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Influence of the Target Material and Disturbance Sources in the Accuracy of Distance Sensors for MAV Applications

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ABSTRACT

Distance sensors are widely used in an extensive variety of applications nowadays, including obstacle detection and avoidance for autonomous navigation. There are multiple options, based on different working principles, possessing different distance ranges, reading rates and accuracies that could vary according to the type of sensor and the environment of operation. This paper focus in analyzing the response of distance sensors for UAV applications. The chosen sensing technologies are ultrasonic, infrared and LiDAR, which were selected based on several parameters, such as, weight and accuracy. The sensors response was evaluated considering different target materials (wood, cardboard, polyethylene foam and Perspex), aiming to analyze their behaviour towards each material. Initially, in a controlled environment, without disturbances, a target was placed at several known distances from the analyzed sensor, within its operational range. For each one of these distances, the sensor output was compared with the known distance, in order to evaluate its accuracy. This procedure was repeated for all of the analyzed sensors. Furthermore, aiming to verify how much the sensors performance deteriorated in the presence of disturbance sources, the same procedure was repeated to the sensors em- bedded in a MAV, with its motors and propellers running during the test, aiming to replicate real flight conditions. The obtained results lead to conclusions about which kind of technology is more appropriate for this application, providing more reliable measurements, with increased accuracy, and, consequently, allowing the performance enhancement of collision avoidance algorithms.

1 INTRODUCTION

Nowadays, Unmanned Aerial Vehicles (UAVs) are being employed in an increasing number of fields, such as environmental monitoring, border patrol, search and rescue operations, disaster relief, among others. Besides, in the next years, UAVs market is expected to provide billions of dollars in economic growth since it is rapidly growing in a lot of civilian and commercial industries such as agriculture, energy, utilities, mining, construction, real estate, news media and film production [1]. These applications often require small and agile UAVs, capable to fly at low altitudes or even inside buildings, becoming exposed to many hazards and obstacles. However, current UAVs technology in automatically sensing, detecting and avoiding fixed and moving obstacles is still immature compared to manned aerial vehicles. Obstacle detection is essential for collision avoidance systems, that play a key role in autonomous navigation. Several types of sensors can be placed in a UAV to detect and identify obstacles along its path. The data acquired by these sensors are gathered and processed using collision avoidance algorithms, that define the avoidance action based on the processed obstacles information [2].

It was chosen to analyze sensors that measure distance. The examined technologies are ultrasonic, infrared and LiDAR. These three types are vastly used in drone applications, hence, justifies deeper investigation. Ultrasonic sensors measurements are made via sound wave propagation, so, noisy environments might interfere with the results accuracy if there is a sound component in the same frequency of the wave emitted by the sensor [3, 4] . Infrared sensors, on the other hand, emits an infrared beam and measures the intensity of its reflection. Consequently, for targets with too high or too low reflectivity the measurements are not reliable. Another kind of environment that harms the accuracy of infrared sensors are those which have much infrared light emission, however, these are not very common. LiDAR functions by emitting a laser pulse and measuring the phase difference between the emitted and received wave. Therefore environments with high power wave propagation in the LiDAR's frequency might interfere in its functionality.

Once the sensor process is known, it is possible to analyze how the measurement is affected by the reflection. Dif-

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ferent materials produce different reflection distortions, thus, it is also important to characterize how they interfere on the final result. The materials chosen to examine are wood, cardboard, polyethylene foam and Perspex. This selection is due them being relatively common in collision avoidance problems. Furthermore each one has diverse structural properties which make the analysis more complete.

Usually, knowing the right sensing technology for an application is not an easy task, since it requires to study several variables included in the system and his surroundings.To simplify this study, the sensors were tested in an minimum noise environment, with and without an UAV system, i.e, with and without being embedded in an MAV. The objective is making minimal the dependency of the location and maximize the correlation between the material, system properties and the sensors' measurements [5].

This paper proposed experiment should be useful for precising the reliability of the sensors considering only inner MAV disturbances and the effect caused by different materials. Provided by this results, the decision of which sensor should be used for each case tends to be more precise because it gives a relation of real sensor accuracy considering the materials of environment's application.

2 SENSORS

As described in section 1, nowadays the use of autonomous drones is becoming a trend in the modern society. There are many ways to implement an autonomous drones, but there are some basic sensing that are required to make it possible. So it's reasonable to assume that some sensors cannot be removed completely, especially distance sensors. This study analyses the response of 3 sensors that are mostly used for that purpose but with different working principles. In Sections 2.1, 2.2 and 2.3, a brief presentation about the characteristics and specifications of the sensors used is made.

2.1 *Ultrasonic*

The ultrasonic sensor tested was the MaxBotix MB1242, which sensor is fully equipped with a real-time noise rejection and real-time auto calibration features. This sensor has a internal circuit that allows a very easy-to-use experience. It converts the reading from the sensor into a 16 bit integer that is split into two 8 bit numbers there is sent through the I^2C bus. The 16 bit number is the range that the sensor read in millimeter. There is only one easy and well documented I^2C address and mode configuration there has to be done so that the sensor can start sensing.

The ultrasonic sensor has a range of 20 cm to 765 cm. It has also a digital output of 16 bit for the reading, so the resolution is fixed and has a precision of 1 cm, it has a 40 Hz acquisition rate, only weights 6 g and a angle of acceptance of 19^o.

2.2 *LiDAR*

The LiDAR sensor tested was a Makerfocus LiDAR range finder (TFmini Infrared Module). It has, like the ultrasonic sensor, a circuitry designed to convert the reading from the sensor to a serial output. The data from that reading is, also, a 16 bit number that is split into two 2 bytes number, sent trough the serial output and read in a micro-controller.

This sensor weights 6.1 g, has a 100 Hz acquisition rate, a 2.3^o acceptance angle, an accuracy of 1% at any distance lesser than 6 m, the precision is 2 cm and a range of 30 cm to 1200 cm.

2.3 *Infrared*

The infrared sensor tested was a Sharp GP2Y0A02YK0F IR Range sensor. Unlike the others sensor tested, the response of it is not linear nor easy to use right out of the box and can be seen in Figure 1. So to make it more easy to use, a function fitting was needed. This can be done in many different ways, one of them is using the points shown in the response of the sensor , using Excel's fitting function (knowing that the response of the sensor follows the diode law) and them trying to solve the fitted function in voltage (or y) instead of distance (or x).

$$y = 10650.08 \times x^{-0.935} - 10 \tag{1}$$

This infrared sensor has a range of 20 cm to 150 cm with analog output that varies from 2.8 V (at 20) to 0.4 (at 150 cm) V, so the resolution depends only on the ADC – for the rig used the resolution was 4.88 mV), with 2 cm precision, an angle of acceptance of 5^o, the acquisition rate can be limited to approximately 20.8 Hz to 35.7 Hz. And weights only 5 g, the lightest of them all.

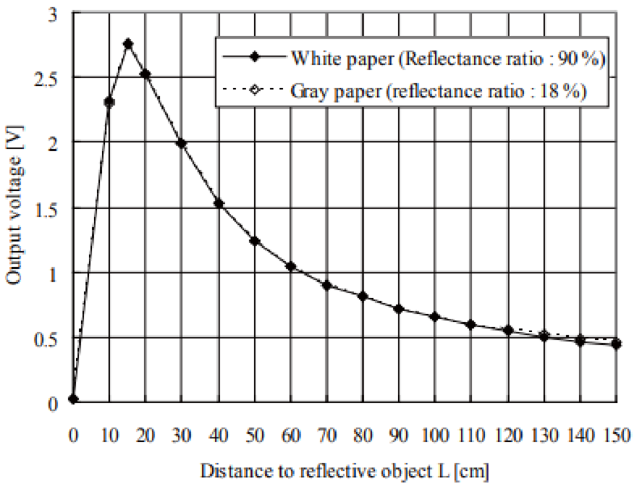

Figure 1: Output of the sensor vs. the distance.

To make it simple and direct, Table 1the summarizes the sensor's specifications and characteristics.

Specification	Ultrasonic	LiDAR	Infrared
Precision [cm]	1	2	2
Range [cm]	20 - 765	30 - 1200	20 - 150
Angle []	19	2.3	5
Rate [Hz]	40	100	26.3
Weight [g]	6	6.1	5

Table 1: Sensors specification summary

3 METHODOLOGY

The measurements were performed using a class 250 quad-copter MAV. The MAV's powertrain is specified in Table 2. Its control is done with the Navio2 autopilot platform, connected to a Raspberry Pi 3 running the ArduPilot firmware and radio controlled using a RFD900x telemetry radio with PPM pass-through.

Component	Specification
Motor	E-Max 1806 - 2280
Propeller	Carbon Fiber - 3-Blade - 5X3.5
ESC	E-max BLHELI-S 12A 2-4S
Battery	LiPo 3S (11.1 V) - 1400mAh - 40C

Table 2: Powertrain specifications.

The sensors were mounted individually in the MAV (i.e. during the infrared test, only the infrared sensor was mounted in the MAV) due to sizing limitations and in order to remove any chance of interference of different sensors technologies. They were positioned in the MAV's direction of movement in a place that the propellers would not be inside its field of view.

Figure 2 shows a picture of the MAV used with the LiDAR sensor mounted, right below the camera.

Figure 2: MAV used during the tests with LiDAR sensor mounted.

For the ultrasonic and LiDAR sensors, the measurements were taken within a range from 0 to 300 cm, increasing the distance in steps of 10 cm. For the infrared sensor, the range used was from 0 to 150 cm, with steps of 10 cm. This difference in the range for the IR sensor is due to its nominal range being smaller than the other sensors.

The target material dimensions were selected based on the sensor's field of view to guarantee that the sensor would be measuring only the intended material. The dimensions were calculated considering the biggest distance that was going to be measured (300 cm). Table 3 shows the field of view radius for the three sensors considering the distance of 300 cm.

Sensor	FOV Angle	FOV Radius @ 300 cm
Ultrasonic	19^o	50.2 cm
LiDAR	2.3^o	6.02 cm
Infrared	5^o	13.1 cm

Table 3: Sensor's field of view.

All the target material were selected with dimensions bigger than 100.4 cm. The MAV was positioned at a height that would permit the sensor to detect only the target material, without being influenced by the floor. The setup of the test is represented in Figure 3.

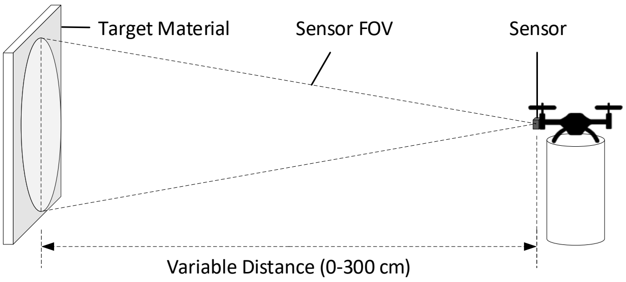

Figure 3: Test setup

To analyze the sensor's performance for different target materials, and to provide a benchmark comparison for the following test, the first round of tests were performed with the MAV motors powered off, that can be considered an scenario in which the sensors would provide the best performance. This controlled environment permits to decouple the analysis of the varying performance according to the different target materials to the analysis of the influence of the disturbance sources.

To simulate real flight conditions, considering vibration from the motors and turbulence caused by the propellers, the same test were performed with the motors powered to 70% of throttle while the MAV was attached to a 10 kg steel block that did not permit its movement. This restriction of movement allowed the correct positioning of the sensor to permit accurate comparisons with the measured distance.

The procedure for both the tests was strictly the same, the measurements started from the closest distance (10 cm) and it was increased in steps of 10 cm until it reached the maximum distance (150 cm to the infrared sensor and 300 cm to the ultrasonic and LiDAR sensors). Then, the distance started decreasing to provide a more accurate representation of the measurement and to reduce the sensor's hysteresis influence on the result. The values shown in Section 4 are the average between the increasing and the decreasing measurement. Since this paper do not take in consideration timing response of the sensors, a waiting period of 5 seconds was performed between measurements to allow proper stabilization of the measurement.

In total, 24 tests were conducted and the results are shown in Section 4.

4 RESULTS

The experiment described in Section 3 was performed for the three sensors and the Sections 4.1, 4.2 and 4.3 shows the results obtained. After compiling all the acquired data from the sensors, a statistical analysis was performed in order to evaluate the results.

4.1 LiDAR Results

Figures 4 and 5 show the distances measured by the LiDAR sensor in function of the actual distance, for different target materials: wood, cardboard, polyethylene foam and Perspex. The measurements presented in Figure 4 were performed with the MAV motors turned off, while the results presented in Figure 5 were acquired with the MAV motors turned on.

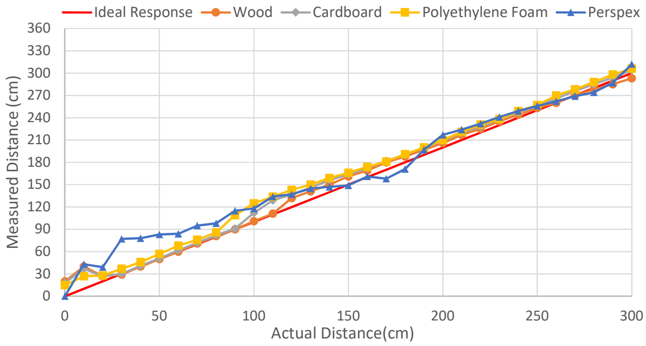

Figure 4: LiDAR experimental response with electric motors off, for different target materials

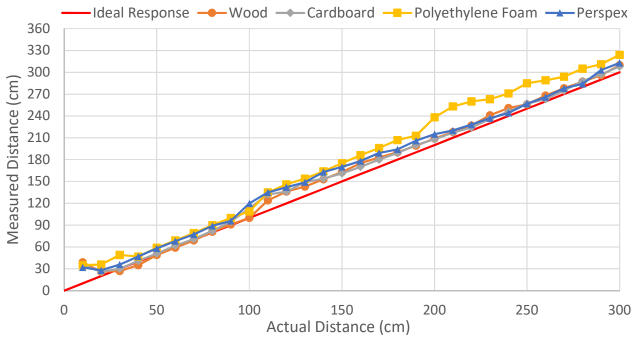

Figure 5: LiDAR experimental response with electric motors on, for different target materials

4.2 Ultrasonic Results

Figures 6 and 7 show the distances measured by the ultrasonic sensor sensor in function of the actual distance, for different target materials: wood, cardboard, polyethylene foam and Perspex. The measurements presented in Figure 6 were performed with the MAV motors turned off, while the results presented in Figure 7 were acquired with the MAV motors turned on.

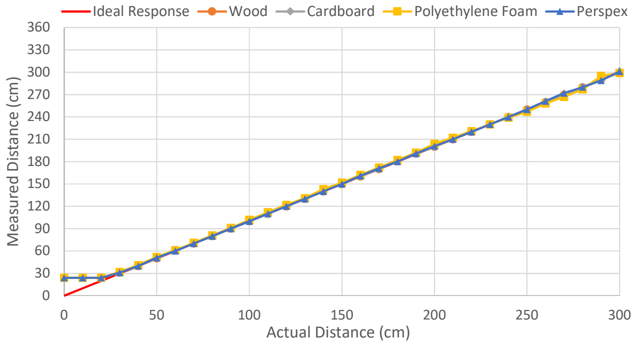

Figure 6: Ultrasonic experimental response with electric motors off, for different target materials

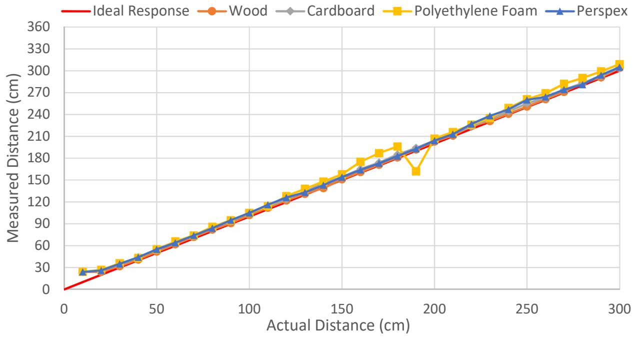

Figure 7: Ultrasonic experimental response with electric motors on, for different target materials

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4.3 Infrared Results

Figures 8 and 9 show the distances measured by the infrared sensor in function of the actual distance, for different target materials: wood, cardboard, polyethylene foam and Perspex. The measurements presented in Figure 8 were performed with the MAV motors turned off, while the results presented in Figure 9 were acquired with the MAV motors turned on.

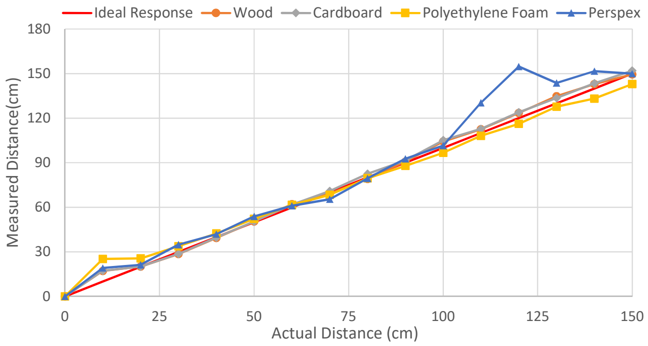

Figure 8: Infrared experimental response with electric motors off, for different target materials

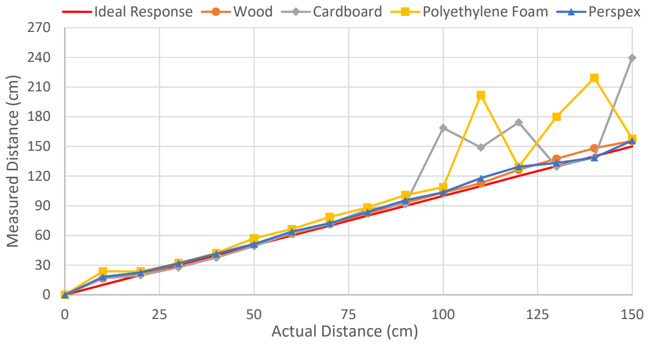

Figure 9: Infrared experimental response with electric motors on, for different target materials

4.4 Statistical Analysis

Considering the measurement results highlighted in the previous subsections, a statistical analysis was performed. Figure 11 shows the RMSE achieved for the sensors (LiDAR, Ultrasonic and Infrared), in relation to each target material. On the other hand, Figure 11 presents the standard deviation of the measurements performed by the sensors.

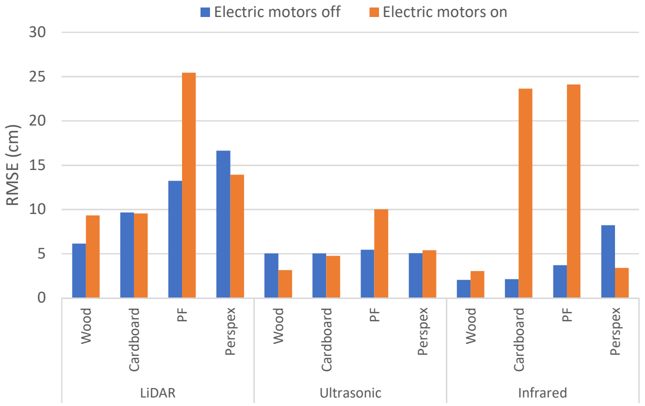

Figure 10: Root mean square error (RMSE) of the measurements.

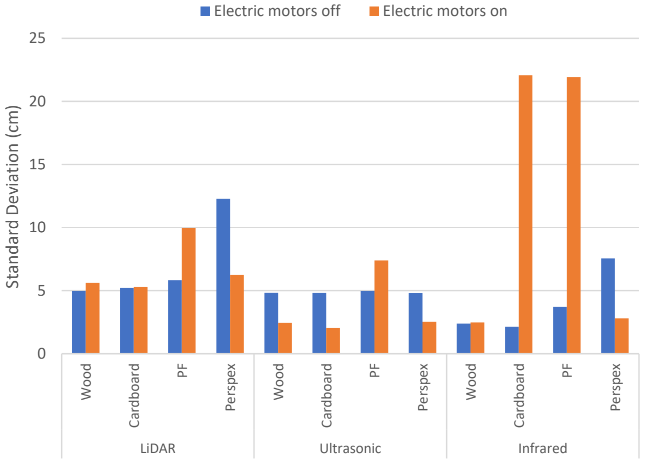

Figure 11: Standard deviation of the measurements.

5 DISCUSSION

Based on the results showed in Section 4, it is possible to extract some conclusions regarding the sensor's performance.

The LiDAR sensor was the one with the worst performance among the three sensors. It provided poorly measurements with high RMSE for all tested scenarios.

In addition to the poor overall performance, when using Perspex as target material it provided the worst measurement (RMSE = 17 cm), among all measurements performed with electric motors powered off. This error was more than two times higher than the error achieved for other target material. Perspex is a highly reflexive material, and the LiDAR working principle takes into consideration the time of flight that a laser pulse takes between its emission and reflection back to the sensor, therefore, having a target with different reflexivity characteristics affects directly the measurement.

On the other hand, the ultrasonic sensor provided the best overall results among all sensors. It provided reliable measurements, with high degree of correlation independently of the distance, target material and presence of disturbances

During the first round of tests, with motors powered off, the ultrasonic sensor provided equivalent performance for all target materials, with similar RMSE and standard deviation. On the other hand, with electric motors powered on, the measurements performed by the ultrasonic sensor remain satisfactorily good for all materials. However, it is noticed a considerably increase in RMSE and standard deviation values obtained for polyethylene foam target. Nonetheless, the archived measurement precision remains acceptable, even in this case. The foam absorbability of sound waves is bigger than the other materials, and since the ultrasonic sensor relies on the time of flight of ultrasonic sound waves, it is expected that it underperforms when it comes to this kind of material.

The infrared sensor showed an excellent response for tests performed with motors powered off. However, the results were considerably affected by the target materials. Besides, the precision of the measurements varies with the measurement distance. For smaller distances, the sensor was able to provide accurate measurements within the tests with and without disturbances, but with bigger distances it provided some unreliable measurements. This unreliable measurements were maximized in the tests with the motors powered on.

6 CONCLUSION

Nowadays, several solutions are commercially available for distance measurements in embedded applications. When it comes down to MAV design, cost, weight, precision and power consumption of each one of these sensing technologies should considered. Each sensor provides better results according to given boundary conditions, such as: distance range, target material and immunity to disturbances induced by propellers rotation. The experiments performed in this work showed that these 3 factors have great influence on the overall performance of each sensor and, consequently, should be taken in consideration when it comes to selecting the proper technology.

By comparing the RMSE and standard deviation associated to each sensor, it is noticed that the ultrasonic (US) sensor presented the best overall result. Its error remains considerably low for all target materials (always below 10 cm) and it shows good immunity to disturbances produced by propellers rotation. However, it should be mentioned that infrared (IR) sensor outperformed ultrasound in some particular cases, but its behavior is significantly compromised when MAV motors are on. Tables 4 and 5 summarizes the best and worst sensor's performance for each target material in both the conditions tested, with and without disturbances.

Condition	Material			
	Wood	Cardboard	PF	Perspex
Motors off	IR	IR	IR	US
Motors on	IR/US	US	US	IR

Table 4: Sensor with best performance in the tested conditions for different materials

Condition	Material			
	Wood	Cardboard	PF	Perspex
Motors off	LiDAR	LiDAR	LiDAR	LiDAR
Motors on	LiDAR	IR	LiDAR	LiDAR

Table 5: Sensor with worst performance in the tested conditions for different materials

Besides, compared to LiDAR and Infrared technologies, ultrasonic sensors are low power and lightweight devices. The highlighted aspects indicate that, among the analyzed distance sensor technologies, ultrasonic sensors are the most suited devices to be embedded in MAVs for distance measurements.

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