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Testing ToF Sensors for Use in Obstacle Detection Systems

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Abstract. ToF (*Time of Flight*) sensors have been gaining popularity in recent times as a cheap and accurate way to take distance measurements. They may prove to be a key component of obstacle detection systems in the near future. This paper presents a stepper motor system with two measurement modules containing ToF sensors. The results of distance measurements made with these modules relative to a flat surface for different sensor modes are presented. Standard deviations were determined for the measurement results and a polynomial fitting was performed using the linear least squares method. The results were used to select the sensor for further work in terms of its use in an obstacle detection system.
Keywords: distance measurement, ToF sensors, obstacle detection

1. INTRODUCTION

Distance measurements are one of the most common measurements performed in industries with automated production processes. For example, distance sensors can detect approaching objects or check the correctness of processes in production lines. One of the technologies at work in the field of distance measurement is ToF (*Time of Flight)* sensors which rely on measuring the transit time of a beam of light from the sensor to the object and back [1]. Such time-of-flight measurement has already been used successfully in ultrasonic distance sensors, but the development of beam-based sensors in combination with a camera has made it possible to achieve colour mapping effects of the environment in three-dimensional space. The rapid development of industrial robots is driving today's ToF sensor market. The sensors are increasingly used in computer vision systems, including augmented reality [2, 3, 4] and, for example, in 3D object reconstruction (in combination with cameras) [5].

Due to the use of light beam-based phenomena, the measurement process itself is extremely fast, thus allowing the use of ToF sensors in real-time systems [6]. With real-time capability, high measurement frequency and machine learning development, it is possible to use ToF technology sensors to obtain real-time information about objects in space, which provides a basis for their use in obstacle detection systems. Examples include the use of ToF sensors in car parking assistance systems [7], mobile robotics [8, 9, 10], and in robotic assistance [10]. Obstacle detection systems using ToF can also be used to improve workplace safety or be part of electronic aids such as mobile obstacle detectors.

At the same time, ToF technology has two major limitations. The first is the impact of lighting conditions on measurement error, mainly when a large amount of infrared light is included in the lighting. The second limitation concerns transparent objects that reflect the laser beam to a small extent.

This paper presents the results of distance measurements made with low-cost ToF sensors for their selection for use in an obstacle detection system.

2. SENSORS USED IN RESEARCH

Two types of miniature sensors were used for this study: VL53L3CX (hereafter referred to as L3) and VL53L1CB (hereafter referred to as L1). They employ surface emission lasers with a vertical resonant cavity. Single-photon avalanche diodes (*SPADs*) with a physical infrared filter are used as emitters. Typical beam widths radiated by the emitter are 25° and 27°, respectively, and the sensors enable distance measurements at up to 300 and 400 cm, respectively. The former sensor can be used for multi-object detection in addition to single-point distance measurement. The second one enables single point distance measurement and region of interest (ROI), where the user can program the zones in which the measurement is taken.

Both sensors have 3 adjustable pre-set modes (Short, Medium, Long). Each of these modes has a different range and measurement error depending on the lighting conditions. The manufacturer reports high dependence of the measurement results on lighting conditions. The *Long* mode, for example, is designed for measurements up to 360 cm in an environment without infrared components, and up to 73 cm in an environment with infrared components, while the Short mode will allow for correct measurements up to a maximum of 136 cm (without infrared components) and 135 cm (with infrared components). For the sensors, the measurement modules shown in Fig. 1, which contain three sensors of each type, were developed and drafted.

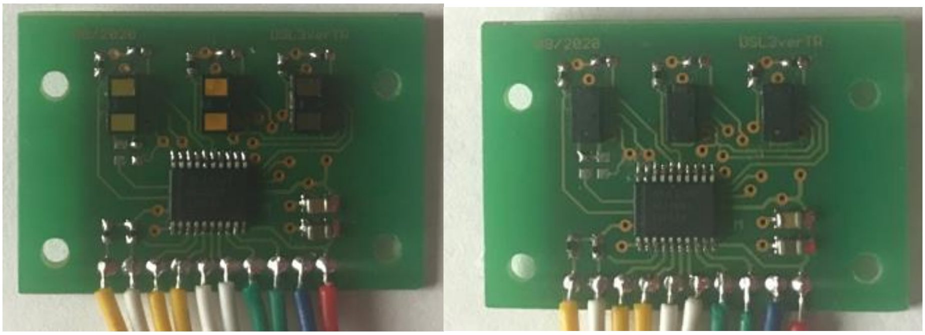

Fig. 1. Measuring modules with 3 L1 (left) and L3 (right) sensors

Each sensor has an integrated controller to control how the sensor operates and triggers the measurement. The sensors are controlled via a dedicated application programming interface (API). The sensors were controlled by a Teensy 4.1 single-board computer using the I^{2}C bus.

3. RESEARCH SUBJECT AND PROCEDURE

The subject of the research was ToF sensors to be used in a mobile obstacle detection system, developed in one of the projects carried out in the Central Institute for Labour Protection – National Research Institute. By definition, the system will change its position and tilt relative to its surroundings, so verification of the ToF sensor's suitability cannot be based on the distance measurement value alone, but on the correct interpretation of a series of measurements. It is important to note that some measurements will be made when the sensor is positioned at a certain angle to the objects. For this purpose, a multi-point measurement and information about the values of the parameters related to the position of the sensors (e.g. rotation angle) in which the measurement was performed is necessary. Interpretation of the measurement could then depend on differences in measurements for specific positions, especially related to flat surfaces.

The test procedure involved taking measurements for a flat surface. The distance measurements were performed relative to the adopted reflecting surface under the same lighting conditions, i.e. in a room with a window (measurements performed during the day) and LED lighting. A flat white projection screen was used as a reflective surface. The measurement modules presented in the previous section were assembled in a single system with a stepper motor that controlled the angle of rotation of the modules relative to the reflecting surface (Fig. 2).

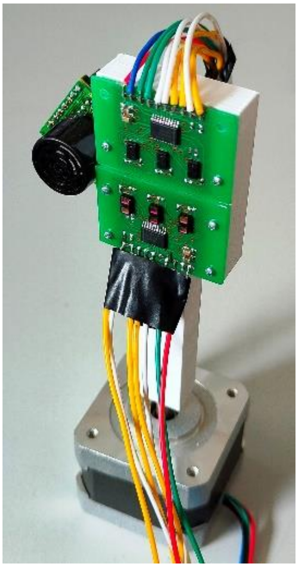

Fig. 2. Sensor system with stepper motor

The scope of the study included a point distance measurement for each sensor for 7 different setup distances of the stepper motor sensor system (50 cm, 75 cm, 110 cm, 135 cm, 160 cm, 185 cm, 210 cm) for each ToF sensor mode (short, medium, long) and 25 stepper motor positions. The focus of the study was to correctly determine if the results of the distance measurements to the mapped object could be approximated by a function with a regression model and to determine the standard deviation for each series of measurements. The precision of determining the position for which the measured value is lowest provides a reference when verifying the presence of a flat obstacle.

4. RESULTS OF THE STUDY

Point distance measurements were taken for 25 stepper motor positions (1.8° increments). The modules on the stepper motor were installed in such a way that the central sensor on both modules was positioned relative to the motor's axis of rotation.

Since the sensors were installed on the same plane at a short distance from each other (5 mm between sensors) in both modules, it was assumed that the measurements for each sensor were taken at the same point. When the plane defined by the modules is parallel to the plane of the reflecting surface, the value of the distances measured by the sensors should be the lowest. A graph showing the results of distance measurements taken with the centre sensors on both modules for a minimum distance of 110 cm and two operating modes (short and medium) is shown in Fig. 3.

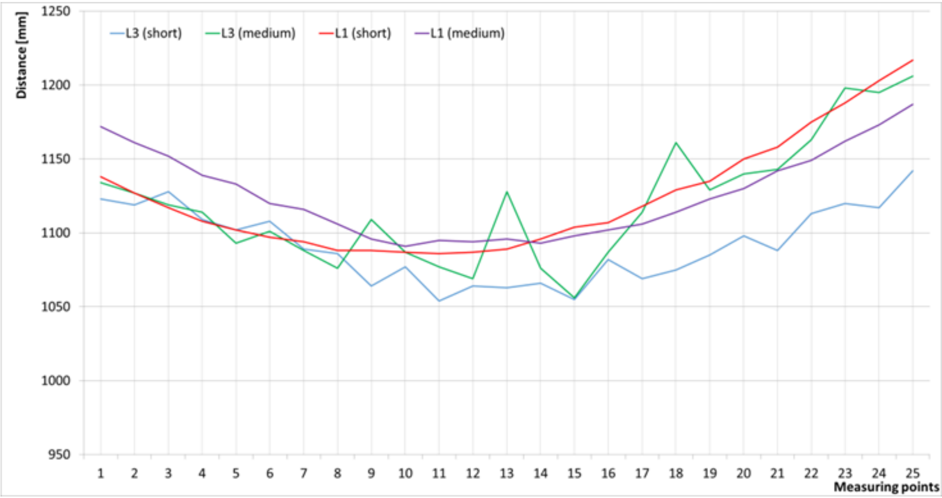

Fig. 3. Measurement results of the centre distances of the L1 and L3 sensors for a minimum distance of 110 cm

As expected, the more the sensor system was deviated from the parallel plane, the larger the values measured by the sensor. Measurements were performed sequentially from right to left, with the 13th measurement performed when the system with modules and the projection screen were parallel to each other. The graph shows large differences in the read distances (sometimes reaching 40 mm) with successive measurements with the L3 sensor. The results obtained with the L1 sensor do not show large differences between successive measurements, and the graphs formed from them show a parabolic character. Knowing the value of the rotation angle for the stepper motor step and the position in which the modules with the ToF sensors are placed parallel to the surface of the projection screen, it is possible to determine the value of the perpendicular straight line l’ crossing the plane of the projection screen and the plane parallel to the projection screen passing through the measurement point as in Fig. 4.

For each step, the value of l’ was calculated using the cosine function. The desired results would be graphs with constant functions corresponding to values of the system’s distance from the projection screen. The results are shown in Fig. 5 for sensor L1 and in Fig. 6 for sensor L3.

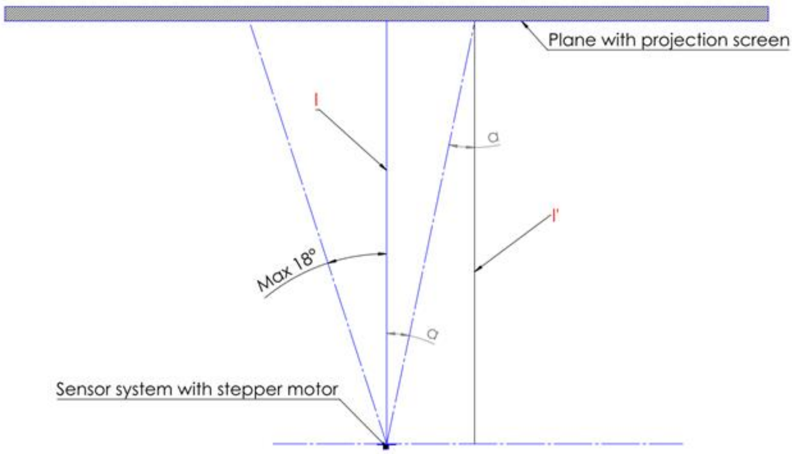

Fig. 4. Simplified measurement diagram

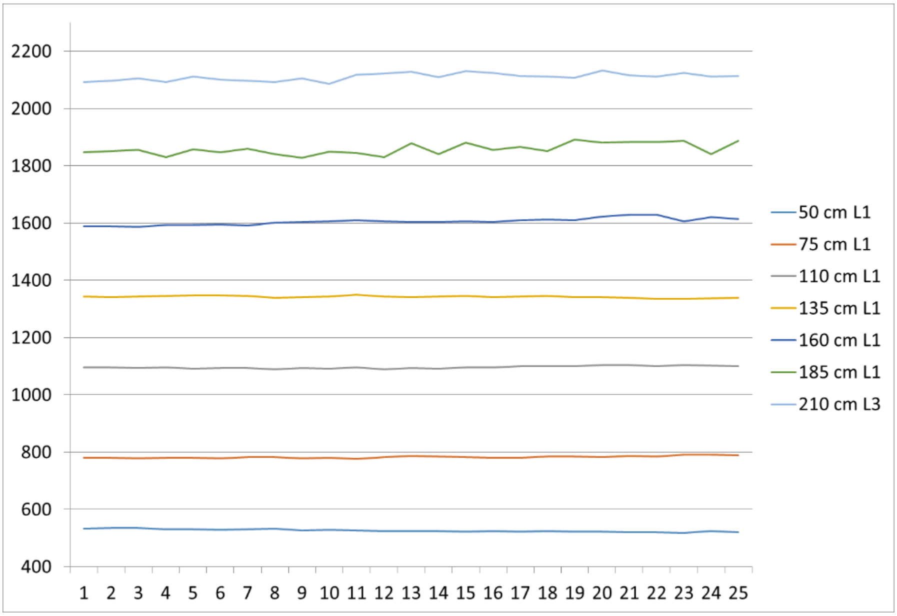

Fig. 5. Values of l’ for individual measuring points
when measuring with sensor L1.

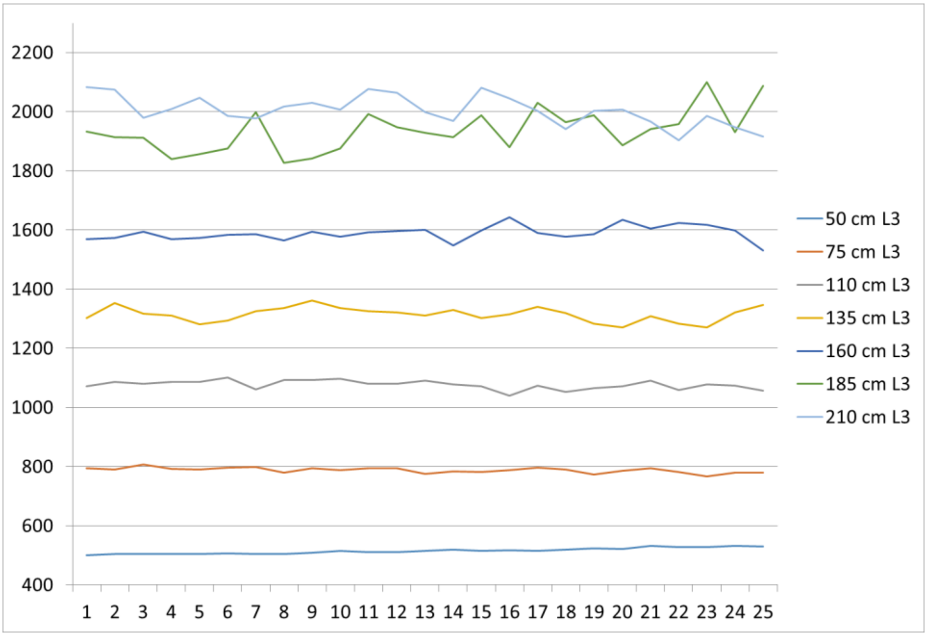

Fig. 6. Values of l' for individual measuring points
when measuring with sensor L3.

In the case of sensor L1, the conversion results for measurement values between 50 cm and 160 cm show little variation, proving that the measurement is correct when the obstacle is at an angle to the sensor. Slightly higher trends of change occur for distance measurements of 185 cm and 210 cm. The graph showing the l' values for the L3 sensor, on the other hand, already shows a large variation from a distance of 110 cm. For each series of measurements, a measure of variability was determined, i.e. the standard deviation by sensor, mode, and minimum distance. The results are provided in Table 1.

Table 1. Standard deviation values for L1 and L3 sensors in different operating modes and minimum distances tested.

	L3									L1								
	short			medium			long			short			medium			long		
Distance	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
50 cm	17	12	10	25	20	18	13	10	7	9	6	5	12	8	8	13	9	10
75 cm	9	12	15	24	21	21	47	52	74	3	4	4	3	7	6	13	10	8
110 cm	15	19	18	21	18	14	41	30	25	5	9	9	17	13	13	4	8	7
135 cm	38	42	45	21	25	26	35	51	44	6	4	4	3	4	4	5	6	4
160 cm	34	46	28	25	31	30	58	49	46	12	9	9	47	54	51	12	18	17
185 cm				79	83	74	71	83	87				39	46	45	20	24	25
210 cm				65	69	50	74	74	84				13	30	22	21	26	25

Based on the results presented, it is possible to determine which sensor exhibits greater resistance to distance measurements from surfaces placed at an angle.

However, the results are subject to misalignment of the parallelism of the projection screen planes and the sensor system with respect to each other. Therefore, it was decided to perform the model calculation by fitting a second degree polynomial by minimising the sum of squares of the residuals i.e. the least squares method. The results, in the form of correlation coefficient for the fit of each measurement series, are shown in Table 2.

Table 2. Correlation coefficient for least squares polynomial fitting for L1 and L3 sensors in different operating modes and minimum distances tested.

	L3									L1								
	short			medium			long			short			medium			long		
Distance	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
50 cm	0,99	0,98	0,99	0,97	0,97	0,98	0,95	0,90	0,90	0,97	0,97	0,99	0,98	0,98	0,99	0,96	0,91	0,94
75 cm	0,88	0,90	0,83	0,94	0,94	0,93	0,70	0,57	0,82	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,98	0,99
110 cm	0,80	0,88	0,90	0,89	0,82	0,86	0,73	0,80	0,70	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99
135 cm	0,86	0,80	0,80	0,73	0,64	0,79	0,48	0,47	0,58	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99
160 cm	0,46	0,13	0,61	0,80	0,69	0,60	0,35	0,32	0,73	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99
185 cm				0,44	0,24	0,40	0,73	0,34	0,59				0,99	0,99	0,99	0,94	0,95	0,95
210 cm				0,21	0,13	0,46	0,42	0,37	0,57				0,98	0,96	0,97	0,92	0,87	0,88

The green colour in the table indicates the highest values of the correlation coefficient (not less than 95%), while the red colour indicates its lowest values. For the L1 sensor, low correlation coefficients were obtained, indicating high variability of the results at successive measurement points. This variability can significantly affect the interpretation of measurements at a distance of 135 cm and higher. This is different for the L3 sensor, where the worst-case correlation coefficient was 0.87, demonstrating the high fit of the second-order polynomial model to the results of the measurements.

5. CONCLUSIONS

This paper briefly discusses the use of ToF sensors in distance measurement procedures. The results of distance measurements using sample ToF sensors relative to a flat surface are presented. Measurements were made for several different distances, for different angles of incidence of the beam emitted by the sensors, and their different modes of operation. The standard deviation values obtained indicate that the distance measurements are valid for an object angled to the plane of the sensors. A fit of the distance measurements to a second-degree polynomial was also performed using the least squares method. The correlation coefficients for the measurements made with the L3 sensor prove a good fit, thus confirming the validity of the measurement results. The presented test results enable the selection of the better sensor for use in a mobile obstacle detection system.

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Badania czujników ToF pod kątem ich wykorzystania w systemach detekcji przeszkód

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Streszczenie. Czujniki ToF w ostatnich czasach zdobywają popularność jako tani i dokładny sposób na dokonanie pomiarów odległości. W niedalekiej przyszłości mogą okazać się kluczowym komponentem systemów detekcji przeszkód. W ramach niniejszego artykułu przedstawiono układ z silnikiem krokowym na którym zainstalowano dwa moduły pomiarowe zawierające czujniki ToF. Zaprezentowano wyniki pomiarów odległości przeprowadzonych przy użyciu tych modułów względem płaskiej powierzchni dla różnych trybów działania czujników. Dla wyników pomiarów wyznaczono odchylenia standardowe oraz dokonano dopasowania wielomianu za pomocą liniowej metody najmniejszych kwadratów. Wyniki posłużyły do doboru czujnika do dalszych prac pod kątem jego wykorzystania w systemie detekcji przeszkód.
Słowa kluczowe: pomiary odległości, czujniki ToF, detekcja przeszkód