Project: Line Following Robot

Due:	13th March 2016
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Abstract

As technology improves around the world at an exponential rate, so does medicine and life expectancy. In fact, global life expectancy had increased by 6 years from 1990 to the end of 2014[1]. This has also meant that the median age of the population has increased, and in the UK, this figure has risen from 35.5 years to 40 years in the same time span[1]. The percentage of elderly citizens (65+ years old) has also risen from roughly 16% to almost 18%[2]. As of 2010, more than 735,000 people in the UK live in assisted living settings[2], many of who wish to be more independent. Assisted Living Technology (ALT) is a relatively new area of study, and is aimed toward helping those who have physical disabilities, possibly due to old age, achieve this.

The Following Robot Carrier is a small, wheeled robot and ALT, which will follow the user, and will have a surface on which to conveniently place heavy objects. A working, full-scale version of the product was expected to be constructed for the purposes of this project, but budget and time constraints led to a small prototype being made instead. This will be used to demonstrate the functions of the proposed product, the feasibility of the project and to gain insight into its technical aspects.

After the prototyping was done, a conclusion was drawn that although a robot could be made to follow a user under the right conditions, there would be too many factors in the real world to enable the robot to work as intended. However, the robot could be adapted towards other purposes, such as carrying suitcases in airports for those who have a lot of luggage.

Introduction

Since the inception of computers, automation and robotic technologies have been utilised to create consumer products that increase life quality. An example of this is the automated robot vacuum cleaner, which has become increasingly common across the world. Although vacuum cleaning may seem like an extremely minor problem to be solved, one such brand of these products, the Roomba, has sold over 10 million units worldwide[3], which clearly shows that there is extremely high demand for such products.

The Following Robot Carrier aims to utilise such technology to solve another common issue: carrying heavy items. There are many issues associated with carrying heavy items, ranging from health concerns[4] to simply being a nuisance. The Following Robot Carrier therefore aims to eliminate such problems by being a helpful robot that can carry almost any kind of item whilst following the user in an accurate and unobtrusive manner. Although this robot would be useful for people of all ages, this project's main demographic is the elderly (65+) and those with physical disabilities.

Since mid-1974, the population of those aged 65 or over has increased by 47% and now make up nearly 18% of the population, while the number of those aged 75 or over has increased by 89% and makes up 8% of the population[5]. Approximately one-third of independent adults aged 65 or over experience a fall, many of which occur because of instability caused by groceries[6]. Citizens with physical disabilities make up roughly 9% of the population of England[7]. The Following Robot Carrier would greatly increase the level of safety for those who want more independence from human care.

There is currently no aide on the market that helps to carry objects for those who need it. The closest competitor would be the Starship[25] robot, which is designed to make package deliveries. ALT is a rapidly expanding part of the worldwide market for robot systems in 2014 was estimated to be around $32 billion[8], with government subsidies being planned for such products[9]. Thus the Following Robot Carrier could make a name for itself as a staple piece of technology for this large proportion of the population. However, this product must be designed with extra criteria in mind, as although there is a trend of the elderly becoming more technology savvy, the large majority are still finding it difficult to understand technology[10]. To cater towards this, the robot must be made to be very simple to operate. Furthermore, the robot should be easy to set up for use to make it accessible for those with physical impairments.

For the prototyping of the robot, features such as obstacle avoidance will be excluded, and the main focus will be on optimising the way in which the robot follows the user. Specifically, the robot should be able to travel in the same path behind the user at a constant distance that is far enough not to affect their walking. This requires the robot to have to speed up and change direction accordingly.

Design Criteria

By evaluating the needs of the main demographic (the elderly and physically impaired/disabled), and the purposes of the robot and its functions, the following Product Design Specification (PDS) criteria were identified to be the most important to successful robot design.

Operating Environment

The final design must be able to operate in indoor and outdoor environments, as users may want to take it for trips to the supermarket. Hence, it requires a certain degree of robustness in its construction, so that components do not get damaged or knocked out of place by small falls or bumps in the road.

The average height of a mountable curb in the UK is four inches[11], and given that sometimes it is necessary to go across curbs, it is imperative that the robot can withstand a fall of such a height. It must also traverse small bumps and potholes in the road, meaning the robot has to withstand both large impacts and constant rattling. This can be resolved by using integrated circuits such as PCBs and sturdy materials.

The robot should also be waterproof, as it may start raining during the user's trip, so all electrical components should be protected with a waterproof casing. This will also provide some protection toward humidity and moisture.

Many of these design aspects must first be tested out on the prototype, but because the prototype is of smaller size and will be built differently from the final product, tests for criteria such as robustness and its ability to handle falls cannot be carried out accurately.

Installation

As the product's main demographic is expected to be senior citizens and those with physical impairments, the installation process needs to be as simple as possible. Ideally, the robot will work straight out of the box, as all hardware will be put together during the manufacturing process.

From a software standpoint, the final product must be as straightforward as possible to operate with all software already installed and optimised. To reduce the amount of confusion for those less adept with technology and software, there should only be one setting for the robot's operation, i.e. there will be no way to alter any settings or variables in the code. This includes the values that determine how far behind the user the robot should follow and turning speed. This eliminates any possibility of the user changing the settings to options sub-optimal values, without knowing how to change them back. Therefore the

software must be tested and written such that the absolute optimal settings are found during the prototyping stage.

For the robot to follow the user, the user must wear a device in order for the robot to detect what it should be following. This device will be shipped with the robot and must also be ready to use straight out of the box. It should also be easy to attach onto the user, as a large portion of the demographic will have varying degrees of physical impairments, and be one-size-fits-all. The nature of this device depends on what technology is used by the robot to detect the user, and may be electronic or passive.

During prototyping, there will be experimenting to find the optimal ways to build the robot such that no installation will be required after initial manufacturing, as well as the optimal settings for the software. A prototype of the user worn device will also be built and optimised to be as comfortable and easy to set up as possible.

Performance

The final robot must be able to carry luggage and follow the user without going off course. It will also need to avoid obstacles along the path, make its way around them automatically and find the user again. Therefore the robot must be able to vary its speed, approximately from standstill to a brisk walking pace. It is crucial for the robot to be fully automated and perform these tasks without user intervention otherwise the user may forget the robot and lose it.

The average walking speed of a younger pedestrian is 4.95 feet per second, and that of an average elderly pedestrian is 4.11 feet per second. Although the target demographic is the elderly, the robot must also be usable by the average human, and thus a speed of at least 4.95 feet per second must be able to be achieved under the same conditions as US Road's study[12]. The robot must also have sufficient power to make sure that these speeds can still be achieved whilst carrying a load. Given that the average human eats around 1.5 kilograms of food a day, the average weekly shop may weight around 10.5 kilograms. This is the weight that the robot should be able to carry and achieve its required speed.

The final robot would also have to have a certain surface area in order to accommodate the load without having to pile too many items on top of each other. The average surface area of a shopping trolley is 100cm x 50cm[13]. Thus the robot must have a surface area of at least 0.5m^2 as this would mean that any shopping that would be bought at the supermarket can also fit onto the robot.

For the prototype robot, the main focus is to optimise the "following" function. One other problem is how the user would approach the robot, as if it is programmed to always keep a certain distance from the user, the user would never be able to interact with and place grocery bags onto it. The prototype can be used to test the best methods of solving this problem.

The prototype will also be used to determine weight-speed characteristics. Using this information, it will be possible to estimate how much power the final robot will require in order to achieve the performance requirements as stated above.

Target Product Cost

The consumer demographic for the final product is expected to comprise heavily of the elderly. The average income of an individual older than 65 years of age was found to be $22,248[14] in 2014. This is less than half of the average income of $51,939 for the whole population. Because of this, it is crucial to make the final product as cheap as affordable as possible.

A projected price can be estimated from the costs of building the prototype. The parts required are the chassis (£30), logic unit and sensors (£40), components for the circuit including transistors and voltage regulators (£10), which total £80. In addition to this, labour and shipping costs apply, and also for the sensors. Even after labour costs, the retail price of the prototype would not exceed £100. Extrapolating this to the final product would be inversely exponential as an economy of scale comes into play. Further research needs to be done to accurately predict a price, as research costs, worker's salaries and profit margins must also be considered.

Quality and reliability

The final product should require as little maintenance as possible, as this may not be able to be carried out by the target users. This emphasises a need for the product to be high quality and very reliable. The robot must therefore be mechanically robust and built well enough so that parts will not break or become loose under use. With consultation from a mechanical engineer, it was determined that an aluminium-magnesium-silicon (6000) alloy would be ideal for this task. This material has a fatigue resistance value of up to 12000 newtons/cm^2 [15] meaning a weight of roughly 120kg would have to be placed within a square centimetre of the material to cause damage. As the robot is designed mainly for uses such as carrying groceries for the elderly and will normally not be made to bear such weights. Legal documents should be written to ensure that if a certain weight for the load is exceeded, the warranty for the robot should be voided. The strength of the material is also largely unchanged by temperature[15].

In addition to the strength of materials, the robot should be built in a way that means that components will not be knocked out the way by small impacts, such as driving off of a pavement curb. The circuitry should also not be able to be tampered with, and will be enclosed in a screwed shut box that should only be opened by proper engineers. The circuitry itself will be in the form of a PCB, ensuring maximum robustness.

For the purposes of the prototype, a breadboard will be used, as it is the most convenient way to assemble circuits for testing and altering circuits.

Concept Designs

This section documents the design for the prototype robot alone and the main focus therefore, is to design a small robot that can follow the user. Four main concept design problems were identified for this purpose: the chassis and motors, sensors, circuit design and logic.

For the chassis, a pre-manufactured robot car was bought, as the timeframe and budget did now allow for a bespoke chassis to be built. The selected robot was a SparkFun 4WD robot chassis and platform, purchased from Hobbytronics[27]. At £27.60, it was one of the more affordable robot chassis, as many of these could reach up to £150, which would stretch uncomfortably far into the budget.

The main motivation behind the selection of this chassis was its abundance of attachment points to easily attach and test a multitude of controllers, drivers or sensors. Its 6.5cm diameter wheels would also add extra stability, allowing more accurate testing. Smaller wheels would have made the robot unstable and cause the speed to differ, as evidenced by the first year EEBug, where the wheels would struggle to drive over even a small pebble on the floor. The large 165mm x 157mm surface area on the topside of the robot would also allow for weight bearing testing to be done. In particular, weight-speed characteristics to predict the amount of power the final robot might need to achieve its required speed.

The final product will have a bespoke manufactured chassis that fits the needs of the design criteria and PDS. These include being made of polycarbonate polymer for strength and having soft edges for safety.

The robot should be able to turn on the spot in case the user walks in a backward arc, by spinning the wheels on either side in opposite directions, which is possible using the motors that come with this chassis. This meant that the circuit that drives the motor would have to have a design that would allow current to flow in both directions.

To follow the user, the robot must have suitable sensors to detect the position of the user in relation to the robot. The biggest issue would be the method and technology in which this would be done. Technical difficulties such as noise and accuracy in communication between the user and robot must be solved too.

In the interim report, three designs were proposed: Global Positioning System (GPS), Inertial Measurement Units (IMU) and Ultrasonic Sensors (US). Since then, a fourth design has also been proposed: Camera with image processing. Because this was the biggest consideration for building the prototype, the design selection section is deal mainly with the selection process of this aspect of the robot's design.

The general logic of the robot is very simple: wherever the user goes the robot goes as well. The most simple logic to implement would be that the robot would detect what angle the user was at in reference to the robot 's forward direction at discrete intervals, and adjust its path each time accordingly. Although this may

seem like it would work, many problems would be encountered in the real world. For example, if the user turns at a 90-degree angle, the robot would try to cut the corner. If the user walked this way due to a physical obstacle such as the corner of a wall, the robot would try to drive into the wall ultimately fail its task. Logic must be developed to solve this problem.

The robot must also be able to detect how far away the user is and maintain a certain distance by speeding up or slowing down according to the user's distance, as to avoid driving into the user or being too far away.

Design 1 - Ultrasonic Sensors
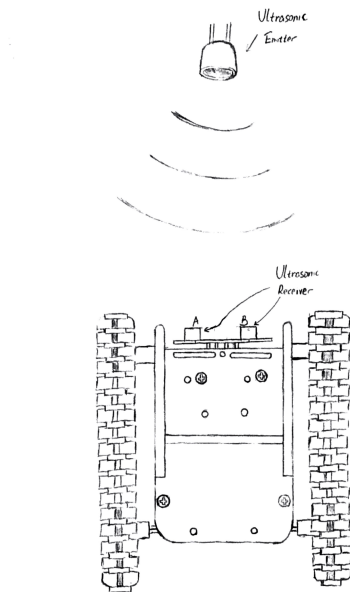

Design 1 – Ultrasonic Sensors

The first design was to use Ultrasonic Sensors (US). The idea behind this would be to attach an ultrasonic emitter on the user, and to place two receivers on the robot, one on the left and one on the right. The logic unit on the robot would then compare the strength of the signals on the two receivers, and whichever was stronger would mean that the user was closer to that side, and implies that the user was turning in that direction. The frequency of the signals could then be used to determine the speed of the robot (Doppler Effect).

The advantages of this design included its low cost, and robustness, as the average price of an ultrasonic sensor is £10, and has a warranty of 2 years. These aspects would contribute to improving the target cost, reliability and lifespan of the robot. The power consumed by the sensors is also very little, allowing for more power from the batteries to be dedicated towards the motor, increasing the maximum speed and the speed aspect of the robot's performance.

However, sonic waves decay inversely proportionally to distance, meaning that the operating distance of these devices are fairly short at a range of 1 to 3m. This normally will not cause a problem, but in the unlikely scenario that a glitch happens and the robot falls too far behind the user, it would be difficult to detect the user again. Furthermore, the ultrasonic sensors are susceptible to noise from

other devices that emit waves of a similar frequency. Ultrasonic waves also do not penetrate surfaces, so if there were something in between the emitter and the receivers, no signal would be received at all.

Design 2 - Inertial Measurement Unit
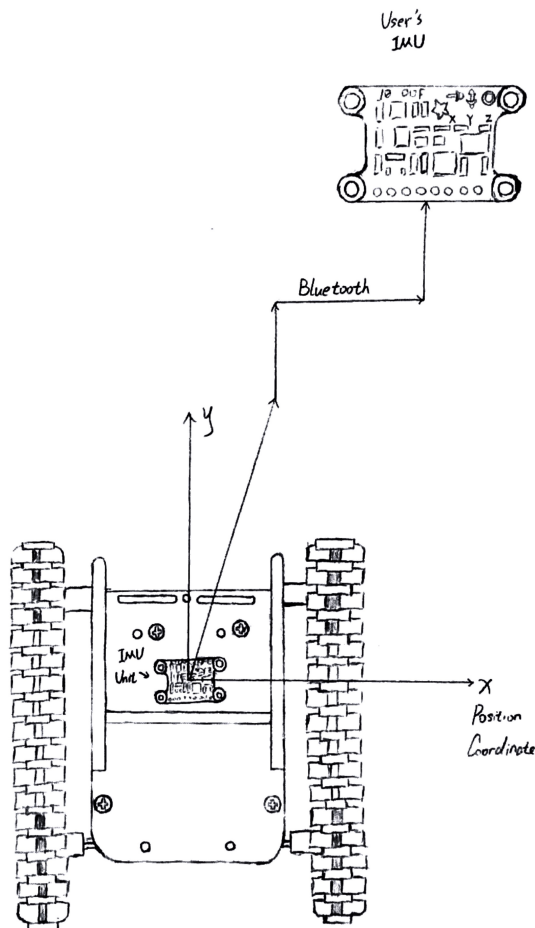
Design 2 - IMU

The second design involves mounting one IMU onto the user and one onto the robot. Using a combination of accelerometers, gyroscopes and magnetometers IMUs have the function to measure specific forces acting on the body from which angular pitch and roll, yaw, position, velocity, and net acceleration can be calculated[16]. Hence by programming the two IMUs, and allowing them to communicate via Bluetooth, the displacement of the user can be recorded and the robot can react accordingly. The IMUs have the advantage of being able to calculate the displacement of the user directly, as opposed to the ultrasonic sensors, where the displacement is calculated using maths, which requires more processing power. The data measured by these devices can be fairly accurate within a short distance. They operate both indoors and outdoors with low power consumption. Furthermore, the cost of an IMU is very reasonable, at an average of £24. However, there are critical disadvantages that cannot be ignored. Since the raw data collected by an IMU is integrated multiple times to obtain useful information such as position and direction, the error accumulation is enormous. Research by Cambridge University found that an

average IMU accumulated an average positional error of 150m after 60 seconds[17]. This figure may be smaller if an extremely accurate IMU is used, but these are typically outside of the budget allocated for this project. In order to eliminate such errors, the robot must be stopped and recalibrated after a short time in order to reset the data. This decreases the performance of the robot in terms of convenience for the user.

The IMU is also susceptible to external noise from magnetic fields and EM waves which may cause inaccuracies to the system.

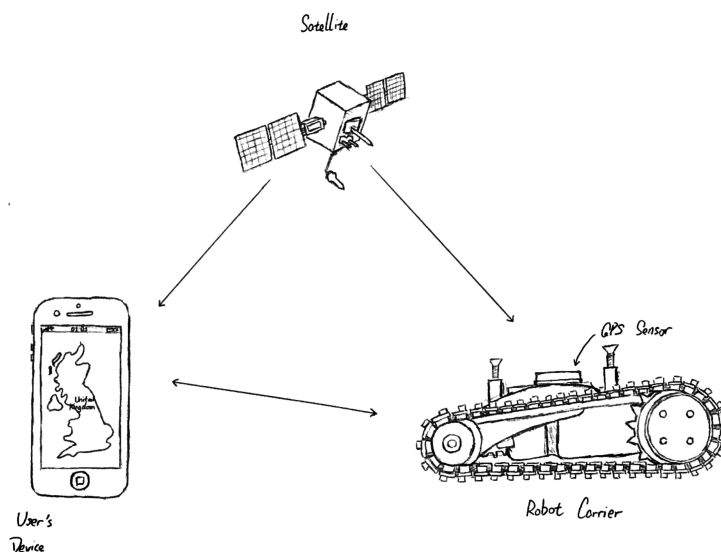### Design 3 - Global Positioning System

Figure 3 - GPS

The third design solution is to use Global Positioning System (GPS). This would work by having a GPS on both the robot and the user worn device. The coordinates of the user would then be sent to the robot via Bluetooth, which would be compared to the robot's coordinates by the logic unit, and the direction that the robot has to move in would be calculated from the longitudinal and latitudinal values. The logic behind this would be very simple to implement, as it would just require simple mathematical operations. As GPS has extensive range, the robot would have little problem with finding the direction to go and turn to. This design would also open doors to advanced features such as self-driving abilities and a method of locating the robot if it is lost or stolen. However, GPS is only accurate to about 10 meters worst case[19], and often does not work indoors, causing large inaccuracies, which is detrimental to the performance requirements. Receivers that are accurate enough for the needs of this project are beyond the allocated budget[20].

The user would also have to wear a GPS device with its own power supply. GPS devices are expensive in terms of power compared to USs and IMUs, consuming 33mA at 3.3V[18]. The average time spent in a shopping centre is 47 minutes[21] so the total power required for an average shop is $47 * 60 * 3.3 * 33m = 307.098W$. A power bank that can supply this amount of power has dimensions of 16 x 8 x

2.3 cm and weighs 463g. This device would be heavy and unwieldy, especially for the elderly or physically handicapped.
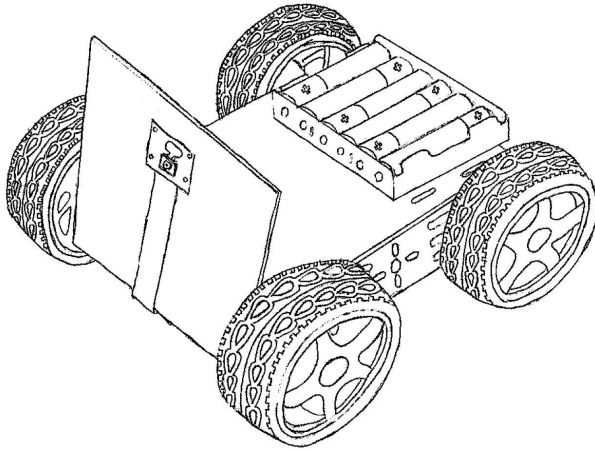
Design 4 – Camera

Figure 4

This design solution utilises image-processing techniques. This involves installing a camera onto the robot and putting a distinguishing mark on the user for identification purposes. The camera could then determine if the mark was become smaller or bigger, which would in turn cause the robot to accelerate or decelerate accordingly. It could also be determined whether the mark is moving towards the left or right, and at what magnitude. The robot could then turn at a corresponding angle. The advantages of this design are that there is very little room for noise, as the camera would not be affected by ultrasonic waves or EM waves and the robot's movement can be made to be very accurate. The user would also only have to wear a piece of fabric on their leg which is much less intrusive than all other designs, which require electrical components to be strapped to the user's leg, which would be uncomfortable and easy to break. The camera also allows for many advanced features to be introduced. However, its downfall comes from the fact that the programming associated with it may be very complex, and the processing power required will be much higher than the other solutions. In particular, we find that at a distance less that 1 metre, 320x240 resolution is enough to distinguish movement[22]. Using this resolution, the maximum frame rate is 90 frames per second (fps) [23], but because image processing would be carried out using python, a relatively inefficient language, only 10fps could be achieved. If the FPS is too low, the robot will only be able to take samples of the user's position at large intervals, resulting in jagged movement of the robot. However, there is advanced software pipelining techniques that would improve these figures. The camera also suffers from a similar issue as the ultrasonic sensors in that any solid object between the user and the robot will disable the robot's ability to follow the user.

Design selection

This section documents the analysis of each different design concept for the sensors. The concepts will be judged depending on how well they will satisfy the design criteria and PDS.

In an ideal world, GPS sensors would be the most straightforward design solution and the one that allows for the best performance due to its effectively infinite range and ability to navigate past obstacles if mapped into the robot's logic. In reality however, this is not the case as GPS sensors are easily electrically shielded indoors. The GPS sensors that fit this project's budgets also have large margin of error, which would render it useless for the purposes of this project, which require high accuracy within a small range.

IMUs would be extremely easy to implement and in an ideal world, would allow the robot to take an identical path to the user, naturally avoiding stationary obstacles. The IMU can also detect changes in all 3 axis of movements and does not require a direct line of vision to the user in order to work, meaning it would overcome changes in height and be unaffected by moving obstacles that would go in between the user and the robot. However, research points to the fact that real-world IMUs are extremely inaccurate when used for a long period of time due to error accumulation.

On the surface, ultrasonic sensors seem like a very good choice. Its accuracy and simplicity made it the best option at the time of the interim report, but further consideration and discussion unveiled some critical flaws. One issue was that if the user turned to either direction slightly, the ultrasonic sensors would not be sensitive enough to distinguish the slight angle taken. The robot would then keep travelling in a slightly skewed direction from the user until the angle of the user and robot's paths were large enough to be distinguished, at which point the robot would have to turn sharply to rectify its angle of travel. Another problem was that some ultrasonic sensors would only give a digital signal. This meant that if the ultrasonic sensor receiver did not receive a signal from the emitter, it would not give a voltage signal to the microprocessor. However, if it did receive a signal, it would give a flat voltage signal regardless of the level of signal strength. Analogue ultrasonic receivers are available, meaning the signal strength would determine the signal voltage transmitted from the receiver to the microprocessor, but these sensors came in the form of an emitter-receiver pair, which were placed adjacently on a board, and can not be taken apart. These work by using the emitter to send a signal, which would bounce off of a solid object and back to the emitter, much like sonar. This would not be able to distinguish the user from any other solid object.

The last design, the camera, would seem like the most complicated design solution to implement, as the programming required seemed daunting. However, it avoided many of the major issues associated with the other designs. It does not have a problem with the electric shielding and positional inaccuracies that affects GPS. It also did not accumulate error as the IMU did, and would be able to distinguish the position of the user much more finely than the ultrasonic sensors.

This meant that if the programming challenges could be overcome, the camera could possibly allow for the most accurate user detection out of all the methods. It would also allow for the most simple and comfortable user worn device, as it would not have to have electronic components.

Based on the information above, a criteria matrix was constructed to provide quantitative reasoning for concept selection.

Criteria	Concept 1 - US	Mark	Concept 2 - IMU	Mark	Concept 3 - GPS	Mark	Concept 4 - Camera	Mark
Performance	Consistent, but angle precision is an issue	3	Accumulation error causes large inaccuracies over time	2	Completely ineffective in certain environments and poor accuracy	1	High accuracy given sufficient resolution	5
Operating Environment	Obstacles and sharp turns cause problems	3	Unaffected by obstacles in environment	5	Indoor environments can electronically shield the GPS signals	1	Line of vision may occasionally be compromised	4
Product Cost	Sufficient USs are available at a very cheap price	5	Sufficiently accurate IMUs would be far too expensive	1	Sufficient GPS devices would be extremely expensive	2	Compatible Camera with sufficient resolution available at cheap price	4
Installation	No installation required	5	Recalibration may need to be done	3	No installation required	5	No installation required	5
Quality and Realiability	Ultrasonic sensors are extremely reliable	5	Large number of components in IMU allow for more possibilities for breakdown	3	GPS sensors can break often and Bluetooth device required also causes room for error	2	Largely reliably device	4
Overall Score		16		14		11		17

As the scores for USs and the camera were so close, both were initially purchased, but the order for the USs never came through. This meant that solely the camera method was built and tested.

Concept Development

The first step in concept development was to come up with a complete design for the hardware. Originally, the prototype was going to be the same size that the final product would be, but it quickly became apparent that a chassis of this size would be extremely expensive and not readily available. Thus a decision was made to buy a small robot chassis and focus on developing the other aspects of the robot more, such as designing the optimal circuit for the motors and how best to achieve the method for robot following the user.

The chassis purchased allowed for a breadboard to be mounted vertically on top of the robot, allowing extra surface area for placing other components such as the camera, and also weights for testing weight-speed characteristics.

To determine which other components would be needed a circuit design was proposed. This was a H-bridge because this would allow current to flow in both directions through the motor, thus allowing the motors to turn backwards too. To construct this, diodes, BJT transistors and various resistors would have to be purchased. Calculations to determine the values of these components can be found in the appendix.

A user worn device was also assembled, but this was simple for the camera as it could be as simple as a piece of paper with a block of colour drawn on with felt tip pen. For testing purposes, a black square was drawn onto white paper for high contract.

After all the required components had arrived the chassis was assembled and tested to ensure all measurements reflected the data sheet, and 2 tasks were identified that could be carried out in parallel to save time: hardware and software development.
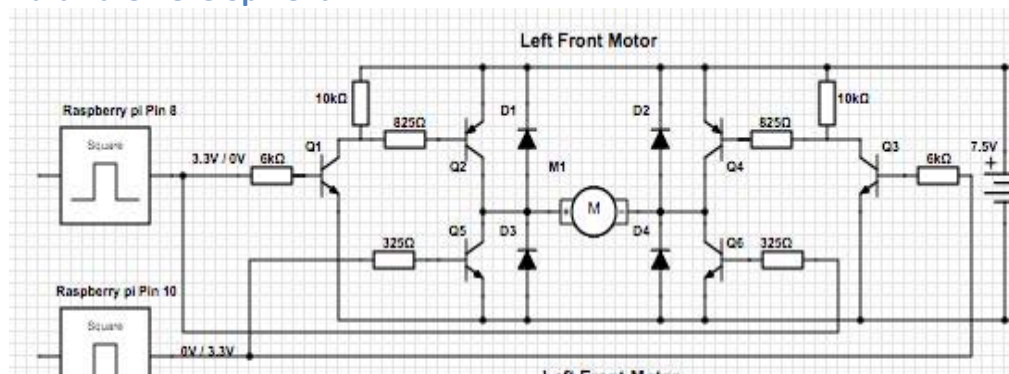
Hardware Development

Figure 5

Figure 5 shows the H-bridge circuit for the front left motor. All other motors will have an identical circuit. When the wheel must turn forwards, Pin 8 will be at 3.3V, and Pin 10 at 0V. This causes Q1, Q2 and Q6 to go into saturation mode, and all others will be off. This induces a voltage across the motor, which draws up to 0.16A of current and turns the wheel runs. Normally Q1 and Q3 would not be included in an H-Bridge as the supply voltage would be 5V, and the voltage of 3.3V would be enough to drive Q2 and Q4 into saturation. However, the supply voltage for this robot is 7.5V, and so the resistors above Q1 and Q3 will draw voltage and allow these transistors to bring current to ground, reducing the effective voltage in Q2 and Q4. The diodes protect the motor by providing a current path for when one set of transistors is switched off and the others are switched on.

The resistor values were initially determined to be R1 = 6kΩ, R2 = 10kΩ, R3 = 825Ω, R4 = R5 = 325Ω. These calculations can be found in the Appendix.

When tested, it was found that the circuit could run the motor at 0.16A. By filming the wheels turning and viewing in slow motion, the wheels were found to be spinning at 7 revolutions per second, corresponding to a horizontal velocity of ~143cm/s, or ~4.7feet/s. This satisfies the speed performance required, as specified in the design criteria. It should also be noted that at the start of operation, the current could reach 0.2A, as extra torque is required to start the turning of the wheels.

Software Development

Whilst the circuit was being designed, the software for the robot was being developed concurrently. A Raspberry Pi 2 with Python was used to implement the logic, in favour of the slower Arduino. C++ would have been a better language to use for real time programs, as it compiles and optimises code before execution, as opposed to Python's real time compiling, but Python has much more resources relating to the project[32]. In order for the Raspberry Pi to communicate with the camera, OpenCV[33] was downloaded. This is an online computer vision and machine-learning software library, with function libraries such as "PiCamera" that contain functions that retrieve data from the camera to the processor.

The main portion of the code is an infinite while loop. Inside this loop, the code constantly requests RGB data from the camera and introduces random Gaussian noise in order to cut out unpredictable high frequency noise. This data is then transferred to grey scale to compress the data to increase the efficiency of the processing. The "Canny edge detector" function in OpenCV[31] is then called to detect edges and recognise polygons. In real life, not many objects are of a square so if the user worn device is made to be a square, and the robot made to detect all objects with a height-width ratio between 0.8 and 1.2, the user can be easily isolated. The code then determines the midpoint of the square and places it on a coordinate system. The robot turns left or right if the midpoint is to the right or left of the origin of the coordinate system respectively. Essentially, the robot is trying to move the midpoint of the square to the origin. Physically, the robot turns by rotating the wheels on one side of the robot forwards and the others backwards. A characteristic line on the coordinate system as mentioned above determines the turning speed, and the equation of the line can be changed to alter the behaviour of the robot. To make the robot drive more smoothly when moving forward, a dead band of radius 10 pixels was initially defined around the origin. This means that if the user meanders 10 pixels worth of distance to either side, the robot will still only travel forwards. This was only a temporary figure and further testing would have to be done to find the optimal value.

The distance between the robot and the user can be calculated using using triangle similarity described by the equation $d = \frac{F \times W}{P}$, where d is the distance, P is the width that the camera perceives in pixels (320 pixels), W is the width of the user worn device (11.5cm) and F is the focal length (the distance between the camera and the user worn device for the user device to fit the whole width of the field of vision, found also to be 11.5cm). The robot can then be made to speed up or slow down according to this figure.

To control the motors, 2 pins of the Raspberry Pi were assigned to each motor, one for forward and one for backwards. Only one of each pin on the motor can have current at once. A pulse width modulated signal is sent to the motors is sent to the motor. The frequency of this signal can be set to anything higher than 1kHz where the motor will only respond to the average voltage of the signal, which can be changed by altering the duty cycle, which therefore determines the speed of the motor.

When running the program, a Boolean argument can be optionally set that when true, provides a live feed of the camera and other parameters, such as current distance, and motor speed.

A Wi-Fi adapter was also installed onto the Raspberry Pi and allowed the robot to be controlled wirelessly, the operation of which can be found in the Appendix, along with the code in its entirety.

Testing

To assemble the robot, the Raspberry Pi, camera, and two breadboards with the circuit had to be placed onto the chassis. These did not fit as anticipated so improvisations had to be made to fit all components comfortably. This involved 3D printing long screws to create another level for placing components. A picture of the final robot's construction can be found in the Appendix.

After all the elements of the prototype were assembled and trouble-shooting was done to fix any small mistakes that would prevent the robot from working, testing was carried out. The first test was to test whether or not the robot could follow the user at a fixed speed. To make the test fair, the robot would have to follow something travelling at a constant speed. This was done by attaching a sheet of paper with a block of colour drawn on for the robot to detect, attaching it to a flat base and a piece of string, and pulling at it smoothly at a constant speed. It was found that the robot would initially start travelling at a slower speed than the target but would quickly speed up until it was slightly faster, then slow down again and stabilise at a speed that was almost identical to that of the target. The robot would also follow at a distance of about 60cm. The robot therefore meets the requirements of being able to travel at the same speed as the user and at a comfortable distance.

The next step in testing involved having the robot actually follow a human. When this was done, it was found that since the user worn device was attached onto one leg, the robot would travel in a jerky motion, as one foot would travel forward quickly, then stop as the other foot went forward, meaning the target that the robot had to sense would move forward, then stop, and then move forward again and so on. To smooth the motion of the robot, the code was altered to take the average motion over two steps. This equated to averaging the motion of the user of 1.2 seconds as the average human takes a step every 0.6 seconds[24]. This completely fixed the stop-start aspect of the robot's movement, and would only slightly decrease the reaction time for dealing with a complete stop.

The next test was to see how accurately the robot would imitate the user's turning by observing how the robot dealt with turns of different angle sizes. A protractor was used to measure the angle and a path was marked onto the floor using sticky tape. The following table shows the results for each angle.

Test Number	Angle (Degrees)	Result (Pass/Fail)	Notes
1	10	P	
2	20	P	
3	30	P	
4	40	P	
5	50	F	
6	45	P	
7	47	F	

This illustrates that if the user turns at an angle of more than about 45 degrees, the robot will not be able to follow the user. This is because as the user turns, so does the square on the user worn device, and as the camera only sees 2 dimensional images, it perceives the square to be a skewed polygon. Further work must be done to design a solution to this problem.

Project management

In order for the team to work cohesively as a team, communication was essential. Therefore a Facebook group was created in order to communicate and share files or information. This was crucial in ensuring that no time could be wasted in miscommunication e.g. two members working on the same task without knowledge, or not being able to carry out a task because of a lack of information or files e.g. unable to build website because of a lack of images.

However, it can often be difficult to express difficult technical concepts via text, so regular face-to-face meetings were scheduled not only with other team members, but also with the project supervisor. These meetings were scheduled for Wednesday afternoons. If more face-to-face time was required, different meetings could be set up easily by communicating via the Facebook chat. Minutes were taken at every meeting to ensure that no information was forgotten, and that members who were unable to attend the meeting could later understand what was discussed and what tasks they were assigned next. Sample meeting minutes can be found in the Appendix.

To tackle the project, the whole timeline was estimated in advance. Different aspects of the project were also identified, and the time required for each of those different tasks were also estimated. To streamline all work, different tasks that could be carried out at the same time as others were identified and a Gantt chart was created in order to visually represent which task needed to be carried out at what date, and by what time.
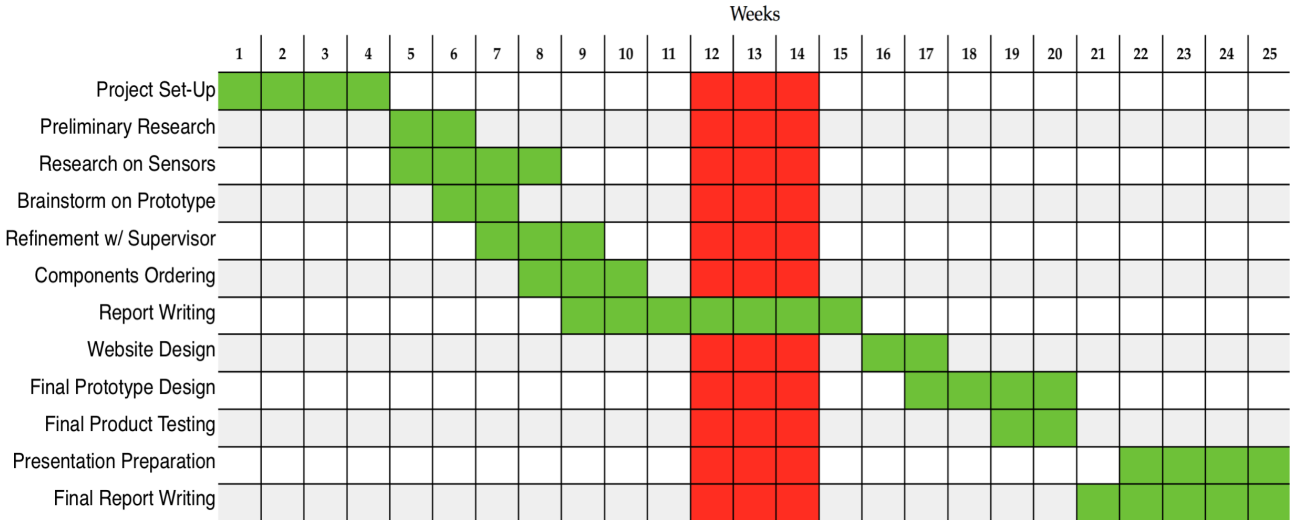

Figure 6 – Gantt Chart

This also allowed each project member to choose which task they wanted to work on and let this play to their strengths. For example, those who were confident at programming would work on the robot's logic and code, and those who were stronger at electronics would work on designing the robot's circuitry. As these tasks did not require one to be completed before the other, they could be carried out in parallel.

A lab book was kept to record the robot's construction procedure to make sure that this information was not forgotten at a later date. Results for the testing of the robot were also recorded on the lab book. The lab book was also used to keep a physical copy of the budget and spending to make it as easy as possible to keep track of funds and ensure that overspending did not happen. Due to good planning, only essential components were purchased, and in total, only £150 of the £200 was spent. A complete breakdown of the spending can be found in the Appendix.

Future Work
The prototype robot's testing phase has not yet been completed. Crucially, the issue with the robot's restricted turning angle must be solved. This could be done by either making the user worn device an active piece of technology that can turn towards the robot, or implement more code so that the user's movement can be predicted after the user worn device can no longer be detected. The latter option might require extra processing power to implement, but advanced programming and pipelining techniques could be used to increase the efficiency of the code. Currently, only two cores of the quad-core CPU on the

raspberry pi are being utilised, so there is much more processing power that can be extracted.

Although the prototype robot can follow its user, this is not enough for it to be a useful product for consumers. To be useful in real life situations, the robot must be able to navigate past moving and stationary obstacles. Therefore further work must be done to allow the robot to anticipate the trajectory of possible objects such as cars or walking humans who have not spotted the robot. The robot must then be able to avoid or overcome these situations. This may be done either with more advanced image processing techniques using the camera or with other components such as ultrasonic sensors. Many of these methods may require more battery and processing power, so another step would be to upgrade the robot's current components.

Had more time been allocated for the project, a Bluetooth sensor would have been installed to allow communication between the robot and the user's phone. A mobile application would then be developed for smartphones, which would allow the user to remotely start and control the robot.

As the robot would be out of sight of the user for most of its operating time, it would be easy to steal. Therefore theft detection or prevention should be implemented. Methods for achieving this include an alarm that activates if the robot detects that it has been picked up and is being moved away from the user. Lost robot recovery solutions could include a GPS sensor that can be remotely activated and used to track the location of the robot.

Extra safety measures should also be implemented. Since the movement of the robot would be unpredictable, there should be an indicator that can warn pedestrians of what direction the robot will travel so that they can avoid walking into the robot. In the case that a collision does happen, the robot should have soft edges to minimise the possibility or severity of the injury that the pedestrian sustains.

Before bringing the robot to market, a second prototype must be made. This one will be made using knowledge gained and techniques learned whilst building the first prototype, such as what circuit to use, what battery size and what code to use for the processor. It will also be made to fit the physical specifications of the final robot and possibly the chassis that will be used for the final product.

This prototype will allow testing to be done to determine what changes must be made in order for the product to meet the design criteria. This includes testing its maximum load and speed, as well as quality assurance tests. Different factors that can affect the robot's performance such as the friction of the road and weather should also be tested and accounted for in the final design of the robot. Alterations can be made to parts of the robot to ensure that all elements of the PDS are met.

As with all products, user manuals and legal warranty documents must be written.

After this stage, a manufacturing process must be established. Depending on the demand for the robot, a manufacturing line such as those to mass-produce cars may be implemented to mass-produce these robots.

Conclusion

In the allocated time, a fully functioning prototype was built that would follow the user using image processing techniques. Although a fully functioning product that could be the used in the real world was not constructed, a lot of valuable knowledge was gained and potential pitfalls were identified.

Unfortunately, such a robot is far from becoming a reality, as there are many problems with the operation of the robot in the real world, and the development of this technology has not yet reached a point where it can perform its tasks as desired. However, the group is hopeful that as more research is done and technology improves, such a product can be materialised and help millions of elderly and disabled people around the world be more independent.

Appendix

Product Design specification

1. Performance

The robot must be able to carry luggage and follow the user without going off course. It must therefore be able to travel at varying speeds, from a standstill to a brisk walking pace. The robot must also be stable enough to travel on various surfaces without getting stuck or tilting.

2. Environment

The product should operate both in and outdoors. Therefore, it should be able to operate in normal conditions in urban environment.

3. Life In Service

Expected life span of 3-5 years without maintenance.

4. Maintenance

Maintenance should be carried out by a professional in the event of a breakdown. The robot should be hard to dissemble as to discourage tampering. Recharging and lubrication can also be carried out by a casual user.

5. Target Product Cost

Each unit should be affordable for individuals. The final design is expected to cost around £100 to manufacture, and be available for consumers at no more than £150 after labour costs. The price of the prototype should be even cheaper - no more than £50.

6. Competition

One known competitor exists, called Starship[25]. Inspecting this design could also give us valuable information on how to proceed. However, this robot is not designed specifically towards helping the elderly and motor impaired, thus giving the Following Robot Carrier an advantage in these markets.

7. Shipping

As the product is fairly heavy and big in volume, it will be difficult to ship. It will have to be delivered in the same way as other large objects would, for example a fridge or a sofa.

8. Packing

The product should be packaged in by parts and shipped to the location of assembly. The assembled product will require large and sturdy container during shipping. This can be thick cardboard with Styrofoam to spread the weight of the robot evenly across the surface of the container, thus decreasing the pressure and possibility of breaking the box.

9. Quantity

Initially, the robots should be made in small quantities, as the demand will be low. As advertising for the robot is set up and word spreads, the demand will

grow and quantity of the robot produced will be increased until equilibrium is found between demand and supply.

10. Manufacturing Facility
A factory should be set to mass-produce the final product if the demand is high.

11. Customer
The main customers are the elderly, although the product is recommended to everyone.

12. Size
The final design should be big enough to accommodate suitcases but small enough to not be intrusive to the surrounding environment. The expected size is 30cm x 60cm x 50cm (H x L x W). This is calculated by using the dimensions of the average suitcase[26]. A robot with a low height would be beneficial as it would be easier to lift items onto it. However, the dimensions of the prototype are much smaller: 16.5cm x 15.6cm x 6.5cm (H x L x W)[27].

13. Weight
The robot should be heavy enough to be stable whilst carrying a load but also light enough that it can be easily carried upstairs if required. The largest contributors to the robot's weight are its motor and battery. We expect the chassis to be made of plastic and thus relatively light. The prototype will be constructed from a chassis weighing 135g[27], a Raspberry Pi 2 weighing 45g[28], and a camera weighing 3 grams[23]. This comes to a total of approximately 193 grams.

14. Materials
The final robot will have a chassis made of aluminium-magnesium-silicon (6000) alloy, pneumatic wheels, a largely metal engine and gearbox and a lithium-polymer battery. On the other hand, the prototype frame is made of laser cut Lexan parts, rubberised tyres and a Lithium Polymer battery.

15. Product Life Span
The final product is made of non-degradable, sturdy materials so depending on the a life span of 3 to 5 years is expected.

16. Aesthetics, Appearance and Finish
The final robot will have rounded edges as this would decrease the number of injuries that may be caused due to sharp edges. The robot should also be painted in a colour that is easily spottable, such as a reflective orange.

17. Ergonomics
The robot should interact with surroundings without any user interaction. This requires obstacle detection protocols. It should also have as few buttons as possible, making the interface very simple to use.

18. Standards and Specifications

The robot should abide to the principles of robotics set by the Engineering and Physical Sciences Research Council[29]. It should also be made to conform and pass any specific laws or regulations implemented by the company or country in which it operates.

19. Quality and Reliability
The product should have good quality since it will be of major importance for the user and be highly reliable so that frequent maintenance is not required.

20. Shelf Life (Storage)
Apart from the rechargeable batteries, there are no degradable components. Therefore, the expected shelf life would be more than 10 years. (Shelf life of batteries: 13 months - 2 years[30])

21. Testing
Testing should be carried out by a professional based on usage. More information is needed to determine the testing interval.

22. Processes
There is an initial prototyping process, where a smaller version of the robot will be created to test the feasibility of the project. A manufacturing process for the components is required, as well as an assembly and programming process. A final testing process will be implemented to make sure that the robot works as desired.

23. Time Scale
The time scale of the project involved 3 months of research (October to December), then it will imply 3 months to finalise the prototype (January to March) and after this there would be other 3 months (April to June) to use the know-how gained with the prototype to produce a real product, with the original specifications.

24. Safety
ALT Robots should be safe, as individuals will regularly be interacting with them. Sharp edges, high voltages, hot surfaces should be avoided. Also, due to obstacle detection any collisions can be avoided.

25. Company Constraints
The current budget for a prototype is £200.

26. Market Constraints
N/A

27. Patents, Literature and Product Data
So far no conflicting patent has been found.

28. Legal

No laws are currently enforced upon ALT robots so no legal issues constrain this project. However, legal documents should be written to enforce warranty terms and conditions.

29. Political and Social Implications
The product should have positive effect on the society by making everyday life of people with specific difficulties (i.e.: with impossibility to carry weights) easier.

30. Installation
Installation should be simple and should take no longer, than a few seconds should as the only requirement for usage is for the user to attach a device onto their body.

31. Documentation
A user manual and maintenance guide must be provided with the purchase of the robot to inform the user of anything that must be done for the initial setup or maintenance of the product.

32. Disposal
Broken component are considered as electrical waste, which is fairly recyclable. Batteries may need extra care.

Component Value Calculations

$$\beta_{npn}=100 \qquad \beta_{pnp}=100$$

$$I_{B1} = \frac{3.3-0.7}{R_1} \qquad \rightarrow \qquad R_1 = \frac{3.3-0.7}{I_{B1}} = \frac{2.6}{I_{B1}}$$

$$I_{B1} = \frac{n\hat{I}_{C1}}{\beta_1} \qquad \rightarrow \qquad \hat{I}_{C1} = \frac{\beta_1 I_{B1}}{n}$$

$$\hat{I}_{C1} = \frac{V_{CC}-0.2}{R_2} - \frac{(7.5-0.7)-0.2}{R_3}$$

$$\hat{I}_{C2} = \frac{\beta_2 I_{B2}}{n} = 0.16A \qquad and \ Set \ n=5$$

$$\therefore \qquad \frac{\beta_2}{n}\left(\frac{6.6}{R_3}\right) = 0.16A$$

$$\frac{\beta_2}{n}\frac{6.6}{0.16} = R_3 \approx 825\Omega$$

$$i.e. \quad \hat{I}_{C1} \approx 8.7mA$$

$$R_1 = \frac{2.6}{\dfrac{n\hat{I}_{C1}}{\beta_1}} = \frac{2.6\beta_1}{n\hat{I}_{C1}} \approx 6k\Omega$$

$$\hat{I}_{C3} = \frac{\beta_3 I_{B3}}{n} \qquad I_{B1} = \frac{3.3-0.7}{R_5}$$

$$\therefore \qquad \frac{\beta_3}{n}\left(\frac{3.3-0.7}{R_5}\right) = 0.16A$$

$$R_5 = \frac{\beta_3}{n}\frac{2.6}{0.16} = 325\Omega$$

$$R_1 = 6k\Omega \ , \ R_2 = 10k\Omega \ , \ R_3 = 825\Omega \ , \ R_5 = 325\Omega$$

Code

Wi-Fi Operation

https://www.doc.ic.ac.uk/~ajd/Robotics/RoboticsResources/wifi_setup.txt

Meeting Minutes

General meeting 1

MINUTES	JANUARY 12, 2016	13:00	EEE CAFE

TYPE OF MEETING	General
FACILITATOR	Eric Wen
NOTE TAKER	Evan Li
TIMEKEEPER	Simone Bertaiola
ATTENDEES	Eric Wen, David Anderle, Frederic Kwan, Simone Bertaiola, Evan Li, Andrew Zhou, Ivan Ong

Agenda topics

30 MINUTES | *SENSOR IMPLEMENTATION*

DISCUSSION	
What type of sensors would work best for our purpose?	

CONCLUSIONS	
Each of the sensors has its own merits. More research will be needed	

ACTION ITEMS	PERSON RESPONSIBLE	DEADLINE
Do research into the detailed implementations of IMUs, GPS, and ultrasonic sensors	David, Federic	30/1/2016

45 MINUTES | *PARTS TO ORDER*

DISCUSSION	
Which parts can we order from stores?	
What are the dimensions of our chassis?	

CONCLUSIONS	
A pre-manufactured robot car will be bought, as the timeframe and budget does not allow for a bespoke chassis to be built.	
The wheels of the chassis will have to be large enough to be able to override small bumps in the road	

ACTION ITEMS	PERSON RESPONSIBLE	DEADLINE
Look at the manufacturer's websites for prices	Andrew	14/2/2016

Meeting with supervisor

MINUTES	FEBUARY 17, 2016	13:00	ROOM 1123

TYPE OF MEETING	Supervisor meeting
FACILITATOR	Dr Andras Gyorgy (supervisor), Eric Wen
NOTE TAKER	Ivan Ong
TIMEKEEPER	Simone Bertaiola
ATTENDEES	Dr Andras Gyorgy (supervisor), Eric Wen, David Anderle, Frederic Kwan, Simone Bertaiola, Evan Li, Andrew Zhou, Ivan Ong

Agenda topics

30 MINUTES REPORT REVIEW

DISCUSSION	
What can we improve from our interim report?	
CONCLUSIONS	
We could have focused more on defining a specific social problem that we needed to address	
We need to conduct more market research on similar products, as well as to ascertain demand for our product	

ACTION ITEMS	PERSON RESPONSIBLE	DEADLINE
Read marker's comments from the interim report	David, Federic	29/2/2016
Start on final report	Andrew	

45 MINUTES ORDERING PARTS

AGENDA	
Checked stores for availability of products	

ACTION ITEMS	PERSON RESPONSIBLE	DEADLINE
Collect orders	David	25/2/2016

Technical meeting

MINUTES	MARCH 1, 2016	16:00	EEE LABORATORY

TYPE OF MEETING	General
FACILITATOR	Eric Wen
NOTE TAKER	Evan Li
TIMEKEEPER	Simone Bertaiola
ATTENDEES	Eric Wen, David Anderle, Frederic Kwan, Simone Bertaiola, Evan Li, Andrew Zhou, Ivan Ong

Agenda topics

2 HOURS *ASSEMBLING OF DEVICE*

PROCEDURE		
Tested capacitor and biasing resistor values		
Looked last year's EEbug circuit and proposed modifications		
ACTION ITEMS	**PERSON RESPONSIBLE**	**DEADLINE**
Design analogue circuit	Simone, Federic	5/3/2016
Assemble Chassis	Simone, Federic	20/3/2016
Write software for raspberry pi	David	20/3/2016

45 MINUTES *WEBSITE*

DISCUSSION		
What platform do we use for web development?		
What pages will our website comprise of?		
CONCLUSIONS		
We will use Dreamweaver to develop our website		
ACTION ITEMS	**PERSON RESPONSIBLE**	**DEADLINE**
Create content for website	Ivan	5/3/2016
Create website design	Eric	7/3/2016

Budget

Component	Quantity	Price Each / £	
Raspberry Pi RPI Standard Camera Board Report	1	16.95	
RS Pro USB 2.0 Cable Assembly, Male USB A Plug to Male USB Micro B Plug, 150mm	1	2.41	

TE Connectivity Right Angle Type A USB Connector, Through Hole Socket	1	1.63	
Multi-Chassis - 4WD Kit (Basic)	1	27.6	
40kHz Ultrasonic Transducer	2	6.99	Order did not come through
Zip Switch MS-333 Slide switch 6 Pin DPDT On-Off-On	1	0.73	
Raspberry Pi 2 Model B Quad Core 1GB RAM	1	26.4	
Raspberry Pi Camera Board Video Modue	1	15.99	
RS Pro USB 2.0 Cable Assembly, Male USB A Plug to Female USB A Socket, 1m	1	2.00	
Texas Instruments LM1084IT-5.0/NOPB, LDO Voltage Regulator, 5A, 5 V, 2.6 25 Vin, 3-Pin TO-220	1	1.87	
Raspberry Pi USB Wireless Adapter	1		
Wurth Elektronik Right Angle SMT Type B Version 2.0 Micro USB Connector Socket, 30 V ac, 1A 629105 WR-COM	1	1.19	
MIKROE-512, 10 Piece Breadboard Jumper Wire Kit	2	2.16	

Group Management and Roles

Each group member was given a role depending on his or her strengths. This helped to streamline decisions about which tasks would be assigned to whom.

Group Leader: Minghe Wen
Secretary: Ivan Ong, Chenglei Li
Treasurer: Simone Bertaiola
Counter Signatory: David Anderle
Hardware Developer: Fu Yee Kwan, Simone Bertaiola
Software Developer: David Anderle, Andrew Zhou
Technical Director: Minghe Wen

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