Light Source Localisation using Infra-Red Sensors

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***Abstract*—Fighting fires puts human life at risk on a daily basis. This paper investigates the fire detection capability of the Pololu 3Pi+ through light source sensing and localisation. An artificial light source was used to represent the source of a fire, the Pololu 3Pi+'s localisation capability was assessed by measuring light intensity readings from it's two forward facing light sensors at several intervals during a 360° on the spot rotation. It was shown that polar localisation, with respect to the 3Pi+'s local coordinate system, is possible with an accuracy of ± 5° provided suitable filtering is applied to the results. Light intensity as a function of distance from the light source was also investigated and shown to vary, as expected, by the inverse square. These experimental results add to the current research on IR sensing and navigation technologies for mobile autonomous systems able to travel into areas that remain unsafe for people.**

I. Introduction

This report investigates the ability for a robot to localise the source of infra-red light. This could be useful in various applications, in particular in firefighting environments where firefighter robots are used to avoid putting the lives of humans at risk. Their tasks include exploring hazardous environments to assess the severity of the fire, alerting human teams to prevent further spreading or damage, and in some cases extinguishing the fire. With advances in automated technologies, there is a growing need for effective implementations of autonomous systems to retrieve accurate data for fire control and suppression procedures. One of the main challenges considered is not only to reliably detect a source of fire but to report its precise location in unpredictable environments inaccessible to human exploration.

A. Literature Review

1) Background work: There are several inspiring instances of autonomous mobile robots in literature used for multi-sensory fire detection, extinguishing and odour source detection in firefighting scenarios but also for distance estimation, as demonstrated in the context of object avoidance and navigation [1], [2], [3], [4]. In particular for fire source detection, previous work has demonstrated the usefulness of mobile autonomous robots for detecting flames, thus enabling early fire source detection and control. For instance, an autonomous Fire Fighting Robot with multi-sensor fire detection using a PID controller was designed by Rakib and Sarkar in 2016 [5]. Their robot was able to locate fire using both temperature and flame sensors. In the same vein, Ihsan A. Taha and Hamzah M. (2018) provided a fire-extinguishing robot based on Arduino using flame sensors for detection [6]. More recently in 2020, Prasojo et al designed firefighter robot using multiple sensors such as UV and ultrasonic sensors [7]. Similarly, Kirubakaran et al (2021) showed a very effective implementation of an Arduino Uno based firefighting robot capable of assessing both the severity of the fire and the form of gases present [8].

However, to the best of our knowledge, no experiments were reported on autonomous mobile robots in which both fire-source detection and estimation of source localisation were investigated. Based on this observation, this experiment is evaluating the capability of a mobile robot, the Pololu 3Pi+, to detect a light source by sensing infra-red light intensities with varying distance and location. This technique, is a form of localization that records data from the robot's sensors to estimate its position (odometry) and nearby light intensity. Based on the experimental results, this work will then evaluate and discuss the system's sensitivity and performance in reliably estimating the angular localisation of the light source with respect to its position for potential applications in firefighting scenarios.

2) Experimental Motivations: We were given a mobile robot, the Polulu 3pi+ with bump sensors which were used for light source detection as they can detect changes in ambient light intensity. Previous work in the literature have used IR reflectance sensors, typically in electronics and robotic applications to measure light reflectance for instance, for obstacle detection but also for localisation and avoidance tasks. [9], [3], [4].

Accordingly, we chose to use light as a proxy for heat, as there is evidence that the bump sensors will easily detect and measure varying light intensities. With this set-up, our main objective was to assess how good the robot is at estimating the localisation of a light source. The performance of mobile robots control using light source detection or light-following with potential applications for real-world scenarios can be found in the work of Kuang-Yow Lian, (2019) [10] and Najia Manjur (2015) [11].

In our experiment, light intensity was recorded using the two front facing light reflectance sensors on the Pololu 3Pi+; the phototransistors on each sensor use light as an input to decay voltage output over time. This gives an inversely proportional relationship between light intensity and decay time. Whilst this is useful in determining light intensity, a limitation is that the decay time varies slightly for each measurement, therefore introducing some noise into the results. This was addressed by applying some filtering to the data. Some initial tests were carried out where the robot was programmed to output readings to the serial monitor. Whilst there was a systematic difference between the two sensors, it was not possible to use them to determine the direction to a light source as they are placed too close together to differentiate between readings. As such, for all tests, a sum of the two sensor readings was used to measure the total light intensity.

Four tests were carried out to assess the localisation capability of the Pololu 3Pi+. The first three tests assessed polar localisation capability by recording light intensity at various intervals whilst the 3Pi+ rotated on the spot. This was completed with a light source at the start heading in both the clockwise and anti-clockwise directions (Phase 1), with varying light intensity measurement intervals (Phase 2) and with varying light source locations (Phase 3). Phase 4 investigated the relationship between light intensity and distance from the light source.

These tests will further support current findings in literature, which evidence the usefulness of assessing sensitivity of sensors with varying distances in firefighting scenarios [1].

B. Hypothesis Statement

- We predict that the bump sensors will provide accurate readings of reflected light, suitable for detecting a single source of light.
- With this experimental design, we first expect to get faster read times when the sensors detect a bright source of light, and second, that these readings will provide enough information for the robot to estimate the direction of the light source. This will in turn enable estimations of light source localisation with respect to the robot's own local coordinate system.
- We expect that light intensities will be inversely proportional (squared) with distance.
- Since we will get readings of light intensities as inversely proportional to distance, we expect it to be plausible to calculate actual distances between the robot and the light source, allowing for true light source localisation.

To demonstrate the above, our work is organised as follows: Section II provides details on implementation. Section III covers the experiment methodology, breaking it down into four test phases for polar localisation and distance estimation. In Section IV, we present our observations and results. Section V will discuss the significance and potential applications of our system, which will then conclude our paper.

II. Implementation

A. Hardware Setup

The localisation of the 'fire' source was achieved through the collection of both odometry and light sensor data. Three light sources were compared to represent the fire, a 220V, 15W, small screw, filament light bulb, an LED bicycle light and a 15W UVB bulb. The filament bulb was chosen for the experiment as it was most similar to the light and heat emitted from a fire. The bulb was placed in a lamp base which was taped down with one side of the bulb resting on the table adn the top of the bulb facing the 3Pi+. All tests were completed on a pine coloured artificial wood table top.

The two light sensors on the front of the 3Pi+ were used, these are fixed in place and are too close to each other to differentiate light source direction. The total time for both phototransistor output voltages to decay was taken as inversely proportional to the light intensity. The distances between the robot and the light source were measured directly using a tape measure. As we were measuring an external light source, all tests were completed with the IR LED's switched off, and the white outer casing removed.

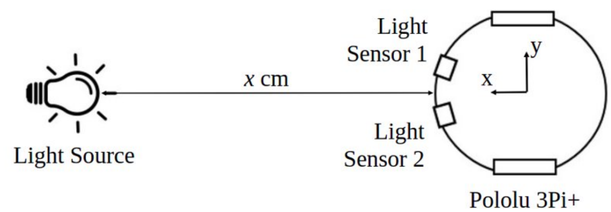

Fig. 1. Hardware setup where x is the distance, in cm, between the forward most point of the Pololu 3Pi+ and the lightbulb

B. Software Setup

In all cases the robot was operated at a constant wheel velocity, this was controlled using one PID controller per wheel. In all tests, the robot was set to spin on the spot and record light intensity data at a predefined radial increment, therefore producing sufficient data for a polar plot of light intensity versus heading.

The software controlling the robot was largely based on work done during the first half of this course - the forward facing IR sensors were operated identically to the bottom-facing line sensors by simply changing the pin number, and the code for interfacing with the rotary encoders and motors and handling kinematics and PID control was all identical. The top-level script was very simple- every iteration through the main loop, the kinematics were updated and the heading was compared to the heading goal. While the robot was still approaching the heading goal, the rotational speed of the robot was kept steady with a PID controller on each wheel and the IR sensors were measured at the desired interval. Once the desired heading was reached, the robot stopped and began broadcasting the array of measured intensity readings over serial. Keeping the software simple was a deliberate choice- it allowed minimal time to be spent writing new code, as 90% of it could be reused from previous work, allowing us to proceed quickly to testing and data collection.

C. Preliminary Odometry Testing

The localisation of a light source can be split into two parts, the sensing of IR light intensity, and the location at which that sensing is recorded. The latter was investigated through some initial experimentation to quantitatively assess the accuracy of the global position sensing capability of the 3Pi+. All light localisation tests were completed by rotating the 3Pi+, on the spot, through 360°, hence this motion was assessed.

Initially, a 360° protractor was printed onto a sheet of paper. The robot was placed on the protractor, facing 0°, and was programmed to rotate to an angle of 180° (test no. 1), and 360° (test no. 2) in both clockwise and anticlockwise directions. The test was completed using a heading PID controller which controls the rotation and stops the robot at the desired heading. For each test, the final rotation angle was measured and compared to the odometry data and an error measurement was recorded.

For the second part the motors were excluded, instead the 3Pi+ was rotated per hand, in increments of 10 degrees, as measured from the printed protractor (test no. 3). At each 10° increment, the angle given by the robot's odometry was recorded and the error was calculated by comparing the two values.

The mean rotational error for both test no. 1 and test no. 2 was respectively 3.30°, which is greater than the error in test no.3 (1.06°). This was because because a systematic error was introduced in the code in those first two tests. The motors were controlled by a nested heading controller which rotated the Pololu 3Pi+ to an angle plus/minus a given tolerance. This tolerance was causing a systematic error in the results. The systematic error was not addressed for the localisation tests, instead the heading controller was removed and the robot was rotated on the spot by simply setting an equal and opposite rotational speed for each wheel. This method was chosen as the heading to which the 3Pi+ rotated to was not important, provided the 3Pi+ rotated through a full 360° and was able to accurately report on it's heading.

In test no. 3 however, even without any motor control, there is an average error of ± 1.06 degrees, a random error due to the hardware limitations of the encoders.

Due to the nature of measuring small angles by eye, the errors in these tests are also subject to a human error of $\pm 1°$. It was suspected that the variance in the results would be within this human error bound. The conclusion therefore is that the random error, inherent to the hardware limitations of the Pololu 3Pi+, is $\pm$ 2°.

III. Experiment Methodology

Experimentation was split into four phases. Three phases assessed the polar localisation of the Pololu 3Pi+. Polar localisation is defined as the ability to localise a light source in the robot's local, polar coordinate system. The output of such is the angle between the light source and the 3Pi+'s x-axis. All three tests were completed by rotating the 3Pi+ through 360° and recording light intensity measurements at predefined radial intervals.

The first test assessed the 3Pi+'s ability to localise a light source in it's local polar coordinate system whilst rotating in the clockwise and anticlockwise directions. This was used to understand the accuracy at which the 3Pi+ was able to locate a light source from a single starting position. The second test was used to assess how a difference in the angular intervals at which light intensity was recorded, effected the accuracy of polar localisation results. The first two phases were completed with the light at a single starting location of 0° and 90° respectively, Phase 3 tested the accuracy of the polar localisation results with starting locations that were incrementally further from away from the 3Pi+'s initial heading. This was used to assess whether error would accumulate throughout the rotation and to measure any changes in accuracy as a result.

The fourth phase assessed was not used to assess polar localisation but instead the change in light intensity readings with distance from the light source. More detailed information for each step is given below.

A. *Phase 1: Polar Localisation Test 1*

The first polar localisation test was setup to understand how accurately the Pololu 3Pi+ could localise a light source in its local polar coordinate system. This test was completed with a single starting location for the light source, and measurement intervals of 10 degrees. The methodology is given below:

1) The control conditions were setup as per Section III-E;
2) The Pololu 3Pi+ was placed such that the forward extent of the robot was 50cm from and directly facing the 15W light bulb;
3) Start the program - the Pololu 3Pi+ rotated, at a constant speed, as set by the motor PID controllers. Rotation continued until the angle of rotation was 360 degrees;
4) The Pololu 3Pi+ recorded sensor data at increments of 10 degrees. The recorded data was a sum of the two sensor readings;
5) The Pololu 3Pi+ was reconnected to a computer and the light sensor results were extracted;
6) The experiment was repeated five times;
7) The experiment was completed with the 3Pi+ rotating in both the clockwise and anticlockwise directions.

B. *Phase 2: Polar Localisation Test 2*

The polar localisation test 2 assessed the effect of light intensity recording interval on the accuracy of light localisation. Two recording intervals were assessed, in the first case, results were recorded every 2 degrees, in the second case results were recorded every 10 degrees. The methodology and code was the same as that used in Phase 1 aside from the starting position of the light source and the varied recording intervals. In this case the light source was placed at an angle of 90 degrees from the x-axis of the 3Pi+, the 50cm separation remained the same. This change was to ensure that the light source was measured whilst the robot was rotating. The results from Phase 1 showed that there was no notable difference between clockwise and anticlockwise results, hence Phase 2 was only completed with rotations in the anticlockwise direction.

C. *Phase 3: Polar Localisation Test 3*

For Phases 1 and 2, the light source was placed at a single location. In order to assess whether the accuracy in polar localisation changes as the light source is moved further from the 3Pi+'s starting heading, light source locations were incrementally increased from 0° to 90° and then to 270° relative to the 3Pi+'s local x-axis. Five polar localisation tests were completed at each light source location. As in Phase 1, the measurement increment used was 10 degrees and as in Phase 2, all tests were completed with rotations in the anticlockwise direction only. Otherwise, the methodology and code were the same as that used in Phase 1 2.

D. Phase 4: Distance Tests

The distance tests were carried out to investigate the effect of distance from the light source on polar localisation and light intensity readings. By using the same methodology and code as that used in Phases 1-3, both of these aspects coul be tested. All tests were completed by rotating the 3Pi+ i the anticlockwise direction at the following distances from th light source: 50cm, 100cm, 150cm and 200cm.

E. Discussion of Variables

- **Controlled Variables**: The robot was placed in a darl arena with shut blinds such that there was no ambien light. The 'fire' was represented by a single 220V, 15W halogen light bulb of constant intensity. The light bull was taped to the table. The surface used was kept th same, a pine coloured, artificial wood, desk top. The robc was making 360° turns at a constant speed. Both front facing sensors were used and the sum of their decay time were taken as inversely proportional to light intensit measurement. (temperature?)
- **Independent Variable for Phase 1**: Polar localisatio was assessed in both the clockwise and anticlockwise rotation directions.
- **Independent Variable for Phase 2**: Polar localisation was assessed at measurement increments (bins) of 2° and 10°.
- **Independent Variable for Phase 3**: The light source location relative to the starting position of the robot was varied, three chases were chosen, 0°, 90° and 270° from the 3Pi+'s x-axis.
- **Independent Variable for Phase 4**: The distance between the 3Pi+ and the light source were varied. Distances of 50cm, 100cm, 150cm and 200cm were tested.
- **Dependent Variable(s)**: The light intensity at incremental headings was measured as a function of the local polar coordinate system (Phases 1-3). The light intensity at given distances was measured for Phase 4.

F. Discussion of Metric(s)

The primary metrics used to assess the Pololu 3Pi+'s ability to localise light sources were light intensity and polar coordinates, both of which are measured by the robot. Light intensity is inversely proportional to the voltage decay time of the phototransistors in the light sensors, hence all recorded values of light intensity are presented in milliseconds where the lower the time the greater the light intensity. Polar coordinates are given in degrees from the 3Pi+'s x-axis where anti-clockwise is the positive direction. These metrics were together compared against the actual position of the light source to quickly and easily understand the accuracy of the measured position.

Due to the nature of the phototransistor sensors, the voltage decay time varies slightly between readings. Therefore when taking multiple readings, some averaging or filtering was required to reduce the noise across the different result sets. (see Section IV).

IV. Results

A. Phase 1: Polar Localisation Test 1

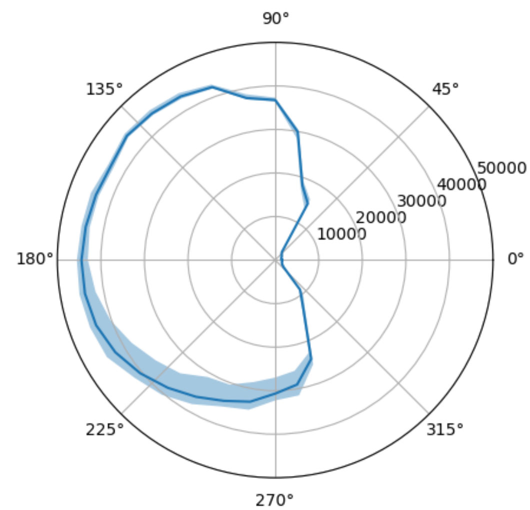

Fig. 2. Polar plot of sensor read time (μs) against heading angle for light source at 0 degrees

Figure 2 shows some results from the first set of polar localisation tests, being a polar plot of sensor read time against heading angle for five tests carried out with clockwise rotation. Anticlockwise vs. clockwise rotation showed no significant difference in performance, suggesting that any systematic rotation errors that may have been influenced by rotation direction were less significant than other sources of inaccuracy. The polar plots show very distinct regions around the correct heading, visible between roughly 45 and 315° in figure 2, where the sensor read times drop sharply to a very low value (ie. light intensity is high). (This is potentially a consequence of the field of view of the IR sensors, but we have not been able to locate the part datasheet to examine this.) Within this low-valued region, individual readings are quite susceptible to noise, while the bounds of the region are less so. Consequently, we examined using this window for localisation vs. simply taking the heading with the largest light intensity. The mean localisation accuracies over all the tests done in this phase for our various data processing methods are shown in table I. The processing methods used are as follows:

- **One-shot, direct**: For each captured dataset, the lowest sensor read time is selected, corresponding to the highest light intensity. The associated heading is taken to be the correct heading towards the light source.
- **One-shot, windowed**: For each captured dataset, the lowest sensor read time is selected. A window is generated as a consecutive sequence of sensor read times within 20%

of the lowest, and the mean heading of this window is taken to be the correct heading.

- **Averaged, direct**: For each set of 5 captures with the same experimental setup, the sensor readings for each heading are averaged over the 5 captures and the smallest averaged sensor reading is selected. The associated heading is taken to be the correct heading.
- **Averaged, windowed**: For each set of 5 captures, the 5 sensor readings for each heading are averaged and the lowest mean is selected. The windowing and selection process as described above is carried out.

Table I shows that windowing reduced mean error magnitude for both one-shot and averaged datasets, but there was no significant change in mean error magnitude from averaging groups of 5 datasets. Windowing also appeared to significantly reduce error variance- this was expected, since as previously discussed we expected it to be more robust to noise and consequently less variable. Averaging groups of 5 datasets also decreased variance, which again in unsurprising, as averaging values tends to reduce the effect of noise.

Selection method	Mean error magnitude	Error variance
One-shot, direct	8.5°	134
One-shot, windowed	4.95°	52.4
Averaged, direct	7.5°	84
Averaged, windowed	5.6°	31

TABLE I
ANGULAR LOCALISATION ERRORS

B. Phase 2: Polar Localisation Test 2

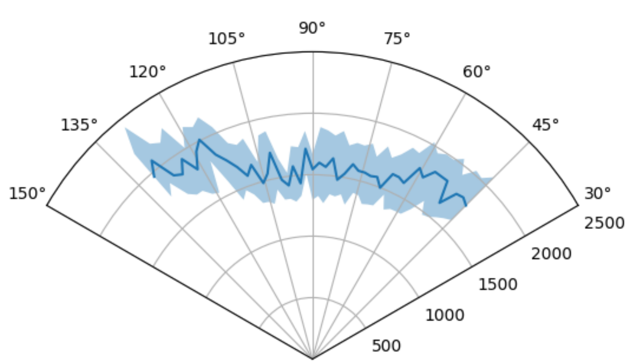

Fig. 3. Polar plot of sensor read time (μs) against heading angle for 2 degree bins, zoomed on the direction to the light source

The tests carried out with 2° bins (as opposed to 10° bins) showed similar results. As shows in table II, the non-windowed heading estimates were significantly less accurate than for 10°. This is likely due to the increased sampling rate amplifying the effect of noise close to the true heading, which was expected- Figure 3 is a section of a polar plot for 5 tests with 2° bins with the light source at 90°, showing the noisy low-valued region previously discussed for 10° bins, with mean and distribution for the 5 tests shown. Once again, windowing offers significant performance improvements, even bringing mean error magnitude down to similar levels as for the 10° bins, likely because the boundaries of the lower-valued region are much less susceptible to noise than individual measurements within it. This is because additive noise has a greater relative effect for smaller signals (for constant noise power), but the large changes in signal value associated with the boundaries of this region are relatively robust to noise.

Selection method	Mean error magnitude
One-shot, direct	10.2°
One-shot, windowed	7.6°
Averaged, direct	15°
Averaged, windowed	4.5°

TABLE II
ANGULAR LOCALISATION ERRORS FOR 2° BINS

C. Phase 3: Polar Localisation Test 3

Tests were carried out with the light source at 90° and 270° relative to the starting orientation of the robot. Due to time constraints, only one set of 5 tests was carried out for each setup- the resultant data is not of a large enough sample size to give a meaningful statistical comparison to our previous results, however the behaviour observed did indicate that performance was similar to with the light source at 0° relative to the initial orientation of the robot, and no unexpected behaviour was observed. Further testing would allow a degree of certainty here, as discussed in section V.

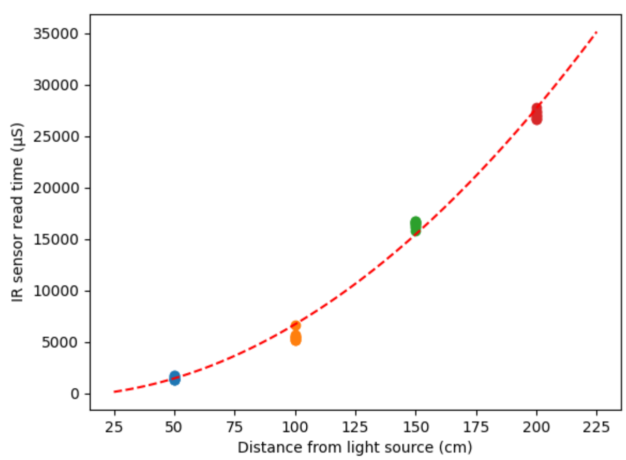

Fig. 4. Sensor read times vs. range, fit to an r^2 curve

D. Phase 4: Distance Tests

The test as described in Phase 1 was repeated at distances of 100, 150, and 200cm from the light source. Phases 2 and 3 were not repeated in this way due to time constraints. The read times associated with the one-shot direct heading estimates for each test are shown against distance from the light source in Figure 4, overlaid with a curve of form $ar^2 + c$ fit to the measurements. Based on this, the sensor read time appears to vary with r^2, which is expected- light intensity from a point source varies as $\frac{1}{r^2}$, and we would expect read time to vary inversely with light intensity. This result indicates that it could be possible to easily estimate distance to a light source, as is discussed further in section V.

V. Future Work

Two major areas which would benefit from additional work are increased data collection, in order to more thoroughly characterise behaviour and draw more statistically sound conclusions, and exploring positional localisation of a light source with this system, rather than just angular localisation relative to the robot.

If more time were to be allocated to data collection, taking a larger number eg. 20 measurements at each of the distances used in the phase 3 testing for the light source at $0°$, $90°$, $180°$, and $270°$ relative to the starting orientation of the robot, for both $10°$ and $2°$ bins, would really be the complete dataset that we've collected a subset of. This would allow more more rigorous comparison and analysis of all the aspects of performance that we've been examining, and could potentially reveal issues that we simply do not have enough data to have seen.

As mentioned in the distance test discussion, as the sensor read time varies as $\frac{1}{r^2}$ with distance from the light source, this could be used to estimate distance to the light source, as well as its direction. Once an estimate of direction is established, the robot could move some distance in that direction and take another sensor reading. The two readings, along with a known distance between them, could then be used to estimate the distance to the light source based on the established relationship between change in distance and change in light intensity. Implementing and testing this would be a natural next step in this work. Alternatively, triangulation could be used to estimate the position of the light source- once the direction to the light source is determined for one known robot position, the robot could move to another position and determine the direction to the light source from that position. As we are only considering the 2-dimensional case, this would then be sufficient information to estimate the location of the light source. Implementing and testing this, and comparing it to the range-based approach previously discussed, could be an interesting continuation to this work.

VI. Discussion and Conclusion

Our first three hypotheses- that measured light intensities will vary as $\frac{1}{r^2}$, that the bump sensors on the robot will be able to detect a bright source of light, and that the sensors will provide sufficiently high quality information to estimate the direction of a single light source to a reasonable degree of accuracy- were all assessed and found to be correct during the course of this work. Our final hypothesis, that the robot could be able to determine distance to a light source as well as direction, is supported by our results but has not been explicitly tested.

Over all, this work was successful- we were able to tackle our hypotheses and produce compelling evidence in favour of them. As mentioned in section V, more time to collect a more thorough amount of data and directly test our final hypothesis would have been good, but within the time we had, the system we implemented performed well enough to collect a reasonable amount of data of sufficient quality to present a fairly thorough approach to this problem.

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