2012 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 7-12, 2012. Vilamoura, Algarve, Portugal

Construction of a compact range image sensor using a multi-slit laser projector suitable for a robot hand

Kazuya Iwasaki, Kenji Terabayashi and Kazunori Umeda

***Abstract*— In this paper, a compact range image sensor used for short-range measurements is constructed with a multi-slit laser projector. Three-dimensional (3D) information obtained with a sensor is important for a robot that grasps an object. Sensors attached to robots for measurement are often hindered by occlusion by the hand immediately before an object is grasped. The constructed sensor is compact enough to be attached to a robot's hand, and occlusion can thus be avoided Compactness of the sensor is achieved by using a small CMOS camera and a laser projector and setting the baseline length between them as short as possible. The short baseline length also enables measurement in a short distance. Some experiments verify that the constructed sensor obtains accurate 3D information of objects in a short distance.**

I. INTRODUCTION

When a robot executes a task, such as grasping an object or avoiding an obstacle, three-dimensional (3D) information of the target is usually necessary. A humanoid generally carries a vision sensor at its head and recognizes, grasps or avoids objects using the vision sensor. Some robot manipulators use a vision sensor that is set apart from the robot hand to measure a work.

In such applications, a range image sensor is often used as a vision sensor. Many range image sensors have been developed and practically used. Currently, compact time-of-flight (TOF) range image sensors are being marketed that can capture range images in real time[1], [2], [3]. A stereo camera[4] and a sensor that scans a slit light[6], [7] also achieve real-time measurement. Microsoft Kinect[5], which is a range image sensor based on active stereo, also achieves real-time measurement and is widely used.

On the other hand, these sensors are generally unsuitable for grasping by a robot hand. One reason is that measurement with a sensor attached to the body rather than the hand of a robot is frequently hindered by occlusion by the hands immediately before grasping an object. Hebert et al.[8] combine a range image sensor and a force sensor and achieve efficient grasping. Arisumi et al.[9] adopt a similar combination and achieve the grasping of a door knob by a humanoid. Park et al.[10] support a grasping task by estimating an object's pose with a range image sensor based on active stereo. However, in these systems, a range image sensor is set apart from the robot hand and, thus, measurement just before grasping an object becomes impossible. A range image sensing system that is robust to the occlusion is required for a stable grasping task.

A compact range image sensor that can be used in a short distance is thought to be effective for the requirement. Khokar et al.[11] use range information obtained with a laser range finder attached to a robot hand for a teleoperated manipulator. Their sensor is small, but a smaller sensor would be preferable in a narrow environment. A 3D scanner PULSTEC TDS-A[12] can be used to construct a high-resolution 3D model from a short distance. However, the sensor is slow and unsuitable for real-time applications. In Hasegawa et al.[13], net-shaped proximity sensors are attached at the finger tips instead of a range image sensor and a robust grasping is achieved by combining proximity and touch seamlessly. However, the measurement range is short and global positioning of a robot hand and a target object is difficult.

We constructed a compact range image sensor that combines a laser projector that projects multi-slit lights and a CCD camera and proposed a humanoid obstacle avoidance system[14]. However, the sensor is not small enough to attach to a robot hand, and, in addition, it is incapable of the measurement in a short distance. In this paper, we construct an improved compact range image sensor that can be attached to a robot hand and used from a short distance.

II. CONSTRUCTION OF A COMPACT RANGE IMAGE SENSOR

A. Structure of the sensor

Figure 1 illustrates the structure and principle of the sensor, which are almost the same as those in the former sensor[14]. The sensor consists of a small laser projector and a small CMOS camera. The laser projector projects multi-slit lights, and images containing the projected slit lights are captured by the CMOS camera. The coordinates of the slit images are obtained, and the distances corresponding to the slit images are calculated by triangulation. As multi-slit lights are used, what is called the correspondence problem, i.e., the ambiguity of correspondence of projected laser slits and captured slit images occurs. We restrict the measurement range to remove the ambiguity. By rotating the laser projector with respect to the CMOS camera[14], the range of the image where a laser slit image can move without ambiguity becomes wider, and, consequently, the restriction to the measurement range can be relaxed. This is illustrated in Fig.2 and Fig.3.

K. Iwasaki is with the Course of Precision Engineering, School of Science and Engineering, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan iwasaki@sensor.mech.chuo-u.ac.jp

K. Terabayashi and K. Umeda are with the Department of Precision Mechanics, Faculty of Science and Engineering, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan {terabayashi, umeda}@mech.chuo-u.ac.jp

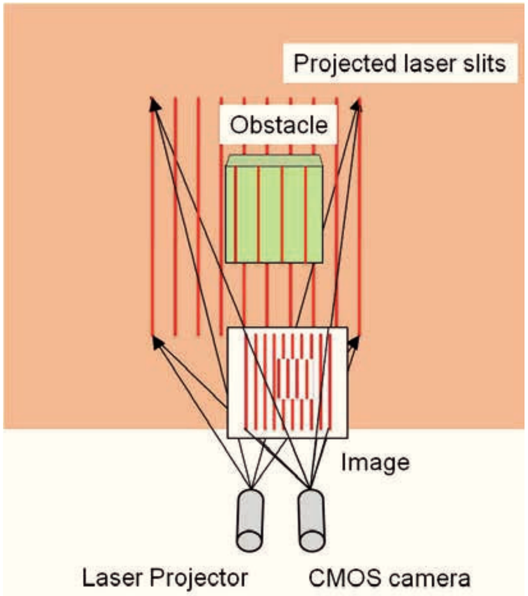
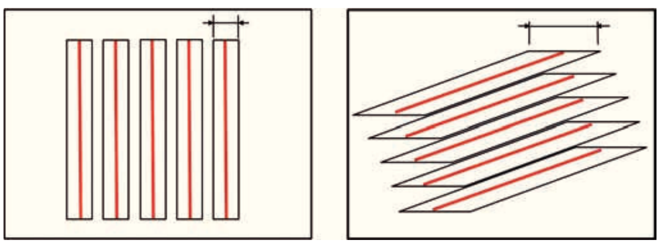


Fig. 1. Structure of the range image sensor using a multi-slit laser projector



(a) Without rotation (b) With rotation

Fig. 2. Restriction for the epipolar line of each slit

B. Sensor hardware

To achieve the compactness, each component should be small. We adopt a laser projector Coherent Mini-715L and a CMOS camera ARTRAY ARTCAM-022MINI. Although the laser projector is the same as the former sensor, the CMOS camera is much smaller than the former one. The wavelength of the laser is 660nm, and its power is 35mW. The laser projector projects 15 slits with 45° projection angle. The angle between adjacent slits is 2.37°. The camera resolution is 752×480pixel. The focal length of the camera lens is 3.6mm. A Fujifilm SC-68 optical filter is attached to the lens to cut disturbance lights under 680nm wavelength.

Fig.4 shows the constructed compact range image sensor. Its dimension is 17mm (height) × 34mm (width) × 52mm (depth), and its weight is approximately 40g. The optical axes of the camera and the laser projector are set parallel. To achieve measurement in a short distance, where disparity tends to change significantly, we set the baseline length to 13mm, which is the shortest with the components. This short baseline length is achieved because both the laser projector and the CMOS camera are small (thin). The rotation angle of the laser projector is 70°.

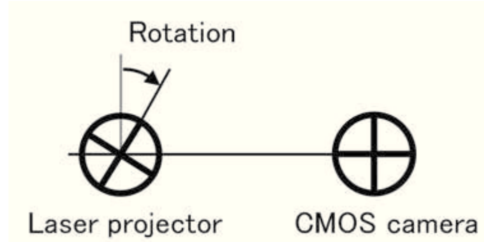


Fig. 3. Rotation of laser projector to increase the measurement range

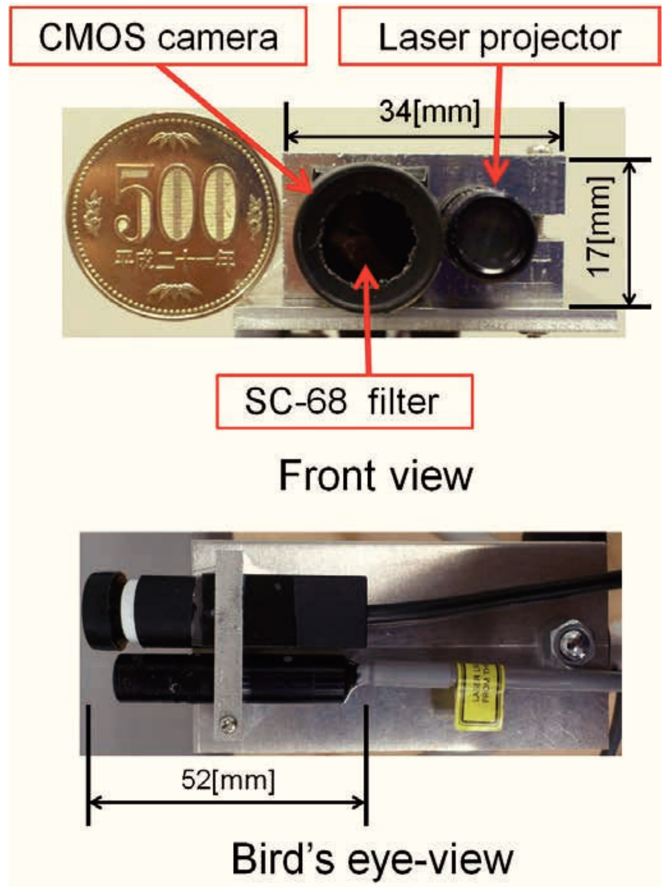


Fig. 4. A compact range image sensor using a multi-slit laser projector

C. Calibration of the sensor

In the image plane, each slit image moves along the epipolar line horizontally according to the distance[15]. We first assign movable ranges of slits in the image. The aim of the sensor is to measure a short distance. When the distance is shorter than 100mm, the projected laser slits blur and the precision of detecting the position of slit image becomes lower. Therefore, we set the minimum measurable distance to 100mm.

The movable range and the maximum measurable distance are derived from the minimum distance. The disparity is given by the following equation[16].

$$d = \frac{b \cdot f}{p \cdot z} \quad (1)$$

z: distance to object [mm]

b: baseline length[mm]

f: focal length of the lens [mm]

p: width of each element of CMOS image sensor [mm/pixel]

d: disparity [pixel]

We set the reference position of each slit image at a distance of 150mm. The disparity at a distance of 100mm and 150mm is approximately 78 pixels and 52 pixels, respectively, from (1). Therefore, the left-side (for nearer distance) movable range from the reference position is 26 pixels, which permits the minimum distance. In addition, it is necessary to consider the width of the slit image. The maximum width of the slit image at a distance of 100mm is approximately 20 pixels. By adding 10 pixels, a half width of the slit image, to 26 pixels with some margin, we set the left-side movable range to 40 pixels.

The horizontal distance between adjacent slit images is 75 pixels at the minimum. Therefore, we can assign 35 pixels to the right-side (for further distance) movable range from the reference position. With this movable range, the maximum measurable distance becomes approximately 300mm as follows. The disparity at a distance of 300mm is approximately 26 pixels, which is approximately 26 pixels from the reference position. The maximum width of slit image at a distance of 300mm is 15 pixels (smaller than at 100mm). The sum of the half width of the slit image 7.5 pixels and 26 pixels is smaller than (and comparable to) 35 pixels. Fig.5 shows the camera image at a distance of 150mm ((a)) and the movable ranges assigned to each point of the slit ((b), (c)).

We then calibrate the position of the slit image assuming that the distance is infinite k_∞ and a coefficient to calculate the distance α from the position of the slit image at two or more known distances. k_∞ and α are given in the following equation.

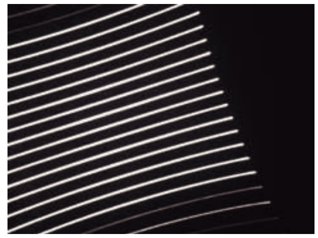
$$z = \frac{b \cdot f}{p \cdot d} \equiv \frac{\alpha}{d} \equiv \frac{\alpha}{|k - k_\infty|} \quad (2)$$

where k is the position of the slit image at distance z.

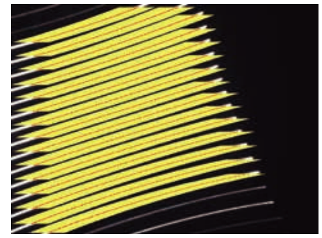
When a range image is obtained, the slit image is detected within the movable range, and the distance to each point of the projected slit is then calculated from (2) using the obtained parameters.

D. *Specifications of the sensor*

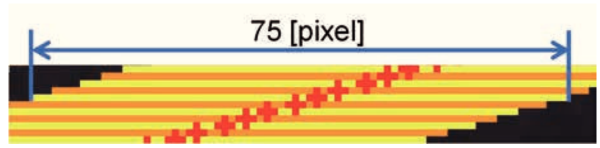
Fig.6 shows the measurement space of the sensor. The space between adjacent slits is 4.1mm and 12.4mm at distances of 100mm and 300mm, respectively. The number of total measurement points is approximately 1800, i.e., 120 points on average for each slit. The angle between adjacent points of the center slit is 0.25°, and the angle between adjacent slits is 2.37°. The frame rate is 15fps.



(a) CMOS camera image



(b) Assigned regions



(c) Magnified image of (b)

Fig. 5. Assigned regions to obtain disparity

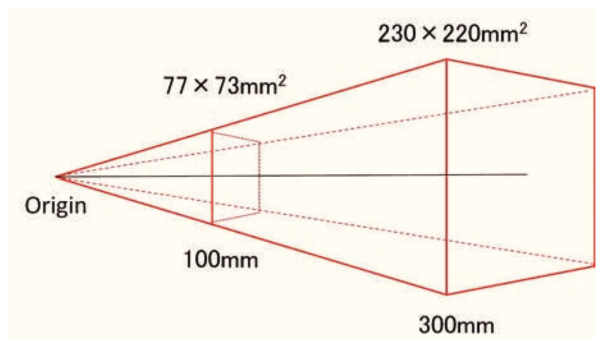


Fig. 6. Measurement space of the sensor

III. EVALUATION OF THE ACCURACY OF THE SENSOR

We evaluated the measurement precision at each distance. We measured a plane that is perpendicular to the sensor's optical axis as shown in Fig.7 and then fitted a plane to the obtained range image. Fig.8 shows the results. Each point represents the standard deviation of the distance from the fitted plane at the corresponding distance. The measurement error becomes larger according to the increase of the distance. When the distance is measured based on triangulation, the measurement error is proportional to the square of the distance[16]. The sensor, for the most part, obeys the principle. When the measurement distance is close to 100mm, the errors are larger than theoretically expected. This is because the measurement precision of the slit image becomes low because of the blur of the projected laser slit.

IV. COMPARISON WITH OTHER SENSORS

The proposed sensor characteristics are compactness and capability to measure from a short distance. We compared the sensor with commercially available ones that have similar capabilities. In this comparison, we considered only active

Fig. 7. Experimental scene to evaluate accuracy

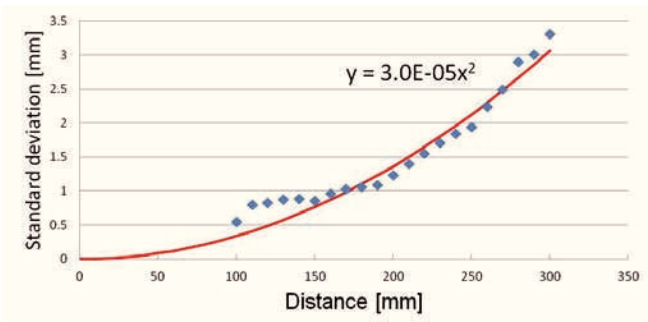


Fig. 8. Standard deviation of the residuals from the fitted plane

sensors, since we believe that robust measurement using an active method is necessary for robot hand applications, especially when a target does not have sufficient texture. We selected a 3D scanner, PULSTEC TDS-A[12], which can construct a high-resolution 3D model of a nearby object, and MESA SR4000[3], which is a typical TOF range image sensor. In addition, we selected the sensor that we had constructed beforehand[14]. The comparison is shown in Table I.

The proposed sensor achieves the measurement at a shorter distance than the SR4000 and our former one. Although TDS-A also achieves the measurement at a short distance, its measurement range is narrow, and it requires longer measurement time, which is critical for real-time use such as robot hand applications. The proposed sensor is the smallest and most light-weight, shown in Fig.4 and Fig.9. There are fewer measurement points (1800) than with our former sensor (4700) because there are fewer pixels in the proposed sensor camera than in the former one. With the capability of measuring from a short distance and the compactness of the device, the proposed sensor is most suitable to robot hand applications.

V. EXPERIMENTS OF MEASURING OBJECTS

We used the sensor in experiments to measure ordinary objects. The sensor was set in front of a wall at a distance of 150mm, and each object was set on the wall. The measured objects are a LAN cable (diameter 6mm), a white rectangular parallelepiped (50mm$\times$25mm$\times$25mm), and a Ping-Pong ball (diameter 40mm). The measurement results are presented in Figs.10–12. In each figure, (b) and (c) show the obtained range image seen from the front and a bird's-eye view, respectively. Fig.10 shows that the sensor can measure even a thin cord. Fig.11 shows that the sensor can measure the shape and size of the rectangular parallelepiped appropriately. Fig.12 shows that the sensor can measure a curved surface.

Next, the distance from the wall was set at 200mm, and an airplane model (100mm (vertical) $\times$ 110mm (horizontal)) was measured. The results are presented in Fig.13. It is shown that an object with complex shape can be measured with the sensor. Notice that the points at the lower-left part are not noises but correspond to the stand.

Finally, the sensor was set on a plane with an elevation angle of approximately 50 degrees and a height of 135mm. The measured object is an airplane model (50mm (vertical) $\times$ 50mm (horizontal)). The airplane model runs at a speed of 300mm/s using a spring. In this experiment, the sensor measured the running model as shown in Fig.14 to verify whether it can be used in a dynamic environment. The results to measure a series of six frames are presented in Fig.15. It is verified that even an moving object can be measured with the sensor.

In summary, the experimental results verify that the sensor can measure the 3D shape and size of ordinary objects at a short distance with reasonable spatial resolution.

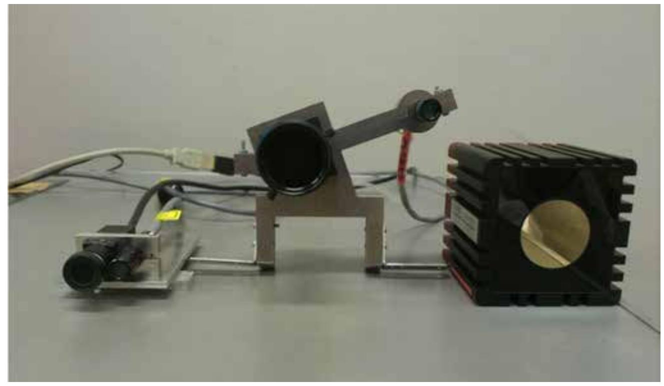


Fig. 9. Comparison with SR4000 and our former sensor (left: the proposed sensor, middle: our former sensor, right: SR4000)

VI. DISCUSSION

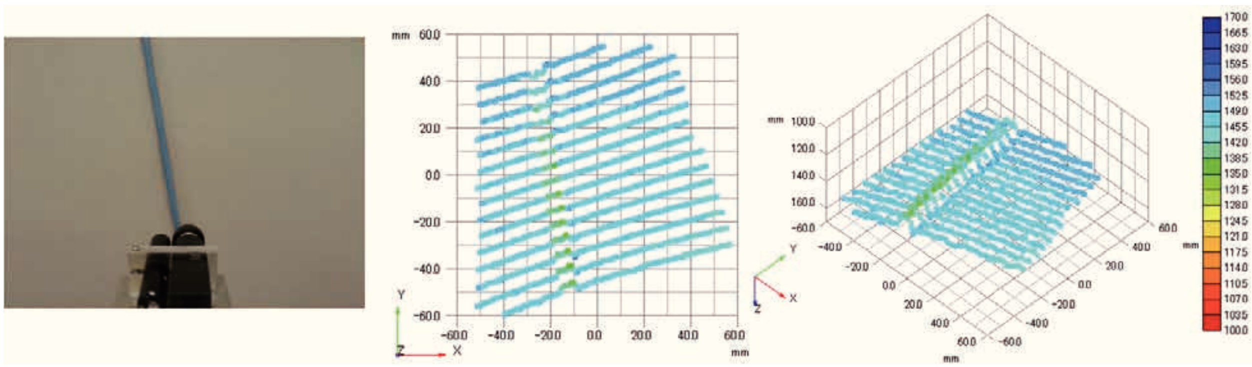
The range image sensor is compact and is assumed to satisfy the requirement as a range image sensor attached to a robot hand. To improve the sensor and make it more suitable for a robot hand, two problems should be solved. First, it should be more compact. For this, smaller components should be used. As for the camera, a smaller one, such as the type used in smart phones or cell phones, could be used. However, there are no commercially available smaller laser projectors.

When smaller components are used, a shorter baseline length is possible, and, consequently, a wider measurement

TABLE I

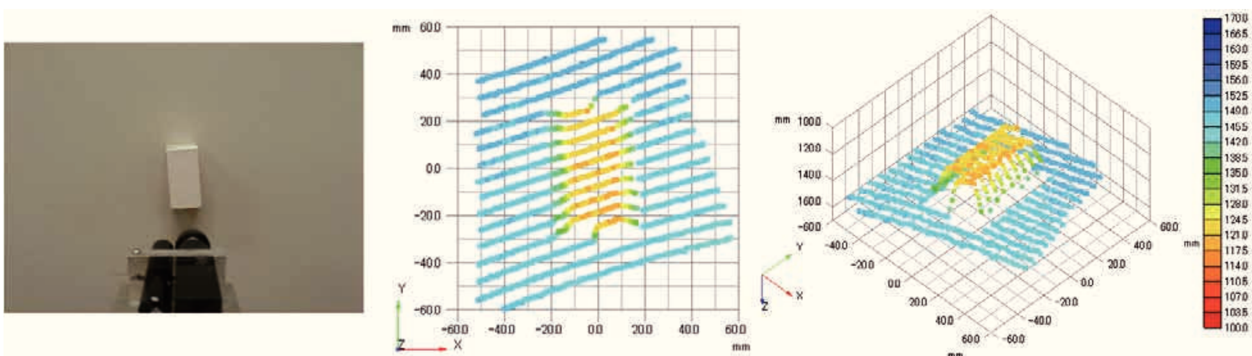
COMPARISON WITH OTHER COMPACT RANGE IMAGE SENSORS

	Constructed sensor	Former sensor	TDS-A	SR4000
Number of measurement points	approx. 1800	approx. 4700	129×100	25344
Angle resolution [°]	0.25×2.4	0.14×2.3	0.14×0.14	0.24×0.24
Measurement distance [mm]	100–300	380–800	90–120	300–5000
Size [mm]	17×34×52	90×110×85	71×132×138	65×65×68
Weight [g]	40	250	1400	470
Frame rate [fps]	15	30/8	0.4	50



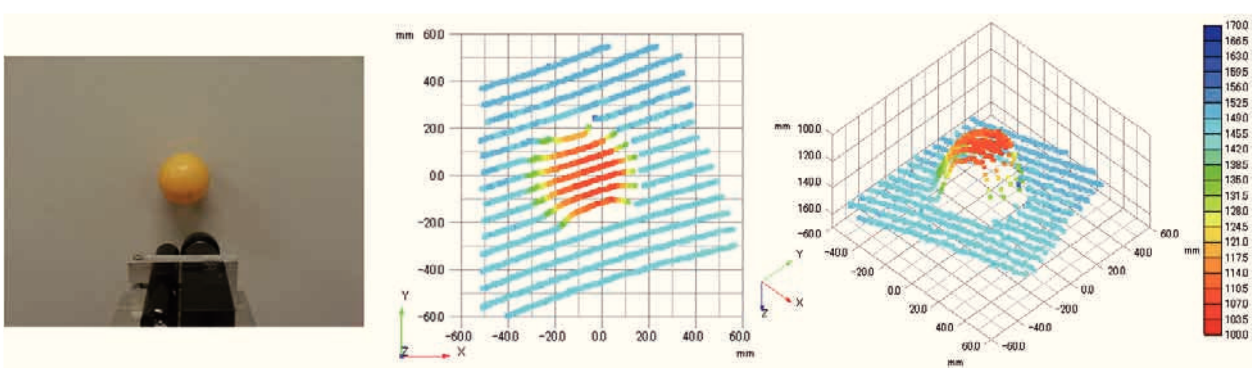
(a) Target scene (b) Front view (c) Bird's-eye view

Fig. 10. Range image (LAN cable)



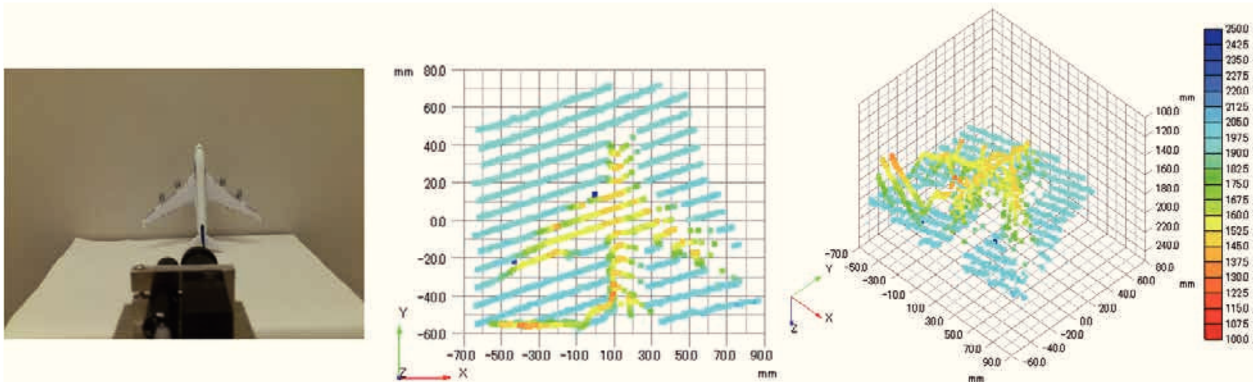
(a) Target scene (b) Front view (c) Bird's-eye view

Fig. 11. Range image (rectangular parallelepiped)



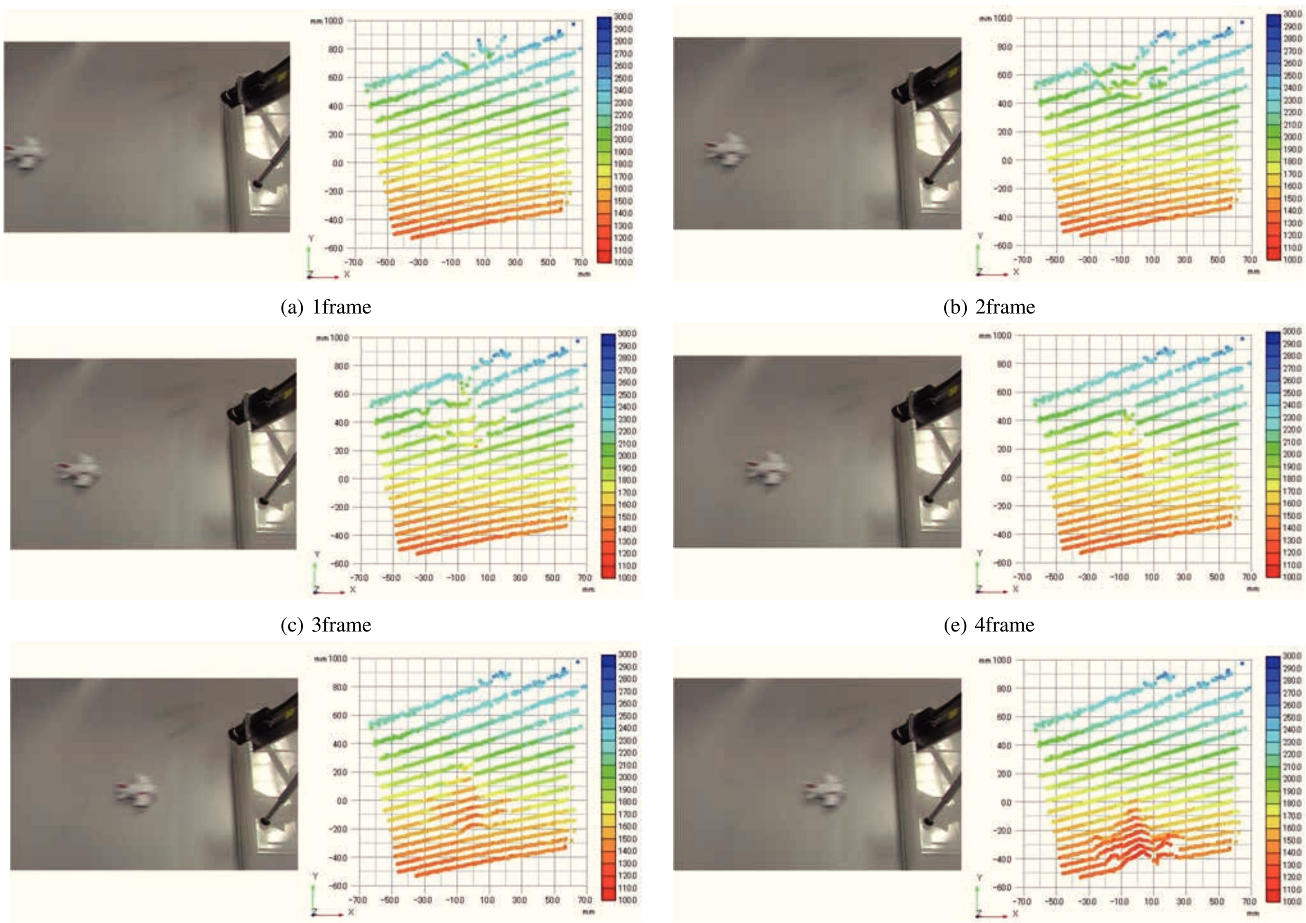
(a) Target scene (b) Front view (c) Bird's-eye view

Fig. 12. Range image (Ping-Pong ball)



(a) Target scene (b) Front view (c) Bird's-eye view

Fig. 13. Range image (airplane model)



(a) 1frame (b) 2frame

(c) 3frame (e) 4frame

(f) 5frame (g) 6frame

Fig. 15. Experimental scene and range image

range from a shorter distance can be achieved. However, the problem of the blur of the laser slit remains. Fig.16 shows the CMOS camera image of laser slits at 60, 80, 100, 300, 500, and 800mm (notice that the measurement range of the current sensor is 100–300mm). We can see that images of laser slits at less than 100mm blur considerably. The development of a smaller laser projector that does not result in an unacceptable blur remains challenging. In addition, Fig.16 demonstrates that the images of laser slits larger than 300mm are quite dark. A novel detection method of laser slit images that are robust to the change of brightness of the slit images is required.

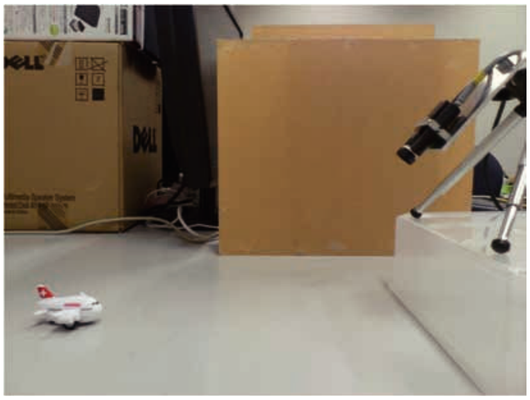
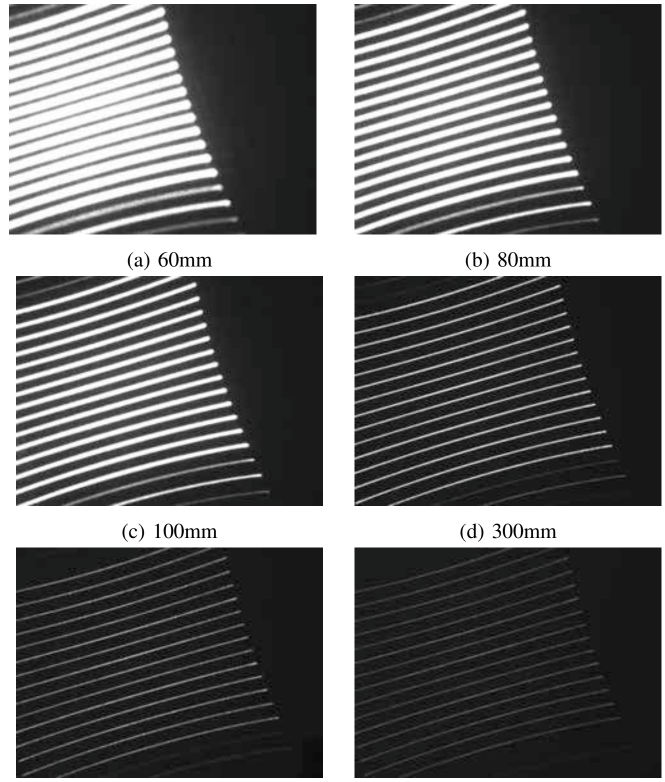


Fig. 14. Experimental scene

VII. CONCLUSION

In this paper, we constructed a compact range image sensor with a small multi-slit laser projector and a small CMOS camera. Compactness is achieved by using small components and establishing a baseline length that is as short as possible. The short baseline makes measurement possible from a short distance. The performance of the range image measurement from a short distance was demonstrated in some experiments.

In the future, we want to make the sensor smaller by using smaller components and apply the sensor to real manipulation tasks using a robot hand.



(a) 60mm (b) 80mm

(c) 100mm (d) 300mm

(e) 500mm (f) 800mm

Fig. 16. Images of laser slits at different distances

REFERENCES

[1] T. Oggier et al., “3D-Imaging in Real-Time with Miniaturized Optical Range Camera,” Proc. of the Opto-Conference, 2004.

[2] S.B. Gokturk, H. Yalcin, and C. Bamji, “A Time-of-flight Depth Sensor, System Description, Issues and Solutions,” IEEE Workshop on Real-Time 3D Sensors and Their Use in Conjunction with CVPR, 2004.

[3] MESA Imaging, http://www.mesa-imaging.ch/

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

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

[6] K. Sato, A. Yokoyama, and S. Inokuchi, “Silicon rangefinder - a realtime range finding VLSI,” Proc. Custom Integrated Circuits Conf., 1994.

[7] T. Kanade, A. Gruss, and L.R. Carley, “A VLSI sensor based rangefinding system,” Robotics Research Fifth International Symposium, pp.49–56, 1990.

[8] P. Hebert, N. Hudson, J. Ma, and J. Burdick, “Fusion of Stereo Vision, Force-Torque, and Joint Sensors for Estimation of In-Hand Object Location,” Proc. of IEEE International Conference on Robotics and Automation, pp.5935–5941, 2011.

[9] H. Arisumi, N. Kwak, and K. Yokoi,“Systematic Touch Scheme for a Humanoid Robot to Grasp a Door Knob,” Proc. of IEEE International Conference on Robotics and Automation, pp.3324–3331, 2011.

[10] Y. Park, A. Shiriaev, S. Westerberg, and S. Lee, “3D Log Recognition and Pose Estimation for Robotic Forestry Machine,” Proc. of IEEE International Conference on Robotics and Automation, pp.5323–5328, 2011.

[11] K. Khokar, K.B. Reed, R. Alqasemi, and R. Dubey, “Laser-Assisted Telerobotic Control for Enhancing Manipulation Capabilities of Persons with Disabilities,” Proc. of 2010 Int. Conf. on Intelligent Robots and Systems, pp.5139–5144, 2010.

[12] Pulstec Industrial Co., Ltd., http://www.pulstec.co.jp/en/index

[13] H. Hasegawa, Y. Mizoguchi, K. Tadakuma, A. Ming, M. Ishikawa, and M. Shimojo, “Development of intelligent robot hand using proximity, contact and slip sensing,” Proc. of IEEE International Conference on Robotics and Automation, pp.777–784, 2010.

[14] T. Kuroki, K. Terabayashi, and K. Umeda,“Construction of a compact range image sensor using multi-slit laser projector and obstacle detection of a humanoid with the sensor,” Proc. of 2010 Int. Conf. on Intelligent Robots and Systems, pp.5972-5977, 2010.

[15] O.Faugeras: “Three-Dimensional Computer Vision,” MIT Press, 1993.

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