20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

NEW INFRARED TIME OF-FLIGHT MEASUREMENT SENSOR FOR ROBOTIC PLATFORMS

M. Ruffo[2], M. Di Castro[1], L. Molinari[1], R. Losito[1], A. Masi[1], J. Kovermann[2], Luis Rodrigues[2]

[1.] *CERN, Switzerland*
[2.] *Terabee, France*

***Abstract* – Autonomous robots are becoming essential for a vast range of applications ranging from inspection to manipulation, often used for unstructured and harsh environments. Navigation sensors are part of the framework needed to operate such robots. In this paper a novel range finder sensor based on Time-Of-Flight technology is presented, this being suitable for integrating in aerial and ground robots. Speed, low weight and scalability are improved unique features compared to the state of the art in range finding solutions. Preliminary test results and comparison with other sensors of similar scope are shown.**

I. INTRODUCTION

Mobile robots are being increasingly considered for different applications in harsh or dangerous environments with the aim of replacing humans and increase operation safety. For instance, in underground scientific tunnel facilities such as at CERN (European Organization for Nuclear Research), mobile robots could help remote inspections and radiation surveys in different areas [1–6]. Stable position measurements are becoming an essential issue for every kind of autonomous system. All moving parts in a robotic platform need to know, with accuracy and at all times, where they are in a 3 dimensional space. This is a crucial point for implementing efficient strategies in navigation, environment mapping and related issues, such as obstacle avoidance and incident prevention.

A diverse range of technologies, exploiting different physical principles, have been developed during the last decades in order to ensure accurate measurements. A summary of the state of the art is given in the next section.

A new sensor based on the Time-of-Flight (ToF) is then presented and compared with the state of the art. The advantage of the new technology is anticipated in being high reading frequency, significantly lower weight and size, and potential scalability towards multi-pixel acquisition.

II. STATE OF THE ART

The most commonly used technologies for distance detection in autonomous navigation systems are ultrasound and laser triangulation.

A. Ultrasonic range finder

Ultrasonic transducers [7-13] generate high frequency sound waves and evaluate the echo received back after reflection from the target (Figure 1). The distance to the target is obtained by evaluating the time interval between the emitted signal and the received echo; hence this is considered a Time-of-Flight technology, based on ultra-sound waves. Some ultrasonic range finders are equipped with temperature sensors and a compensation circuit which corrects the estimated distance in case of temperature fluctuations in order to compensate for changes in the speed of sound due to different atmospheric conditions.

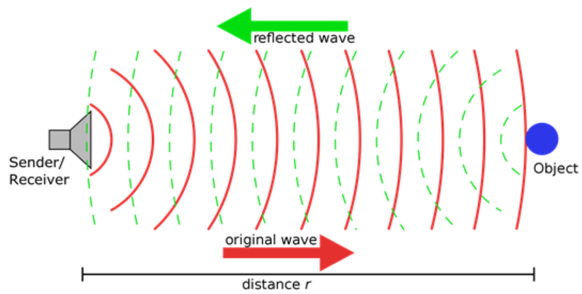

Fig. 1. Ultrasonic range finder operation.

B. Time-of-Flight-based range finder (LIDAR)

The Time-of-Flight sensor [18-21] works on the principle of measuring the time between the emission of a signal and its return home after being reflected by an object (Figure 2). The signal travels at constant velocity which allows the calculation of the distance. Light is preferred to sound because of its travel speed allowing higher measuring frequency. Infrared light is typically

ISBN-14: 978-92-990073-2-7

chosen because it ensures less disturbance and easier distinction from natural ambient light. A possible application in autonomous navigation is using rotating mirrors to create a 2 dimensional scanning platform able to cover an angle or field of view (Figure 3).

Fig. 2. Time-of-Flight technology operation.

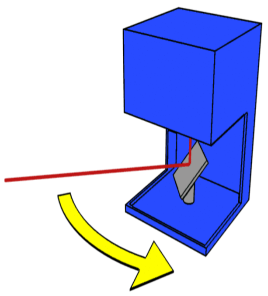

Fig. 3. 2D LIDAR operation

C. Summary of state of the art

Ultrasonic sensors are extensively used in autonomous navigation, especially in the field of obstacle avoidance [7-13]. With an ultrasonic sensor it is possible to detect an obstacle at a certain distance, but it is not possible to know where exactly the object is within the cone shape of the wave propagation. According to this, phenomenon the main difference to laser rangers is that the scanned area is not a single point but a whole conical volume.

Moreover, the simultaneous use of multiple sensors creates common cross-talk problems. Also the read out frequency is limited due to the speed of sound and the required detection range.

Due to their higher precision and directionality, laser scanners are preferred in the map-building and localization applications. To overcome the lack of sampling points of a single laser pointer, LIDAR (Light Detection and Ranging) can be used for 2D scans and increase the scanned area dimensions.

In summary, ultrasonic distance sensors offer a much lower cost but less accurate response compared to laser sensors today. However, they are preferable in situations such as outdoor navigation where laser scanners cannot work properly, mainly because of sunlight presence. Ultrasounds are also less influenced by different surface reflectivity (surface finish and colour which may or may not reflect infrared light) also if they are still highly dependent on some type of materials, such as sound absorbing surfaces (e.g. lawn, carpet etc.).

III. OBJECT OF THE STUDY

The novel sensor, subject of this study and called TeraRanger One[i], exploits the Time-of-Flight technology. It works similarly to a single point LIDAR system but without using a laser. It works exploiting the finite propagation speed of light, which is emitted from a source and received from an optical system, as in Figure 2. The sensor can operate in two different modes: Precision and Speed, which are self-explanatory. In precision mode, the sensor can compensate light and temperature variations.

The breakthrough comes from the use of LEDs as a source of a modulated infrared signal. The receiver matches the phase shift of the light modulation after its return to the sensor to calculate the distance to the reflecting object. The research for this new type of sensor is pushed by the need of a different approach to the indoor geo-localization problem. In order to measure and track even smaller movements, a higher measurement rate for a single point can be preferable to a larger number of acquired points (point cloud) at a lower rate. Another important factor is the stability of the reading – no sensor has a perfect still value and there is always a minimal jitter, but some sensors (i.e. ultrasound) are known to have big jumps in readings even at constant distance to a target. This implies a need to filter values which makes the sensor even slower than its usable refresh rate.

TeraRanger One is able to reach (in speed mode) an update rate of >1000 Hz which, compared to any other sensor on the market, shows an increment of up to 2 orders of magnitude. It must be noticed that this speed depends on distance (Figure 7) and on reflectivity properties of the target object.

By design, TeraRanger One tends to be very fast when the target is approaching the sub 6m range. Tests shown in this paper have been performed in both precision mode (PM) and speed mode (SM) in order to properly underline advantages and disadvantages of both the modes of operation. Speed mode is devised for collision avoidance, and in this case precision becomes a secondary purpose. Precision mode is necessary when the aim is navigation and hence a precise positioning system is preferred.

Precision and accuracy are important issues to be solved for a navigation system but those features are heavily restricted by the weight of the sensor. Robotic platforms, such as wheeled robots and drones, are usually payload-limited and in this case TeraRanger One, with its lightweight feature (it weighs less than 20g), allows users to employ it even in payload-critical situations.

A. Test Protocol

A test protocol has been defined and performed by CERN (fully independently from all sensor manufacturers) in order to fairly compare rangefinders based on different technologies.

The reference position is ensured by a measuring tape with ±2 mm accuracy and confirmed through a commercial high precision Laser Distance Meter with accuracy of ±2 mm. Taking into account uncertainty sources related to the test sensor positioning (parallax) the overall accuracy of the sensor positioning relative to the target can be estimated to be ±3 mm.

The target was illuminated by diffused sunlight (typical indoor light condition with windows).

The standard sensor parameters are evaluated: C.a non-linearity; C.b resolution; C.c accuracy; C.d precision; C.e measurement frequency.

These parameters have been calculated at different measurement ranges: 0.5 m (short range), 1 m, 3 m, 5 m, 8 m, 10 m and 13 m (long range where possible). For the Lidar rate evaluation, it has been considered that the measurement rate is referred to one single shot out of the overall 360 degree scan, so that the behaviour is similar to a laser rangefinder.

Considering that the TeraRanger's speed mode is devised for short range obstacle detection the test range has been fixed to <4.5 m in this mode.

B. Tested Transducer

This is the list of rangefinders tested, each one representing a specific technology:

- XL MaxSonar EZ Series MB1200 representing ultrasonic range finder technology [14]
- IR Laser range finder SF01 INT from LightWare Optoelectronics representing Laser or LIDAR.[17]
- UTM 30LX from Hokuyo Automatic Co. representing Lidar technology [22]
- TeraRanger One (TR One) representing Time-of-Flight IR LED technology, from Terabee.[23]

Table 1 shows a summary of sensors' specifications according to their datasheets [10, 13, 15].

Table 1. Declared specifications comparison.

	MB1200	*SF01-INT*	*UTM 30LX*	*TeraRanger One*
Resol.	1.0 cm	1.0 cm	1.0-10 cm	0.5 cm
Current req.	3-4 mA	150 mA	700-1000 mA	50-150 mA
Voltage req.	3.3-5.5V DC	4.5-5.5V DC	10.8-13.2 V DC	10-20 V DC
Weight	5.9 g	205 g	370 g	<20 g
Dim.	20x22x25 mm	60x52x155 mm	60x60x87 mm	32x27x15 mm
Max. Range	7.65 m	60 m	30 m	14 m
Op. T	0 – 65 ˚C	-10 – 50 ˚C	-10 – 50 ˚C	-10 – 50 ˚C
Meas. Rate	10 Hz	8 Hz	40 Hz(1)	1000 Hz(2)
Approx. Price	40 € VAT incl.	480 € VAT incl.	4600 € VAT incl.	150 € VAT incl.

(1) Rate is referred to one single shot out of the overall rotational scan.

(2) 1 KHz is the maximal value reachable in speed mode (reduced precision) and preferable conditions such as <4.5m distance on non IR absorbing materials.

Fig. 4. Hardware overview.

C. Experimental results

a. Non-linearity

The non-linearity [24] is evaluated quantifying the maximum deviation of the measured values from a first order polynomial fit (between the reference and measured values) and expressed as a percentage of the total range. In the table 2 the non-linearity values of the four sensors are compared.

Table 2. Non-linearity tests results.

	MB1200	*SF01-INT*	*UTM 30LX*	*TR One (PM)*	*TR One (SM)*
%	1.33 (6 m)	0.34 (13 m)	0.25 (13 m)	0.29 (13 m)	4.16 (4.5m)

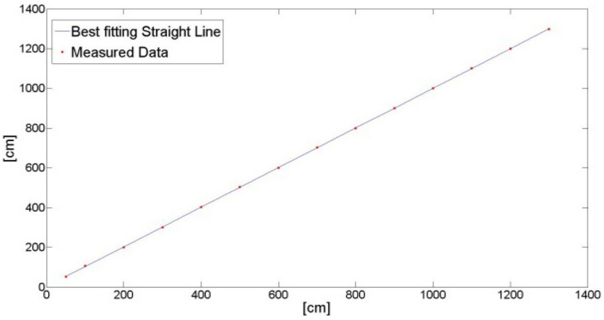

Fig. 5. TeraRanger One (PM) Linearity evaluation

b. Resolution

The resolution is evaluated as the smallest detectable displacement increment. In table 3 the results summary for the different measurement ranges are shown.

Table 3. Resolution test results (cm).

Range	*MB1200*	*SF01-INT*	*UTM 30LX*	*TR One (PM)*	*TR One (SM)*
50 cm	*1.0*	*0.5*	*1.0*	*0.5*	*> 5cm*
100 cm	*1.0*	*0.5*	*1.0*	*0.5*	*> 5cm*
300 cm	*1.0*	*0.5*	*1.0*	*0.5*	*> 5cm*
500 cm	*1.0*	*1.0*	*1.0*	*1.0*	*OoR**
800 cm	*OoR*	*1.0*	*1.0*	*1.0*	*OoR**
1000 cm	*OoR*	*1.0*	*2.0*	*1.0*	*OoR**
1300 cm	*OoR*	*1.0*	*2.0*	*1.0*	*OoR**

**OoR: Out of Range*

c. Accuracy

The accuracy is defined as the maximum deviation of the measured displacement with respect to the reference value. The measured value is obtained by a mean of 400 sequential values read.

Table 4. Accuracy tests results (cm).

Range	*MB1200*	*SF01-INT*	*UTM 30LX*	*TR One (PM)*	*TR One (SM)*
50 cm	*5.0*	*1.0*	*1.0*	*2.0*	*2.0*
100 cm	*6.0*	*2.0*	*1.0*	*2.0*	*3.5*
300 cm	*8.0*	*1.3*	*2.0*	*2.0*	*>10*
500 cm	*9.0*	*2.0*	*2.0*	*2.2*	*>10*
800 cm	*OoR*	*1.5*	*2.0*	*2.2*	*OoR**
1000 cm	*OoR*	*2.0*	*2.0*	*2.3*	*OoR**
1300 cm	*OoR*	*3.0*	*3.0*	*3.2*	*OoR**

Table 5. Maximum deviation from mean value (cm).

Range	*MB1200*	*SF01-INT*	*UTM 30LX*	*TR One (PM)*	*TR One (SM)*
50 cm	*0*	*0.7*	*1.2*	*1.2*	*1.5*
100 cm	*0*	*0.8*	*1.0*	*1.3*	*3.0*
300 cm	*0*	*0.8*	*1.2*	*2.1*	*>10*
500 cm	*0*	*1.2*	*1.1*	*1.8*	*>10*
800 cm	*OoR*	*1.8*	*1.7*	*2.2*	*OoR**
1000 cm	*OoR*	*1.6*	*1.6*	*1.8*	*OoR**
1300 cm	*OoR*	*2.5*	*2.1*	*2.7*	*OoR**

d. Precision

The precision is evaluated as the standard deviation of repeated displacement measurements. At each measurement range 400 measurement values have been read. Table 6 summarizes the precision values for the four sensors at the different measurement ranges.

Table 6. Standard deviation (cm).

Range	*MB1200*	*SF01-INT*	*UTM 30LX*	*TR One (PM)*	*TR One (SM)*
50 cm	*0.0*	*0.44*	*0.52*	*0.58*	*0.43*
100 cm	*0.0*	*0.45*	*0.48*	*0.49*	*1.17*
300 cm	*0.0*	*0.43*	*0.48*	*0.74*	*8.14*
500 cm	*0.0*	*0.46*	*0.52*	*0.83*	*23.51*
800 cm	*0.0*	*0.49*	*0.64*	*0.92*	*OoR**
1000 cm	*OoR*	*0.53*	*0.68*	*0.81*	*OoR**
1300 cm	*OoR*	*0.68*	*0.74*	*1.13*	*OoR**

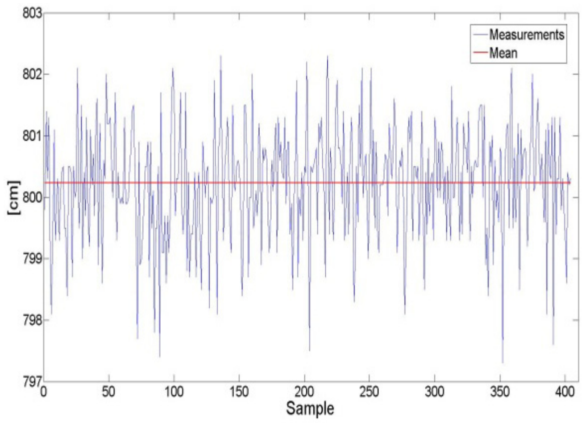

Fig. 6. TeraRanger One Reproducibility evaluation (8 m)

e. Refresh rate

The measurement rate has been evaluated by counting the number of returned values in a fixed interval time of 1 minute. In this case it has been decided to test it at different measurement distances (0.5 m, 1.0 m, 3.0 m, 5.0 m, 8.0 m, 10 m, and 13.0 m) in order to underline contingent dependencies from the measured value. Table 7 gives a quantification of the real valid rate at different distances of the sensors.

Table 7. Speed evaluation (Hz).

Range	*MB1200*	*SF01-INT*	*UTM 30LX*	*TR One (PM)*	*TR One (SM)*
50 cm	*9.8*	*7.6*	*39.7*	*514.9*	*1046.5*
100 cm	*9.9*	*7.9*	*39.8*	*444.5*	*1046.7*
300 cm	*9.8*	*7.9*	*39.9*	*194.2*	*1047.9*
500 cm	*9.9*	*7.9*	*39.9*	*66.3*	*1049.3*
800 cm	*OoR*	*7.9*	*39.9*	*18.2*	*OoR**
1000 cm	*OoR*	*7.8*	*39.9*	*9.3*	*OoR**
1300 cm	*OoR*	*7.9*	*39.9*	*4.6*	*OoR**

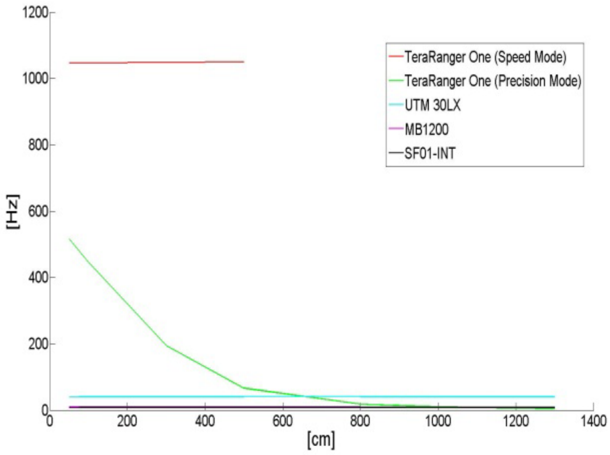

Fig. 7. Rate comparison

IV. CONCLUSIONS AND FUTURE WORK

A novel distance ranging device for autonomous navigation, its lightweight makes it suitable for all kinds of robotic platforms, even in payload-limited conditions (flying devices such as drones, wheeled robot, robotic arms). Its good accuracy combined with its high speed allows using it for autonomous system position definition and navigation.

Next step of a further analysis of this range finder is the study of performance under different ambient conditions.

V. CITATIONS AND REFERENCES

[1] G. Benet, F. Blanes, J.E. Simó, P. Pérez, “Using infrared sensors for distance measurement in mobile robots”. Departamento de Informática de Sistemas, Computadores y Automática, Universidad Politécnica de Valencia

[2] G. Benet, J. Albaladejo, A. Rodas, P.J. Gil, “An intelligent ultrasonic sensor for ranging in an industrial distributed control system”, IFAC Symposium on Intelligent Components and Instruments for Control Applications, Malaga, Spain, May 1992, pp. 299–303.

[3] Nagatani, K.; Kiribayashi, S.; Okada, Y.; Tadokoro, S.; Nishimura, T.; Yoshida, T.; Koyanagi, E.; Hada, Y. “Redesign of rescue mobile robot Quince”. 2011 IEEE International Symposium on Safety Security and Rescue Robotics, 2011, pp. 13–18.

[4] Murphy, R.; Kravitz, J.; Stover, S.; Shoureshi, R. “Mobile robots in mine rescue and recovery. Robotics Automation Magazine”, IEEE 2009, 16, 91 –103.4.

[5] Kershaw, K.; Chapron, F.; Coin, A.; Delsaux, F.; Feniet, T.; Grenard, J.L.; Valbuena, R. “Remote inspection, measurement and handling for LHC”. Particle Accelerator Conference, 2007. PAC. IEEE, 2007, pp. 332 –334.

[6] Fabry, T.; Vanherpe, L.; Baudin, M.; Theis, C.; Braesch, C.; Feral, B. “Interactive intervention planning in particle accelerator environments with ionizing radiation. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated”, Equipment 2013, 708, 32 – 38.

[7] Tsutomu Tanzawa, Noriaki Kiyohiro, Shinji Kotani, Hideo Mori, “The Ultrasonic Range Finder for Outdoor Mobile Robots”, Dept. of Electr. Eng. & Comput. Sci., Yamanashi Univ., Kofu, Japan

[8] Roman Kuc and Billur Barshan : "Docking Mobile Robots Using a Bat-like Sonar", IEEE/RSJ International Conference on Intelligent Ro1ior.P and Systems. pp. 1439-1444. 1994

[9] Yoshiaki Nagashima and Shin'ichi Yuta: "Ultrasonic sensing for a mobile robot to recognize an environment": IEEW/RSJ International Conference on Intelligent Robots and Systems. Vo1.2, pp.805-812, 1992

[10] Soo-Yeong Yi, Byoung-Wook Choi, “Autonomous Navigation of Indoor Mobile Robot Using Global Ultrasonic System”, Dept. of Electrical Engineering, Seoul National University of Technology, Republic of Korea

[11] H. Seki, S. Kobayashi, Y. Kamiya, M. Hikizu, H. Nomura: “Autonomous / Semi-autonomous Navigation System of a Wheelchair by Active Ultrasonic Beacons”, Department of Mechanical Systems Engineering, Kanazawa University.

[12] Akihisa Ohya, Akio Kosaka, and Avinash Kak, “Vision-Based Navigation by a Mobile Robot with Obstacle Avoidance Using Single-Camera Vision and Ultrasonic Sensing”, ieee transactions on robotics and automation, vol. 14, no. 6, december 1998

[13] Dirk Langer and Charles Thorpe: "Sonar Based Outdoor Vehicle Navigation and Collision Avoidance": IEEWRSJ International Conference on Intelligent Robots and Systems, pp. 1445-1450, 1992

[14] Data sheet for XL-Maxsonar-EZ MB1200 High Performance Sonar Range Finder, MaxBotix Inc.

[15] Rainer G. Dorsch, Gerd Häusler, and Jürgen M. Herrmann “Laser triangulation: fundamental uncertainty in distance measurement”, Physics Institute, University of Erlangen-Nürnberg

[16] Kazuhiro Yoshida and Shigeo Hirose, “Laser triangulation range finder available under direct sunlight”, Tokyo Institute of Technology

[17] Data sheet for SF01 Laser Range Finder, LightWare Optoelectronics

[18] Ari Kilpelä, “Pulsed time-of-flight laser Range finder techniques for fast, high precision measurement applications”, Department of Electrical and Information Engineering, University of Oulu

[19] Saurabh Ladha, Deepan Kishore Kumar, Pavitra Bhalla, Aditya Jain, Prof. Dr. R.K. Mittal, “Use of LIDAR for Obstacle Avoidance by an Autonomous Aerial Vehicle”. Birla Institute of Technology and Science Pilani, Dubai Campus, UAE

[20] Uland Wong, “Terrain Obstacle Detection and Analysis using LIDAR”. PROSPECT Group Robotics Institute Carnegie Mellon University

[21] Norbert Haala, Michael Peter, Jens Kremer, Graham Hunter “Mobile lidar mapping for 3d point cloud collection in urban areas”

[22] Data sheet for UTM 30LX, Hokuyo Automatic Co

[23] Data sheet for TeraRanger V2, Terabee

[24] Keneeth Emancipator and Martin H. Kroll “A quantitative Measure of Nonlinearity”