Distance Estimation for Mobile Robots using an Ambient Light Sensor

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***Abstract*—This project characterises the ambient light detection (ALS) module present within the VL6180X Time-of-Flight sensor. According to the well established light-based Inverse-Square Law, the approximate distance between a light source and ALS can be calculated using the value obtained from the sensor. This project, therefore, aims to verify the claim above through a simple motion stop procedure on a mobile robot - Pololu Romi 32U4, and with a multi-coloured LED light source. The results of the experiment show that the distances computed using the ALS were fairly accurate when the LED light source was green, but largely inaccurate for the colours red and blue. A comparative analysis is presented between the calculated and obtained distances from the ALS and proximity sensor respectively. Based on the analysis, some suggestions for future work to achieve more accurate results using ALS were stated. This project uniquely contributes to research as it aims to apply and consequently verify the light-based inverse-square law within the context of Robotic Systems.**

I. Introduction

It is necessary for mobile robots to detect objects in close range to prevent the possibility of damage through collisions [1]. For such purposes a proximity sensor is conventional solution, as it can measure the scalar distance between a robot and an object. These sensors operate based on infrared or sonar pulses, and while they integrate well within various robotic systems, the limited detection range and observable margin-of-error act as limiting factors [2]. The effects of these identified issues when the sensor is present within autonomous vehicles could lead to life-threatening injuries. Therefore, it is necessary to conduct research into alternative and unconventional methods for measuring proximity of nearby objects.

One strategy that can be used to prevent collisions in autonomous vehicles is an emergency or motion stop procedure, wherein the vehicle is completely halted if it is within a certain threshold distance to an object. Building on from this, perhaps there is a way to utilize the tail lights of vehicles to estimate the in-between distance? This paper aims to investigate just that, i.e exploit the tail light feature of vehicles to compute the distance between two cars. To test this theory, methodologically designed experiments were conducted using a multi-coloured LED light source and the ambient light sensor (ALS) contained in Pololu's VL6180X sensor[1].

The project was divided into a few objectives: the first was to find a relevant equation for the conversion of ALS readings to a distance measurement. This meant carrying out a brief literature review. The other objectives were to design an experiment with the available equipment, and to perform a comparative analysis on the experiment results.

A. Related Works

Given the limitations of conventional proximity sensors, a brief review of the works involving an ALS for distance . Once such study by Pelka et al. [3] involved testing the distance estimation theory in underwater conditions. They were able to obtain precise distance measurements through a light-based inverse-square law (ISL) for underwater depths as far as 25 metres, with an average error of only 0.66 metres. Another instance of the usage of light-based ISL is in Kinoshite et al.'s [4] publication. First, two photodiodes were utilised to determine the lux value (SI derived unit of illuminance) of a luminous object. Then, with the obtained lux values, they were able to calculate the distance between the photodiodes and luminous object. The results stated that the accuracy of the detection was not optimal. However, the authors suggest that an adapted inverse-square law may provide greater accuracy. An adapted equation for the inverse-square was used by Salinas et al. [5]. The authors modified the aforementioned equation to account for the shape of the luminous object, and their experiments showed promising results.

Thus, given that light-based ISL has been investigated in several different domains for distance estimation, we believe that it can also be applied in the field of robotics.

II. Proposed investigation

A. Technical Background

The VL6180X Time-of-Flight Sensor is a hardware component that is primarily used to measure distances. The sensor contains a proximity sensor that can provide accurate measurements for objects placed up to 20-60cm away. The measurements are obtained in the unit millimeters. As the sensor operates on Time-of-flight technology, it is able to record reliable results irrespective of the reflectance and colour of the target object [6]. However, the disadvantages of this technology include its limited range for measurement, its angular dependency and the existence of a dead-zone, within which a target object is considered out of the field of view[2].

[1] https://www.pololu.com/product/2489

[2] https://www.st.com/content/dam/technology-tour-2017/session-1_track-4_time-of-flight-technology.pdf

Also contained in the VL6180X sensor is an ambient light sensing module (ALS) that allows one to measure the ambient light levels over a wide dynamic range. The unit of measurement here, *Lux*, is defined as the intensity of light per unit area. This sensor is most commonly found in mobile phones to vary its brightness levels according to the surrounding light levels. Thus, an ALS is generally designed to detect light in a manner similar to the human eye (scientifically referred to as *Photopic Response*, shown as the dotted-red curve in Fig. 1). However, a disadvantage of the ALS module is the noticeable dip in the spectral response plot, suggesting that it does perfectly match the photopic response graph. This feature could act as a bottleneck to this project.

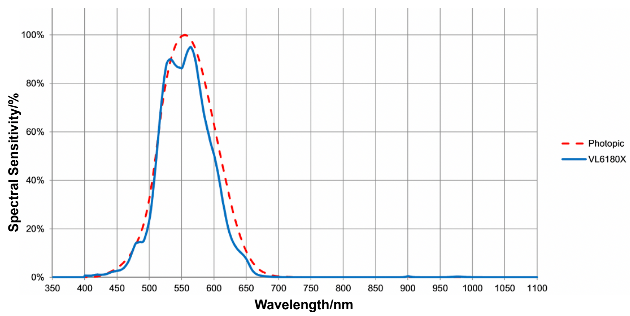

Fig. 1: Spectral Response of the ALS Compared to Photopic Response. Source [6]

As mentioned in Section I-A, the lux values obtained from an ALS can also be used to measure the distance from itself to a light source through *Light-Based Inverse-Square Law*. This law describes an inversely proportional relationship between the intensity of light and square of its distance from the source. It can expressed by the equation below:

$$lx = \frac{lm}{4.\pi.d^2} \tag{1}$$

where lx is the intensity of light per unit area or lux, lm is the lumens of a light source which emits in all directions, and the denominator is the spherical surface area (since the light spreads spherically). Thus, the variable d is the distance between the light source and the surface it falls upon [3]. The caveat of this law is that Equation 1 only applies to point-sized sources of light. The rule of thumb relevant to such light measurements is the "five times rule", which states that, to apply the ISL, the distance to a light source should be five times greater than the largest dimension of the light source [7]. This was taken into consideration when designing the experiment.

Based on the results found by [5], the ISL can provide better results if the equation is adapted according to the shape of the source of light. The LED light source involved in this project was shaped like a hemisphere. Thus, Equation 1 can be modified by substituting the denominator with the surface area of a hemisphere:

$$lx = \frac{lm}{2.\pi.d^2} \tag{2}$$

where lx is the lux, lm is lumens of the bulb and d is the distance of the light source to the surface that it is incident upon.

B. Hypothesis Statement

Based on the features of the available technical components and the adapted equation of ISL, we state our hypothesis as follows:

> *As the ALS module of VL1680X provides the lux value of a light source, and given the fixed lumens of a light source, the distance between ALS and the light source can be calculated using Equation 2. We hypothesise that this calculated distance will be accurate* ***at all times****, proving that the inverse-square law for light holds true.*

The hypothesis will be investigated through a controlled experiment involving a mobility stop (or m-stop) procedure on Romi the mobile robot. We believe that this experiment uniquely contributes to research as it provides a way for estimating distances through use of the light-based inverse-square law, and is tested in the context of robotic systems.

III. Implementation

A. Romi Characteristics and Added Components

Given that Romi functions through a control board[4], the programming for the project was done through the Arduino software and interface, in the C/C++ programming language.

The VL6180X sensor was attached to the front of Romi, and the necessary connections were made (described in Section IV). The built-in functions 'readMillimetersSingle()' and 'readAmbientSingle()' were used to record the measurements taken by the proximity and ambient light sensor respectively. To program movement in the Romi, a scalar value for power was sent to the motor of each wheel using 'analogWrite()' function while the direction of wheels (forward and backward) was achieved through the 'digitalWrite()' function.

To compute a distance measurement from the lux values provided by the 'readAmbientSingle()' function, the adapted Equation 2 is shown below:

$$d = \frac{lm}{\sqrt{2.\pi.lx}} \tag{3}$$

Once the distance values from both sensors was extracted, the implementation of the m-stop procedure was fairly simple since involved setting a fixed threshold value for the expected stopping distance. If the distance values obtained from the sensors are greater than or equal to this threshold, a power value of 0 was sent to the motors causing Romi to stop immediately.

[3]https://www.ifa.hawaii.edu/ barnes/ASTR110L_S03/inversesquare.html

[4]https://www.pololu.com/docs/pdf/0J69/romi_32u4_control_board.pdf

B. PID

Due to the resistance of the wheels of Romi, it is unable to travel in a straight line even if the exact same power value was provided to both motors. Therefore, to minimize any error caused by this issue while observing the angular dependency of the proximity and ambient light sensors, a PID (Proportional, Integral and Derivative) controller had to be implemented. The black line pictured in Fig. 2, was used as a guideline to monitor whether the Romi was travelling in a straight line or not. In the first step of building the PID controller, the general motion of each wheel was noted and velocity of each wheel was then calculated through the use of encoders with unit 'counts per second', where millis () function was used to measure the duration parameter. A demand velocity (or the required velocity), i.e. a scalar value, was set for each wheel and the difference in velocity (referred as velocity_error) was observed through Equation 4 below.

$$velocity\_error = demand\_velocity - wheel\_velocity \tag{4}$$

Next, a specific value, called P_gain, was multiplied by the 'velocity error' to form a P_term (as shown in Equation 5). The P_gain value was selected through a trial-and-error process with the aim of matching the demand velocity to the actual velocity of both wheels. A trade-off between shorter velocity rise-time and minimisation of initial turbulence of the wheel was considered when selecting the P_gain, and in the end the most optimal value was chosen.

$$P\_term = velocity\_error * P\_gain \tag{5}$$

To further dampen the initial turbulence of the wheel (when attempting to reach the demand velocity value at the start), a negative magnitude (D_gain) was set through a trial-and-error process. This gain value was multiplied by change in error (D_error) over a small duration of time to produce a D_term (shown in Equation 6).

$$D\_term = D\_error * -D\_gain \tag{6}$$

Even though the initial turbulence of each wheel was minimised, both the P_term and D_term were insufficient for each wheel's velocity to reach the demand velocity. Thus, an I_gain value was introduced, and selected based on another trial-and-error process. As shown in 7, the I_term was calculated by multiplying the I_gain with an integral error (which multiplies the velocity error with a short duration of time). The inclusion of I_term with P_term and D_term allowed for the velocity of both wheels to be consistently matched to the demand velocity with minimal turbulence. The final power set on the wheels can be described by Equation 8.

$$I\_term = integral\_error * I\_term \tag{7}$$

$$wheel\_power = P\_term + I\_term + D\_term \tag{8}$$

C. Implementation Requirements for Qualitative Analysis

Given that the velocity of each wheel was matched, it was possible to conduct a m-stop experiment and produce a distance calculation for qualitative analysis. To show this analysis, a plot of distance measurements for each sensor over time was visualized. To complete this procedure, separate Python program was used to log the serial output of Arduino, and stored the incoming data in a CSV file while Romi was in motion. The Python program was linked to the Arduino code through a state system implementation in the Arduino code, allowing data to be collected strictly when the Romi is manually switched on through 'button 14'.

IV. Experiment details

To verify the calculated distance based on the ALS readings, the experiment involved comparing these distances to the baseline distance obtained from the proximity sensor. A simple motion-stop or m-stop mechanism was chosen. Appropriate distinction should be made between real-world implementations for an emergency-stop procedure (Kwon et. al. [8]) and the simple mobility-stop procedure executed in this project [5]. This project uses the distance measurements obtained from each sensor and fixes a threshold value, above which the robot must stop moving immediately.

In constructing the experiment, the characteristics of the sensors were taken into consideration. The datasheet shows that the spectral response of ALS (Fig. 1) attempts to replicate the photopic response [6], which implies that the sensitivity of ALS varies depending on colour. Due to this, a multi-colour LED light source was used and several trials of the m-stop procedure were performed for red, blue and green light separately. Modifications were made to the LED light source in order to satisfy the point-source requirements of ISL. This included the removal of the outer frame and focus lens in front of the LED light source. For collecting the most accurate readings, and due to the angular dependency of the sensor (discussed in Section II-A), Romi (with sensor attached at the front) needed to approach the light source at angle of 0°. To minimize such errors, a PID system was implemented (further elaborated in Section III).

An overview of the components involved in the experiment and its set up can be seen in Fig. 2. Note that the position of Romi is considered as 0cm, and thus the light source is x cm away during the start of each trial. Also pictured is an LED light source, whose colour can be changed using a remote control.

A. Quantitative Methodology

The stationary Romi present at the starting position is located 70cm away from the light source. A single trial of the experiment begins with a button press, causing Romi to travel in a straight line towards the light source with constant speed. A fixed distance threshold is set at 15cm. As Romi approaches the light source, the distance measurements read

[5]http://robotsforroboticists.com/proper-e-stops-m-stops/

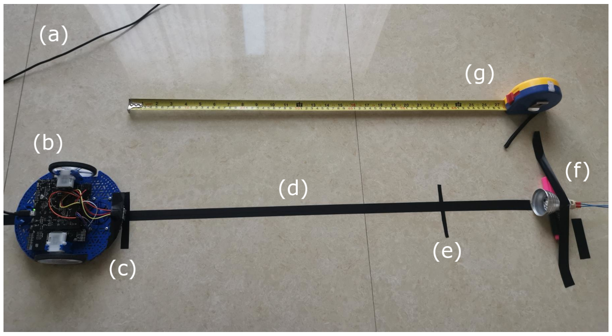

Fig. 2: Set up for carrying out experiments where: (a) is the wire connected to Romi, (b) is Romi, (c) is the 70cm mark, (d) is the referenced straight line track, (e) is the 15cm mark, (f) is the LED light source and (g) is the measuring tape

by the respective sensor decreases. Once it passes the specified threshold, the Romi stops its motion.

A total of 120 trials were conducted across the whole experiment, which were split equally into two scenarios: one with the surrounding lights on and another with them off. This was done to consider the different ambient light environments possible when an autonomous car is used in the real-world. For each scenario, first the m-stop mechanism was tested based on the calculated distance measurement from ALS and then with the distance obtained from the proximity sensor. 10 such trials were conducted per sensor per light colour. While this experiment aims to inspect the stopping distance for each light colour, it does not provide any insight on the sensitivity of each sensor during the run-time of a trial. Understanding the change in distance values over time illustrates the sensitivity of ALS in comparison with the proximity sensor. This makes for a qualitative analysis of a trial using *both sensors at the same time*.

B. Qualitative Methodology

As discussed above, the sensitivity of each sensor had to be observed through plotting the change in distance over time. An experiment trial for this was slightly different to the methodology detailed in Section IV-A. Instead, the starting distance of Romi was set to 38cm away from the light source, and the threshold distance was set to 10cm. As both sensors values were being plotted at the same time, the stopping distance threshold applied *only to the proximity sensor* since it is unaffected by different coloured light. The distance of 38cm was chosen as opposed 70cm (used in the quantitative methodology), because the range of the proximity sensor is capped at around 34cm, and a smaller stopping distance was set so that a larger profile of each sensor could be visualised.

C. Control Variables

The key variables within the experiments are stated below.

1) Hardware:

- The VL6180X sensor was connected to Romi via ports: SDA2, SDA3, GND and 5V.
- MR16 **80 lumen** LED with remote control to change colours [6].
- Position of LED light source was slightly elevated to be spatially aligned with the position of the sensor.

2) Software: The variables of software that are fixed throughout the m-stop experiment are:

- PID gains were set to: P_gain = 40.0, I_gain = 0.002083, D_gain = -2.0.
- The distance threshold for the m-stop procedure was fixed to 15cm.

D. Other Variables

1) Independent Variables:

- For each of the above environment conditions, the colour of the LED light was varied (i.e. Red, Green, Blue) for each sensor.
- The surrounding lights were varied (i.e ON and OFF).

2) Dependent Variable:

- The Distance between the final position of Romi and the light source, i.e the *stopping distance* is measured at the end of each trial.

E. Discussion of Metric(s)

To conduct a meaningful analysis of the quantitative results in the m-stop procedure, two metrics were used:

1) Mean of stopping distances:: An average stopping distance across the 20 trials was taken for each colour. This indicates the general performance of each of the experiment scenarios. However, given that the average does not compare the actual stopping distance of Romi to the expected stopping distance (15cm). An additional metric had to be chosen.

2) Mean Square Error (MSE):: To compare the overall performances of the two sensors at the individual colour level, MSE was calculated. This metric indicates how close a value is compared to the expected value, reiterating the level of the error for each trial. The equation for MSE is defined as:

$$MSE = \frac{1}{N}\sum_{i=0}^{N}(x_i - 15)^2 \tag{9}$$

where x_i is a data point, and N is the total number of trials (in our case that is 10 for each colour). As seen in the equation above, each data point of the stopping distance is compared to the expected stopping distance (15cm). The MSE calculated values cannot be negative, and those that are closer to 0 indicate greater accuracy of the specific trial. While a general disadvantage of using MSE is that it is vulnerable to outliers (causing a skew in the results), we believe that the hypothesis will hold true, which implies that the probability of recording outliers in this experiment will be minimal.

[6]https://www.amazon.co.uk/Dimmable-Changing-Daylight-Ambiance-Lighting/dp/B07HF91KNQ/

V. RESULTS

A. Quantitative Results

The average stopping distances for the different experiment scenarios are shown in Tables I and II. The results indicate that the proximity sensor readings show more consistent performance with different light source colours as opposed to ALS. The averages for ALS vary drastically based on the colour of LED light. For the case of blue and red light, the average stopping distance recorded by ALS (in both experiment scenarios) was much more inaccurate to that recorded by the proximity sensor. However, the average stopping distance with ALS for the green light source is much closer to the expected 15cm. The error difference between red and blue light, compared to green is further highlighted in Figs. 3 and 4, which displays the MSE values. The bar charts suggest that the MSE of ALS with green light source is much lower than the other colours. To verify whether the readings of ALS with the green light source are reliable (i.e. whether the inverse square law holds), a profile observation was conducted using both sensors.

TABLE I: Average stopping distance for both sensors with surrounding lights off.

	Average stopping distance (cm)	
Colour of Light	Proximity Sensor	Ambient Light Sensor
Red	12.96	8.45
Green	13.06	18.91
Blue	12.99	5.72

TABLE II: Average stopping distance for both sensors with surrounding lights on.

	Average stopping distance (cm)	
Colour of Light	Proximity Sensor	Ambient Light Sensor
Red	12.91	7.93
Green	12.7	19.54
Blue	12.64	5.14

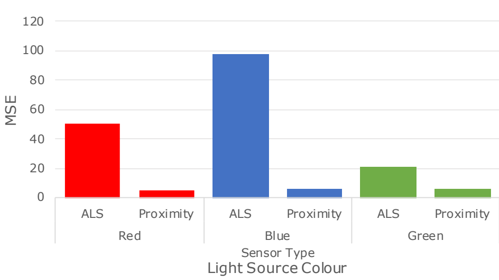

Fig. 3: Mean Squared Error for Stopping Distance during Lights On

B. Qualitative Results

The results of the qualitative tests for m-stop with green light can be seen in Figs. 5 and 6. As visualised from both graphs,

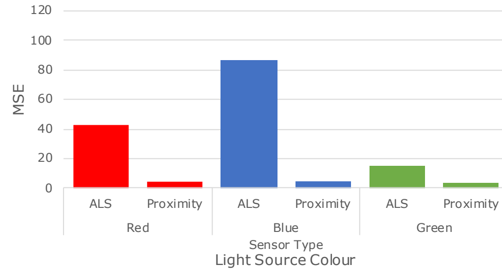

Fig. 4: Mean Squared Error for Stopping Distance during Lights Off

both sensors show a decreasing linear trend in distance values as Romi approaches the light source with constant velocity. This proves that ISL holds. Additionally, the stopping distance for ALS is close to that of proximity sensor (within few units of the expected 10cm). However, at distance values less than 34cm from the light source, the proximity sensor showed slightly more accurate readings compared to ALS. As an example, at 4500ms, the proximity sensor started detecting the light source at 32cm while ALS recorded 25cm.

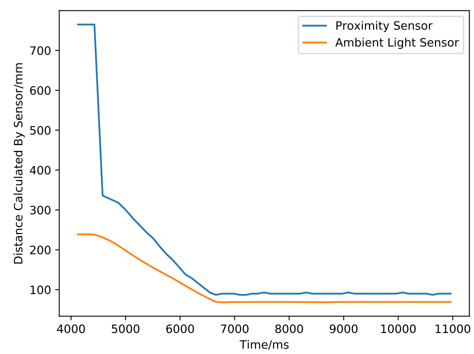

Fig. 5: Plot of the distance values over time with *Green light off*

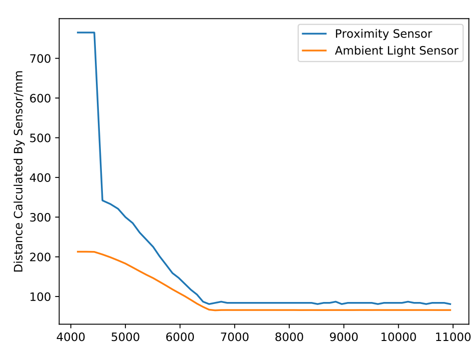

Fig. 6: Plot of the distance values over time with *Green light on*

VI. Overall Analysis of Results

The hypothesis aimed to show that the calculated distance based on the lux values provided by ALS will always be accurate. As highlighted by the results (Section V), the hypothesis does not hold true. Several reasons for this will be elaborated below.

As shown in the Fig. 3 and 4, the MSE values of the proximity sensor are much lower than those of ALS, for surrounding lights on and off. One issue that may have contributed to the error is the nature of the specific LED light source used. While many formulaic and hardware changes were made to the light source (discussed in Section II), it was still not a perfect point source. For example, the outer frame of the light bulb (that could not be removed) can cause unpredictable reflections of light towards the ALS. This in combination with the need for perfect conditions for ISL to give accurate distance measurements could partially justify the erroneous results.

Another reason that may explain the unexpected results is that certain variables could not be 'perfectly' controlled during the experiment. Once such variable, is the ability of Romi to travel 'robustly' straight towards the light source. Though a PID system was implemented to match the velocity of each wheel, the angular response graph shown in Fig. 28 of the Pololu VL6180X datasheet [6] illustrates that even a slight deviation from straight line path can cause significant changes in lux levels. This would have considerable effects on the calculations of Equation 3 due to the lower resultant lux readings recorded. Such readings can explain why the stopping distance measurements for red and blue colour lights are slightly lower than the expected value of 15cm. However, further explanation is required to justify the high stopping distance values of ALS with a green light source.

The MSE readings state that for the green light source the error is much lower than for other colours, which implies that the calculated distance measurements were fairly accurate. Fig. 1 suggests that ALS measurements are sensitive to the different colours of light. We believe this is related to the *luminous efficacy* of light (which is a measure of how well a light source produces visible light). Luminous efficacy implies that different colour wavelengths have different intensity levels [9]. Since the wavelength of green light is associated with a high luminous efficacy [7] [10] compared to other colours, the light source projects this colour at a value close to the maximum lumens possible (in our case, the maximum is 80 lumens). This explains why the stopping distance of Romi for the green light case has a much lower MSE compared to other red and blue lights. To further analyse the results for the blue and red light source: since the luminous efficacy values are small for these colours, the lumens produced by the LED are lower than the maximum. Thus, given the directly proportional relationship of lumens and distance, and the inversely proportional relationship of lux and distance, the low lumen levels of red and blue light cause the stopping distance measurements to be much lower than the expected 15cm.

Finally, we suspect that the dip in the centre of the spectral sensitivity (Fig. 1) of ALS for wavelengths near the colour green is the main reason for the stopping distance values for green light not being *precisely* 15cm. Through the qualitative results, it is evident that ALS provides an underestimation of the distance readings. This could be beneficial in real-world applications since it may allow an autonomous vehicle to make a m-stop at a greater distance from the vehicle ahead of it, as compared to using a proximity sensor that overestimated the distance.

[7] http://hyperphysics.phy-astr.gsu.edu/hbase/vision/efficacy.html

VII. Conclusions

Overall, this project tested an unconventional method of measuring the distance between a sensor and a light source. An ambient light sensor was used to estimate the distance (through an adapted, light-based inverse-square law), and a m-stop experiment was conducted to verify the inverse-square law within a robotics context. The results suggested that the proximity sensor provided more accurate readings compared to ALS across all the different light and environmental conditions. While this implies that the hypothesis for this project was false, we believe that modified light sources and changes to the equipment (such as using an improved ambient light sensor that has the exact same spectral response of photopic vision) could potentially prove the hypothesise to be true.

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