Using PID output and real-time battery voltage to measure the inclination of a 2D plane.

George Stainsby 2076001, Monty Salt-Cowell 2080379, Thomas Nguyen 2085896, David Fielding 2088721

***Abstract*—This project aims to use a Romi 32u4 to calculate the angle of incline of the plane on which the Romi system is traveling on. By using PID to ensure that the Romi travels at a constant speed, the battery output voltage can be found, which will have a proportional relationship to the angle of incline. This proportional relationship will have to be calculated for each Romi system as the there are too many unknowns within the system such as the overall resistance of the system and charge of the battery among many others. The results show that there is a inverse relationship with the battery voltage against the angle of inclination, and a linear proportional increase with the PID value to the angle, hence the angle can be determined by the Romi this can be embedded within the code itself. Standard deviation increases with angle of incline therefore, results from this project become less reliable at higher angles of incline. however, this deviation is less than the typical increase in voltage with step in incline therefore results are accurate to 3 degree steps for the test range.**

I. Introduction

In this experiment, the inclination of the plane, or the topography, on which the robot is moving is studied. This study seeks to know if the Romi could infer the surface inclination due to the resistive forces acting upon it due to gravity, which can provide extremely useful applications for exploration in unknown areas. In this report, the aims are to investigate the effect of increased surface inclination on the battery voltage and the output of the PID controllers and gain an appreciation for the relationship between the variables, by plotting the battery voltage and PID output against the surface inclination to produce a graphical understanding of their relationship. This project will only focus on (X,Y) inclination i.e. no twist in the inclined plane.

A. Hypothesis Statement

The experiment involves measuring the battery voltage and the output from the PID controllers as the Romi travels on different surface inclinations. The principal hypothesis is that:

> As the surface inclination increases the battery voltage reading and the output from the Romi's left and right wheel PID controllers will change proportionally.
> This will produce predictable repeatable behaviour by which the Romi can be calibrated to state the angle of inclination from the power output when traveling at a constant speed. In addition, the noise on the readings will increase proportionally with the surface inclination.

This hypothesis is investigated by using an inclined plane upon which the Romi travels. Data is collected throughout the experiment and then processed to verify the correlation between the inclination and the readings from the Romi.

II. Literature Review

The testing in the report is done using a Romi robot, comprised of an 'Romi 32u4' micro-controller based on an Arduino Leonardo development board, two motors with quadrature encoders on each, infra-red sensors for line detection, wheels with rubber tires and a battery pack with AA batteries, the board also has LEDs, buttons, switches and general IO ports. The Romi chassis is circular with a diameter of 165mm, the drivewheels are located on the diameter, this allows for turning and spinning in place. A fixed ball caster provides stability to the system. The Romi has many general purpose mounting holes so that additional hardware can be added such as a sensor, actuator or microcontroller [1].

In this report the experiment seeks to find out if a Romi can be used as a digital inclinometer. Inclinometers measure the orientation angle of an object with respect to the force of gravity. This is done by means of an accelerometer, which monitors the effect of gravity on a mass suspended in an elastic support structure. When the device tilts, this mass will move slightly, causing a change of capacitance between the mass and the supporting structure. The tilt angle is calculated from the measured capacitances.' [2].

In this project, instead of using the accelerometer or inertial measurment unit (IMU), the battery voltage and PID output values will be observed to determine the resistance applied to the robot motion.

The Romi aims to acquire the angle of incline from the output of a PID (Proportional Integral Derivative) controller. 'The (PID's) date back to 1939, when the Taylor and Foxboro instrument companies introduced the first two PID controllers' [3] which all PID controllers since have been based on. PID's essentially have 3 components: a sensor, actuator, and a microcontroller. The sensor detects the current status of the system, and from this the microcontroller determines to what extent the actuator needs to be used; changing the value of the sensor thus changing the requirement of the actuator. This process is in a feedback loop to maintain the system at the desired state. A classic example is a heating system, when the sensor (thermometer) finds that the temperature is too low, it tells the microcontroller to turn on the actuator (heater) until it has heated the system to the desired temperature; at which point the actuator stops until the temperature drop is detected by the sensor again. this system type includes differential gains and losses to account for over shoot.

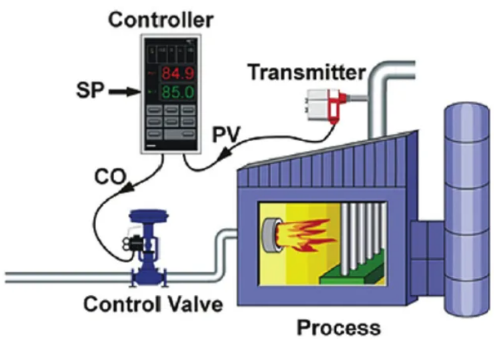

Fig. 1. PID Diagram

It is important to the success of the experiment that the power output of the PID is dependant on the angle of incline. This can be shown in newtons first and second laws [4] which states ‘In an inertial frame of reference, an object either remains at rest or continues to move at a constant velocity, unless acted upon by a force’ and ‘In an inertial frame of reference, the vector sum of the forces F on an object is equal to the mass m of that object multiplied by the acceleration a of the object: F = ma.’ this directly applies to the project experiment as the sum of the forces should be zero as the Romi is moving at a constant speed which allows the project participants to more accurately calculate the forces that have been summed to zero. From this a standard particle diagram can be constructed.

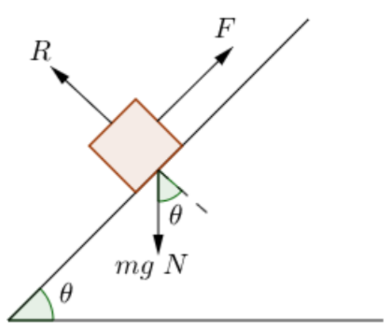

Fig. 2. Partical Diagram

Figure 2 clearly shows that at constant speed the magnitude of F is dependent on the angle of incline, θ. A simple equation demonstrates this, taking all forces in the plane of R, $R - mgcos\theta = ma$ [5]. This shows a relationship between angle of incline and the driving force of the Romi which can be exploited within this project

https://www.overleaf.com/project/5fbb9942c5344af449e22623

A. proof of relationship

Starting by taking forces in the horizontal plane, with $F_d =$ the driving force of the motors, $F_r =$ the frictional force, $\theta =$ the angle of incline and $R =$ the restive force acting at normal to the direction of motion .

$$F_d \cos\theta = R\sin\theta + F_r \cos\theta \tag{1}$$

Substitute in equation for R and F_r

$$R = Mg\cos\theta \tag{2}$$

$$F_r = \mu R = \mu Mg\cos\theta \tag{3}$$

therefore,

$$F_d \cos\theta = Mg\cos\theta\sin\theta + \mu Mg\cos^2\theta \tag{4}$$

Cancelling and rearranging gives:

$$\frac{F_d}{Mg} = \sin\theta + \mu\cos\theta \tag{5}$$

As μ is assumed to be constant the RHS of the equation is just a function of.

$$\frac{F_d}{Mg} = f(\theta) \tag{6}$$

The driving force, F_d, is proportional to the output of the battery voltage (v_{out}) as the motors are powered by the battery and F_d is caused by the motors .

$$F_d = g(v_{out}) \tag{7}$$

$$\frac{1}{Mg}g(v_{out}) = Cg(v_{out}) = f(\theta) \tag{8}$$

$$g(v_{out}) \propto f(\theta) \tag{9}$$

this therefore proves that there is a relationship between battery voltage output and angle of incline that can be exploited by this project. as these are in functions and ’proportional to’ not ’equal to’ this relationship must therefore be calibrated for each Romi.

III. Implementation

A. Hardware Setup

The Romi test rig was built using pine construction wood for the main structure and hardwood ply for the main slope. Two wood screws were inserted into the vertical frame for each angle increment to position the plywood board at the desired angles. The plywood board had a small mortised cut along the backside to allow the screws to lock into the board.The vertical distances for each set angle were found using trigonometric identities. The experimental setup went through two stages. The first stage was setup so that the plywood slope would be increased in 10 degree increments up to a maximum of 90 degrees. This proved to be the incorrect range of values as the robot wasn’t able to make it past 30 degrees in initial testing. So the setup was changed to 3 degree increments from 0 degrees up to 30 degrees.

Fig. 3. Experimental hardware setup

The testing sequence was as follows. Step one was to setup and check the slope to make sure it was on the correct angle for the data being taken. Step two was to place the Romi with its wheels in their start box's that were laid out with black electrical tape as can be seen in figure 3. Step three was to press a button to start the robots constant speed phase. This will continue for a set distance and then stop. Step four was to connect the Romi to the computer and upload the data, this worked was initiated with a second press of a button. This was repeated 3 times for each angle increment. The inclination was increased until the wheels began to slip.

B. Code

This experimentation assumes an existing code base such as but not limited to: basic motor control, ability to detect input from a push button, ability to read the battery voltage, a working PID class and finally a Kinematic class including motor encoders to record the robot position. In the case of this project, the base code was provided as part of the module resources.
The code uses a finite state machine to perform the sequences of tasks involved with the experiment. State changes occur at the completion of a task or when input is received via the push button. Figure 4 summarises the functionality of the code.
The sampling period was set at 20ms but in reality occurred between 21 and 24ms. Filter 10 was applied with an α value of 0.8 to reduce high frequency noise.

IV. Experiment Methodology

A. Overview of Method

The Romi was tested using the test rig described in III-A. The Romi was programmed to store data and then output

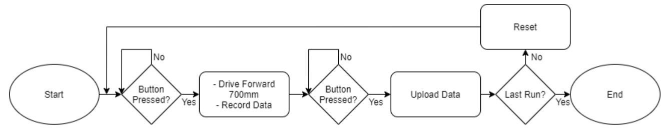

Fig. 4. Code Flowchart

the data after the test has finished. This is essential as the connecting wire may introduce frictional pulling forces on the Romi, preventing it from travelling further or applying unwanted forces on the Romi. The data output by the Romi were: the sampling interval, the battery voltage and PID values, these were observed and collected using the Serial Monitor/Plotter in the Arduino IDE, which allowed for a visual understanding of what is currently happening inside the Romi's "mind". A decrease in voltage would indicate that the Romi is experiencing higher resistance, and will increase the PID value to compensate for this.
Physical variables were also recorded, such as the length of the test rig, mass of the Romi, and the angle of the slope. These are recorded for the purpose of calculating an equation involving the resistive force and the inclination of the slope, which is used to check whether the two variables are proportional to each other.

B. Discussion of Variables

- **Controlled Variables**: Control variables are consistent parameters which do not change throughout the experiment. One variable which was not changed was the testing rig; three out of four tests were conducted on the same platform to minimise potential differences where introducing a different test rig might. Another control variable would be to only utilise the same Romi for each experiment. Due to manufacturing differences, some may have more efficient motor, and so will require different amounts of power to perform the task. To minimise this effect, using one Romi for each experiment will mitigate the effects of these variations in Romis. Repeats of the experiment can use different Romis, however they cannot be interchanged whilst in the middle of the experiment.
The same code was used for all of the experiments, by doing this, variation in results was reduced. These include: the set target value for the left and right motor PID controllers, the sampling rate and the noise filtering on the readings.
- **Independent Variable**: The independent variable in this study was the angle at which the Romi is travelling at. After the Romi reaches the end of the platform for each experiment, the inclination of the slope was increased by 3 degrees, and was done each time until the Romi could not travel up the slope any further.
- **Dependent Variable(s)**: The dependent variables which are measured are the PID output values and the battery voltage. The differences in values allow for a calculation of the resistive forces, and consequently plotted against

the angle of inclination to understand whether there is a linear relationship, or a inverse relationship.

C. Discussion of Metric(s)

Two metrics were used for the purpose of analysis and these were the mean, and the standard deviation. Mean was calculated within the data analysis software which averaged the voltages to provide an estimation of the centralised value. Similarly, a parametric standard deviation test was applied to the data set. This is the measure of spread within the data set from the mean, i.e are these values close or far from the average? Mean itself has advantages of providing quick analysis of the data for an average value which is useful since it takes into account all of the data points, representing all of the data and hence output accurate results. That said, mean itself also has disadvantages. As it takes into account all data values, those which are considered "outliers" (values which are abnormal), will skew the mean either negatively or positively. This would decrease the accuracy of the results if the outliers are included in the calculation. To help alleviate the issues of inaccuracy, standard deviation was used. The advantages of the standard deviation is that it is less affected by fluctuations in data, whereas compared to other measures of dispersion may be affected to a greater extent. It also can be used to understand data further as most statistical tests or graphical analysis rely on the standard deviation value. Though, one major drawback of the calculation is that it weighs larger numbers higher due to the squared function, as the square of a smaller number is much less than the square of a large number.

V. Results

Figures 5, 6, 8 and 9 are sample results from one Romi at angle increments between 0 degrees and 21 degrees. The experiment was discontinued at 24 degrees as the robot could no longer advance without slippage.
3 runs were carried out for each inclination including an additional 3 readings to conclude the experiments at 0 degrees to observe any decrease in baseline voltage during the testing. The ground truth surface inclination was measured using the 'Smart Protractor' application for Android installed on a Motorola G5 phone.

Graphs 5 and 8 show the the average of the 3 raw value readings for each angle. Graphs 6 and 9 shows the same data but with a moving average filter as shown in equation 10 where x_n is the new reading at t_n and α a constant value of 0.8

Graph 7 compares the voltage values against the angle of inclination for each Romi tested. These results indicate that the repeatability is high, given very similar results for each of the tests done. There is a negative linear correlation with the voltage and the inclination angle, and a positive linear correlation in graph 10, where the PID value increases as the angle increases.

$$f(t_n) = f(t_{n-1}) \cdot \alpha + x_n(1 - \alpha) \tag{10}$$

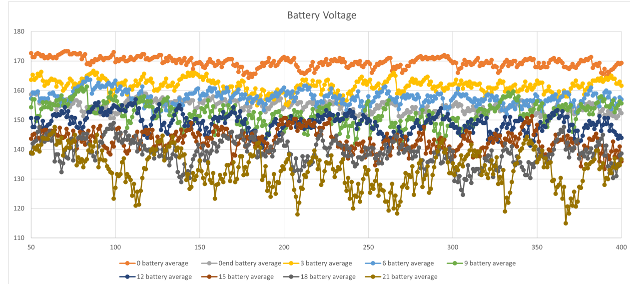

Fig. 5. Raw Battery Voltage Readings

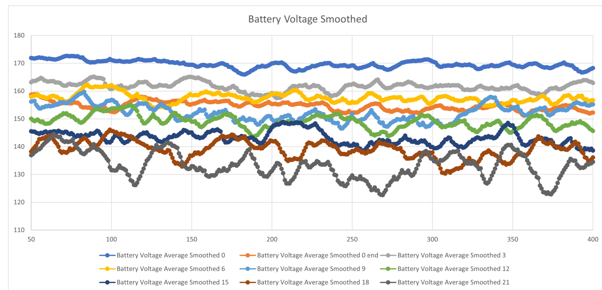

Fig. 6. Smoothed Battery Voltage Readings

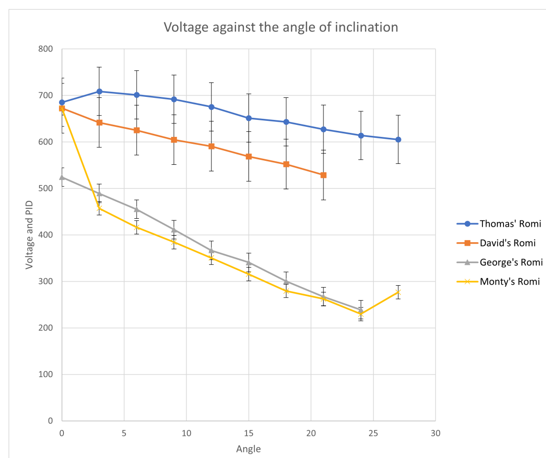

Fig. 7. Voltage against the angle of inclination

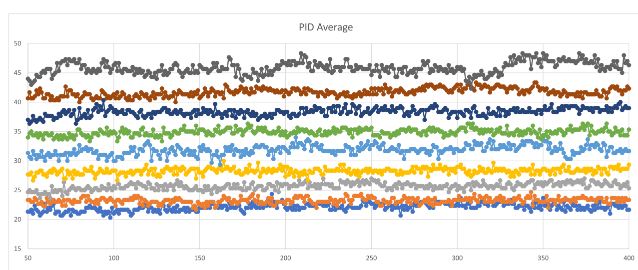

Fig. 8. Raw PID Readings

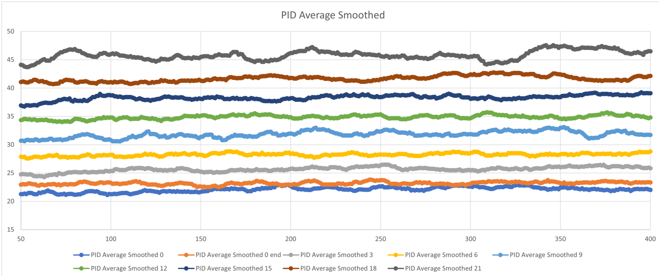

Fig. 9. Smoothed PID Readings

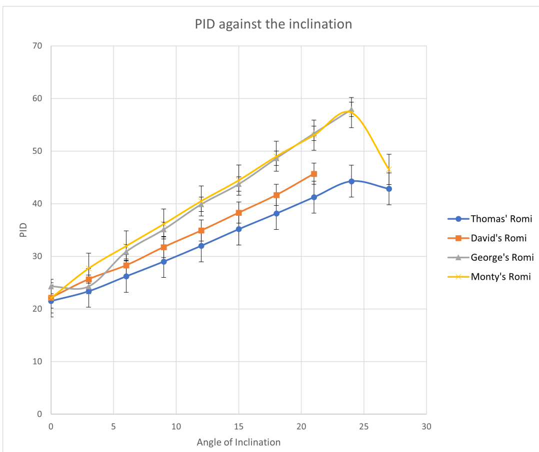

Fig. 10. PID Reading vs Surface Angle

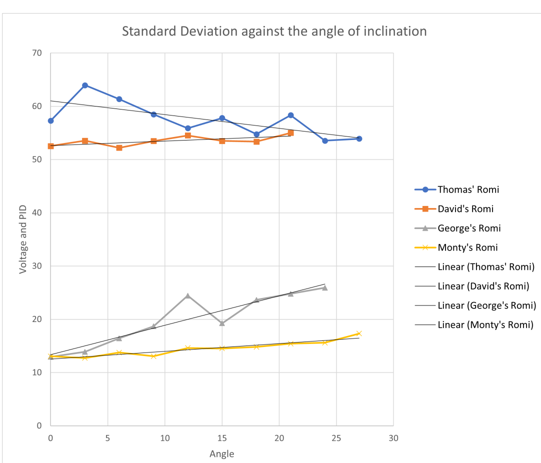

Fig. 11. Standard Deviation vs Surface Angle

Thomas	Degrees	Voltage	ST.Dev	PID values	ST.Dev	George		Voltage	ST.DEV	PID Values	ST.DEV
	0	685.242	57.2895	21.5129136	1.77934		0	524.155	12.9646	24.2674897	0.86596
	3	708.778	63.964	23.3794034	1.91577		3	489.251	13.8983	24.2674897	1.14316
	6	701.24	61.3633	26.2094163	2.63874		6	455.257	16.4386	30.865	1.21303
	9	691.716	58.4924	29.0149149	2.24796		9	411.437	18.678	35.0897119	1.42715
	12	675.427	55.8827	32.0141526	2.74041		12	366.653	24.4323	39.8922056	1.4712
	15	651.238	57.8174	35.1733021	2.76354		15	341.021	19.2615	43.7364532	1.44132
	18	643.206	54.7806	38.1409701	2.74739		18	300.433	23.6424	48.6418528	1.58774
	21	627.211	58.3366	41.2350308	2.93476		21	267.102	24.7793	53.3721122	1.58214
	24	613.93	53.5477	44.2792456	3.17634		24	239.121	25.9353	57.920398	1.7009
	27	605.201	53.9183	42.8274232	7.40507						
David		Voltage	ST.DEV	PID Values	ST.DEV	Monty		Voltage	ST.DEV	PID Values	ST.DEV
	0	672.411	52.5371	22.14788	2.00267		0	672.368	13.0554	22.1004218	2.27508
	3	641.777	53.5495	25.65548	1.6974		3	457.121	12.7305	27.7338	1.97491
	6	625.129	52.2123	28.29416	1.49978		6	416.391	13.7636	31.9818	2.17751
	9	604.628	53.4718	31.76019	2.05398		9	384.42	13.0554	36.1554	2.27508
	12	590.657	54.5235	34.90727	2.10785		12	350.553	14.6136	40.522	2.67086
	15	568.619	53.5082	38.29896	2.08413		15	315.627	14.522	44.4745	2.47492
	18	552.105	53.3708	41.66187	2.45867		18	279.498	14.8172	49.0086	1.95569
	21	529.072	55.0176	45.69544	2.20944		21	262.475	15.4205	53.0298	2.77743
							24	229.953	15.6008	57.3087	2.6026
							27	276.935	17.3342	46.5093	7.4603

Fig. 12. Voltage and PID Values for each ROMI

VI. Discussion, Limitations

A. Discussion

The hypothesis for this experiment was that as the surface inclination increases, the battery voltage reading and the output from the Romi's PID will change proportionally. As demonstrated by the results of the experimentation, a proportional correlation between the PID output and the surface inclination can be observed. Concerning the battery voltage, the correlation is inversely proportional.
Additionally, the inductive nature of the motors means that the frequency response of the battery reading would prevent this system from being used to measure changing inclinations.
An interesting and useful application of the proposed method is to use the angle prediction to calculate the robot displacement on a 2D plane. Using trigonometry the distance travelled is obtained, as measured by the encoders (the hypotenuse) and the perceived surface inclination to calculate the actual distance travelled, see figure 13.

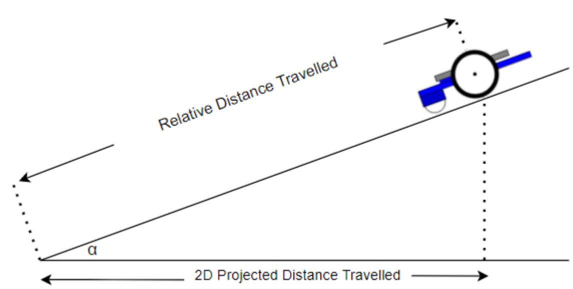

Fig. 13. Romi Distance Travelled and 2D Projection

Figure 7 shows a significant difference in Y intercept between each robot. By looking at figure 7 it can be seen that the starting battery voltage at 0 degrees is different. The hypothesis that the battery voltage is therefore the most likely cause of the Y intercept difference can be suggested. This indicates unsurprisingly that the battery voltage level has a strong influence on the readings and thus the ability of the robot to make an accurate prediction of the surface inclination from those readings. To compensate for this, the robot would need to perform calibration at regular intervals under identical conditions to establish the current battery voltage. This would perhaps require the robot to pause all current drawing activities and take a set of calibration readings. The voltage would then need to be factored into the angle calculations. Additionally, it would be interesting to establish whether the baseline battery voltage difference can also explain the difference in slope observed in figure 10.

B. Limitations

The limitations of this method for determining the surface inclination are principally the noisy nature of the readings. In particular the battery voltage which had a high degree of fluctuation. Within the setup, the principal draw on the battery was the two drive motors, however in a mobile system with additional actuators or other high current devices, the battery voltage would be subject to varying loads and would not be a reliable indicator of the surface inclination.

In such a case, the value from the PID controller would be more reliable as it is more closely coupled with the effort required by the motors. However it would still require the robot to travel at a constant speed and for the surface to be regular.

Due to limited memory on the Romi, the data was stored as byte data type. This causes some loss in precision due to rounding errors during type casting from float to byte. Additionally, with respect to the battery voltage reading, the precision loss is increased fourfold as the analogRead function used to read the battery voltage returns a 10bit value (0-1024) which then was divided by 4 in order to be stored in a single byte (0-255).

C. Further Study

Although this report investigates the effect of using PID output and real-time battery voltage to measure surface inclination, not all the ideas which were proposed could investigated. Due to the current situation regarding the Covid-19 Pandemic experimentation was difficult due to restrictions. If further study was to be conducted, experiments looking into combining PID feedback with the Battery voltage could improve the accuracy of incline prediction as well as improving kinematic pose estimation on inclined surfaces.

VII. Conclusion

The hypothesis was that the increase in inclination will result in a proportional change in the battery voltage and PID value. The results support this where the battery voltage is at a proportional decrease and PID a linear increase to the angle. Variations in the Romi lead to differing results, however each are consistent with the ideas and concepts presented. There are limitations to this experiment which can be adjusted and accounted for in further experimentation, mainly a much better performing robot with similar functions as the Romi will provide much more accurate results. This is because of the existing Romi suffering from memory limitations and also motor limitations when travelling up inclines; this would mean that it would benefit from substantially larger, more powerful motors or perhaps tyres and a surface with higher friction coefficients. Additionally, a better memory storage system would allow larger amounts of more precise data to be collected.

Lastly , this project had lots of potential for further study and further implementation. This came in the form of taking the code and giving it to a more rugged higher power robot, which could have the potential to be used as a hazardous area topology mapping tool. By taking and storing all measurements of inclination and using it to update a kinematic model, low fidelity maps could be generated. As well as this, it was discussed that this type of functionality could be used as a fail-safe if other, more precise, hardware were ever to break in situ.

References

[1] Pololu. (2020) Pololu romi chassis user's guide. [Online]. Available: https://www.pololu.com/docs/0J68/all#:~:text=The%20Romi%20chassis%20is%20a,holder%20for%20six%20AA%20batteries.&text=The%20chassis%20uses%2070%C3%97,quadrature%20encoders%20for%20position%20feedback

[2] Posital. (2020) Inclinometer specifications. [Online]. Available: https://www.posital.com/en/products/inclinometers/mems/MEMS-Technology.php

[3] L. Payne. (2014) The modern industrial workhorse: Pid controllers. [Online]. Available: https://www.techbriefs.com/component/content/article/tb/pub/features/articles/20013#:~:text=Proportional%2DIntegral%2DDerivative%20(PID,many%20other%20industrial%20process%20variables

[4] I. Newton, *Newton's Principia : the mathematical principles of natural philosophy*. Daniel Adee, 1846.

[5] ncl. (2018) Inclined planes(mechanics). [Online]. Available: https://internal.ncl.ac.uk/ask/numeracy-maths-statistics/mechanics/dynamics/inclined-planes-mechanics.html