Optimisation of Distance Measurement in Autonomous Vehicle using Ultrasonic and LIDAR Sensors

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Abstract – *Autonomous Vehicles are sharply gaining popularity in the engineering and technology sector. This study aims to optimise the distance measurement of an Autonomous Vehicle using an ultrasonic sensor and LIDAR sensor for education purposes. An experiment is performed to find an indoor operating range of an ultrasonic and LIDAR sensor. In addition, Full-Factorial design is used to experimentally find the effect of angle, distance and object shape on the sensor measurement error rate and the object detection rate. The result shows that an ultrasonic and LIDAR sensor has indoor operating ranges different from the manufacturer's specifications. Both sensors are sensitive to angle, distance and object shape. It is concluded that the ultrasonic and LIDAR sensor has indoor operating ranges of 2000 mm and 250 mm. The ultrasonic sensor has minimum measurement error for cylinder shape objects, 0° angle and a distance value of 500 mm. It has a maximum object detection rate for cuboid shape objects, an angle value of 0° and a distance value of 500 mm, respectively. LIDAR sensor has a minimum measurement error for cuboid shape objects, 0° angle and a distance value of 250 mm. It has a maximum object detection rate for cuboid shape objects,0° angle value and distance value of 250 mm, respectively.*

Key Words: Autonomous Vehicles, Full Factorial Design, Ultrasonic sensor, LIDAR sensor, Distance measurement.

1. INTRODUCTION

The autonomous vehicles (AV) market is expected to rise by about 59% between 2020 and 2023 [1]. AV uses different sensors to interact with the environment to automate the process. The software's used to increase the productivity of the automated technology. AVs are used in private vehicles, transportation and the farming industry. LIDAR sensors are used in AV to detect objects 200m to 300m away and emit short pulses to measure more than a million points per second. It creates three-dimensional maps of the environment to visualise the object around the environment. They assist in covering a 360° view and help create a 3D map to have a clear sight of what is happening around the vehicle and make it capable of "seeing "[2]. Google AV company Waymo started designing and producing their LIDAR sensors to reduce costs and develop AV for the mass market. Tesla AV can help auto steer, auto park, auto lane change and fully self-drive long distances on highways for a significant period without human assistance.

However, Tesla is not using LIDAR sensors costing 75000 dollars per unit. Instead, it uses ultrasonic sensors for car detection and collision prevention [3]. Ultrasonic sensors are a cheap alternative to LIDAR sensors for object detection systems and algorithms in AV. It sends ultrasonic impulses that are then reflected by the obstacle. Therefore, it helps AV to perform according to the barrier. Ultrasonic sensors can range up to 5.5m and have limitations such as difficulty in detecting objects going at a fast speed. They are vulnerable to jamming and spoofing attacks leaving the sensor physically unable to function and creating false positives. It could lead to a potential incident without user supervision[4]. The measurement of the ultrasonic sensor is sensitive to temperature and the angle of the target. In addition, some materials are more absorbent than others, and these will reflect less ultrasound [5]. Therefore, it complicates measuring the distance with an ultrasonic sensor alone.

On the other hand, the LIDAR sensor cannot recognise transparent objects. So it is advantageous to use an ultrasonic sensor and LIDAR sensor to detect transparent objects [6]. Instead of taking 100 measurements per measuring location in an ultrasonic sensor, 20 measurements per measuring location create a relatively good environment occupancy grid utilised for robot navigation tasks [7]. The operating distance commonly stated by manufacturers of air ultrasound range finding modules and devices can be very misleading. It should be estimated experimentally [8].

The literature review indicates that using ultrasonic and LIDAR sensors for distance measurement is more advantageous than utilising either sensor alone. Therefore, this study aims to optimise the distance measurement of an AV using an ultrasonic sensor (HC-SR04) and LIDAR sensor (VL53L0X) for education purposes. The main objectives of this research are 1) To experimentally find an effective indoor operating range of an ultrasonic sensor and LIDAR sensor; 2) To experimentally find the effect of an angle, distance and object shapes on the error rate and detection rate of an ultrasonic sensor and LIDAR sensor. The study intends to contribute to the literature on optimising the distance measurement of an AV using ultrasonic and LIDAR sensors.

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2. EQUIPMENT

2.1 Autonomous Vehicle

The AV body (Fig. 1) is built with upper and lower plastic sheets. A geared motor is attached to each of the four wheels mounted on the side of the plastic sheets. An ultrasonic sensor is mounted on the breadboard. LIDAR sensor is mounted on the front side of the AV between the lower and upper plastic sheet. The LIDAR sensor is located on the centre line between the transmitter and receiver of the ultrasonic sensor. The breadboard is powered with an Arduino Uno microcontroller through the laptop. Ultrasonic sensor Trig and Echo pins are connected to pins 10 and 9 on Arduino. LIDAR sensor's SDA and SCL pins are connected to analogue pins A4 and A5 on Arduino.

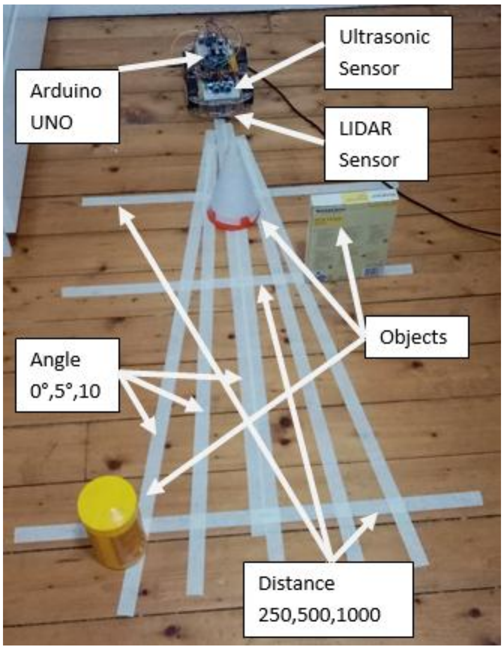

Fig -1: Experiment setup

2.2 Arduino Uno Microcontroller

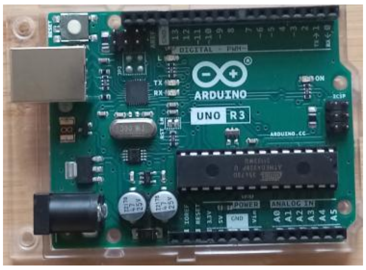

Fig -2: Arduino Uno microcontroller board

Arduino Uno microcontroller (Fig. 2) technical specifications are Atmega328P; operating voltage:5V; Input voltage (recommended): 7-12V; Input V. (limit): >6, <20V; PWM Digital I/O Pins:6; Analogue Input pins: 6; DC current per I/O: 20mA; DC current for 3.3V: 50Ma; Flash Memory: 32KB,0.5KB used by loader; Clock speed: 16MHz; Length, width, weight: 68.6mm,53.4mm,25g respectively.

2.3 Ultrasonic Sensor

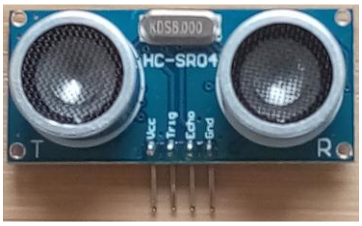

Fig -3: Ultrasonic sensor (HC-SR04)

Ultrasonic sensor (Fig. 3) technical specifications are Current voltage (V): DC 5V; Ground volatge (G): 0V; Working current (C): 15mA; Working frequency (F): 40KHz; Range (Max/Min): 400 cm/2 cm; Angle measure: 5-15 degree; Trigger signal: 10uS TTL pulse; Echo signal: Depend on max range of TTL; Dimensions: 45 mm x 20 mm x 15 mm respectively.

2.4 LIDAR Sensor

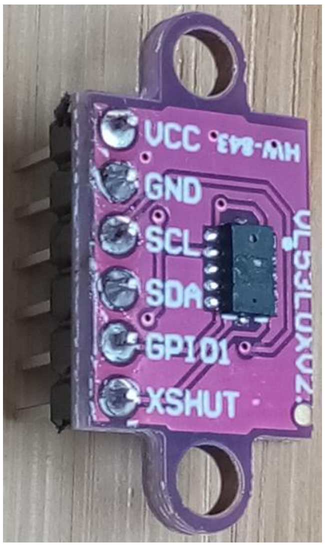

Fig -4: LIDAR Sensor (VL53L0X)

LIDAR sensor's (Fig. 4) technical specifications are Package: Optical LGA12; Size: 4.40 x 2.40 x 1.00 mm; Operating voltage: 2.6 to 3.5V; Operating tempertaure: -20 to 70°C; Infrared emitter: 940 nm; I^2C: Up to 400 kHz (FAST mode) serial bus Address: 0X52 respectively.

2.5 Three dimensional objects

Three 3-dimensional objects used are Cuboid: 156 x 3 x 213 mm; Cylinder: Diameter 85 mm and height 167 mm; Cone: base diameter 113 mm and vertical height 242 mm respectively.

2.6 Arduino Program

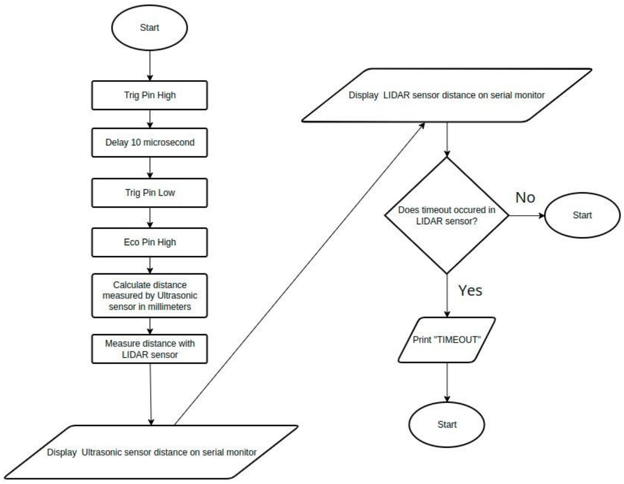

Fig -5: Flowchart of Arduino program

3. EXPERIMENT

3.1 Parameters, Levels and Responses

Table 1 shows the three-level settings of the parameters such as shape, angle and distance. The sensors' measurement error rate and object detection rate are selected as the response.

Table -1: Process parameter levels

Parameter	Level 1	Level 2	Level 3
Shape	Cuboid	Cylinder	Cone
Angle (deg)	0°	5°	10°
Distance (mm)	250	500	1000

3.2 Design of Experiment

Initially, the Minitab 2019 software is used to design the random run order for the full-factorial experiment. The parameters are chosen as categorical in nature. It consists of 27 points (Run 1-27), one replicate and one block, as shown in Table 2.

Table -2: Full Factorial Design of three factors with three levels

Run Order	Shape	Angle (deg)	Distance (mm)
1	Cylinder	0°	500
2	Cone	5°	500
3	Cone	10°	1000
4	Cylinder	5°	250
5	Cuboid	5°	250
6	Cylinder	0°	1000
7	Cylinder	10°	500
8	Cone	10°	250
9	Cuboid	10°	500
10	Cuboid	10°	250
11	Cuboid	10°	1000
12	Cone	0°	1000
13	Cuboid	0°	500
14	Cylinder	0°	250
15	Cylinder	10°	1000
16	Cuboid	5°	1000
17	Cone	5°	250
18	Cylinder	5°	1000
19	Cone	5°	1000
20	Cone	10°	500
21	Cylinder	5°	500
22	Cuboid	5°	500
23	Cylinder	10°	250
24	Cuboid	0°	1000
25	Cuboid	0°	250
26	Cone	0°	500
27	Cone	0°	250

2.6 Procedure

First, the cuboid shape object is placed at an angle of 0° at a distance of 250 mm, 500 mm, 1000 mm, 2000 mm and 3000 mm, respectively. Twenty measurements of both the sensors are recorded at each distance value.

Second, the object is placed as per the shape, angle, and distance's first run order values, as shown in Table 2. Ten distance measurements are recorded for both the Ultrasonic sensor and LIDAR sensor, as shown in Fig. 6. During the experiment, it is noted that when the LIDAR sensor cannot detect an object, it offers an enormous value of 8190 mm or 8191mm. Similarly, when an Ultrasonic sensor cannot detect an object, it shows an immense value of 11652 mm Etc. In such cases, it is considered that the sensor with a maximum measurement error rate and no detection. Among the ten recorded values for each measurement location, the mode value is used as the sensor's reading. The maximum error reading is recorded as the measurement in the absence of mode. It is used to calculate the sensor error rate.

Similarly, out of ten recorded measurements, if the enormous value is recorded six times, the sensor detection rate is calculated as 40%. Again, the response values are recorded for the ramining run orders as shown in Table 2. Afterwards, Minitab software is used to analyse the full-factorial design.

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No.1Ultrasonic sensor distance: 1885.13 mm
No.1Lidar sensor distance: 8191.00 mm

No.2Ultrasonic sensor distance: 1880.54 mm
No.2Lidar sensor distance: 8190.00 mm

No.3Ultrasonic sensor distance: 1885.13 mm
No.3Lidar sensor distance: 8191.00 mm

No.4Ultrasonic sensor distance: 1893.46 mm
No.4Lidar sensor distance: 541.00 mm

No.5Ultrasonic sensor distance: 1897.71 mm
No.5Lidar sensor distance: 8190.00 mm

No.6Ultrasonic sensor distance: 1885.30 mm
No.6Lidar sensor distance: 8190.00 mm

No.7Ultrasonic sensor distance: 1881.56 mm
No.7Lidar sensor distance: 8190.00 mm

No.8Ultrasonic sensor distance: 1898.56 mm
No.8Lidar sensor distance: 8190.00 mm

No.9Ultrasonic sensor distance: 1897.71 mm
No.9Lidar sensor distance: 8190.00 mm

No.10Ultrasonic sensor distance: 1880.54 mm
No.10Lidar sensor distance: 8191.00 mm
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Fig -6: Serial monitor sensor measurement dispaly

4. RESULTS

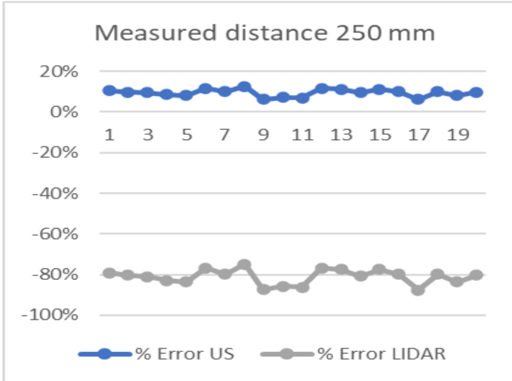

Fig -7: Sensors distance measurement at 250 mm

The graph in Fig. 7 shows that for twenty measurements of the exact measurement location, an ultrasonic sensor can measure the distance of 250 mm with a measurement error of about 10%. On the other hand, the LIDAR sensor has a measurement error of about 80%.

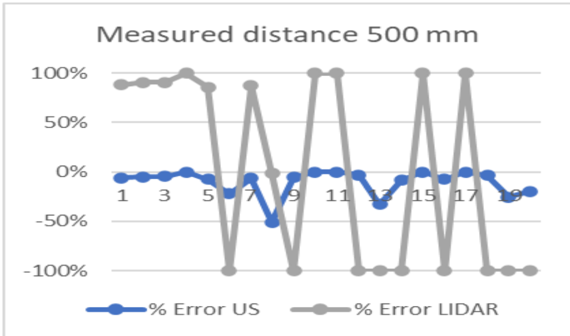

Fig -8: Sensors distance measurement at 500mm

The graph in Fig. 8 shows that for twenty measurements of the exact measurement location, an ultrasonic sensor can measure the distance of 500 mm with a measurement error below 10%. On the other hand, the LIDAR sensor has a measurement error of about 100%.

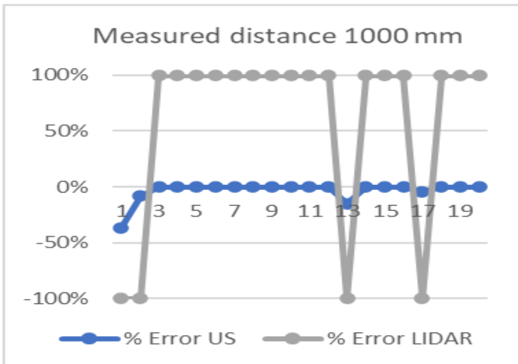

Fig -9: Sensors distance measurement at 1000mm

The graph in Fig. 9 shows that for twenty measurements of the exact measurement location, an ultrasonic sensor can measure the distance of 1000 mm with a measurement error below 5%. On the other hand, the LIDAR sensor has a measurement error of about 100%.

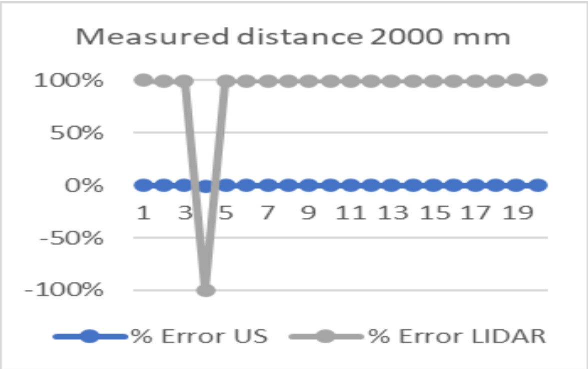

Fig -10: Sensors distance measurement at 2000mm

The graph in Fig. 10 shows that an ultrasonic sensor can measure the distance of 2000 mm with a 0% measurement error for twenty measurements of the exact location. On the other hand, the LIDAR sensor has a measurement error of about 100%.

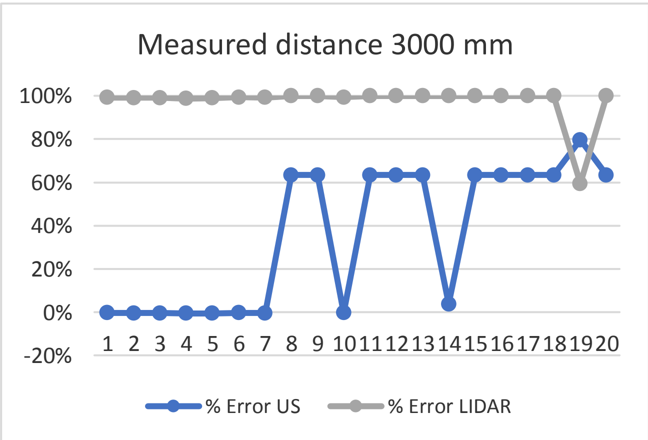

Fig -11: Sensors distance measurement at 3000mm

The graph in Fig. 11 shows that for twenty measurements of the exact measurement location, an ultrasonic sensor can accurately measure the distance of 3000 mm for the first seven readings. It has a measurement error of about 60% for the remaining readings. On the other hand, the LIDAR sensor has a measurement error above 95%.

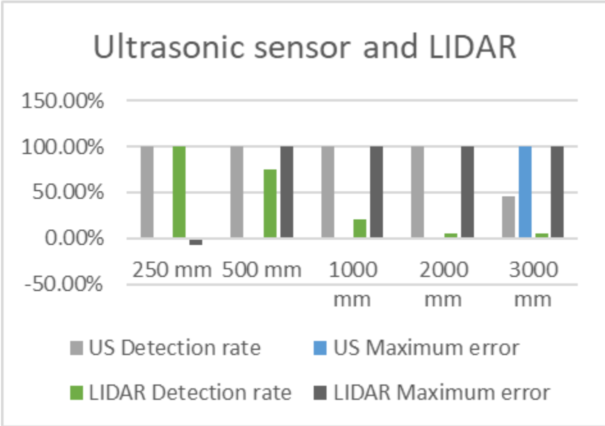

Fig -12: Sensors detection rate and error rate

The graph in Fig. 12 shows that the ultrasonic sensor has an almost negligible measurement error for a distance up to 2000 mm and has a 100% measurement error at a distance of 3000 mm. Second, the LIDAR sensor has an almost negligible measurement error up to the distance of 250 mm and has a 100% measurement error for the other distance values. Third, the ultrasonic sensor has a 100% object detection rate for distances up to 2000 mm and around a 40% object detection rate for distance values of 3000 mm. Fourth, the LIDAR sensor has object detection rates of 100% at a distance of 250 mm, approximately 75% at a distance of 500 mm, about 25% at a distance of 1000 mm and below 5% for remaining distance values.

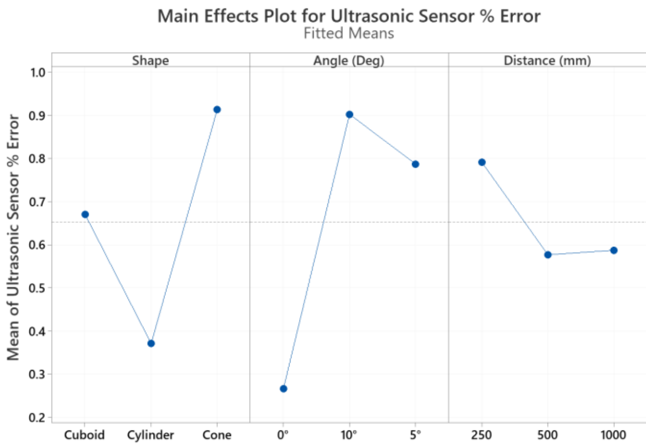

Fig -13: Parameters and Ultrasonic sensor error rate

The graph in Fig. 13 shows that an ultrasonic sensor has minimum measurement error for cylinder shape objects, 0° angle and a distance value of 500 mm. It has maximum measurement error for cone shape objects,10° angle value and distance value of 250 mm, respectively.

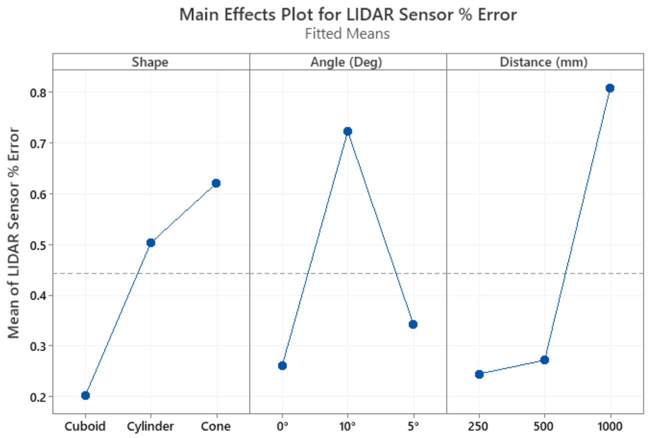

Fig -14: Parameters and LIDAR sensor error rate

The graph in Fig. 14 shows that the LIDAR sensor has a minimum measurement error for cuboid shape objects, 0° angle and a distance value of 250 mm. It has maximum measurement error for cone shape objects,10° angle value and distance value of 1000 mm, respectively.

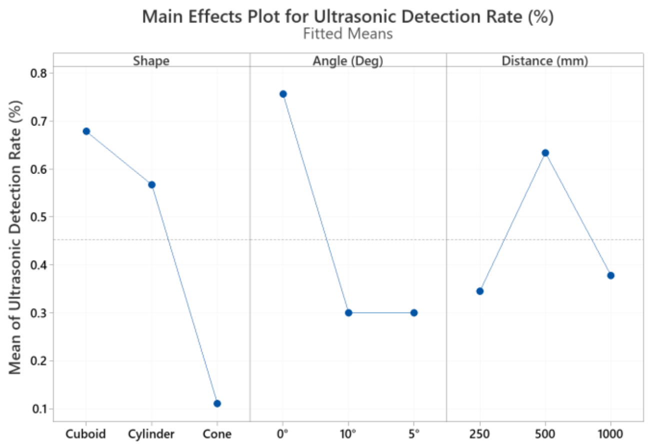

Fig -15: Parameters and Ultrasonic sensor detection rate

The graph in Fig. 15 shows that an ultrasonic sensor has a minimum object detection rate for cone shape objects, 10° angle and a distance value of 250 mm. It has a maximum object detection rate for cuboid shape objects,0° angle value and distance value of 500 mm, respectively.

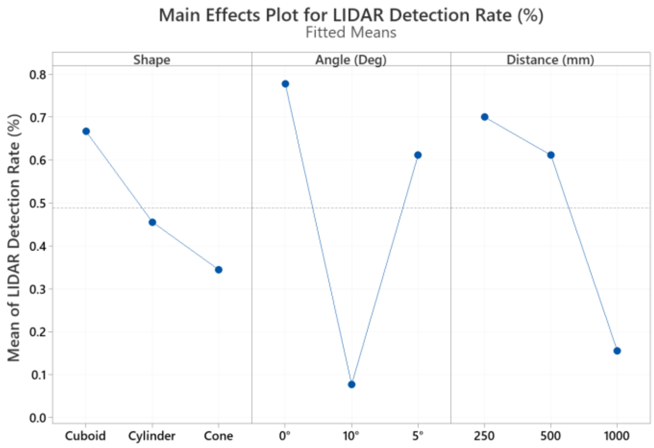

Fig -16: Parameters and LIDAR sensor detection rate

The graph in Fig. 16 shows that the LIDAR sensor has a minimum object detection rate for cone-shaped objects, 10° angle and a distance value of 1000 mm. It has a maximum object detection rate for cuboid shape objects, 0° angle value and distance value of 250 mm, respectively.

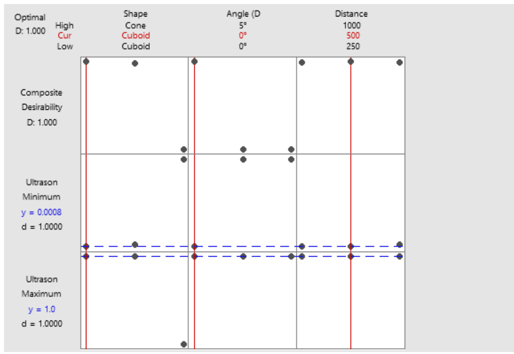

Fig -17: Optimal settings of Ultrasonic sensor

The graph in Fig. 17 shows that in an ultrasonic sensor, to maximise the object detection rate and minimise the measurement error rate, the optimal settings are an object of cuboid shape, angle value of 0° and distance value of 500 mm, respectively.

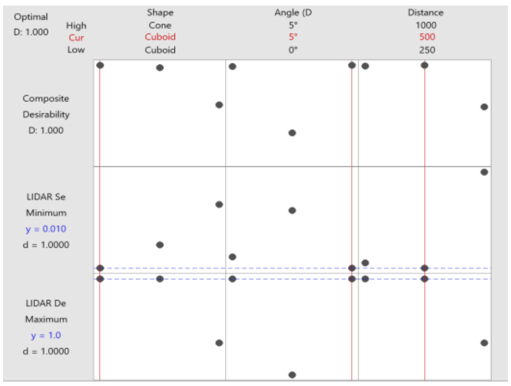

Fig -18: Optimal settings of LIDAR sensor

The graph in Fig. 18 shows that in the LIDAR sensor, to maximise the object detection rate and minimise the measurement error rate, the optimal settings are an object of cuboid shape, angle value of 5° and distance value of 500 mm, respectively.

5. DISCUSSION

First, for an ultrasonic sensor, an effective indoor operating range with minimum measurement error and maximum detection rate is 2000 mm (Fig. 12). However, after the initial seven accurate measurement readings at a distance value of 3000 mm, the ultrasonic sensor starts giving a measurement error of above 60% (Fig. 11). It might be possible for an ultrasonic sensor to provide an accurate distance measurement reading for a more significant size object at a distance of 3000 mm. Alternatively, the use of two ultrasonic sensors in front of the AV might reduce the measurement error and maximise the detection rate of the sensor at a distance value of 3000 mm or more. This study agrees with [8] to experimentally estimate the operating distance of air ultrasound range finding modules and devices. Second, for a LIDAR sensor, the indoor operating range with minimum measurement error and maximum object detection rate is 250 mm (Fig. 12). However, the LIDAR sensor has around a 75% detection rate at a distance value of 500 mm and approximately a 25% object detection rate at a distance value of 1000 mm. It might be possible to use a LIDAR sensor effectively above 250 mm to increase an object detection rate by making it rotate within an angle range continuously in front of an AV with the help of a motor rather than keeping it stationary. It might be possible for the LIDAR sensor to measure more significant size objects with minor measurement error at distance values above 250 mm. Third, an ultrasonic sensor measurement error rate and object detection rate are sensitive to the object's shape, angle and distance, as shown in Fig. 13 and Fig. 15. In addition, the graph in Fig. 17 indicates that the optimal settings for an ultrasonic sensor are objects of cuboid shape, angle value of 0° and distance value of 500 mm, respectively. The finding of the optimal settings of an ultrasonic sensor for the cuboid body is in agreement with [9]. It indicates that more than one ultrasonic sensor may be used on an AV to increase distance measurement reliability with an ultrasonic sensor for different shapes, angles, and distances. Fourth, the LIDAR sensor's measurement error rate and object detection rate are sensitive to the object's shape, angle and distance, as shown in Fig. 14 and Fig. 16.

In addition, the graph in Fig. 18 shows that the optimal settings for the LIDAR sensor are an object of cuboid shape, angle value of 5° and distance value of 500 mm, respectively. It shows that the LIDAR sensor and an ultrasonic sensor increase the object detection zone in front of the AV. It indicates that both sensors should be used in conjunction to improve the reliability and accuracy of the distance measurement and an object detection with them rather than using them alone. This finding agrees with [10] that a more reliable car operation is achieved by using data from sensors after sensor fusion.

6. CONCLUSIONS

This study aims to optimise the distance measurement of an AV using an ultrasonic sensor (HC-SR04) and LIDAR sensor (VL53L0X). The main objectives of this research are 1) To experimentally find an effective indoor operating range of an ultrasonic sensor and LIDAR sensor; 2) To experimentally find the effect of an angle, distance and object shapes on the error rate and detection rate of an ultrasonic sensor and LIDAR sensor. First, the findings are for an ultrasonic sensor, an effective indoor operating range with minimum measurement error, and a maximum detection rate is 2000 mm. Second, for a LIDAR sensor, the indoor operating range with minimum measurement error and maximum object detection rate is 250 mm. Third, an ultrasonic sensor has minimum measurement error for cylinder shape objects, 0° angle and a distance value of 500 mm. It has maximum measurement error for cone shape objects,10° angle value and distance value of 250 mm, respectively. Fourth, an ultrasonic sensor has a minimum object detection rate for cone-shaped objects, 10° angle and a distance value of 250 mm. It has a maximum object detection rate for cuboid shape objects, 0° angle value and distance value of 500 mm, respectively. Fifth, the LIDAR sensor has a minimum measurement error for cuboid shape objects, 0° angle and a distance value of 250 mm. It has maximum measurement error for cone shape objects,10° angle value and distance value of 1000 mm, respectively. Sixth, the LIDAR sensor has a minimum object detection rate for cone-shaped objects, 10° angle and a distance value of 1000 mm. It has a maximum object detection rate for cuboid shape objects,0° angle value and distance value of 250 mm, respectively. The limitation of this research is that all measurements are recorded while the AV is stationery. The suggestion for further research is to perform the distance measurement with moving AV and use the data from the sensors after sensor fusion to detect the objects and measure distance.

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BIOGRAPHIES

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