000	300-5000	850-4000
Resolution of color image [pixel]	640×480	176×144	640×480
Measurement in sunlight	Yes	No	No



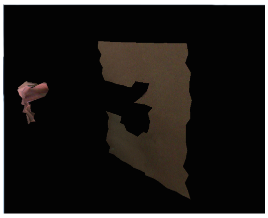
(a) front view



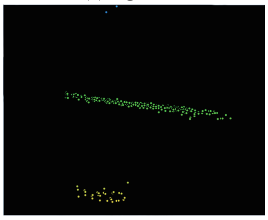
(b) front view



(a) right view



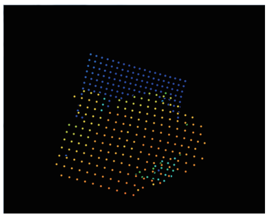
(b) right view



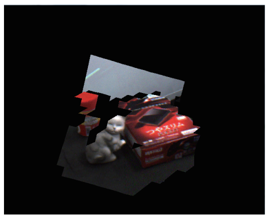
(a) top view

(b) top view

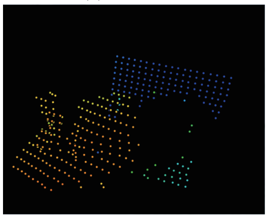
Fig. 13: Measurement results for Fig.9 (left: range image only, right: range image with color texture)



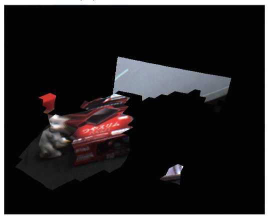
(a) front view



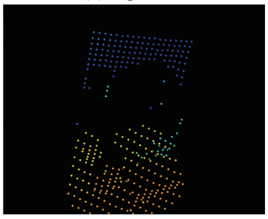
(b) front view



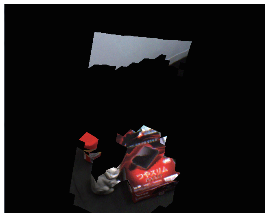
(a) right view



(b) right view



(a) top view



(b) top view

Fig. 14: Measurement results for Fig.9 (left: range image only, right: range image with color texture)

[5] J. A. Beraldin, F. Blais, M. Rioux, J. Domery, and L. Cournoyer, “A video rate laser range camera for electronic boards inspection,” Proc. Vision’ 90 Conference, pp. 4-1-4-11, 1990.

[6] SwissRanger SR4000, http://www.mesa-imaging.ch/

[7] K. Nakazawa and C. Suzuki, “Development of 3-D robot vision sensor with fiber grating: Fusion of 2-D intensity image and discrete range image,” Proc. of 1991 International Conference on Industrial Electronics, Control and Instrumentation (IECON’91), pp.2368-2372, 1991.

[8] Y. Watanabe, T. Komuro, and M. Ishikawa, “955-Fps Real-Time Shape Measurement of a Moving/Deforming Object Using High-Speed Vision for Numerous-Point Analysis,” Proc. of 2007 IEEE International Conference on Robotics and Automation, pp.3192-3197, 2007.

[9] S. J. Koppal, S. Yamazaki, and G. Srinivasa, “Exploiting DLP Illumination Dithering for Reconstruction and Photography of High-speed Scenes,” Narasimhan International Journal of Computer Vision, Vol. 96, No. 1, 2007.

[10] Microsoft Kinect, http://www.xbox.com/en-US/kinect

[11] M. Tateishi, H. Ishiyama, and K. Umeda, “A 200Hz small range image sensor using a multi-spot laser projector,” Proc. of 2008 IEEE International Conference on Robotics and Automation, pp.3022-3027, 2008.

[12] H. Ishiyama, K. Terabayashi, K. Umeda, “A 100Hz Real-time Sensing System of Textured Range Images,” Proc. of 2010 International Symposium on Optomechatronic Technologies, SP-SH-7, 2010.10.

[13] V. Popescu, E. Sacks, and G. Bahmutov, “The ModelCamera: A handheld device for interactive modeling,” Proc. of Fourth International Conference on 3-D Digital Imaging and Modeling, (3DIM 2003), pp.285-292, 2003.

[14] StockerYale, Inc., http://www.stockeryale.com/

[15] Edmund Optics Inc., http://www.edmundoptics.com//

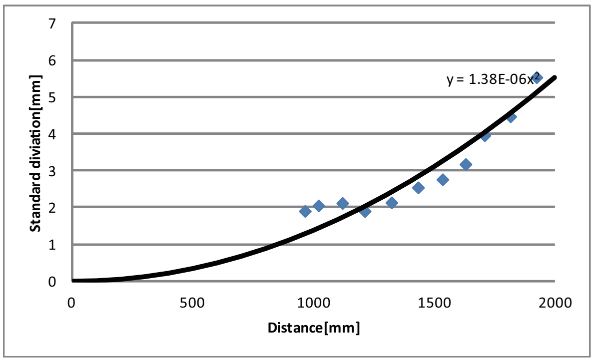


Fig. 15: Accuracy of the range image

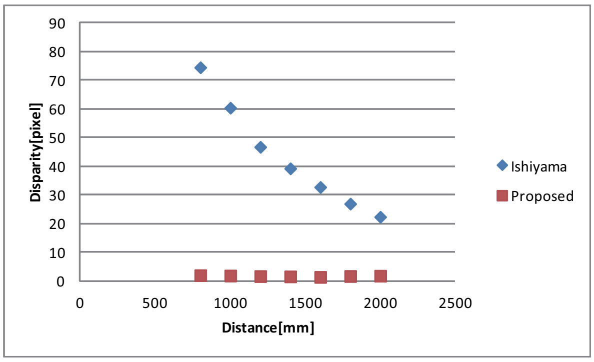


Fig. 18: Disparity of vertical direction

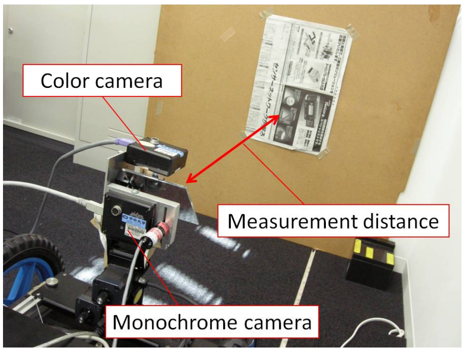
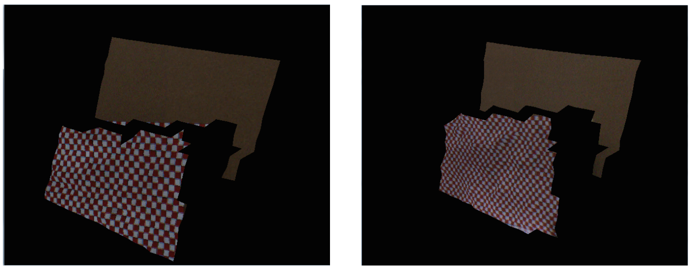


Fig. 16: Experimental setup to verify image disparities



(a) Ishiyama sensor (b) proposed sensor

Fig. 19: Comparison with the Ishiyama sensor

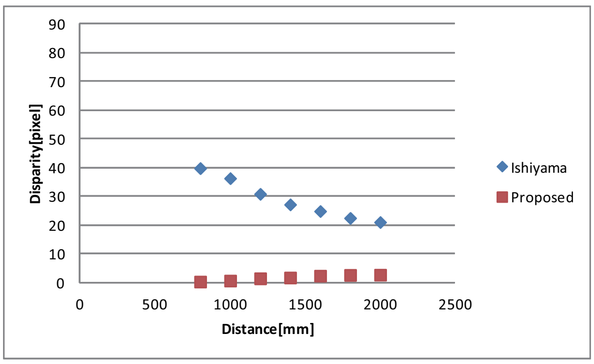


Fig. 17: Disparity of horizontal direction

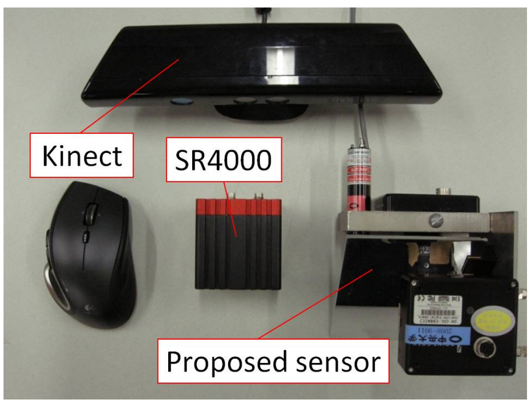


Fig. 20: Proposed sensor and other representative range image sensors