TF-Mini LiDAR Sensor Performance Analysis for Distance Measurement

Fardiansyah Nur Aziz[1], Masduki Zakarijah[2]

***Abstract*—The digitalization development is accelerating, making it possible to measure the distance without touching the objects. Light detection and ranging (LiDAR) sensors are widely available on the market as components for distance measurement. Numerous studies on LiDAR sensor application have been conducted, including research on automated guided vehicle (AGV) robots, quadcopters, and tropical vegetation mappings. Previous research focused on LiDAR sensor application but did not evaluate its precision and features in depth. There are possibilities that the components' performances do not conform with the technical data standards. This study presents the performance testing results of a TF-Mini LiDAR sensor for distance measurement. This TF-Mini LiDAR sensor testing used an experimental method. The sensor performance was determined by the maximum distance reading, accuracy level, objects' color effect, tilt, and material type of objects being read. The testing results showed the TF-Mini LiDAR sensor had an accuracy rate of 3.17% in the range of 0.3 m to 6 m and 3.27% in the range of 6 m to 12 m, with a maximum reading distance of 10 m. Blue and iron were the most readable hue and material, with an average error rate of 2.78% and 3.2%, respectively. The distance reading results on flat objects with a tilt between 10° and 80° (quadrant 1) exceeded the actual distance as objects' angle tilt increased, with the yielded error average of 7%. The average inaccuracy for flat objects with a tilt between 100° and 170° (quadrant 2) was 2.75%. Additionally, the distance reading accuracy improved as the objects' degree of tilt increased. Based on the testing results, the TF-Mini LiDAR sensor could measure distances more precisely when the detected item was between 0.5 m and 10 m away, has a non-light-absorbing color and material, and is in the straight state.**

***Keywords*—LiDAR, TF-Mini LiDAR, Distance Measurement, Digitization, Analysis, Performance.**

I. INTRODUCTION

Currently, digitalization is growing and evenly spread [1]. In measuring distance or length units, distance generally can only be measured using manual instruments such as a ruler, measuring tape, or caliper. However, digitalization has enabled measurement procedures to be conducted without touching devices or objects being measured [2].

Digitalization in measurements has been widely adopted. In unmanned aerial vehicles (UAV), digital measurements are utilized to measure altitude, determine the distance between an object and other nearby objects, and map the terrain. In industrial robots, digital measurement is performed to avoid obstacles (obstacle avoidance), detect the arrival of objects, and determine the size of the room.

Today, measurement is the pivot of the control system because it is crucial for controlling the device to one's liking [3]. Multiple studies and developments have been carried out to manufacture or create smarter, more effective, secure, and efficient digital measurement technologies. The engineers have attempted to create an accurate digital measurement technology to boost efficiency. Utilizing and selecting components whose characteristics match those of the manufactured tools might be a means of achieving this efficiency.

Rapid technological advancements [4] has led to the growing number of factories or manufacturers of digital distance measurement components. As a result, various product options are available, both in terms of quality and cost. Light detection and ranging (LiDAR) sensors are readily available on the market as a component for digital distance measurement. LiDAR is the sensor most commonly used in autonomous cars and is commonly used for localization, mapping, and object detection [5].

Different LiDAR sensor devices with different specifications and quality can provide more options in the design of digital distance measurement systems. The performance parameters of the LiDAR sensor can be determined based on the sensor's response when the object being measured is not in its ideal state, that is when it is tilted to a particular degree. In addition, the accuracy of the sensor in reading the distance of the object being measured affects the measurement performance. The less the difference between the actual distance and the distance from the LiDAR sensor readings, the better the accuracy.

However, the sensor component's performance for digital distance readings may not conform with the specifications provided. Some LiDAR sensors may have a performance mismatch between the technical data contained in the component and the actual performance of LiDAR sensors. It results in a disparity between the outcomes of the tool's design with its performance in actual conditions. Therefore, it is vital to test components before designing a digital distance measurement system to ensure that the results of implementation correspond to the design [6].

Based on these factors, this study evaluated one type of LiDAR sensor used for digital distance measurement in order to determine the sensor's specifications, performances, and characteristic parameters. The type of LiDAR sensor observed in this study was the TF-Mini LiDAR which is manufactured by Benewake.

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Fig. 1 Example of a LiDAR sensor.

II. LIDAR SENSOR TESTING

A. *Light Detection and Ranging (LiDAR)*

The principle of *LiDAR* technology is to measure objects' distance using a laser light. LiDAR is an efficient technology used to collect distance data of an object [7]. Fig. 1 depicts the LiDAR sensor.

In the work principle, LiDAR sensors determine the length or distance of an object based on its time of flight (ToF). When operating, this sensor emits infrared laser waves. The resulting infrared waves are modulated over a certain period, and they reflect light when hitting objects. The LiDAR sensor obtains ToF by measuring the alternating phase difference, then calculating the relative distance between the sensor and detected object [8]. Fig. 2 depicts the scheme of ToF principles.

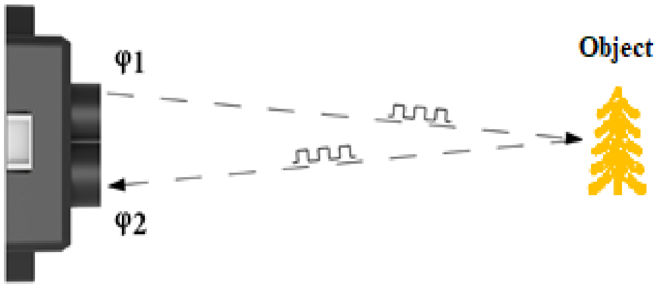

Fig. 2 Time of flight (ToF) principle.

$$ToF = nT + \frac{\varphi}{2\pi}T. \quad (1)$$

Equation (1) is a formula for calculating ToF based on the phase difference (∏) between the transmitted wave and the reflected wave from an object, where *n* is the number of full waves and *T* is the time required for light to travel one wavelength.

$$D = \frac{C * ToF}{2}. \quad (2)$$

Once the ToF value is determined, the distance (*D*) can be calculated. Equation (2) is a formula for calculating the distance based on known ToF, where *C* is the value of the light speed in the air [9].

B. *Application of LiDAR Sensor*

Numerous studies on LiDAR sensor usage have been conducted in the past. One study mapped tropical vegetation and land cover using LiDAR sensors [10]. The results showed that the LiDAR sensor could visualize maps of land cover and vegetation in the digital elevation model (DEM), digital surface model (DSM), and orthophoto, which were then processed and used as crown height model (CHM) data.

The implementation of LiDAR sensors functioning as an altitude control for quadcopter robots has also been carried out [11]. The results showed that the quadcopter could fly steadily and the average inaccuracy while using LiDAR was 3.9%. The LiDAR sensor used had a smaller error when the quadcopter was at an altitude of more than 1 m.

Another study utilized LiDAR sensors combined with vector field histograms and supervisory controls in automated guided vehicle (AGV) robots to avoid obstacles [12]. According to the findings of the implementation, LIDAR sensors controlled the AGV robot on a map containing specific obstacles. The implementation of obstacle avoidance problems was successful in simulations at different levels.

Additionally, research on the determination of air conditioning (AC) capacity in a square room using an Arduino Uno-based LiDAR sensor has been conducted [13]. The results showed that the average volume measurement of ten rooms resulted in a deviation of 1.66% compared to manual measurements.

LiDAR sensors have been employed in different research to determine the direction of the aircraft's longitudinal motion in its parking system [14]. The research' findings suggested that the developed tool could provide information for the pilots in the form of a display that guides them to steer the aircraft to the right or left to align with the correct center line position.

Numerous earlier research focused on using the LiDAR sensors without thoroughly examining their accuracy when tested with the variations of the detected objects' distance, color, tilt angle, and surface material. In this study, testing was conducted on the Benewake's TF-Mini LiDAR sensor. The decision to use this sensor type was made due to its popularity among the other LiDAR sensors available today. Since there are so many products available, there may be differences between the performance of the results under real-world situations and the LiDAR parameters provided in the datasheet. It could explain as to why validating the LiDAR sensor's functionality is essential prior to using it for digital distance measurement.

C. *Distance Measurement*

Measurement is the systematic process of determining the number of objects. In the presentation of information and in the advancement of science and technology, measurement plays a crucial function. According to [15], measurement is the process of assigning value to certain attributes or characteristics possessed by certain objects, people, or things based on clear rules and formulations. Another opinion states that measurement is a comparison between the value of the quantity being measured and another quantity serving as a reference (of the same type) [16].

Length or distance is a physical quantity, which is something whose existence can be measured and expressed numerically

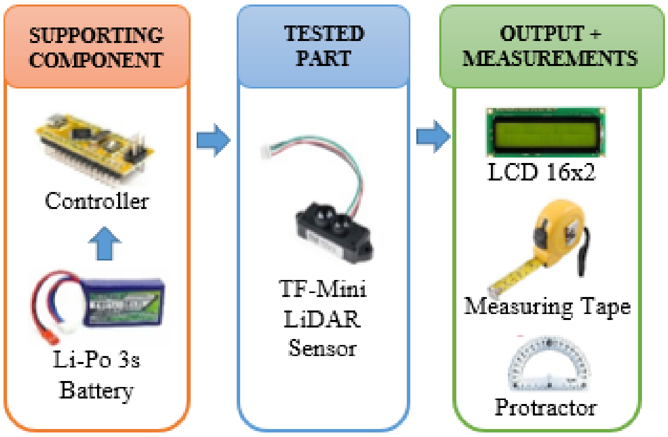

Fig. 3 Schematic of the TF-Mini LiDAR sensor testing.

TABLE I
SPECIFICATION DATA OF THE TF-MINI LIDAR SENSOR

No.	Specifications	
1.	Operation range	0.3 m – 12 m
2.	Operating voltage	4.5 VDC – 6 VDC
3.	Measurement accuracy	1% (range 0.3 m – 6 m) 2% (range 6 m – 12 m)
4.	Operating frequency	100 Hz
5.	Minimum ratio resolution	1 cm
6.	Communication interface	UART
7.	Wavelength	850 nm
8.	Unit of measurement	cm
9.	Acceptance angle/field of view (FOV)	2.3°
10.	Weight	4.7 gr
11.	Light sensitivity	70 klux

[17]. The standard unit of distance is the same as that of length, which is meter (m). Various measuring instruments can be used to determine the distance between two points. The measuring instrument utilized is certainly influenced by objects being measured.

D. *LiDAR Sensor Evaluation Procedures*

In this study, LiDAR sensor testing was conducted using a power supply source, namely Li-Po 3s battery, with a maximum voltage of 12 VDC. The selection of the power supply as the power source was intended to make the testing flexible, that is, it can be anywhere. It was actually feasible to use a power supply/adapter with a power source from the National Electricity Company (Perusahaan Listrik Negara, PLN), but each testing had to be conducted in places adjacent to wall sockets.

The Arduino Nano V3 microcontroller was implemented for LiDAR sensor readings. This microcontroller was selected since the Arduino can be easily configured using Arduino IDE software to communicate with LiDAR sensors serially. In addition to reading data from the LiDAR sensor, the microcontroller also served as a data processor for sensor reading results as well as functioned to display data on a 16 × 2 LCD viewer. The testing schematic for the LiDAR sensor is illustrated in Fig. 3.

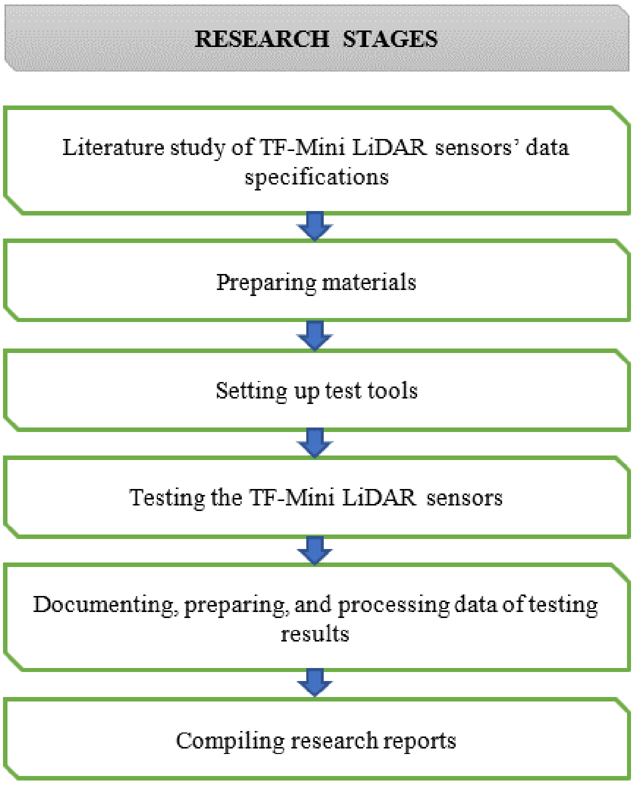

Fig. 4 Flowchart of research stages.

The experimental method was applied in this study. Experiments were conducted to evaluate the performance of the LiDAR sensor. The LiDAR sensor was tested at various distances, after which the sensor's accuracy and maximum distance reading capacity were evaluated. The type of LiDAR sensor observed was the Benewake TF-Mini LiDAR sensor. The objects' color and type of surface material being read were also assessed in addition to the maximum distance and accuracy testing. The testing utilized colors including red, green, blue, white, and black. Various surface materials were used, including plastic, iron, wood, paper, and glass. In addition, testing was performed if the detected flat objects had a tilt range of 10° until 170°.

The obtained data were then analyzed and presented in tables and graphs to show comparison information for each experimental result. Data analysis procedures were carried out by carefully examining each data that had been collected. Then, the process of drawing conclusions was carried out based on data facts obtained in the fields. A good distance reading process that was recommended for digital distance measurement was when the sensor data were stable and close to their original size. The stages of this study are shown through the flowchart in Fig. 4.

III. RESULTS AND DISCUSSION

A. *Data of the TF-Mini LiDAR Sensor Specification*

The testing results for Benewake's TF-Mini LiDAR sensor are presented in this paper. Before conducting an experimental testing for the sensor's performance, a datasheet-based

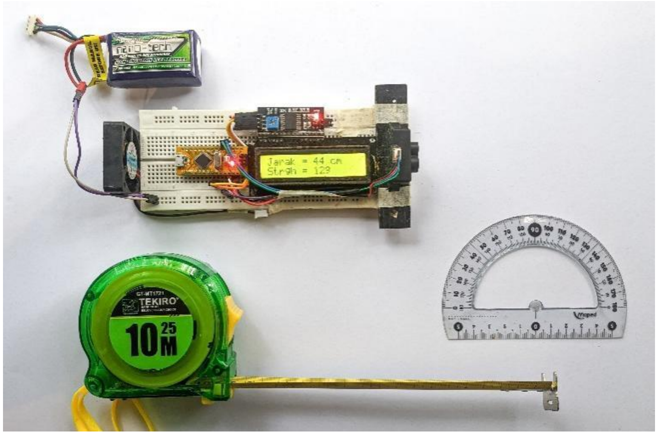

Fig. 5 How to test the TF-Mini LiDAR sensor.

TABLE II
AVERAGE TESTING RESULTS OF THE TF-MINI LIDAR SENSOR FOR DISTANCE MEASUREMENT

No.	Actual Distance (cm)	Distance on Sensor (cm)	Signal Strength	Error (%)
1.	50	48	663	4.000
2.	100	98	647	2.000
3.	200	202	629	1.000
4.	300	309	268	3.000
5.	400	415	145	3.750
6.	500	520	68	4.000
7.	600	627	38	4.500
8.	700	732	28	4.570
9.	800	833	26	4.125
10.	900	941	23	4.560
11.	1,000	1.052	13	5.200
12.	1,100	unreadable	-	-
13.	1,200	unreadable	-	-
Average error (%)				3.700

literature study was used to identify the TF-Mini LiDAR sensor's specifications. The specifications of the TF-Mini LiDAR sensor are shown in Table I [18].

These specifications indicate that the TF-Mini LiDAR sensor can measure the distance up to a maximum of 12 m. Additionally, when the accuracy is calculated, for the distance range of 0.3 m to 6 m, the maximum accuracy is ±6 cm; and for the distance range of 6 m to 12 m, the maximum accuracy is ±24 cm. However, data in Table I cannot serve as actual benchmarks when used in the field, i.e., digital distance measurement. Therefore, this study is conducted to test the TF-Mini LiDAR sensor's actual performance.

B. Data of TF-Mini LiDAR Sensor Performance Testing Results

Testing the performance of the TF-Mini LiDAR sensor was carried out using a source voltage from a Li-Po 3s battery with an output voltage capacity of 12.6 VDC/850 mA. The selection of the Li-Po 3s battery power source was intended to make the testing flexible, that is, it can be anywhere. The prototype tool was tested by putting it on a 50 cm-high chair. The actual distance used for comparison was measured using a measuring tape. The testing method is shown in Fig. 5.

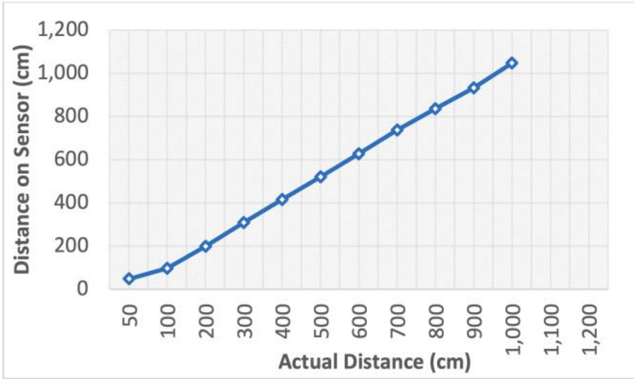

Fig. 6 Graph of the comparison of the actual distance to distance on the sensor.

TABLE III
TF-MINI LIDAR SENSOR'S AVERAGE TESTING RESULTS FOR DISTANCE MEASUREMENT OF OBJECTS WITH COLOR VARIATIONS

Color	Actual Distance (cm)	Distance on Sensor (cm)	Signal Strength	Error (%)
Red	100	110	350	10.00
	200	212	241	6.00
	300	315	107	5.00
	Average error (%)			7.00
Green	100	105	653	5.00
	200	204	626	2.00
	300	311	352	3.67
	Average error (%)			3.56
Blue	100	104	379	4.00
	200	204	335	2.00
	300	307	260	2.33
	Average error (%)			2.78
Black	100	115	169	15.00
	200	192	45	4.00
	300	320	20	6.67
	Average error (%)			8.56
White	100	106	649	6.00
	200	203	631	1.50
	300	308	455	2.67
	Average error (%)			3.38

The testing of the accuracy performance and the distance that could be read by the sensor was carried out from a distance of 50 cm to 12 m. In addition to testing distance readings, this study examined the strength variable, namely the signal strength of the reflected infrared light from the sensor. The testing was conducted during the day with lighting conditions ranging from 27,643 lux. This testing was conducted three times for each distance, and the average was then determined. Table II displays the outcomes of the accuracy testing and the distance read.

The TF-Mini LiDAR can read distances of up to 10 meters, according to the testing results in Table II. In the range of 0.3 m to 6 m, the measurement accuracy was 3.17%; while in the

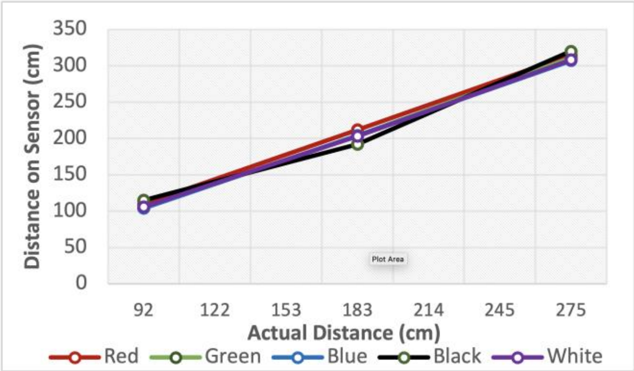

Fig. 7 Graph of the comparison of the actual distance to the distance on the sensor for various objects with color variations.

TABLE IV
TF-MINI LIDAR SENSOR'S AVERAGE TESTING RESULTS FOR DISTANCE MEASUREMENTS OF FLAT OBJECTS WITH DIFFERENT TILT

No.	Actual Distance (cm)	Angle (°)	Distance on Sensor (cm)	Signal Strength	Error (%)
1.	100	10	101	359	1
2.		20	102	325	2
3.		30	103	303	3
4.		40	103	263	3
5.		50	105	232	5
6.		60	108	180	8
7.		70	116	108	16
8.		80	118	84	18
Average error (%)					7
9.	100	100	90	103	10
10.		110	95	155	5
11.		120	98	202	2
12.		130	99	244	1
13.		140	100	280	0
14.		150	101	306	1
15.		160	101	327	1
16.		170	102	341	2
Average error (%)					2.75

range of 6 m to 12 m, it was 3.27%. The overall sensor accuracy rate was 3.70%. When compared to the datasheet (Table I), the results do not conform with specifications. In addition, the strength of the reflection signal from the sensor will decrease as the distance of the detected object increases. A comparison graph of the actual distance to the sensor reading distance is shown in Fig. 6.

The TF-Mini LiDAR sensor would then be tested to detect objects in red, green, blue, white, and black. Variations in the distance of given objects were 1 m, 2 m, and 3 m. This testing was run three times for each distance, and the average was then determined. The testing was conducted during the day with lighting conditions ranging from 27,643 lux. Table III displays the results of the distance measurement testing towards color differences.

According to testing results presented in Table III, the TF-Mini LiDAR sensor could read the distance with a slight error value in blue\ with an error percentage of 2.78%, followed by

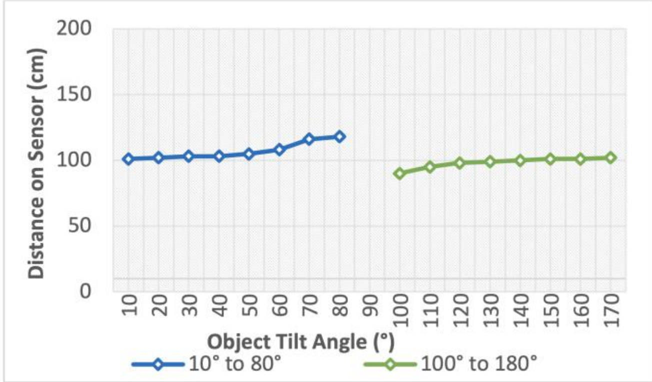

Fig. 8 Graph of the comparison of the measurement distances to angle variation of detected flat objects.

TABLE V
AVERAGE TESTING RESULTS OF THE TF-MINI LIDAR SENSOR FOR DISTANCE MEASUREMENT WITH DIFFERENT SURFACE MATERIALS

Material	Actual Distance (cm)	Distance on Sensor (cm)	Signal Strength	Error (%)
Plastic	100	98	234	2.00
	200	215	560	7.50
	300	326	359	8.67
	Average error (%)			6.06
Iron	100	98	270	2.00
	200	202	502	1.00
	300	320	921	6.67
	Average error (%)			3.22
Wood	100	100	320	0.00
	200	214	645	7.00
	300	320	310	6.67
	Average error (%)			4.56
Paper	100	100	280	0.00
	200	215	463	7.50
	300	325	245	8.33
	Average error (%)			5.28
Glass	100	115	222	15.00
	200	219	416	9.50
	300	331	117	10.33
	Average error (%)			11.61

white, green, red, then black. Additionally, it was known that color affected the reflected signal strength. Red and black had low reflection strength compared to the other three colors. Fig. 7 depicts a graph comparing the measurement distance to the sensor reading distance of objects with different colors.

After that, the TF-Mini LiDAR sensor was tested to detect flat objects with a tilt range of 10° to 170°. The distance from objects was 1 m. This testing was conducted three times for each angle, and the average was then determined. The testing was conducted during the day with lighting conditions ranging from 27,643 lux. The testing results for distance measurement of flat objects with different tilt angles are shown in Table IV.

The testing results in Table IV show that the objects' tilt angle affected the sensor's performance in reading the distance. In the range of 10° to 80° (quadrant 1), the greater the tilt angle,

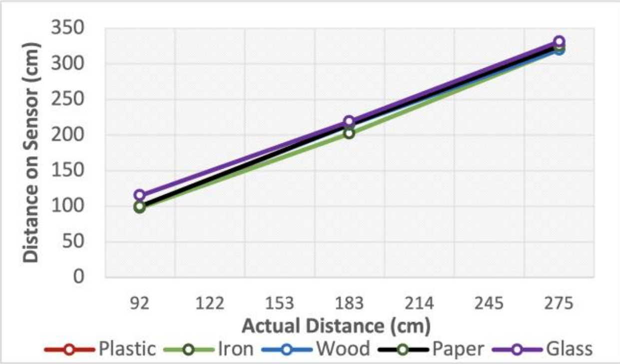

Fig. 9 Graph of the comparison of the actual distance to the distance on the sensor for various objects with different surface materials.

the more read distance exceeded the actual distance. In the range 100° to 170° (quadrant 2), the greater the tilt degree, the closer the read distance was to the actual distance. Fig. 8 depicts the graph comparing the measurement distance to the angle variation of detected flat objects.

The following testing was testing the TF-Mini LiDAR to detect objects with different surface materials, namely glass, paper, wood, iron, and plastic. Variations in the distance of given objects were 1 m, 2 m, and 3 m. This testing was run three times for each distance, and the average was then determined. The results of the distance measurement testing of objects with different surface materials are shown in Table V.

According to the testing data presented in Table V, the TF-Mini LiDAR sensor could read distances with a small error value in iron with an error percentage of 3.22%, followed by wood, paper, plastic, and glass. Additionally, it was found that objects made of iron had the strongest reflected signal, whereas glass objects had the weakest reflected signal. Fig. 9 depicts the comparison between the measurement and sensor reading distances for the detected material difference.

IV. Conclusion

There is a possibility that the LiDAR components' performance is not in accordance with the written technical data specifications. Therefore, testing the components prior to designing a system is required. In this study, the TF-Mini LiDAR sensor used for digital distance measurement was tested to determine its performances and characteristics.

The accuracy of the TF-Mini LiDAR sensors' distance measurement performance varied depending on the detected objects' distance, color, tilt angle, and surface material. The testing results indicated that the TF-Mini LiDAR sensor had an accuracy rate of 3.17% in the range of 0.3 m to 6 m and 3.27% in the range of 6 m to 12 m, with a maximum reading distance of 10 m. When compared to the datasheet (Table I), the results do not comply with the requirements. Regarding objects' color, blue had the most accurate reading, with a 2.78% margin of error. Regarding the tilt of flat objects at an angle of 10° to 80° (quadrant 1), the distance read would exceed the actual distance as the objects' tilt angle increased. The opposite occurred at an angle between 100° and 170° (quadrant 2). Iron was the material which had the most accurate reading, with a 3.22% margin of error. Based on these results, it is clear that to maximize the reading distance accuracy of the TF-Mini LiDAR sensor with a small error value, the detected object must be between 0.5 m and 10 m away and must be made of material or color that does not absorb light. The detected objects' position must be straight, which is close to 0° or 180°.

Conflict of Interest

The authors declare that this study has no conflict of interest. The displayed data are objective and by actual conditions.

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