Development of Small Size 3D LIDAR*

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***Abstract*— We have developed a new type of 3D LIDAR, which is small, light weight and low cost. The size and weight are important factors of the aimed sensor to use with wide range of robot vehicles, helicopters and airplane, and small vehicles. To achieve compact size and light weight construction the sensor has single pair of laser transmitter and receiver, and scanning motor on which a vibrating mirror is placed. The mirror is driven by the resonant frequency current supplied through contactless power supply unit. Experimental results of the prototype shows that the sensor of comparable size and weight with recent 2D sensors can obtain 3D range data of 8000 points in 20 Hz with 270 degree horizontal and 40 degree vertical views both in indoor and outdoor.**

I. Introduction

In past decade scanning laser range sensors have been widely used as eyes of mobile robots in surface and in air. Their wide rage application and popularity can be realized by their reduced costs and compactness. Since total weight of a helicopter or a small airplane is severely restricted, the size and the weight are critical factors of the sensor.

However most of them have only 2D scanning ability. As a next level challenge of a laser scanning sensor, 3D type sensors have been developed. The first attempts were to rotate 2D sensor's body with a new axis [1][2][3]. Those sensors have to move the whole 2D sensor bodies around motor axes back and forth, and require big motor power. The roundly-swinging type sensor [4] [5] reduced the motor load and realized the high-rate scanning of the additional motor. This type has still complex mechanical structure and the sensor size can not be reduced. Some companies are selling 3D LIDARs of small size. HDL-32e of Velodyne Lidar Inc. [6] has 32 lasers in 40 degree vertical view rotating 360 degrees. However this sensor is heavy and expensive. ECO SCAN of Nippon Signal Company [7] has single MEMS (Micro-Electro Mechanical Systems) mirrors to realize 3D laser scanning. For the restriction of MEMS mirrors the ECO SCAN has narrow horizontal field of view (60 degree horizontal and 50 degree vertical). DepthSense Cameras of Softkinetic Inc. [8] uses laser or LED flash and CMOS device and can capture 3D data in high frame rates up to 60 fps, but they have also a narrow field of view and limited use in outdoors.

In this paper we propose a new type of 3D scanning method which makes a laser range sensor small, light, and low cost. The idea is to combine 2D sensor rotation and single MEMS-like resonant mirror to keep simplicity of all structure. A prototype has been developed with the size of 55 mm $\times$ 60 mm $\times$ 135 mm (width $\times$ depth $\times$ height) of the sensor head (excluding circuit boards). The near market design has a size of 87 mm $\times$ 118 mm $\times$ 85 mm (width $\times$ depth $\times$ height) and the 700 g weight of the whole sensor body.

In section II we discuss about our 3D LIDAR structure. We explain about a resonant mirror we developed in section III and its control method in section IV. In section V developed prototypes based on the proposed structure are described. In section VI experimental results measured by the prototype are shown. Section VII is conclusions.

II. Small and Light Weight 3D Scanner

A. Horizontal Scanner and Resonant Mirror

Keeping simplicity and advantage of 2D scanning sensor which can easily scan over 180 degree horizontal views, we add a resonant mirror over the horizontal scanning motor as shown in Fig. 1. The resonant mirror unit itself is very light and small, so that we do not need special motor for horizontal scanning. We used contactless power supply unit to the resonant mirror unit, so that no power cables prevent motor rotation. Because the mirror vibrates around the resonance frequency the supplied power to the resonant mirror unit is small. But still this contactless power supply system occupied the dominant weight of the sensor.

To obtain fixed angular amplitude of a resonant mirror the frequency of vibration cannot be chosen arbitrary and determined by atmospheric condition. The horizontal scanner is to be controlled to synchronize with the resonant mirror vertical scanning.

B. Resonant Mirror Unit

We have developed a resonant mirror unit for the 3D LIDAR. The unit was developed by ourselves to suit the sensor requirements such as size and resonant frequency. The vertical field of view is determined by the amplitude of the mirror vibration, which depends on the magnitude of driving current and its frequency. In addition, resonant frequency characteristic changes by temperature. This means the vibration of the mirror must be controlled according to the changes of temperature. Because the resonant mirror unit is on the rotating axis, the detected mirror angle is hard to

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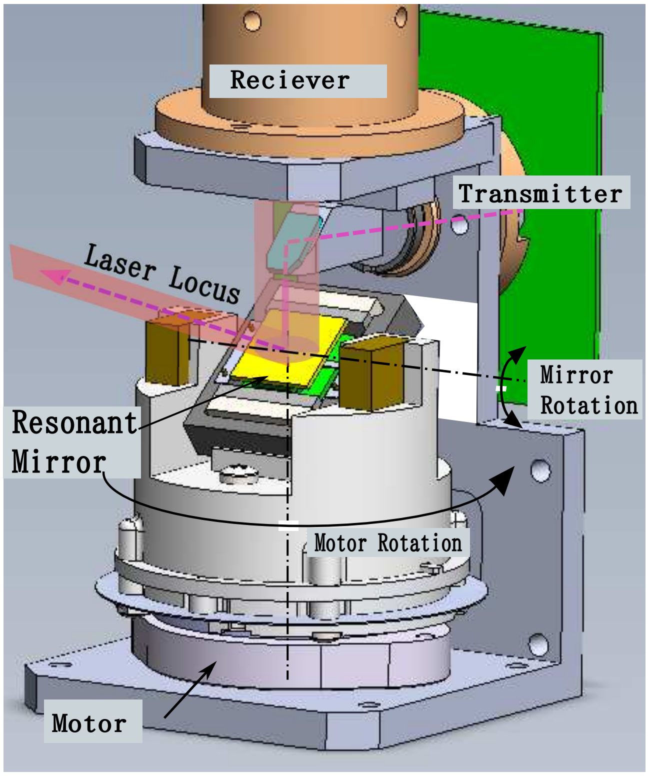

Fig. 1. Head of 3D LIDAR

be signaled out from the mirror unit. We decided not to use mirror angle detector of direct sensing, but to estimate the vibration amplitude using the 3D sensing data of a calibration pattern placed on the back side of the sensor.

C. Laser Transmission and Reception

The sensor has a pair of laser transmitter and receiver as an ordinary 2D scanning sensor. This design makes the sensor simple and compact. The laser transmitter is placed at the back side of the sensor. Its circuit board is shown in the right part of Fig. 1. The receiver is placed at the top. The laser beam from the back side is reflected by a small mirror towards the resonant mirror from the top side which locus is shown by dotted line in Fig. 1. The 3D scanner reflects the laser at the aimed direction. The laser beam goes back to the sensor from the environment and is reflected at the resonant mirror again towards the receiver at the top of the sensor as shown with translucent thick beam in Fig. 1. The laser pulse interval limits sensing resolution and is determined by class 1 laser safety standards.

D. Range Detection and Calculation

The sensor we developed uses time of flight method to calculate the range to an object for its ability of long distance sensing with reasonable implementation cost. For this prototype we used the processing hardware of the same type used in UTM-30LX 2D range sensor of Hokuyo Automatic Corporation which can measure up to 30 m long in 30 mm error.

III. Resonant Mirror

Detectable range of LIDAR is largely affected by size of mirror which reflects received laser light. High speed Galvano mirrors [9] are not suitable for our sensor because of its big size and high power consumption. Small size and light weight MEMS mirrors [10] are suitable to be rotated on the motor, but does not have enough area size to obtain necessary sensitivity of LIDAR. A mirror having appropriate size and weight for our sensor does not seem to be exist in a market.

We have developed new type resonant mirror for 3D laser range sensor scanner. The resonant mirror has the gimbal structure like silicon MEMS scanners. Silicon MEMS scanners are suitable for laser beam scanning but their mirrors for example 4 mm $\times$ 4 mm are too small to detect faint light. However, our resonant mirror has a large surface of 12 mm $\times$ 12 mm and large scanning optical angle of 40 degrees with resonant frequency of 400 Hz. The resonant mirror has dimension of 21.2 mm $\times$ 26.0 mm $\times$ 8.6 mm (width $\times$ depth $\times$ height), and a weight of 12g. The most important advantage of the resonant mirror is that no expensive production systems like silicon manufacturing are required. We can produce this type of mirror at low unit cost.

Fig. 2 shows the resonant mirror structure. Gold coated glass mirror for Infra-Red laser beam and planer coil plate for driving are supported by stainless steel (SUS 304) torsion bars. The moving parts, mirror and coil, are sandwiched by a pair of permanent magnets. As their torsion bars are designed under fatigue limitation, they passed gigacycle fatigue test. Driving of 400 Hz indicates 1.44 megacycle per hour or 12 gigacycle per year. We have now data of non-stop driving for 2 years over.

Fig. 3 shows the principle of the resonant mirror driving. Static magnetic field and AC current applied to the planar coil cause alternating Lorentz Force. Let I be current density induced on a planar coil plate, and B be magnetic flux density in a field, then the Lorentz force is given by (1).

$$F = I \times B \tag{1}$$

Fig. 4 shows the frequency characteristics of the resonant mirror. The resonant frequency of the mirror is given by as follows.

$$2\pi f = \sqrt{k/J} \tag{2}$$

where f is the resonant frequency, J is the moment of inertia, and k is the spring constant of torsion bar.

The resonant mirror in Fig. 4 has a resonant frequency of 388 Hz at 300 mAp-p. Plotted optical degree is twice of mechanical angle of the mirror. We can design precisely the resonant frequency from 380 Hz to 420 Hz on this size of the resonant mirror using FEM (Finite Element Method) software. Resonant frequency driving saves power: it needs less than 0.3 W. Low power consumption is a large advantage of our resonant mirror.

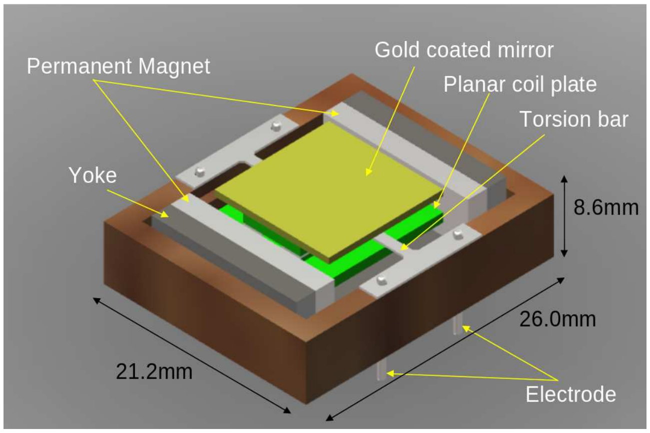

Fig. 2. Resonant mirror unit

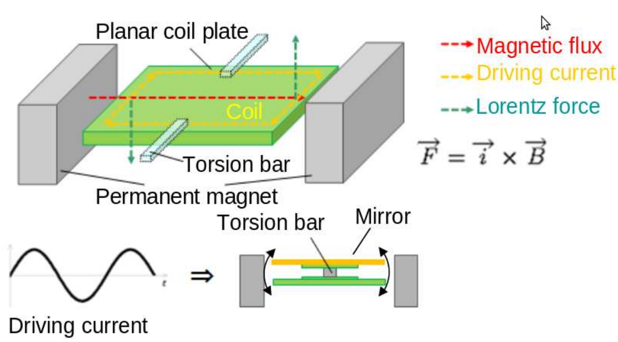

Fig. 3. Principal of resonant mirror driving

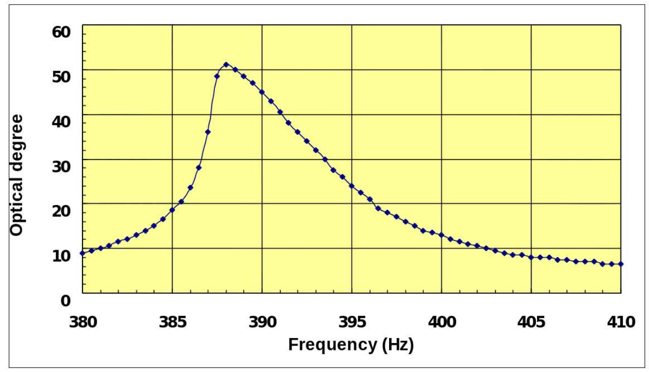

Fig. 4. Frequency and vibration angle characteristic of the resonant mirror

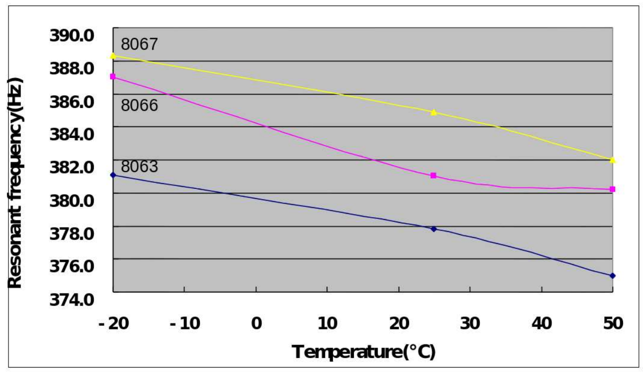

Fig. 5. Temperature response of the resonant mirror

Fig. 5 shows the characteristics of temperature response of the resonant mirror. Three different samples of mirror devices (numbered 8063, 8066, 8067 on the figure) are used. Resonant frequency is influenced by temperature, and changes about 6.4 Hz in temperatures from -20 °C to 50 °C. Therefore resonant mirror must be controlled to account for resonant frequency changes by temperature.

The resonant mirror is arranged on the rotor of DC motor for vertical scanning. We have adopted a contactless power transfer technology using electromagnetic coupling for wireless power supply to a device on the rotor. We constructed the contactless transformer which has a primary coil of 250 turns, a secondary coil of 250 turns and a gap of 0.5 mm. Its gap causes large leakage inductance but we achieved power transfer efficiency of 40 % at 400 Hz.

Fig. 6 shows the structure of contactless transformer. This contactless transformer has the advantage of extremely long life, because it has no contact points like a slip ring.

IV. Resonant Mirror Control

The characteristic of resonant mirror shown in Fig. 4 is affected by atmospheric parameters such as pressure, humidity, and especially temperature. Once we calibrated the sensor, we must control the mirror to obtain constant amplitude of vibration. We achieve this control by changing vibration frequency of the mirror: when the vibration frequency moves far from the resonant frequency, for example, torward right on the right slope in Fig. 4, the amplitude of the mirror will be decreased, and vise versa. The problem is now how to detect the amplitude change of the mirror.

A. Amplitude Detection of Resonant Mirror

While the laser is emitted to backside of the sensor in horizontal scanning, the sensor cannot measure environmental objects being blocked by its own body. Instead the sensor measures a reference reflector inside the body. The measured results of the reference reflector are used for distance calculation or detection of laser failure in 2D scanning sensors. In our 3D sensor we use these back side

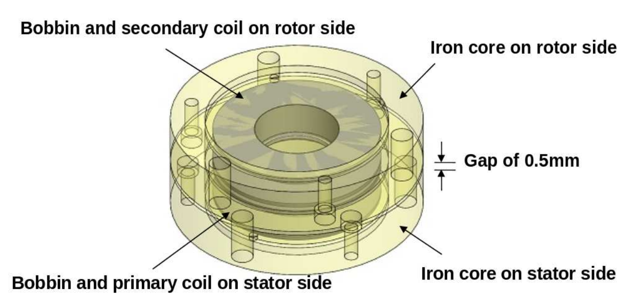

Fig. 6. Structure of contactless transformer

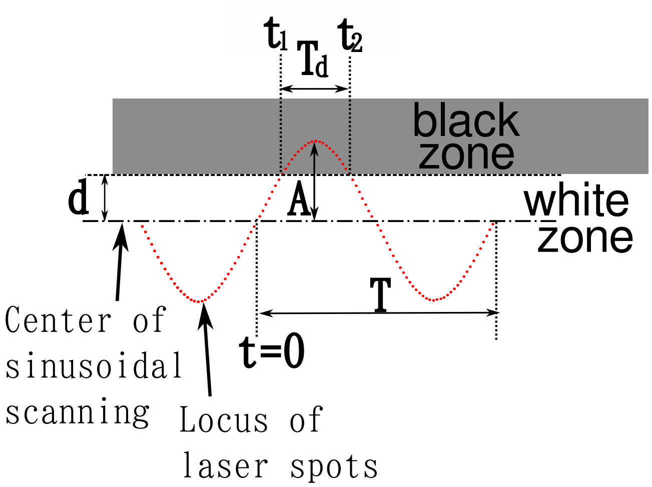

Fig. 7. Locus of the reference stripe on the sensor back.

measurements as detector of the resonant mirror vibration.

We put a stripe pattern plate as the reference reflector on the back of the sensor, so the locus of sensor scanning crosses the black and white boundary of the stripe and forms sinusoidal curve (Fig. 7). The black zone is actually non-reflexive material against laser wave length, and then the detected laser strengths are very different from the black zone to white zone.

We can estimate the time duration between the crossing points of the locus by counting low strength points from the reference reflector. The accuracy of this method depends on the point interval.

B. Controlling Angular Amplitude of the Resonant Mirror

As shown in Fig. 7 let the amplitude of the sinusoidal locus be A, the distance between the center of sinusoidal curve and the boundary to the black zone be d, and the period of resonant mirror vibration be T. In addition we assume the time t is zero when the locus is crossing the sinusoidal center, and let the times of crossing point of the black and white boundary be t_1 and t_2. We assume $t_2 > t_1$, then $T_d = t_2 - t_1$. From the triangular relation we deliver following equations.

$$d = Asin(\frac{2\pi}{T}t_1) \quad (3)$$

$$t_2 = \frac{T}{2} - t_1 \quad (4)$$

$$T_d = t_2 - t_1 \quad (5)$$

From (3), (4), (5), we deliver

$$d = Asin(2\pi(\frac{1}{4} - \frac{T_d}{2T})) \quad (6)$$

Using (6) we can calculate the change direction of A from the change of T_d while T has not been changed. The parameter d does not have to be calibrated directly. We measure T_d and calculate which direction the amplitude A moved, then control the mirror frequency to compensate the moved direction of the amplitude.

The estimated accuracy of T_d is about the point interval time $\Delta\tau$. Since $\Delta\tau$ has a constant value (actually it changes slightly), the accuracy of estimation of T_d/T is inverse proportional to T. However, in the case of higher frequency of vibration, we can add up results in several periods of vibration and taking average, the accuracy will be proportional to the $\sqrt{T}$, then we obtain total accuracy to inverse proportional to $\sqrt{T}$.

In Fig. 4 of the characteristic curve of frequency and amplitude, the right side (higher frequency than the resonant point) is more gently-sloped, so we use the vibration in the higher frequency zone. Therefore we move the frequency lower to increase the amplitude of the vibration, and higher to reduce.

Changes in laser strength affects the threshold level to distinguish black and white boundary, so long term stability of mirror amplitude control is still under investigation.

Fig. 8. First prototype

V. Prototype

The first prototype has been developed and used for validation and evaluation. Fig. 8 is the sensor head of the prototype.

The sensor specification is as shown in Table I. The size of the head is about 55 mm × 60 mm × 135 mm (width

TABLE I

SPECIFICATION OF THE PROTOTYPE

Max. range	30 m
Laser	Class 1 semiconductor laser
Receiver	Avalanche photo diode
Horizontal scanning angle	240 degree
Vertical scanning angle	40 degree
Frame rate	1.6 to 20 fps (50 to 600 ms)
Weight	600 g
Accuracy	$\pm$14 mm σ =7.2 mm (white Kent sheet) $\pm$32 mm σ =16.6 mm (10% reflectivity black sheet)
Angular Resolution (12 field configuration)	0.48 degree (vertical max.) 1.50 degree (horizontal max.)

Fig. 9. Second prototype sensor, which is at the center. UTM-30-LX sensor and a smart phone (iPhone3) are placed on the left and right to compare their sizes.

$\times$ depth $\times$ height). The frequency of the resonant mirror is around 400 Hz. The resonant frequencies of every mirror unit are slightly different because of the manufacturing accuracy. Resonant mirrors of higher frequency are currently under development for up to 2.5 kHz. Horizontal scanning rate is about 20 Hz, so that the resonant mirror achieve 20 vertical scans in a horizontal rotation in 50 ms. There are 260 laser points in a single period of the resonant mirror, and laser interval is longer than 9 μs for laser safety regulations. Fixed laser interval results at most 0.48 degree vertical angular resolution.

The horizontal and vertical resolutions depend on the combination of speeds of horizontal scanning motor and the resonant mirror. In the first prototype the resonant mirror frequency is relatively low, then we implemented phase shifted multiple scan function by which the scanned locus will be interlaced and return to the starting point again after multiple horizontal scans. We call single horizontal scan ‘field’, and multiple horizontal scans ‘frame’ just like interlaced camera or television monitor image scanning. Frame rate is 20 Hz with single field in a frame, or 2 Hz with 10 field in a frame. The number of fields can be set arbitrary up to 12 while measuring environment. Horizontal angular resolution is at most 1.5 degree when the number of field is set to 12.

The first prototype showed the validity of 3D scanning range sensing, and we developed a compact size second prototype. The full body size is about 87 mm $\times$ 118 mm $\times$ 85 mm (width $\times$ depth $\times$ height) including all the circuit boards (Fig. 9).

VI. MEASUREMENT RESULTS

In Figs. 10, 11, and 12 we show indoor and outdoor experiments with the first prototype sensor. Measured results are plotted as 3D graphics in figures and the color of each point represents received laser strength. Red color shows higher strength, and aqua blue color shows lower strength as shown in a scale of Fig. 13. All the measurements are done in 10 interlaced scanning except Fig. 10(a). Grid lines in figures are 1m interval, and sensor position is marked with white translucent circle. Fig. 10 shows measurement results of a meeting room. In Fig 10(a) non-interlaced scanning locus on room walls can be seen. In figures of 10 interlaced measurement from the top (Fig. 10(b)) and top right (Fig. 10(c)) we can see the shape of the room, whiteboard at the top right and corridor at the bottom left. A human body is measured in high strength colored in red at the left side of the sensor.

Fig. 11 shows measurement results of a corridor. A meeting room adjacent to the corridor can be observed at the top right.

Fig. 12 shows experimental result in an outdoor environment. Several objects such as a car, a human, trees, and a sign board can be seen. Strong reflections from the sign board and the front of the car plotted in red color can be observed. This outdoor results show that stable long distance 3D measurement can be achieved with this prototype sensor.

VII. CONCLUSIONS

With combination of horizontal scanner and a resonant mirror, a 3D LIDAR was built in compact size without loosing outdoor measurement ability. Interlaced scanning of relatively low frequency of the resonant mirror enabled dense point measurements of environment with the penalty of slower frame rate. A robot can choose appropriate interlacing parameter for rapid frame rate sensing or for precise point measurement.

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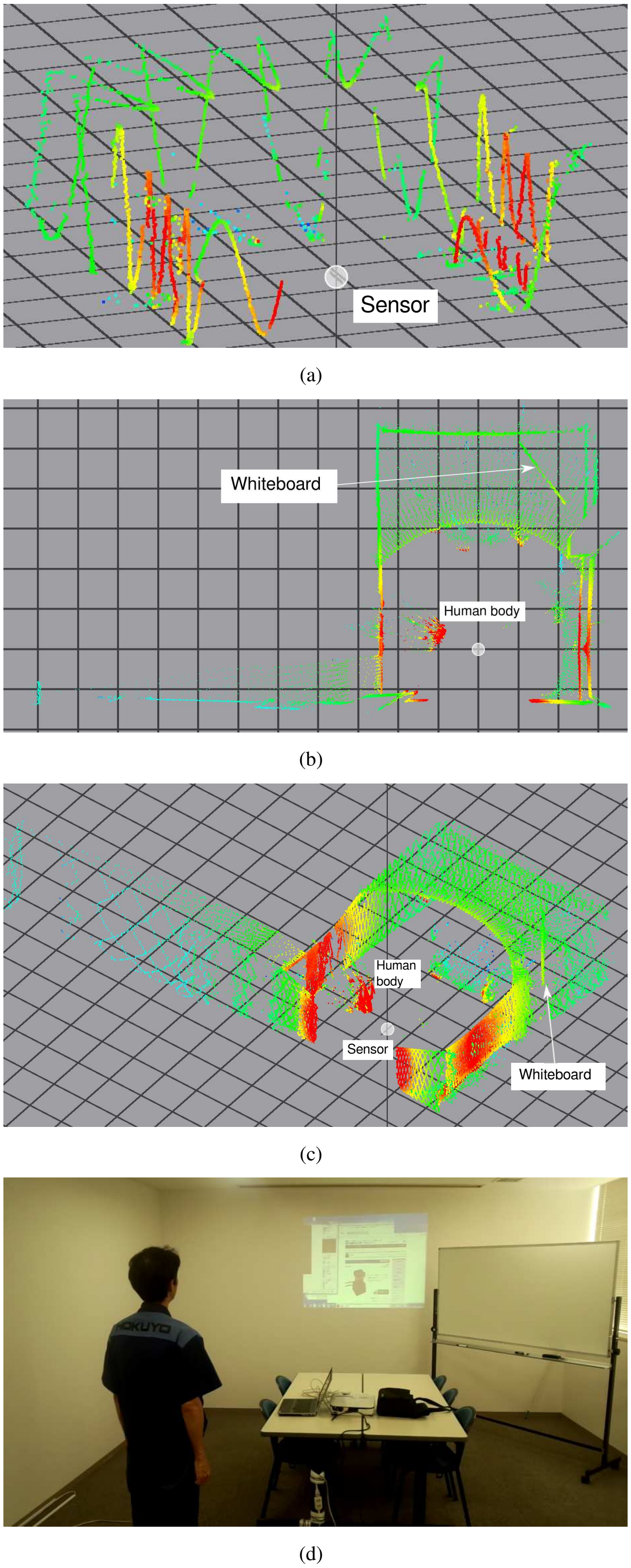


Fig. 10. Meeting room measurement: (a) is a view from top right with a single field scanning. (b) is a view from top, (c) from top right. Plotted colors indicates laser strength. (d) is a picture of the room.

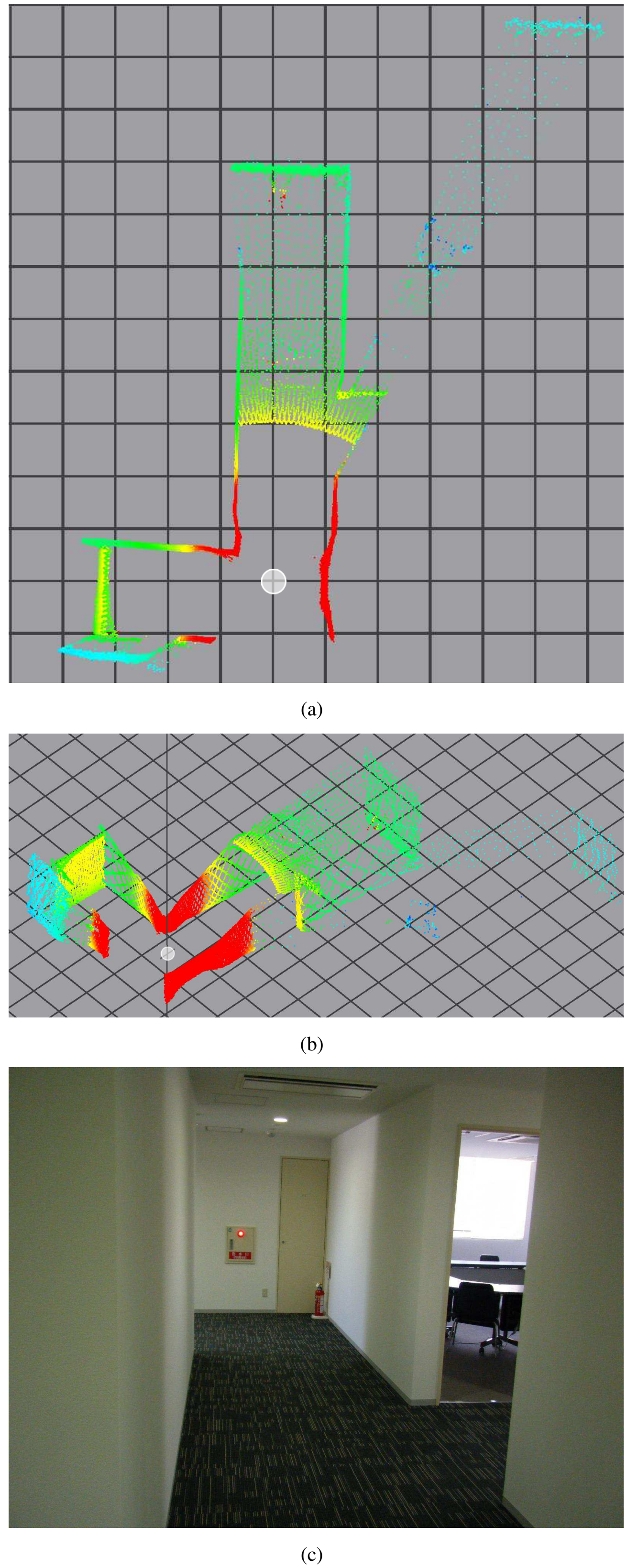
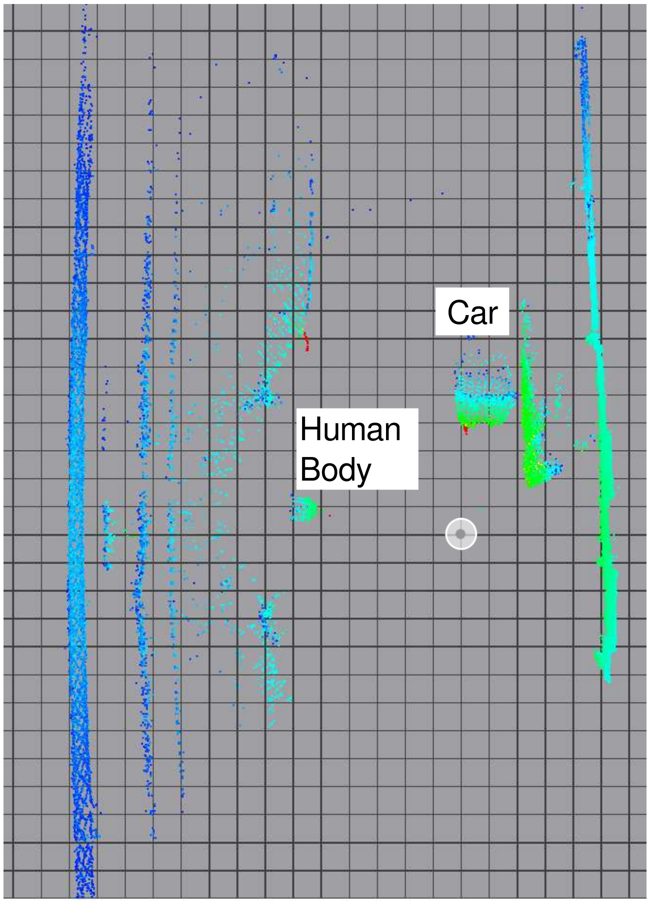
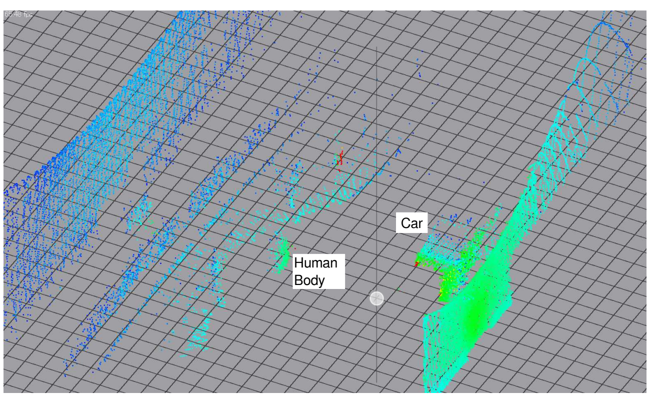


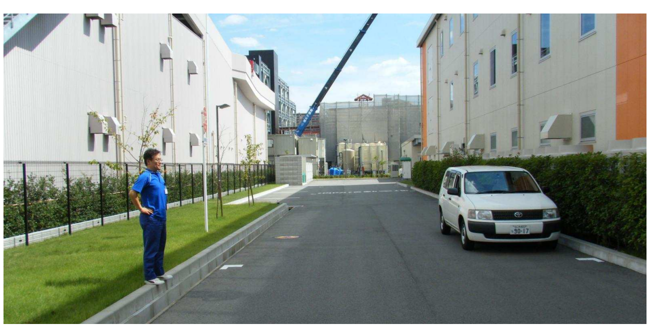
Fig. 11. Corridor measurement: (a) is a view from top, (b) from top right. (c) is a picture of the corridor.



(a)



(b)



(c)

Fig. 12. Measurement in outdoor environment: (a) is a view from top, (b) from top right. (c) is a picture of the outdoor environment.

Fig. 13. Laser strength scale: color of plotted points in experimental results represents received strength of laser.

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