

Development of ultra-small lightweight optical range sensor system

Hirohiko Kawata, Akihisa Ohya and Shin'ichi Yuta

*Intelligent Robot Laboratory
University of Tsukuba
Ten'nodai, Tsukuba, Ibaraki, Japan*

{hiro-kwt, ohya, yuta}@roboken.esys.tsukuba.ac.jp

Wagle Santosh and Toshihiro Mori

*Department of Engineering
Hokuyo Automatic Co., Ltd.
Niitaka, Yodogawa-ku, Osaka, Japan*

santosh@hokuyo-aut.jp, t-mori@hokuyo-aut.co.jp

II. SENSOR

A. Specifications of developed sensor

Fig.1 shows the configuration of the developed laser scanner and Table1 details its specifications.

Light source used in the sensor is infrared laser with the wavelength 785 [nm]. Laser safety is Class 1 regulated by IEC (International Electrotechnical Commission). The amplitude of emitted light is modulated with frequencies of 46.55 [MHz] and 53.2 [MHz].

Index Terms - Optical Sensor, Laser Range Sensor, Range Scanner, Distance measurement, SOKUIKI Sensor

I. INTRODUCTION

Sensors act as eyes for the mobile robots in path planning and obstacle detection in an unknown environment, and play a vital role in map building and localization. Among the different sensors developed for this purpose[1][2], the laser range sensors widely used in robotic research[3]-[5] are mostly too big, heavy and power hungry for practical use by small size mobile robots.

Hokuyo Automatic Co., Ltd.[6] has designed and developed obstacle detection sensor models PB9 and PBS, which are compact, lightweight and power-economic, with LEDs as the source of light. They are widely used in AGVs (Automatically Guided Vehicles) and in robotics due to their compactness[7]. But their applications have been limited to detecting obstacles rather than knowing the environment.

To meet the need for unknown area recognition in mobile robots, we have developed a compact 2-dimensional (2D) laser range scanner. The proto-types offered by Hokuyo Automatic as URG series is designed to test the availability to real robotic problems. It has high lateral and longitudinal resolution in a wide capture range. Furthermore the sensor is also power-economic, small, lightweight, compact and low-cost. We propose a new term "SOKUIKI sensor" for such range scanners.

In this paper we explain the specifications of "URG-X002" which is the third generation of "URG" series proto-type, its components and structure and examples of experimental results.

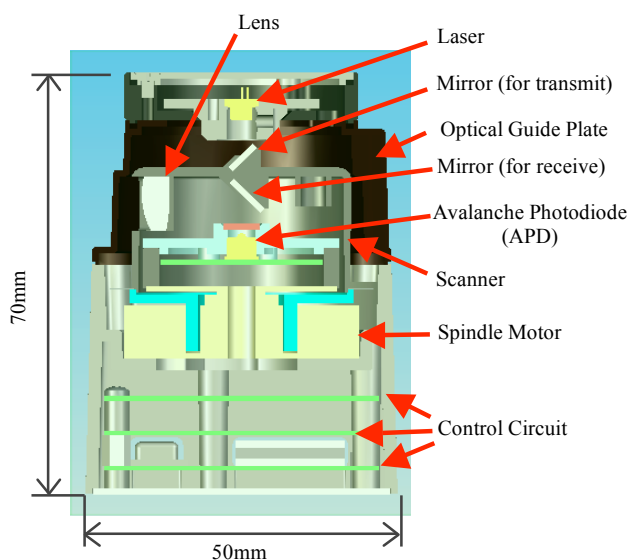


Fig.1 Structure of the sensor "URG-X002"

TABLE 1
Specification of the sensor "URG-X002"

Light source	Infrared laser (785[nm])
Modulated frequency	46.55[MHz], 53.2[MHz]
Motor	Spindle motor
Detection range	20 ~ 4095[mm]
Accuracy	$\pm 10\text{mm}$ (20 ~ 1000[mm]) $\pm 2\%$ of distance (1000 ~ 4095[mm])
Angle	240[degrees]
Angular resolution	0.36[degrees] (360 / 1024)
Response time	100[msec]
Dimensions	ϕ (42 ~ 50) \times 70[mm]
Weight	170[g]
Environment	Indoor

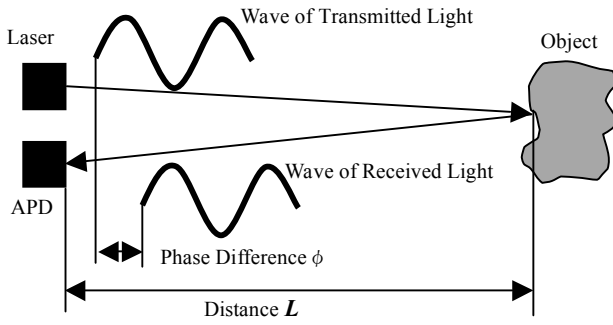


Fig.2 Algorithm of distance detection

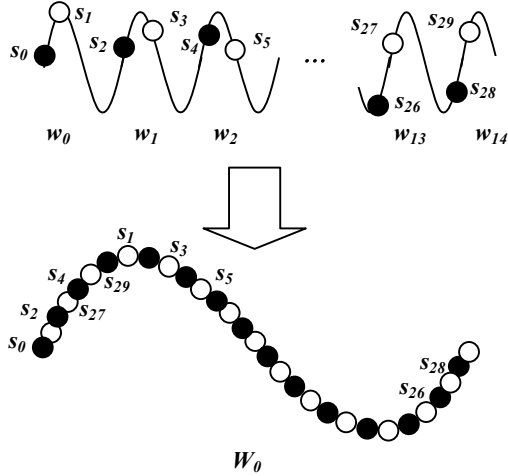


Fig.3 Explanation of Data Sampling

Sensor's motor rotates at 600[rpm] so that measured data for one scan is taken in 100 [msec]. The sensor's maximum measurable distance is 4095[mm], and the precision is ± 10 [mm] between 20 to 1000[mm] and $\pm 2\%$ of distance for more than 1000[mm] (for white Kent sheet under test conditions). The angular detection range is 240[degree] with the resolution of approximately 0.36[degree]. The size of the sensor is 50 x 50 x 70[mm] and weight is approximately 170[g].

B. Measurement of Distance using Phase Difference

In this sensor, the amplitude of the laser light is modulated, and the distance measurement is based on detecting the phase difference between transmitted light from the source and reflected one from the object (Fig.2). The distance to the object is calculated by equation (1).

$$L = \frac{1}{2} \times \left\{ \phi / \left(\frac{f}{v} \times 2\pi \right) \right\} \quad (1)$$

where,

- ϕ : Phase Difference [radians]
- L : Distance to the object form the light source [mm]
- f : Frequency [Hz]
- v : Speed of Light [mm/sec]

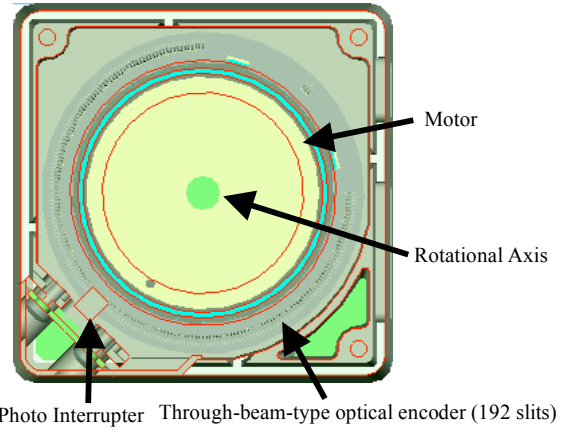


Fig.4 Cross Section of the Sensor

Based on equation (1), we obtain higher precision by increasing the frequency. Due to practical limitations in Application Specific Integrated Circuit (ASIC) design, embedded in the sensor, the frequency was designed to be around 50[MHz].

The problem associated with using single-wave is difficulty in measuring distances with more than a cycle period. We therefore used 2 different modulated-waves transmitted alternately. Phase differences are calculated individually.

We designed to use the basic clock of 13.3[MHz], and made it 14/4 and 16/4 times by Phased-Locked Loop (PLL) for the modulation resulting in frequencies of 46.55[MHz] and 53.2[MHz]. Waveforms are sampled using two Analogue to Digital (AD) converters of 49.875[MHz] (15/4 of basic clock) for making the total samplings of 99.75[MHz]. With this principle, it is possible to sample two data points with the single received wave and reconstruction of 1 wave with sampling data of 15 waves (Fig.3). Sampling large amount of data reduces the effect of noise that may exist while using this principle, resulting in high precision. The phase from the sampling data is calculated using equation (2).

$$phase = \arctan \left(\frac{\sum (s_n \times \cos(2\pi / n))}{\sum (s_n \times \sin(2\pi / n))} \right) \quad (2)$$

Phase difference ϕ is obtained by calculating the phase of transmitted and received waves. The distance to the object is calculated by substituting this phase difference in (1).

C. Design of Sensor

The sensor's main components are optics, a motor, computer boards and a case (Fig.1).

The optics consists of light source and photodiode placed face to face. The vertical light from the source is converted into horizontal beam by the inclined mirror below the source. Similarly, the received beam in horizontal axis is converted to vertical axis using another inclined mirror above the photodiode. To avoid light wraparound, these two mirrors are separated with a scanner casing.

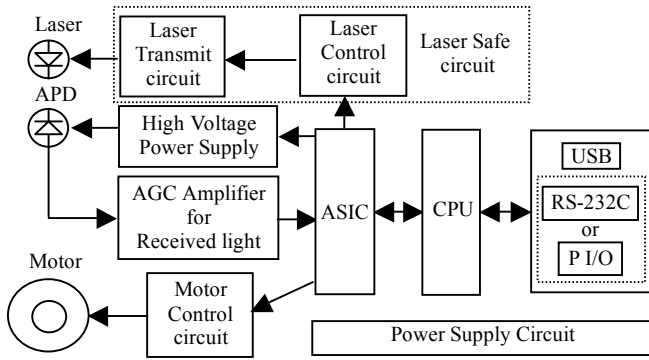


Fig.5 Structure of Electrical Units

The sensor has an extremely silent brush less spindle motor for rotating the mirror. By making the rotational axis hollow and using an outer-rotor mechanism, we could make the sensor compact. The motor rotates the mirror for transmitted and received light. Through-beam-type optical encoder placed below the photodiode governs angular position of the mirrors (Fig. 4).

The two computer boards, one on top of the motor for optics and one on the bottom of the sensor for the control circuit are used. Computer board on the top has the Auto Power Control (APC) circuit to govern the laser emission and maintain class 1 laser safety. The control circuit, which is placed at the bottom of the sensor, has a crystal (13.3[MHz]), CPU (Renesas M16C/62P), IC for motor control, circuits for the communication (RS232, USB) and the ASIC (Fig 5).

The case cover is polycarbonate with aluminium bottom to maintain strength and dissipate heat.

D. ASIC

To design the smallest possible sensor suitable for different robotic platforms and measuring up to 4095[mm] with high precision, we designed an ASIC that reduced size considerably (Fig. 6).

The main clock with a frequency of 13.3[MHz] is converted to burst signals with frequencies of 46.55 and 53.2[MHz] using three PLL and a clock-generator. They also create two clocks with a 90 degrees phase difference having a frequency of 49.875[MHz]. Burst signals are supplied to the laser circuit while the clock is used in AD converter for data sampling.

Two AD converters used in distance measurement are supplied with wave data from the photo diode circuit. Burst signal wave data is supplied to the standard AD converter. The first AD converter processes data during reception and the second data during transmission. They are synchronized and sampled by the clock and sent to the digital calculation circuit. The CPU processes results.

We used a through-beam type optical encoder to determine the angular position of the rotating mirror. It detects the position of the slits on the rotating metal disk that is below the photo diode. Data from the photo interrupter is sent to an angle measurement circuit, and then supplied to the CPU.

These functions are embedded in a single chip of 14×14[mm] (16×16[mm] including pins).

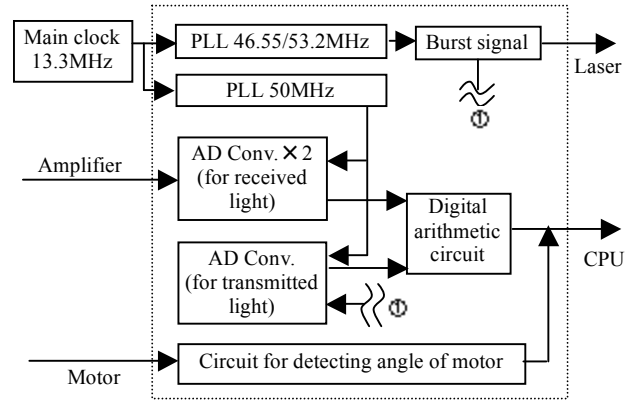


Fig.6 Structure of ASIC

E. Optical System

Avalanche Photodiode (APD) is adopted as a light receiving device, and its multiplication factor (M) is 100. APD is supplied with high voltage in the range 110 ~ 180[v] with DC-DC converter. The sensor controls the power supplied to the APD with Pulse Width Modulation (PWM) and Digital to Analogue (DA) converter in CPU to stabilize the value of M, because the voltage fluctuates extremely with the change in internal temperature of the sensor.

The sensor's light source is an infrared laser with a wavelength of 785[nm]. Laser is of safety Class 1 regulated by the IEC. To meet this standard, the laser is emitted for only 3[μsec] of the total 18[μsec]. As a result, burst emission is increased to 22.2[mW], which is enough power to detect objects far from the sensor.

In usual practice the higher light intensity at closer distance saturates light in the APD. The same phenomenon occurs in highly reflective object even if it is away from the sensor. So we have used an Auto Gain Circuit (AGC) to maintain an even wave at shorter distances and for the highly reflective objects.

TABLE 2
Various Objects and their Measurable Distance

No	Object	Measurable Distance / Margin of Surplus Measurement at 4000[mm]
1	IC Foam	0.8m
2	Black Sheet	1.7m
3	Black Kent Sheet	2.0m
4	Black Board without Gloss	2.5m
5	Black Cloth	3.5m
6	Grey Color Board without Gloss	4m/1.2 times
7	Wooden Plate	4m/1.8 times
8	White Kent Sheet	4m/1.9 times
9	Styrofoam	4m/2.3 times
10	Metal Board without Yellow Gloss	4m/2.3 times
11	Metal Board with Yellow Gloss	4m/2.5 times
12	Colored Metal Board with half Creamy Gloss	4m/3.9 times
13	Stainless Plate	4m/10.7 times
14	Aluminum Plate	4m/12.7 times
15	White Coated Metal Board	4m/21 times
16	Reflector Board	4m/400 times

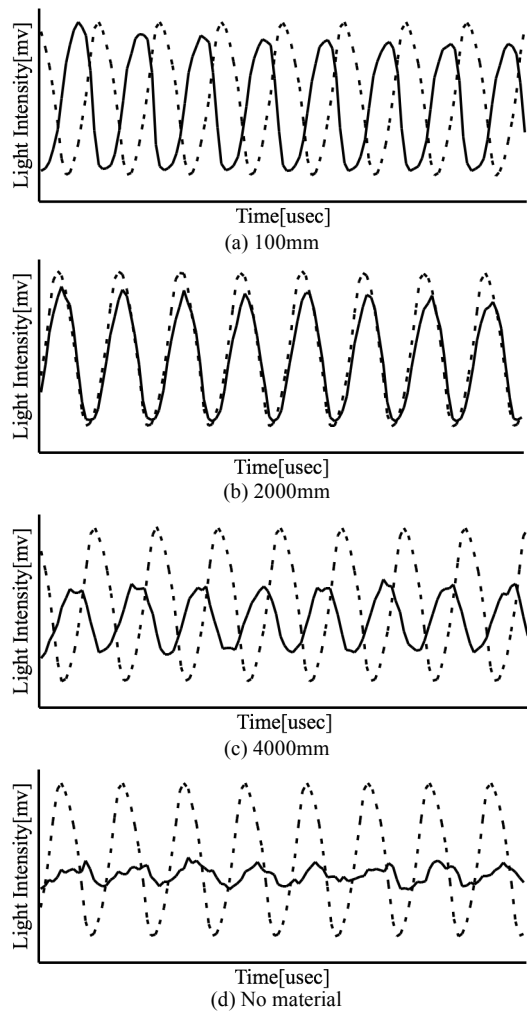


Fig.7 Waveform of transmitted light and received light (Solid line: received light, Dotted line: transmitted light)

F. Communication

The sensor scans 683 points in angular range 240 degrees. The size of full-step distance data is about 1.5Kbytes. As the sensor speed is 10[Hz] it cannot transmit all the data within one rotation of motor (100[msec]) if the baud rate is less than 250Kbps. So it is important for the sensor to support communication speed 250Kbps or more for transmitting full data within one scan.

To facilitate this, the sensor is equipped with two types of I/F. One is RS-232C supporting baud rates 19.2Kbps, 57.6Kbps, 115.2Kbps, 250Kbps, 500Kbps and 750Kbps and the other is USB supporting 12Mbps (Full-Speed). USB follows “Communication Device Class” standard, therefore user can access the sensor without being aware of the I/F.

We also developed new sensor command system named “SCIP (Scanning sensor Command Interface Protocol)” for the scanning range sensor for mobile robots. In this system the host sends different types of command to get the desired information and the sensor replies with the information related to that command. These include commands for getting

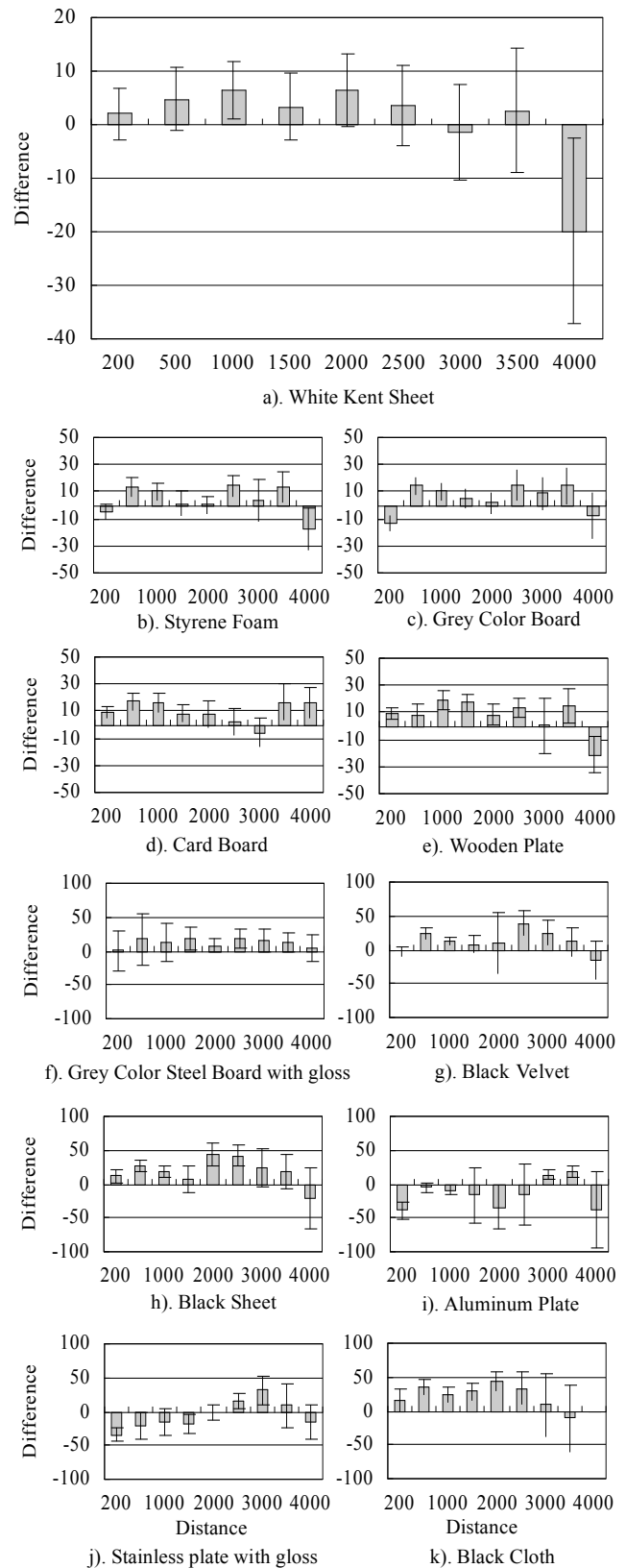


Fig. 8 Output of Sensor with various materials and its 3σ

different kinds of distance data (Ex. Data within certain range or full range, data with low/high resolutions etc). Furthermore, it has time stamp command, communication speed settings command and so on. "SCIP" design is based on ASCII. It has special method to express 16bit data as 3 characters and 12 bit data as 2 characters, though ASCII expresses 16-bit data as 4 characters. In detail, the maximum measurable distance of the sensor is 4095 mm with 1mm resolution. Thus each data can be expressed with 12 bits (0~4095[mm] range). These 12-bit binary codes are encoded to two 1-byte character codes.

III. EXPERIMENTAL RESULTS

A. Preliminary Experiment

We first conducted an experiment to check the waveform. Data is taken by placing white sheet 100, 2000 or 4000[mm] away from the front of the sensor (Fig.7). The dotted curves show transmitted wave while the continuous curves show the received wave. The transmitted wave is satisfactorily received for 4000[mm]. Fig.7(d) shows the wave with noise mixed in the signal that is thought as a result of the laser drive, we are currently looking for the methods to remove this existing noise.

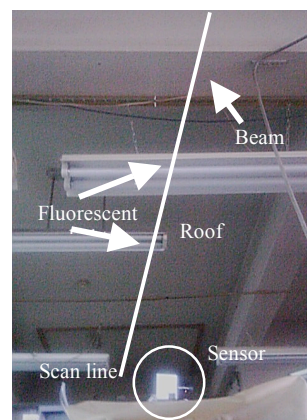
In the second experiment, we examined the measurement ability of the sensor with different objects. Table 2 shows the result of this experiment. So some materials could be detected for more than 4000[mm], maximum measurable distances of such materials are calculated by margin of surplus times 4000[mm]. There are some objects that could be detected only at the close range. Most of such materials had black surface that absorbed light. Thus measurement using the laser is highly influenced by the surface nature of the object. To satisfy the safety class 1, power of the laser could not be increased to detect such objects. We are currently investigating the alternative solution by increasing the sensitivity of APD and finding the measures to reduce noise.

Finally we conducted the experiments with different materials to find measurement accuracy. Fig.8 shows the objects used and the measurement data. As a standard, accuracy in case of white sheet could meet our requirement in the full range of 20 to 4095 [mm]. Similar results were found for the objects that had normal reflecting properties such as wood, cardboard etc. However in case of the materials that absorbed light or had highly reflective surfaces, measurement accuracy was poor. Special data correction techniques are under investigation to cure this problem.

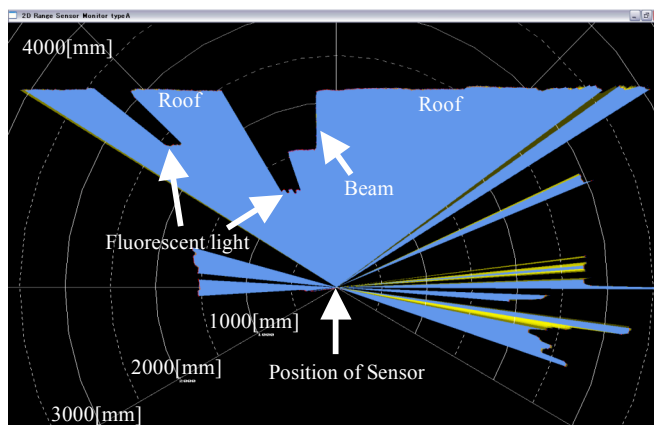
B. Display of real time sensor output

To use the sensor for environment detection in mobile robots it is essential to obtain as much information as possible with high accuracy. As we aim to develop this sensor for such applications we checked the ability of sensor to detect its surroundings.

Fig.9 shows the real environment data scanned by the sensor as a graphical display in the computer screen. It can be seen that the protruding beams and the roundness of the fluorescent lamp are effectively captured. Although with some limitations sensor can be used for the environment detection in



a). Situation



b). Output on PC Display

Fig.9 Display of Sensor Output

the mobile robots. Our future aim is to reduce or eliminate such limitations (detection of low or highly reflective objects) and increase the robustness of the sensor.

IV. CONCLUSION

We have developed small size and high-resolution 2D laser range scanner. And the commercial proto-type is named "URG-X002". We developed the ASIC to reduce size and obtain compact design with very lightweight.

We could achieve anticipated distance of 4095[mm] with high precision.

Our future work will include, developing ways to increase the data processing speed, and to calibrate the distance data. Further, we are also developing the sensor with max 10[m] output with similar principle used in this sensor.

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