Wireless Indoor Mobile Robot with RFID Navigation Map and Live Video

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Samuel Garratt

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Abstract

A mobile robot was designed in order to move freely within a map built in an indoor environment. The aim is for the robot to move between passive RFID (Radio Frequency Identification) tags in an environment that has been previously mapped by the designed software. Passive RFID tags are inexpensive, the same size and shape as a credit card and are attached to other objects. They don't require any power of their own but operate through an RFID reader that induces a magnetic field in their antenna, which then creates power for the tag. This makes the tags inexpensive, and easy to setup and maintain.

The robot is a three wheeled vehicle driven by two stepper motors and is controlled wirelessly through a PC. It has a third omniwheel at the front for maintaining the balance of the robot. Since the PC communicates continuously with the robot, all the major processing and data management can be done on the computer making the microcontroller much simpler and less expensive. Infrared distance sensors are placed around the robot to detect short range obstacles and a sonar sensor at the front can detect obstacles further away. This data is used so that the robot can avoid obstacles in its path between tags. An electronic compass is used to provide absolute orientation of the robot at all times to correct for errors in estimating the angle. A camera is attached to the front of the robot so that an operator can see the robot and manually control it if necessary. This could also be used to a video a certain environment from a robot's perspective.

The sensors and the RFID tags are all inexpensive, making the mass reproduction of the robot feasible and implementation practically possible for small firms. The RFID tags can be quickly attached or detached from an environment leaving no trace of their prior existence. A map can then be formed on a PC automatically by the robot through its detection of the tags.

This makes the entire system very flexible and quick to set up, something that is needed in the present day as changes to buildings and factories become more common.

There are still many improvements needed to improve the stability of the compass's signal in the presence of magnetic fields, the stability of the wheels so that slippage is rare, and the range of the wireless signal and camera.

A flexible, easily configurable moving robot could be used to serve fields such as the medical field by transporting goods within a hospital, or in factories where goods need to be transported between locations. Since the system is flexible, and maps can be formed quickly, the robot can fit in with the changes to an industry's environment and requirements. However, since the robot can only move to approximately five metres from the computer controlling it and the inaccuracy in sensor data, it is not currently ready for industrial use. For example, the sensors are only placed at 6 orientations around the robot and so do not cover a full span of the robots area. These sensors also only detect a two dimensional plane around the robot so could not detect obscure objects that have a part sticking out at height higher than the sensors. Therefore, further work is needed to be done to make the robot reliable, safe, and fault-proof before it could be used in industry.

Since the movement of the robot with inexpensive sensors and motors is bound to have problems in perfectly moving between RFID tags, due to small dead reckoning errors, simple algorithms are shown in this research that moves the robot around its current location until it finds a tag. These algorithms involve finding a path between two RFID tags that will make use of any tags in between them to localise itself and moving in a spiral to search for a tag when, due to odometry errors, it is not detected where it is expected to be.

The robot built has demonstrated being able to navigate between RFID tags within a small lab environment. It has proven to be able to avoid obstacles with a size of 30 x 30 cm.

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List of Abbreviations

ADC	Analogue to Digital Converter
AGV	Automated Guided Vehicle
ASCII	American Standard Code for Information Interchange
DAC	Digital to Analogue converter
DTE	Data Terminal Equipment
EIA	Electronic Industries Association
GUI	Graphical User Interface
IC	Integrated Circuit
I2C	Inter-Integrated Circuit
MIPS	Million Instructions per Second
PAN	Personal Area Network
PC	Personal computer
PWM	Pulse Width Modulation
RFID	Radio Frequency Identification
USART	Universal Synchronous Asynchronous Receiver Transmitter
SCL	Serial clock
SDA	Serial data
TTL	Transistor-transistor logic
TWI	Two-wire Interface

Chapter 1: Introduction

The purpose of this chapter is to introduce the research presented in this thesis and give an overview of its content and structure. A description of the research, its value, and the current status of the system developed, are initially presented. Following are the requirements, constraints, scope, and objectives of the research. A summary of each chapter that shows the structure of the thesis is presented at the end.

Radio Frequency Identification (RFID) technology is a field of research that is being developed by major companies such as Wal-Mart and Tesco and also by the US military. Its current applications include highway tolling, currency tracking and verification, directed advertising, pet identification, monitoring animal health (Hoskins, Sobering, Andresen, & Warren, 2009), locking and indentifying shipping containers, quick identification for voting, providing ID of intrusion detection devices (Swedberg, 2011), and in a limited way, human identification (Anderson & Labay, 2006).

As RFID technology is improving and developing, more applications involve the use of RFID technology to provide solutions for real application problems. This research focuses on the navigation of a mobile robot using RFID technology. The research approach is to build a RFID map to estimate the location of a mobile robot and provide guide a mobile robot in an indoor environment through using a wireless network in which a host computer controls the mobile robot. The RFID tags used are passive, meaning they do not have any power supply of their own but rather use a current induced on their antenna (Braaten, Feng, & Nelson, 2006) from an external RFID reader. With this induced current, their ID information can be transmitted back to the reader which then uses this ID to determine which tag it is near. The benefit of such tags over active ones is that they are cheaper and have little maintenance requirements.

The mobile robot built for testing the design concept uses distance sensors to detect obstacles that need avoiding, a compass to correct the estimated orientation of the robot, and a camera to provide live feedback to a host PC. Through the sensors the robot is able to manoeuvre between RFID tags in an indoor environment while avoiding obstacles automatically. The robot is directed by an operator at a host PC. Once the robot receives a command, i.e., which RFID tag it should go to, the robot will move to the target position without any help from the operator. However, under certain circumstances, the robot may enter into a situation where it is not able to automatically reach its destination, as if the path is completed blocked. The robot then notifies the operator at the host PC, who can then use the camera on the robot to see the surroundings of the robot and manually guide the robot step by step how to move around the obstacle and then allow the PC to continue automatically controlling the robot.

Currently, a test robot has successfully navigated in an indoor environment using a RFID map that contains the information of the RFID tags. The robot is able to avoid simple obstacles that lie on its path toward its next target position. In the case where the robot did not detect the RFID tag it was sent to, since, due to dead reckoning errors its position is slightly off from where it is intended to be, it is able to search around its current area in order to look for the tag.

A simulation software has been developed and used to successfully evaluate and test the algorithms and methodologies used in controlling the robot from the host computer through a local wireless network. By applying the algorithms and rules established in the system, the software is able to make decisions for the robot and give commands to guide the robot to move between RFID tags, avoid obstacles and search to detect a nearby RFID tag. The software traces the robot's current position with respect to a global reference point on a map which is built based on the positions of RFID tags. It uses dead reckoning to estimate the physical location of the robot. This method uses the previously known location of the robot and the direction and speed it is moving to estimate the robot's current position. When an RFID tag is detected, the position of the robot on the computer map is updated to where that tag is, thus eliminating any cumulative error. The compass is used whenever the robot is not turning to correct the orientation of the robot. The path to the robot's destination may have several RFID tags in between it. By using these tags and the compass, the robot is able to

reach its destination with much less cumulative error than simply relying on odometry, meaning that it is more likely to reach its destination.

Two map building methodologies have been implemented in the software, manual map building and a map created through teaching mode. The manual map building relies on the manual input of the RFID tag positions in the global reference coordinate system, i.e., the user needs to have the coordinates of the tag positions in the environment and then put these into a map builder program. Of course, this is a trivial task. A quicker way is to build the map through the teaching mode. In this mode, as the robot moves around the environment, whenever the robot RFID reader detects an RFID tag it will automatically record its location. Once the robot completes a journey that consists of the entire route within the environment, the system will build a map based on the locations of the RFID tags.

The system developed by this research demonstrates that a navigation map for a mobile robot within a global reference coordinate system can be built using a few fixed RFID tags. Once the map is established, whenever the robot travels within the environment, its position can be automatically updated based on the RFID locations. Therefore, the system is able to reduce the cumulated position errors of the mobile robot. Currently, the system utilizes a camera to allow the operator to manually control the robot in complex environments. With further improvement, the robot could utilize this camera to automatically manoeuvre in complex environments.

A robot for testing the concept and algorithms was built using low cost and available components. It is obvious that for industrial applications, a number of improvements must be considered. A wireless communication local network that covers a greater distance between the robot and the PC should be implemented to enable the robot to navigate within a larger area. The capability in obstacle detection has to be improved in order to identify objects in different and difficult situations that are likely to exist in an industrial environment. Finally, to ensure better estimation of the robot's position, more reliable orientation sensors should be used to reduce the orientation error.

1.1 Research topic

The aim of this research is to use RFID technology to develop an automation system that consists of a mobile robot and a PC-based remote control station. The system is able to improve the PC's estimation accuracy of the mobile robot's position when it moves within the environment through the implementation of RFID technology. Ideally, the mobile robot communicates with the control station through wireless communication while the user at a remote site monitors, directs and controls the robot. The topics of this research include:

1) RFID technologies and their related applications
2) Mobile robot accumulated position errors and methodologies that minimise these errors
3) Mobile robot navigation methodologies
4) Wireless communication systems
5) Real time monitoring and control software development

1.2 Scope of research

The research is required to use RFID technology to improve the position error of a mobile robot that is monitored, directed, and, if necessary, controlled by a remote PC-based work station. Based on the literature survey of the research, the technologies available and the available finance, the scope of this research includes:

1) Developing a methodology that is able to reduce the position error of a mobile robot while it moves within a given environment through the application of RFID technology.
2) Establishing a wireless communication system between a mobile robot and a PC-based control station that has the potential to control the mobile robot in real time.
3) Developing a software system that is able to monitor and control a mobile robot on a remote control station.

4) Building a testing system that has a PC-based control station and a mobile robot to test and evaluate the design concept, methodologies and system behaviour. The robot has the ability to avoid obstacles and reach a given destination while a PC processes all the data taken from the robot, provides an interface to an operator and tells the robot what to do.

1.3 The organisation of the thesis

The thesis contains twelve chapters. Each chapter has a short introduction to give an overview of its content. Following is a summary of the chapters. Chapter 1 explains the topics of this research by stating its requirements, objectives and scope. Chapter 2 provides a background to the history behind mobile robots, the available approaches and techniques used in moving a mobile robot around an indoor environment, and the growing need for mobile robots in general. Chapter 3 discusses the methodology used in this research to localise a mobile robot as navigates in an indoor environment. Chapter 4 continues by presenting the way the mobile robot and PC communicate. It firstly mentions the wireless communication whereby all commands to the robot are sent and from which most of the sensor data is transmitted back to the PC. Then the methods of communication between the two microcontrollers on the robot are explained. Finally, the process of displaying live video from the robot's camera on the PC is described. Chapter 5 explains the algorithms used in manoeuvring the robot, the simulation and monitoring of the mobile robot, and how maps containing the location of RFID tags are built. The first way of creating a map is through the operator manually building a map through making their own measurements and the second is to build a map automatically through a teaching model. Chapter 6 describes the environment in which the mobile robot roams and the capability the robot needs to have in planning a path between two RFID tags and in avoiding obstacles that may be between them. It further lays out some of the mechanical designs that can be used for mobile robots and describes the basic structure of the mobile robot used in this research. With this as a base, the motors and sensors

used as well as the motor selection, control, powering and testing are then considered and three tests made on the robot are shown by discussing their testing environment and demonstrating their outcome. Chapter 7 and 8 conclude with the research's future improvements and conclusions.

Chapter 2: Literature Review

The notion of a robot has existed for thousands of years. Hence, this chapter first reviews the history of the development of mobile robots. These robots are becoming increasingly useful in our daily life, in industry, for the military, and for spatial exploration and so a summary of their various uses is also presented. Following this, available methodologies and technologies used in navigating a mobile robot are explained to provide an overview of what is currently used, their benefits, and in particular where further research is required. This overview includes storing the environment through different types of maps, estimating a robot's current position in a map through odometry, using localisation methods to correct odometry errors, reaching a goal in a map which could be blocked by obstacles, and safety issues necessary when sensing obstacles. Through this chapter, some areas requiring further research in terms of indoor mobile robot navigation are established as background to this thesis.

2.1 The development history of mobile robots

The encyclopaedia Britannica defines a robot as: "any automatically operated machine that replaces human effort, though it may not resemble human beings in appearance or perform functions in a humanlike manner." (Moravec, n.d.)

The history of the idea of a robot goes back thousands of years and is seen among many cultures. For example, King Mu of Zhou was given a human-shaped mechanical figure by an engineer in China as early as 1023-957BC, a Greek mathematician invented a mechanical bird propelled by steam in 428-347BC, in 250BC a water-clock was made with moveable figures on it, an Arab inventor created a robotic boat that had automated musicians (AD

1136-1206), and Leonardo Da Vinci thought of building a mechanical knight (AD 1495) (Yates, Vaessen, & Roupret, 2011).

The industrial revolution gave rise to the development of important technological advancements, such as complex mechanics and electricity. This provided a base for more useful robots to be created (Yates, et al., 2011). In the 20th century, the first proper robots were created. The first humanoid robot, Elektro was designed (Noor & Lobeck, 2008) in 1939. The basis for automated vehicle design was established during World War 2 with Germany developing autonomous aircraft and rockets (Dudek & Jenkin, 2010). Soon after, in 1954, the first industrial mobile robot was created. This was a driverless electric cart that was used to pull loads around a warehouse (Moravec, n.d.). In the same year, the first industrial robot arm was designed, something that could be used in many manufacturing environments (Moravec, n.d.).

Due to the development of computers in the 1960s, scientists were able to implement artificial intelligence. This enabled more complex mobile robots to be produced (Dudek & Jenkin, 2010). With this technology, the Stanford Research Institute created Shakey, the first mobile robot with artificial intelligence as shown in Figure 2-1.

Figure 2-1: Shakey, the first mobile robot with artificial intelligence (Dudek & Jenkin, 2010, pg. 9)

With the development of microcontrollers in the 1980s mobile robots were able to perform even more complex tasks (Moravec, n.d.) and be smaller. As computer, sensor, motor, manufacturing and material technology has continued to develop, the ability of mobile robots has increased until the present-day.

2.2 The need for mobile robots

With the fast development in computer science, digital communication and intelligent control system, mobile robots are widely used not only industrially but also in our daily life. More and more mobile robots are being used to replace difficult or tedious work that used to be completed by human beings. Intelligent robots can perform the tasks which humans tend to find boring, monotonous, and dangerous and do them at speeds, accuracy and repeatability that humans cannot (Oriolo, Ulivi, & Venditteli, 1997; Noor & Lobeck, 2008).

Mobile robots are becoming more useful as computer intelligence increases. Their sensors are improving, processing speeds are increasing, and clever methods are being formed to allow more complex tasks to be done. For example, very recently, improvements in image processing have allowed a robot to successfully detect and track a person. This detection and tracking of a person solves one of the most important problems for service robots (Bakar, Nagarajan, & Saad, 2011) since robots need to follow people in order to serve them wherever they go. It also helps to open the door for mobile robots to be useful in more areas than before.

The range of uses for mobile robots include indoor cleaning (vacuuming or sweeping), mowing lawns, watering the garden, picking fruit, caring for elderly, transporting goods, making observations on a farm or of a factory's condition, helping in emergencies, disarming bombs, fighting fires, and enabling people to control a robot remotely. A typical example is that a doctor can control a mobile robot to do a surgery from another hospital through a computer network. There are many new areas that have the potential to use mobile robots. For example, the University of Magdeburg designed an autonomous robot for use in fighting fires (Noor & Lobeck, 2008).

Robots designed to understand when a problem may have occurred could be used as caregivers and emergency aids by providing instant attention when a problem has been detected with a person or situation (Noor & Lobeck, 2008). With the advancement in processing speeds and sensor technology, the application of mobile robots will become common practice in many areas of society.

2.3 The available methodologies and technologies applied in navigating a mobile robot

This section discusses the various methodologies and technologies used when navigating a robot. In order to guide a robot, a map is needed so that a path can be created to get its destination. Hence, this chapter starts by showing different kind of maps used in guiding a robot, followed by six different algorithms used for moving a mobile robot to a certain goal in an environment that could have unforeseen obstacles in its path. These algorithms use the method of 'odometry' to estimate the robot's current position and 'localisation' to reset the robots accumulated error back to zero. Therefore these methods are explained prior to the six algorithms so that they can be properly understood. Following this, the importance of a robot's safety to others and itself is explained since a mobile robot often encounters obstacles. With all of this in mind, consideration is then given to areas that need further research.

2.3.1 Guide by a map

A map is essential for most of the methods used to navigate a robot to a destination. However, some methods, such as the potential field method presented in section 2.3.2.4, do not require a map. A robot that travels between two points needs to determine the best path to travel. This path should both get to its destination as quick as possible and safely avoid obstacles. A map allows the calculation of this best path as well as the recording of obstacles that need to be avoided. While a robot is moving to its destination, its estimation about its position gradually increases and so an error is gradually accumulated. Some use 'landmarks', which are identifiable objects in the environment that a robot can easily detect, to correct against such errors in the position estimation. A map allows the position of these landmarks

to be recorded and retrieved when a robot detects them. When a robot detects the landmark, it looks up the position of the landmark in the map and adjusts its position to the previously recorded one.

As a robot moves to its destination, it is likely to meet obstacles not recorded in its map. Therefore, sensors are needed to detect the position of unknown obstacles so that the robot may safely avoid them. Since distance sensors on a robot are not always perfect, a robot can't rely on a single measurement as conclusive evidence of an obstacle's existence in a certain position. Therefore the robot should only record an obstacle existing in a certain location in its map after repeatedly detecting it (Henlich, 1997). However, if the single measurement would mean immediate obstruction of the robot's path by an obstacle, the robot should stop and wait for its sensors to make more measurements before deciding to continue moving or to avoid an obstacle.

Three different ways for storing items within a map are summarised in Table 2-1. These items could be obstacle locations, landmarks, or other information that would help a robot move within an environment. The simplest storage method is a 2D array that simply records data about every x, y coordinate in a map. To do this, the map needs to be made into a grid so that each part of the environment can be given coordinates. This is very quick to access but uses a lot of memory.

Another method, the linked list, uses less memory but takes longer for the computer to access. When looking through the list, one must always starts from the same node. This node points to another node which in turn points to another until the end of list is reached. The

linked list does not have space in memory for empty spots covering the entire environment whereas the 2D array does. In this way the linked list uses much less memory than the 2D array, depending on how complex the environment is. The problem, however, is when the list is too large. In such a case it would take too much time to access an item in the list as it would need to search from the beginning of the list to the item required in order to get it. To be efficiently used for mobile robots, a linked list would need to cover only a simple environment requiring not too many nodes in the list.

Table 2-1: Advantages and disadvantages of map storage methods, (Robotics/navigation/mapping, n.d., para. 6)

Way	**Advantage**	**Disadvantage**
2D array	Easy/fast access	Wasteful with memory
Linked list	Efficient with memory	Slow access/waste
Quadtree	Very efficient, faster than LL	Hard to implement

A quad tree is very efficient with memory (Ghoshray & Yen, 1996) and is faster than a linked list to access. Each node in the tree has four children, an x, y coordinate, and a value that gives information about the node. If used in a map, the value could indicate an obstacle or landmark in that area. The parent looks at an overview of the entire area and the children store information about the detail of the area. Figure 2-2 illustrates this by showing four levels of a quad tree together with a square that represents the area each level covers. The only problem, however, is that it is often very hard to implement.

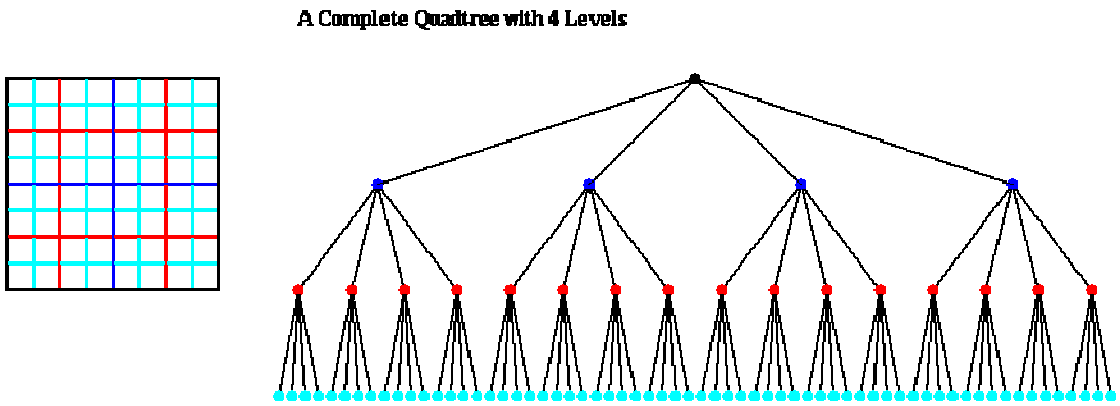


Figure 2-2: Quad Tree of four levels showing four children under one parent and more detailed view in each layer (Demmel, 1996, para. 10)

To accommodate for situations where a mobile robot is moving in a complex and large environment a large and detailed map would be needed. Currently, the size of microcontrollers' memory and processing power is small compared to that of a PC. Therefore, it is useful to store the map for the robot on a PC external to it.

The different types of map storage can use one of two fundamental structures in building a map: metric and topological. A metric map simply records the absolute coordinates of objects and so is easy to understand. A topological map records descriptions about the environment and does not have an absolute reference system. Figure 2-3 shows both a Metric map and a Topological map built from it.

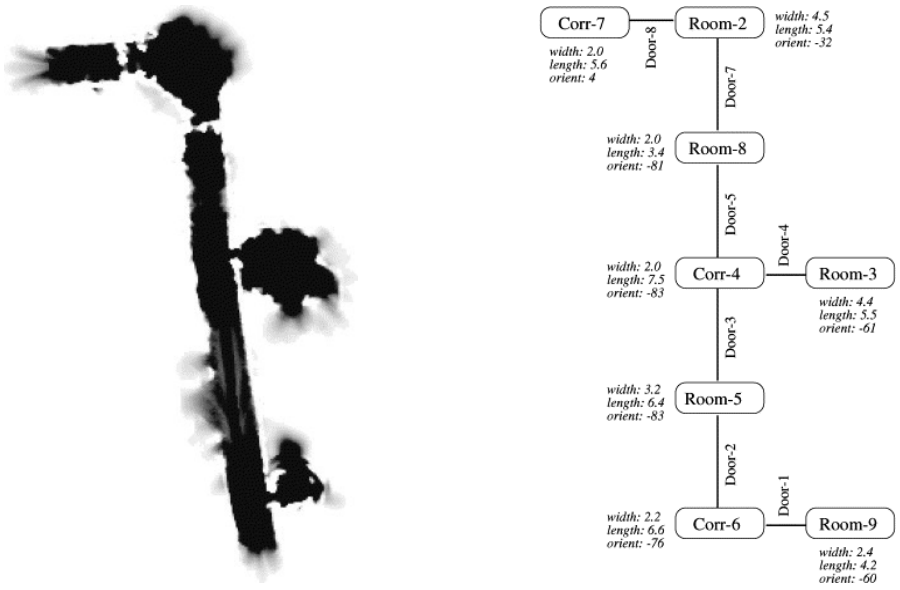


Figure 2-3: Left - Metric map of a set of rooms (Fabrizi & Saffiotti, 2002, p. 92); Right - Topological map of the same set of rooms (Fabrizi & Saffiotti, 2002, p. 94)

There are different methods for recording the data in a topological map (Fabrizi & Saffiotti, 2002). Fabrizi & Saffiotti demonstrate how such a topological map is made and used to navigate a robot. This is shown in Figure 2-3, right side. This topological map records simple descriptions about different areas in a room which are the width and length of a rectangular representation of the room and the orientation of this rectangle when rotating it from north. These simple descriptions are the topological map. This map is much simpler and smaller than the metric map and its components can be quickly converted to absolute metric data allowing the robot to plan a path through it. However, in cases like the above example, the detail of the map stored would be minimal as it stored as simple descriptions. Therefore, a topological map is a method of storing simple descriptions of a room or of landmarks without requiring much memory.

2.3.2 Odometry

Odometry is a method that uses data that indicates how far a robot has moved to estimate where it should currently be. For example, if someone counted the number of steps they took while walking in a straight line they would be able to calculate the approximate distance they were from the place where they started, based upon the length of a step. In a mobile robot, the data used for estimating how far the robot has moved comes from either the record of the commands sent to the moving components (i.e., wheels or legs) or from encoders that provide feedback of the movement.

The vast majority of mobile robots rely on odometry for their navigation (Henlich, 1997; Suksakulchai, Thongchai, Wilkes, & Kawamura, 2000). Many different types of encoders can be used for odometry including: brush encoders, potentiometers, optical encoders, magnetic encoders, inductive encoders, and capacitive encoders. These encoders usually provide a good estimate of the distance a wheel has moved. For example, optical encoders have a thin disc that rotates with the motor wheel. A small light shines through small holes located around the edge of the disc and a detector on the other side of the disc recognises through the light every time a hole is detected. Since the distance between holes on the disc is known, through the number of holes detected, the distance the wheel has turned can be calculated. A magnetic encoder could simply be magnets placed on the motor shaft that move with the motor and whose magnetic field is detected by a Hall Effect sensor. Based upon how many magnets there are on the wheel, the Hall Effect sensor data can then be used to determine how much the wheel has rotated. However, having the wheel turn does not necessarily determine the exact distance it has moved.

Odometry is only an estimate of the location of the robot. This estimate becomes worse as the robot keeps moving since small discrepancies between where the robot should have moved

and where it did only accumulate over time (Henlich, O. 1997). This position error should be corrected periodically through some localisation method as discussed in the next section.

These odometry errors could be caused by factors such as (Kriechbaum, 2006; Park & Ji, 2009):

- Low-quality hardware (e.g., such as slight misalignment in the position of the wheels)
- Noise in the encoder's sensors
- Slippage or sliding of wheels
- An uneven environment surface

Ideally, a robot should be mechanically designed to minimize these errors as much as possible. For example, the wheels should be an equal distance from the centre and be tightly held by the motor so they cannot slip. However, small errors will always exist and for practical use, it cannot be expected that the environment's floor will always be perfectly even. Therefore, other methods to correct the robots position should be used whenever moving a robot a long distance. This correction is discussed in the following section.

2.3.3 Localisation

This section discusses the updating of a robot's absolute position in relation to a global reference point in a map. This updating is called 'localisation'. Localisation is necessary when the robot needs to travel over a large area (Dudek, Jenkin, Milios, & Wilkes, 1991; Kim, 2004; Suksakulchai, Thongchai, Wilkes, & Kawamura, 2000), due to the robot's estimated position accumulating error over time.

The method used to locate the robot depends on the type of environment. In large-scale outdoor environments, a GPS (Global positioning system) that uses time information and position information from at least four satellites to find the object's absolute position can be used. GPS is not applicable to navigating a small indoor mobile robot as the accuracy of GPS is only within 1-3 meters and the room within which an indoor robot moves will obstruct the periodic signals used in GPS (Henlich, O. 1997). Another method of locating a robot outside is shown by Lambrinos, Moller, Labhart, Pfeifer, & Wehner (1999). They illustrate a robot that uses the polarization pattern of light in the sky (illustrated in Figure 2-4) to localise the position of a robot. Obviously, the robot needs to be outside to see such patterns so this is not applicable to navigate a robot indoors either.

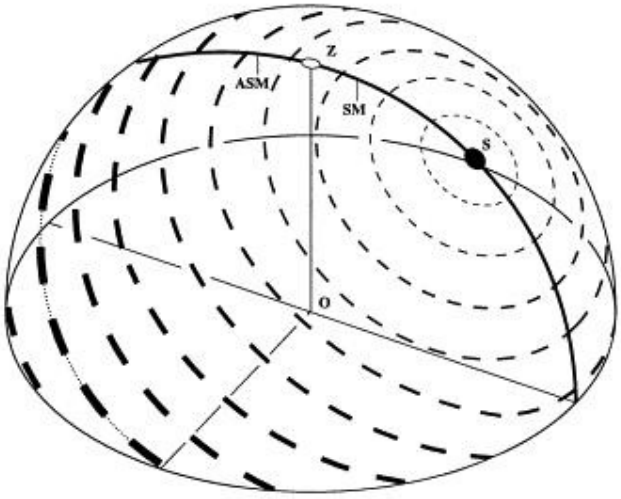


Fig. 2. 3-D representation of the pattern of polarization in the sky as experienced by an observer in point O. Orientation and width of the bars depict the direction and degree of polarization, respectively. A prominent property of the pattern is a symmetry line running through sun (S) and zenith (Z), called "solar meridian" (SM) on the side of the sun and "anti-solar meridian" (ASM) on the opposite side. Adapted from [46].

Figure 2-4: Polarization pattern of light in the sky a mobile robot can use to localise itself (Lambrinos, et. al, 1999, p. 42)

Various methods have been invented for localising a robot indoors. These include the use of:

- a camera mounted above the robot that always observes the robot to see where it is (Gupta, Messom, Demidenko, 2005)
- transmitters placed on the wall or ceiling that bounce off the robot and use the time their reflection took or the signal strength to estimate the robot's position (Henlich, 1997)
- the detection of physical landmarks whose location is previously stored in a map (Henlich, 1997; Kriechbaum, 2006)
- the use of devices that know where they are in a map so that the robot's position can be calculated when they are detected (Batalin & Sukhatme, 2004)

The first two methods mentioned above aim at detecting the robot's location at all times whereas the last two rely on odometry to estimate the robot's position and only localise the robot's position at particular points around the environment.

The problem with using a camera mounted above the robot is that it should continuously be able to detect the robot. Many environments have obstacles that would block the camera's view of a robot if the camera were placed on the ceiling. Transmitters mounted on a wall may not require an obstacle free path as their signals often can go through obstacles, yet their signal is usually obstructed by obstacles that lie between them and the robot.

The detection of recorded landmarks is not troubled by obstacles around the room as the localisation is done by sensors on the robot itself. These sensors (usually a camera) look for landmarks and compare their features to landmark features stored in a map. If a match

between the observation and something in a map is found, the robot's position can then be set to the landmarks recorded position in the map and so eliminate any accumulated error in estimating their position (Henlich, 1997).

Kriechbaum (2006) showed, with a computer simulation running on Matlab, the usefulness of landmarks in localising a robot. Figure 2-5 shows this simulation with landmarks placed between the robot's starting and ending position. Instead of moving straight to the destination, the algorithm makes use of landmarks to correct any accumulated error that could be produced as the robot moves. Therefore the robot plans a path that goes past the obstacles on its way to the goal and uses them to update the robot's actual position when it reaches them.

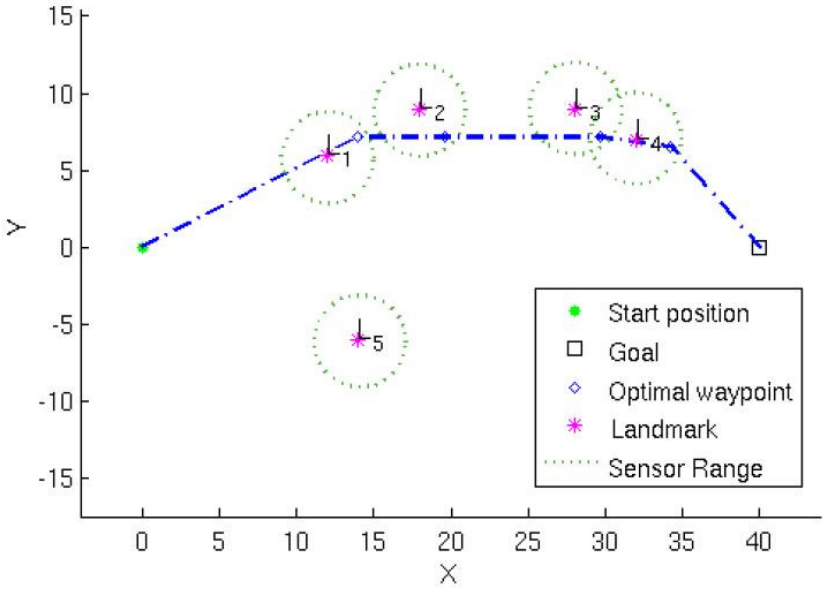


Figure 2-5: Robot using landmarks for localisation when moving towards a goal (Kriechbaum, 2006, p. 84)

Usually, physical objects already present in the environment are used as landmarks. The disadvantage of this is that sensors that detect these landmarks can be noisy and there can be

problems differentiating between landmarks that look similar (Batalin & Sukhatme, 2004). There is also a problem if the environment does not have enough objects that are easily distinguishable that can be used as landmarks. This is one reason why some people create artificial landmarks to localise the robot. These are made with clearly identifiable patterns so that the robot's position relative to the landmark can be easily calculated when they are detected (Henlich, 1997; Kriechbaum, 2006). The type of pattern would depend on the type of sensor used. Distance sensors such as ultrasonic sensors would need a physical shape that is easy to detect whereas cameras would merely need an image that can be easily recognized.

Batalin & Sukhatme (2004) provide a good example of successfully localising a robot within an indoor environment similar to the fourth bullet point mentioned above. They use a network of nine devices called 'sensor nodes' to guide the robot within an environment. A sensor node has information about its neighbours' positions relative to itself. Therefore, the robot can easily move between the devices while travelling towards its destination (which would also be a sensor node). Once a robot reaches a sensor node, the node tells the robot which direction to take to the next node. In this way, the computation can be done among the devices and not by the robot itself. This is beneficial as usually the mobile robot has limited processing power and storage compared with external devices. While moving between devices, the robot is programmed to automatically avoid any obstacles in its path. The radio signal's signal strength is used to determine the position of the robot relative to a device when it reaches it. The experiments presented by Batalin and Sukhatme demonstrate that their method worked well in a large environment even amongst people moving around the robot. These nodes require power and maintenance to keep them going. It would be easier if they could be powered by the mobile robot itself. Then only the robot would need maintenance.

RFID technology can be used either to continuously update the position of the robot or to do so at set points in the environment. Oktem & Aydin (2010) demonstrate the use of three long range high frequency RFID transmitters placed around a room that continuously detect a RFID tag on the robot to provide a continuous estimation of the robot's position. They use the received signal strength of the RFID tag on the transmitter to estimate the distance from each transmitter to the robot. By using these three distances together with the coordinates of the RFID transmitters, the robot's position is estimated. Their results show that this signal strength is obstructed by obstacles due to reflections and diffractions (Oktem & Aydin, 2010) and so has limited accuracy when used in an environment with many large obstacles.

Some indoor navigation algorithms rely purely on localisation through distinguishable landmarks within a room and do not use any odometry. Such applications have the following disadvantages:

- Need enough distinguishable features in the environment
- Require accurate sensors to see features well enough so that the robot's position relative to them can be determined
- Memory has to be large enough to store a map with enough resolution to store enough details about landmarks so that the robot can use them to regularly localise itself (Henlich, 1997).

Despite these disadvantages, such methods would make a robot more robust in environments where odometry may prove ineffective. Such environments would include places with rough surfaces, where the robot could go up and down; and slippery surfaces, where the wheels could easily slip, meaning that the wheel turns but the robot does not move.

With all this in view, it can be seen that there is a need for more research in localising a mobile robot in an environment with complex obstacles that obstruct continuous monitoring techniques. There is also a need for such localisation to be free from maintenance, as active localising devices would require, in order to make the system more self sustainable. This research later presents passive RFID tags as a solution to this problem. Passive RFID tags can be placed at convenient places in a room with complex obstacles and require no power source of their own as they are powered by the reader that reads them.

2.3.4 Goal reaching methodology

In order for a mobile robot to reach a goal, or final destination, the goal reaching methodology must be able to avoid obstacles that lie in their path yet still get to their goal in an efficient amount of time. The goal reaching methodology that can be used depends on:

- the design of the robot (e.g, how many wheels, how are they are driven)
- the complexity of the obstacles (simple rectangles, concave, or having many small rough edges hard to detect)
- the accuracy and range of the sensors

The number of sensors mounted around the robot, their range of detection, and the frequency of their measurement will very much influence the algorithm that can be used to avoid obstacles while the robot travels towards a goal. For example, a robot with only a few distance sensors at set points around the robot would be unable to safely detect small parts of a complex obstacle that stick out into the robot's way of travel.

These algorithms are primarily methods for avoiding obstacles on the way toward a goal. If no obstacles are in the robot's path the robot will simply travel straight towards its goal. However, the Uncertain bug (Section 2.3.4.3) adds more complexity to this by updating its position information through the use of landmarks. The potential field method (Section 2.3.4.4) also stands in a category of its own by using forces to detect obstacles and to get to its goal instead of relying on distance sensors and odometry. The main focus of these algorithms is for a robot to move to its destination and often this involves various methods of avoiding or travelling past obstacles.

Kreichbaum (2006) presents three algorithms that a robot can use in order to reach a goal. These are stated in the next three sections.

2.3.4.1 Tangent bug

Kriechbaum's first method (2006) is called the 'Tangent bug' algorithm. In this algorithm, at each step on the robot's path towards its goal, a local tangent graph (LTG) is produced that consists of nodes and edges as illustrated in Figure 2-6. The dotted circle around the robot represents the range the robot's distance sensors can detect. The robot starts at position x_R and is told to move to a position x_G. An LTG node is put at the robot's position and at the endpoints of detected obstacles. LTG edges are lines that go from the robot's position to the LTG nodes created at the detected obstacle's endpoints. An optional LTG node called Tg, with a corresponding LTG edge, is formed if:

- The distance from the robot to the goal is greater than the detection range of the robot
- There are no obstacles detected that inhibit a straight line between the robot's position and the goal

If these are true, Tg is added on the edge of the circle representing the robot's detection range with an edge proceeding directly towards the goal.

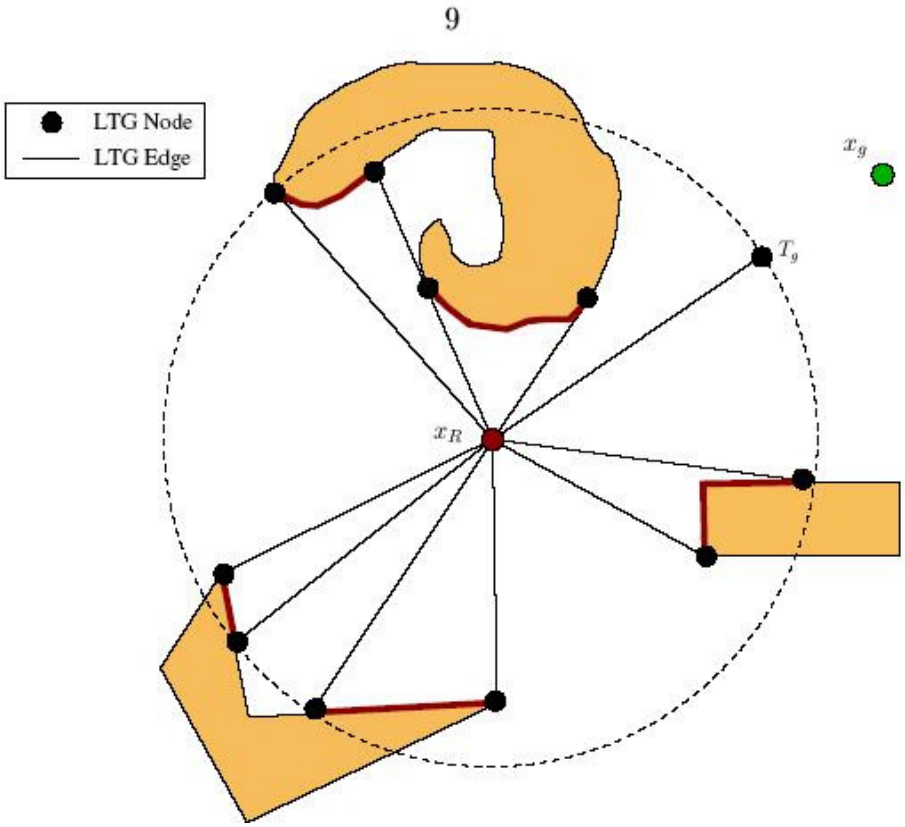


Figure 2-6: Local tangent graph produced at each step of the Tangent bug algorithm to determine what step to take next (Kriechbaum, 2006, p. 9)

The robot moves either in 'Motion to goal' mode or 'Boundary Following' mode. In 'Motion to goal' mode, the robot keeps travelling straight towards the goal until it has either reached it or has found that an obstacle blocks its path. If 'Tg' exists, the robot will be in 'Motion to goal' mode and will move directly towards the goal. Otherwise, the robot will enter 'Boundary Following' mode.

In 'Boundary Following' mode, a direction to travel around the obstacle (i.e., left or right) is chosen and the robot travels around it. It does this until either:

- The goal is reached
- The robot is free from the obstacle and can revert to 'Motion to goal' mode
- The robot detects that the goal is unreachable (since the goal or the mobile robot is completely surrounded by obstacles)

This method assumes that the mobile robot has little or no odometry errors accumulating over time, so is impractical to use if moving the robot for a long time, since all robots have at least some amount of error in estimating their position through dead reckoning.

2.3.4.2 Optim bug

The second navigation method presented by Kriechbaum (2006) is 'Optim bug'. It has a less uniform path than 'Tangent bug' but would more easily extend to three dimensions. It also automatically builds a map of the environment which can be used when travelling over the same area in the environment or when moving in the environment at a later date. Like 'Tangent bug', this method also unrealistically assumes that the robot used has no odometry errors accumulating over time.

In this algorithm, the total area that has been scanned, called the 'visibility set', is labelled 'Vtot'. V(k) represents the visibility set at time step k. V(k+1) is the visibility set added by the robots sensors in the next time step. As shown in the steps below, a time 'step' is only taken when the robot reaches the end of its visibility set. At this point, the mobile robot's sensors will be able to detect obstacles from the end of the visibility set and hence increase the known area, adding V(k+1) to V(k).

Kriechbaum's steps for the optim bug are:

1. Compute the shortest path to travel towards the goal based on the area it has mapped in Vtot.
2. Follow the path to the end of Vtot.
3. Is goal in Vtot?
    a. Yes – success since you know exactly how to move to reach the goal. The robot then simply moves within Vtot until it finishes at Vtot.
    b. No - Extend the visibility of Vtot by moving to the edge of Vtot.
4. Add V(k+1) to the Vtot.
5. If there is no path that can reach the goal without passing through obstacles, finish in failure.

Figure 2-7 shows this algorithm step by step while a robot moves from a position with an obstacle surrounding it to a position where it sees an obstacle free path towards its goal.

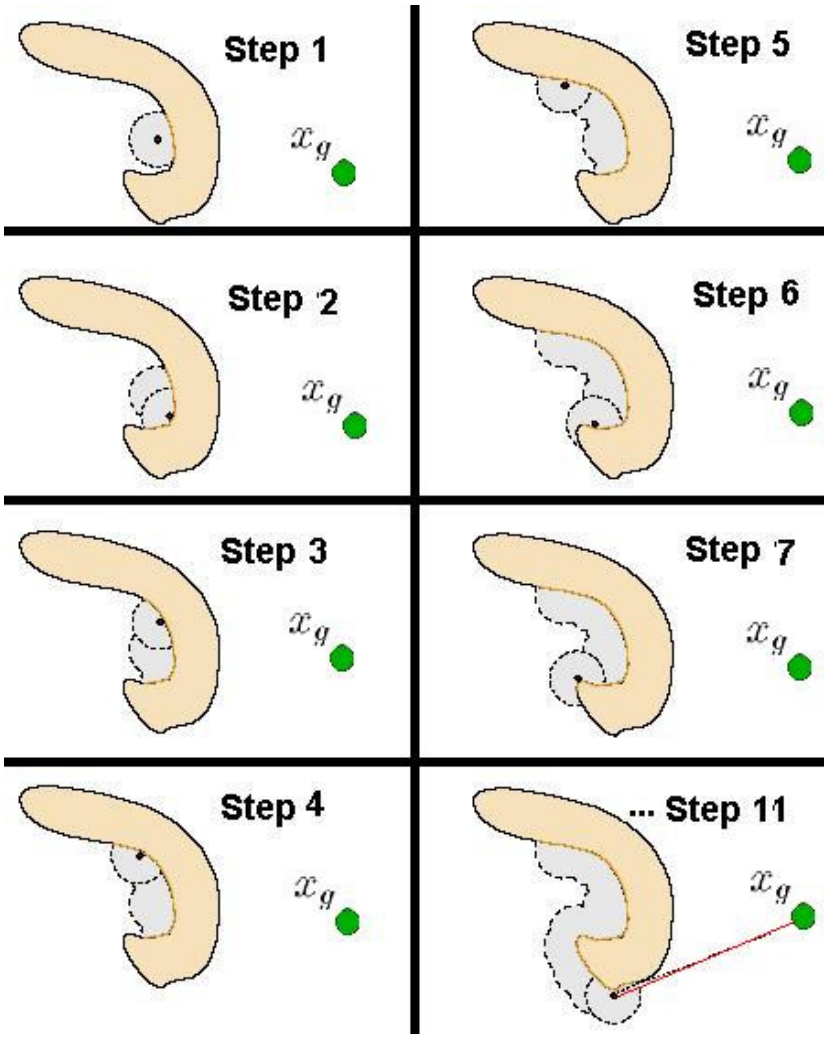


Figure 2-7: Steps for a robot to avoid an obstacle and find the path to the goal using the Optim bug algorithm (Kriechbaum, 2006, p. 67)

The direction that the robot takes is always towards its goal unless obstructed by an obstacle. If no obstacles are seen in a straight path to the goal, then that path is used. Otherwise, the robot moves to the edge of the known boundary of the obstacle it is currently at. It keeps doing this, every time extending its visibility set, until it reaches a point where there are no more obstacles obstructing a straight line between the robot and the goal. Once reaching this point, the process of trying to move straight towards the goal starts again.

Figure 2-8 shows that a robot using this 'Optim bug' trys to find a straight obstacle free path toward the goal (Tangent line T2 in the figure). After following this path, the robot meets

another obstacle. After searching the obstacle ahead of the robot based on optim bug, the robot will eventually arrive at a tangent point on the edge of the obstacle shown as tangent line T1 in Figure 2-8.

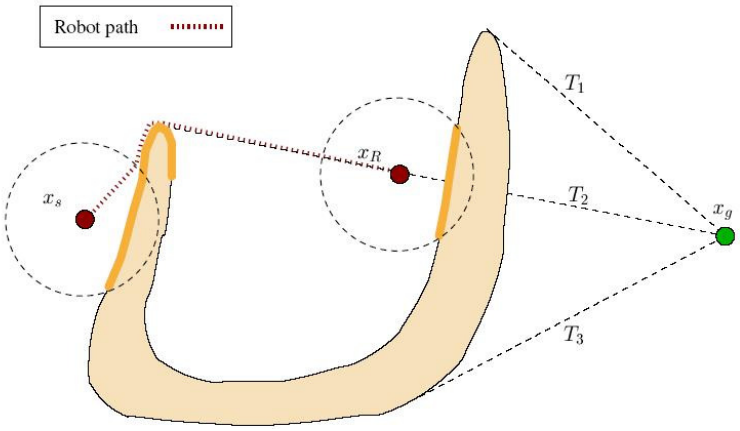


Figure 2-8: Optim bugs avoiding an obstacle, running into another obstacle and the three tangent lines that will reach the goal (Kriechbaum, 2006, p. 68)

2.3.4.3 Uncertain bug

Many studies on mobile robots use algorithms which require a perfect knowledge of the robot's position at all times (Kriechbaum, 2006). The 'Tangent bug' and 'Optim bug' algorithms mentioned previously are two examples. These algorithms would not work realistically over long distances as odometry only estimates the robot's position and this estimate gets worse over time.

Kriechbaum (2006) describes another algorithm called 'Uncertain bug'. It is used for environments that are uncertain which means that the location of obstacles before the robot starts moving is not known. It does not require perfect dead reckoning as the 'Tangent bug' and 'Optim bug' assume. It assumes that odometry sensor data from encoders is noisy and that an error in the robot's estimated position will accumulate over time. This approach

cannot ensure that the robot will ever reach its goal but its aim is to attempt to reach it with an acceptable amount of uncertainty.

To reach its goal with an acceptable amount of uncertainty, the most efficient path to the goal should be taken. The robot only moves within the range of its certainty about the environment. Since the robot only has a certain detection range, it will follow a path created up to the end of this range and then re-calculate its path (in the same way 'Optim bug' does). This means the robot will move step by step with each step determined by the range of its sensors and re-plan its path after each step. If an obstacle that lies in the path is detected, the path will be changed so that the robot moves around it.

Figure 2-9 shows the uncertain bug's recalculation of a path after detecting an obstacle. This algorithm uses landmarks to recalibrate the robot's absolute coordinates. This recalibration will correct for errors accumulated in the estimated position of the robot using odometry. The (pink) asterisks in Figure 2-9 represent landmarks used to localise the mobile robot; the green) dotted circle surrounding them indicates the area in which the robot can detect them; the pink dotted line represents the path the robot takes towards its goal (the square box); and the red and blue lines represent the estimated and true path of the mobile robot respectively as it moves according to its detection range. Therefore, the robot's path does not travel straight to the destination but plans a path that utilises the landmarks so that its position can be regularly localised.

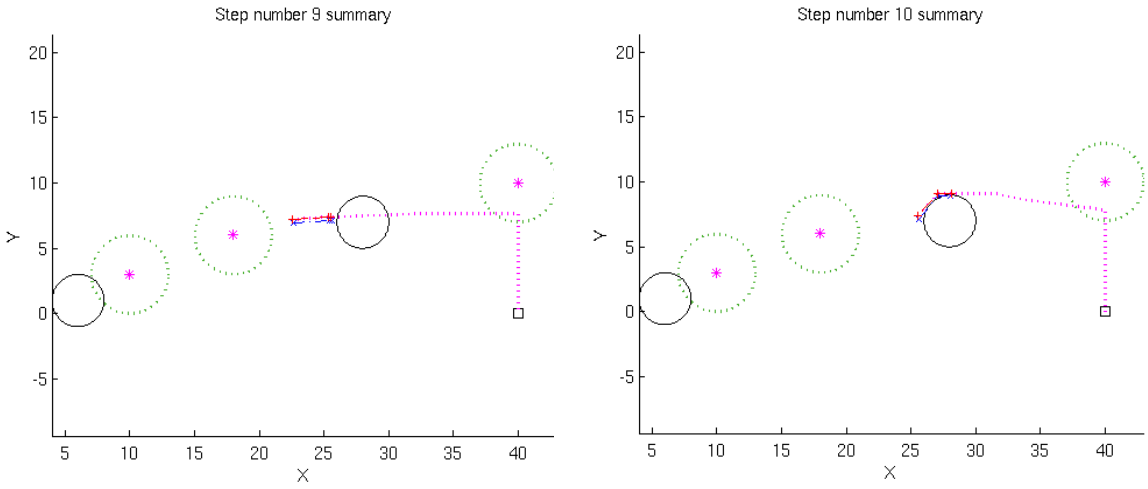


Figure 2-9: Path recalculation using Uncertain Bug (Kriechbaum, 2006, p. 102)

The robot will continue to try to reach its destination until it either does so or needs to travel through an area it has already seen to such an extent that it is not certain (due to odometry errors) that the new area will provide any new information. If the latter is true or it has realised that there is no obstacle free path to its goal, the robot will stop with failure.

2.3.4.4 Potential Field

The potential field method of navigating a mobile robot uses attractive and repulsive forces in order to direct a robot to its goal (Ge & Cui, 2002; Shi, Wang, & Yang, 2010). Ge & Cui (2002) demonstrated using these fields to move a robot in a dynamic environment where both the target and the obstacles are moving. They used mobile robots to represent moving obstacles. Each of these generated a repulsive force that caused the controlled robot to move away from them. An attractive force between the controlled mobile robot and its goal directed the mobile robot towards the goal. In this way the mobile robot could follow a moving goal while avoiding moving obstacles.

This would be impossible for methods such as the Uncertain Bug to use as they assume that the environment is static. Having such attracting and repelling forces provides much more flexibility to a system making it easier to manipulate in industry and to work in environments with moving obstacles. However, in a complex environment it would be difficult to make every obstacle have some sort of repulsive force. Also, if the environment had large static obstacles, this method would provide no way to avoid them and such obstacles would probably interfere with the detection of the attraction and repulsion forces. Other algorithms using sensors such as distance sensors need to be incorporated with this method to allow it to avoid large static obstacles.

2.3.4.5 Side step and look

The following algorithm is purely a method for avoiding an obstacle in a simple environment. For most algorithms the robot will inevitably try to move straight toward a goal (or move past landmarks on the way to a goal) and then move into an obstacle avoiding mode when one obstructs its path. This algorithm and the one following assume that this simple method of moving straight towards the goal is used and provides a simple way to avoid obstacles when they are detected between the robot and its destination.

Robotics/navigation/collision_avoidance (n.d.) shows a simple algorithm for avoiding an obstacle. When an obstacle is detected, the robot will move one and a half times its body length in distance around the side of the obstacle. It will then check if its path is clear and try to move past it towards the target. If it still detects an obstacle in its path, it will keep moving one times its body length to the side of the obstacle until it detects a clear path to move.

This algorithm would be easier for a robot to follow than the boundary following mode of the 'Tangent bug' algorithm. The boundary following mode requires sensors to clearly detect each point along the boundary in order to follow it. This algorithm, however, only moves in set movements and just needs to detect whether an obstacle is directly ahead of it at any one time. Hence, it is more practical for robots with simple obstacle detection sensors than the boundary following mode.

This simple algorithm would work efficiently in very simple environments but not in more complex ones. For example, in the case of trying to move to a goal when the robot is within a 'U-shaped' obstacle, the robot will become stuck, trying to move to the side of the obstacle when it cannot (Robotics/navigation/collision_avoidance, n.d.).

2.3.4.6 Turn till obstacle is clear

A more efficient method in avoiding an obstacle is to turn the robot until it can't measure the obstacle any more so that the width of the obstacle can be estimated. Benmounah & Abbassi (1999) presented this simple method for avoiding an obstacle using a three wheeled vehicle that has only one driven wheel at its front. The robot assumes to move from the start to the goal as can be seen in Figure 2-11. Then the robot determines whether to travel around either the left or right side of the obstacle. The robot first turns on the spot in the left direction until it cannot see the obstacle anymore. The angle the robot is at this point from its original position ($\beta 1$) is recorded and the same measurement is made on the right side of the robot ($\beta 2$). The robot then takes the smallest of $\beta 1$ and $\beta 2$ and chooses that direction to travel in. By using the smallest angle, the distance A2 or A2' (as shown in Figure 2-10) can be calculated and the robot can attempt to avoid the obstacle.

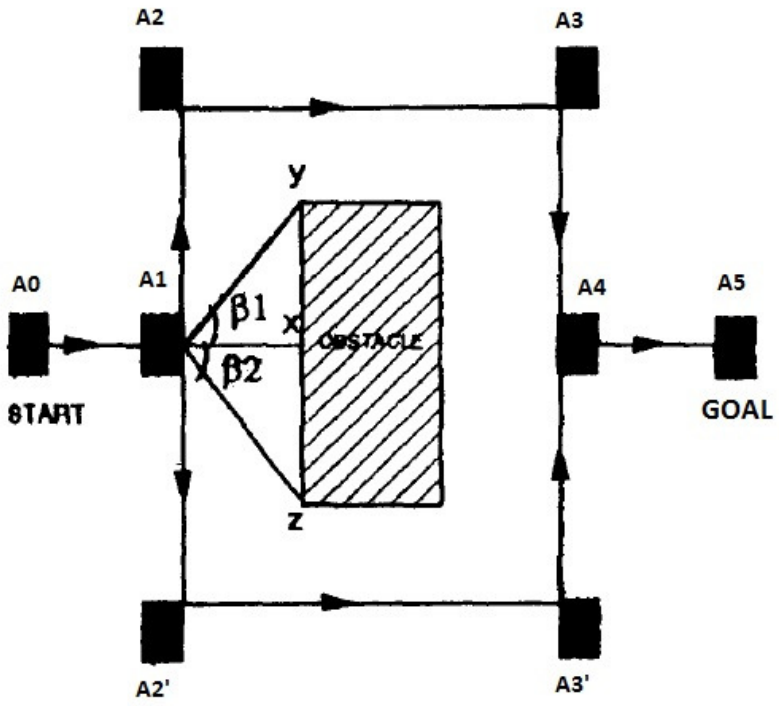


Figure 2-10: Avoiding an obstacle through turning to obstacle edge, (Benmounah & Abbassi, 1999, pg 539)

This method could only move the robot around the robot at steps that would be dependent on the detection range of the front sensor. If the obstacle's edge exceeded the detection range of the front sensor, the robot would need to move to A2 or A2' and then try to find the edge again. Also, a mobile robot would be unable to avoid complex obstacles using this algorithm since it does not take into account situations where another obstacle could be at position A2 where the robot moves to avoid its first obstacle.

2.3.5 Sensing technology (safety issues)

2.3.5.1 Use of various sensors

This research is focused on the methodology of navigating a robot within an indoor environment using RFID tags. Therefore, the various types of sensors has not been

researched in depth. Sensors used for the robot to test this concept are explained in section 6.3.2.

2.3.5.2 Safety issues when moving a robot

In all the different methodologies mentioned above, safety must be observed. Issac Asimov created three laws of robotics in which the first law was that a robot cannot hurt human beings and the third law that a robot should try and protect itself (Isom, 2005). In order for this to be practically possible, the size and power of the robot need to be balanced by the capability and reliability of the sensors on the robot that detect objects external to the robot itself. Some isolate a robot from the danger of contacting people or harmful objects. Mobile robots would usually be used in situations where people or obstacles are around. Therefore, to form a methodology that could be reliably used outside of a testing environment, the safety of the robot to itself and others must be considered.

2.3.6 Conclusion

From the discussion above, the necessity of a map in most navigation methods has been explained. Odometry is important in navigating a robot since it provides a method of estimating the robot's current position within the environment. Localisation is necessary to update the mobile robot's actual position and eliminate the errors that accumulate through using odometry.

The different goal reaching methodologies mentioned provide insight into the various means of navigating a mobile robot within an indoor environment. It can be seen that there is a need for algorithms that do not assume perfect odometry, like Uncertain Bug. These make use of landmarks to localise the robot at definite points within an environment. Potential field

algorithms are very useful in simple dynamic environments. A mobile robot can easily follow a goal that is moving if it produces an attractive force for the robot. Also, moving obstacles can be avoided if they are fitted with something that produces a force that repels the robot. These algorithms are not useful, however, within an environment with large static obstacles unless many repulsive forces are attached to the obstacles. Since environments are complex, there is also the need for algorithms that avoid obstacles that are of a complex shape, such as manoeuvring a robot out of a 'U' shaped obstacle.

With all this in view, it can be seen that there is a need for more research in algorithms that navigate within an environment with complex obstacles and not rely on perfect odometry. Mobile robots also need to be designed so that they are safe both to themselves, other precious objects and human beings.

Chapter 3: Localisation methodology using RFID tags

The last chapter mentioned that localising a mobile robot within an indoor environment that may have static or mobile obstacles is an active area of research. This chapter presents a method of localising a mobile robot in an indoor environment that has stationary obstacles. Odometry has been used to continuously estimate the robot's position. This method accumulates errors over time. In this research, RFID tags were used and installed on certain fixed obstacles in order to update the position information of the mobile robot while it moves within the environment and a compass was used to update the robot's orientation. These tags make it possible to localise a mobile robot within an environment where visual observation from a sensor is not possible. These tags are only required to be detected and a short distance and therefore have no problem with large obstacles that methodologies relying on attractive forces would be disrupted by.

In order for the RFID tags to localise the robot, the position of the RFID tags are recorded in a database based on the IDs of the RFID tags. The system developed by this research uses a computer to communicate with the mobile robot wirelessly. When the system is set in the teaching mode, the user can guide the robot through the environment. Whenever the robot passes by an RFID tag the location and ID of the RFID tag is recorded. With such information, it is able to build a map that has the RFID location information. Therefore, whenever the robot moves in the environment, as soon as the robot detects an RFID tag, the position of the robot can be updated based on the location of the RFID tag detected.

3.1 Low frequency passive RFID tags

RFID technology is gaining popularity and is being developed by large companies such as Tesco and Walmart. An RFID system is composed of RFID tags and RFID readers. It also requires some method of electronically storing a record of the unique IDs stored in the RFID tags together with information for each ID that can have some use in the RFID system. RFID applications include any situation where objects need a unique ID that can be detected at a later date. For example, animals in a farm may be tagged with an RFID tag that holds an ID unique to them. When an RFID reader detects the tag, a database that contains a list of the tags and information about the animals that correspond to these IDs can be looked up. This would allow the one on the farm to know any crucial information stored about the animal they detected.

An RFID tag is composed of a microchip that stores a unique ID of the tag and an antenna that transmits its signal. There are different types of tags. The active types have a battery which they use to power the tag to continuously emit its own RFID. Since they are powered by their own battery, they have a greater detection distance than passive RFID tags however are more expensive and would require battery replacement (Persuad, n.d.).

When a battery is undesired, a passive type of tag is used. With passive tags, inductive coupling occurs in which the RFID tag draws power from the electromagnetic field generated by the coil in an RFID reader (an external device that reads the tags ID). The field generated induces a current in the RFID tag's own antenna (RFID Journal, n.d.). With this current, the tag sends its unique ID to the RFID reader. Figure 3-1 shows a magnetic field produced by a

RFID reader's antenna (on left side of the figure) that energizes the antenna of the RFID tag (on right side of the figure) to sends its data to the RFID reader.

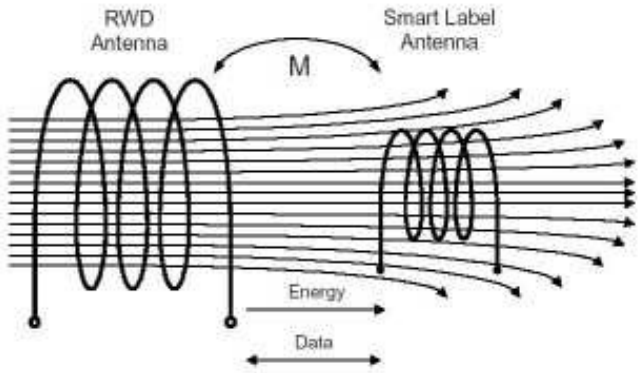


Figure 3-1: Reader generating a magnetic field that powers the antenna to send its data (FerroxCube International, 2009, para. 3)

Passive tags are cheaper than active tags and their detection range is smaller than active tags. This is useful in localising a mobile robot through RFID tags since only a small distance is desired so that, when detected, the robot knows where it must be in a small distance from the RFID tag's position. Some, using active tags use the strength of the signal from the RFID tag to determine the robot's position (Oktem & Aydin, 2010). However, the method here simply assumes that when an RFID tag is detected, the robot must be at the location of the RFID tag. When the robot detects it, the robot position is made the same as this coordinate. Figure 3-2 illustrates this concept. If the detection distance for an RFID tag is too large, detecting it would give a very broad area in which the robot could be and hence the actual location of the robot could not be determined within a narrow enough area to be useful. Due to this, passive tags were chosen over active tags for this method of localisation.

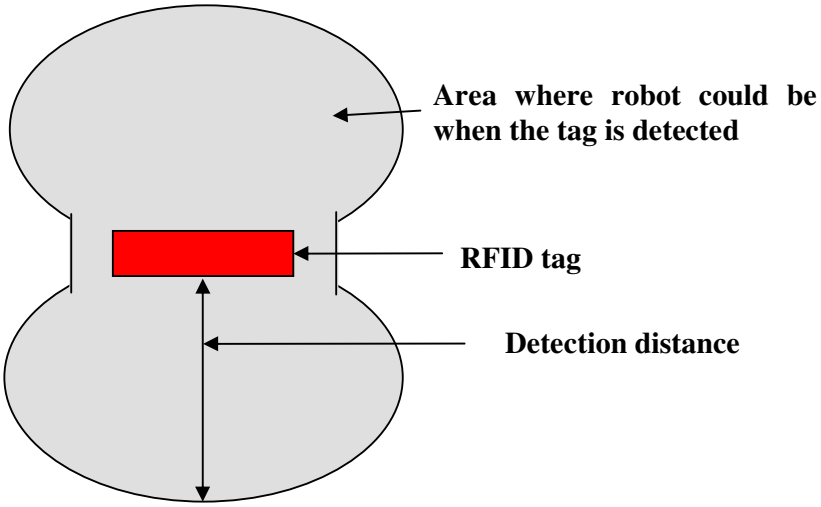


Figure 3-2: Detection distance of RFID tag determining the area where the robot could be

Figure 3-2 also illustrates that there is a particular direction that gives a much larger detection distance than the other. The reason for this is that the coil in the RFID tag induces a current most effectively when it is perpendicular to the RFID detector. Due to this, RFID tags need to be placed so that they are easily detected by the mobile robot as it travels towards them.

When using an RFID system, the frequency to use also needs to be resolved. To avoid interference between different devices that emit radio frequencies, different frequencies bands have been allotted to different applications of radio. Different countries vary slightly in the bands they allow. The frequencies bands that an RFID system is able to use include frequencies such as 125kHz, 134kHz, 13.56MHz, & 2.4-2.5GHz. A greater frequency for antennas of the same size results in a greater distance of detection. Since the distance required is small as previously mentioned, a low frequency RFID system best suits this method's localisation of RFID tags.

Therefore, a 125kHz RFID system was chosen to test this concept. The tag could not be too small (e.g., the RFID button which is only 6mm in diameter shown in Figure 3-3, left) as the mobile robot would need to get impractically close to the tag to detect it. The reason for this is that at this frequency, the antenna takes up nearly the entire tag so the larger the tag, the larger the antenna. To sense this tag the robot would need to get closer than 6cm and so would very likely crash into obstacles before reaching the tag. A flat RFID wallet sized card (Figure 3-3, centre) would be better as it has a larger antenna but the tag might easily break in harsh environments where the tags may be placed. Therefore clamshell tags (Figure 3-3, right) were chosen since they have both a shell that protects them from being damaged and have an internal antenna that allows them to be detected at a reasonable distance.

Figure 3-3: 125kHz RFID tags that hold a unique ID used to localise a mobile robot.

Left – RFID button; Centre – Flat RFID card; Right – Clamshell RFID card

3.2 Localisation through RFID tags

The methodology presented in this thesis to navigate a mobile robot uses odometry to continuously estimate the robot's position, similar to many other indoor navigation algorithms. RFID tags are used to correct the accumulated error caused by this odometry estimation whenever they are detected by the mobile robot as the robot moves within the environment to its destination. The RFID tags are strategically attached to certain fixed

objects and obstacles in the environment to guarantee that, no matter which route the robot takes to reach its destination, there are always a few RFID tags that the robot will pass by. An example of this is shown in Figure 3-4.

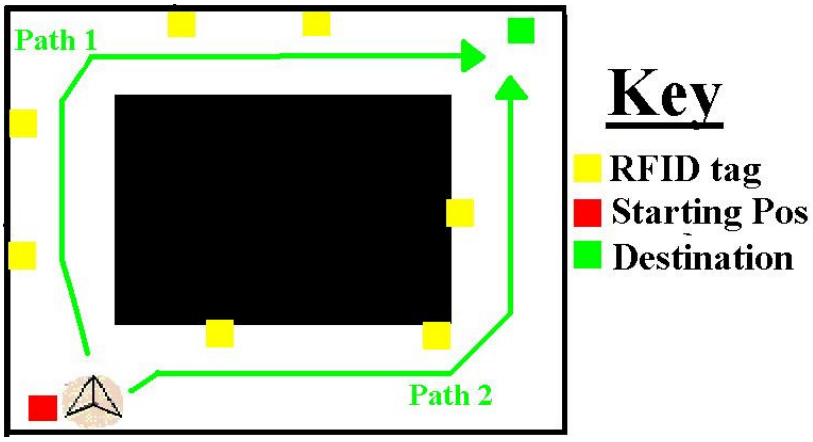


Figure 3-4: A map showing two paths for a robot that each have RFID tags for the robot to utilise

An RFID reader is installed on the robot so that whenever the robot passes by an RFID tag, the unique ID of that tag can be detected. The information of this ID is compared to the RFID database stored in a PC external to the robot. From the map, the coordinates of this RFID tag in the indoor environment is found and used to update the position of the robot. Therefore, when the robot moves to a destination along the setup of RFID tags, any accumulated error occurring due to using odometry will not contribute to a large error between its actual position and the robot's intended destination.

3.3 Fixing orientation error through a compass

A basic compass simply detects the magnetic field in its environment and assumes that there are little or no external magnetic fields that prevent the compass from clearly and simply using the earth's magnetic field to find its orientation (Caruso, n.d.).

These compasses were designed to point to north so that a human user could use them to navigate to a particular destination. However, with the invention of robots that rely on electrical signals, there is the need of an electronic compass that gives an electric signal to a computer that indicates what direction it is currently facing. The three main types of signals sent are

- A serial chain of bits (high and low voltages) whose binary value represents an angle. For example, if a 8 bit signal were used, 1111 1111 could represent 359 degrees, 0000 0001 represent 0 degrees and then all the binary values in between would correspond to different angles
- A pulse whose length of time depends on the angle (e.g. 1ms = 1 deg, 360ms = 360 deg)
- A voltage whose analogue value represents the angle. For example, if 5V were the maximum voltage allowed, it would refer to 360 degrees, 2.5V to 180 degrees, 1V to 72 degrees, etc.

The computer would read these signals and then determine the compass' angle from them. To produce such a signal, a sensor that generates an electrical signal that varies with the earth's magnetic field is needed. Two common electronic sensors (Robert, Christian & Samuel, 2004) that detect this magnetic field are:

- Magneto-resistive sensors that use materials whose resistance changes depending on how the angle of the magnetic field lines up with the current of the material (called anisotropic magnetoresistance). The resistance is greatest when the magnetic field is parallel to the direction of the magnetic current.
- Fluxgate sensors that use two coils of wire wound around a coil of a material that is greatly susceptible to magnetic fields. The first wire has an alternating current passing through it that causes a continuously changing magnetic field to be generated in the material. This magnetic field will induce a current in the second wire that, under no external magnetic fields, will exactly match the current in the first wire. However, under an external magnetic field, the magnetic field in the material will more easily saturate (that is, reach its maximum magnetization) when aligned to the external field and less easily saturate when opposing the field. This will cause a time difference between the first and second wire which is then used to determine the direction of the external magnetic field.

A robot that uses a compass may have magnetic parts (such as iron) on it that frustrate the detection of the earth's magnetic field. These would permanently affect the magnetic field detected by the compass, preventing it from correctly determining the robot's angle. Figure 3-5 shows the disturbance of a uniform magnetic field by a magnetic material. To compensate for this disturbance, usually the compass is rotated and its magnetic field at different angles is measured and recorded. With this, equations can be formed that determine the robot's orientation when in an environment where ferrous materials disturbance the earth's magnetic field.

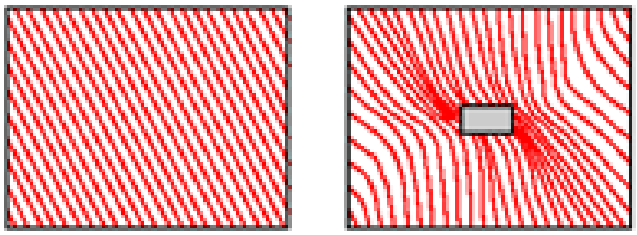


Figure 3-5: Disturbance (right) of uniform magnetic field (left) by a magnetic material (Advanced Safety Devices, 2012, para. 6)

More difficulty comes when objects in the environment are magnetic, or electronic devices or magnets in the robot's environment interfere with the robot's detection of the earth's magnetic field (Suksakulchai, Thongchai, Wilkes, & Kawamura, 2000). Some compasses are able to negate the external fields from the earth's magnetic field. For example, Honeywell's compasses sense the change in the magnetic field detected due to magnetic fields other than the earth and can use this change to determine what the earth's magnetic field is (Honeywell, 2011). These sensors are more expensive but would be necessary to work effectively in environments with ferrous materials and significant magnetic fields. Such sensors were not used in this research but would be useful to improve the localisation of the robot's orientation.

For the mobile robot used to test this concept, an electronic compass is used to correct the absolute orientation of the robot since the RFID tags only localise the robot's position. The orientation of the robot can easily be changed when the robot is turning. With a slight slip of a wheel, the mobile robot may become a few degrees off the orientation it is meant to be. This will result in an ever-increasing position error to be produced. Figure 3-6 illustrates how this difference in position will increase due to an error in the angle. In Figure 3-6, 'AE'

represents the error in the robot's angle, 'PI' the intended path for the robot, 'PA' the actual path of the robot, and 'DP', the difference in the robot's position after moving along a path. From this, it is obvious that a difference between the estimated and actual orientation needs to be corrected otherwise the robot will eventually end up far away from where it is intended to be.

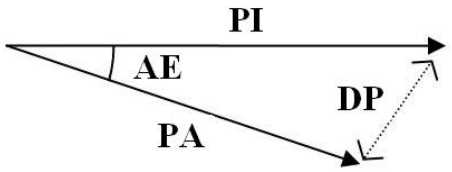


Figure 3-6: Error in orientation causing a difference in position to be created over time

3.4 RFID system setup

The entire robot navigation system is composed of the mobile robot that has the RFID reader and a compass, the host PC that controls the robot and makes all the decisions for the robot's navigation, and RFID tags used for localising the robot's position within the environment. Details about the specific models used are mentioned in section 6.3.2. As explained in section 3.2, when the robot reads a unique ID from the RFID tag, the ID of the tag is sent to the host PC wirelessly (this is explained fully in Chapter 4) which looks up its coordinates in an array containing the location of the RFID tags and their corresponding coordinates are used to update the location of the robot. Since the PC keeps track of the robot's position, there is no need for the robot to store any position information relating to the IDs. Therefore the robot simply passes the ID it receives on to the PC that uses it to update the robot's position. In order to avoid obstacles between RFID tags that the robot may encounter, it is useful to store the location of obstacles as well. These are either stored manually through the map building software (described in section 5.3) and while the robot is moving using its sonar and

photodiode distance sensors (explained in section 6.3.2.2.1 and 6.3.2.2.2). The arrays containing the location of the RFID tags and the location of obstacles in the environment both constitute the robot map and are used to navigate the robot.

The array containing the location of all the RFID tags can be quickly created by an operator simply driving the robot through the environment, while running a software that records where the tag location is. This is called the 'teaching mode' as the system is taught the environment through moving the robot within the environment and recording the RFID tag locations as the robot detects the RFID tags. The procedure works in the same way as people learn a place through passing through it and observing what is in it. When the mobile robot passes an RFID tag and detects it, its unique ID is automatically recorded as well as the coordinates at which it was detected. Since the software uses odometry to estimate the robot's position as it moves through the environment, the operator needs to move the robot step by step and manually correct the robot's position whenever they see it slipping or not moving as it should do. Although the map produced will not be the exact coordinates of the RFID tags, they will be sufficient to localise the robot when it moves around in the map. The building of a map of the environment through the teaching mode is further described in section 5.3.

The users of the system may also calculate the location of the RFID tags in the environment manually and then type the location information into the system. This would take more time than the teaching method and may not be any more accurate. Therefore, when building a map, the teaching mode is preferred over the manual method.

To form the array containing the location of the obstacles in the environment, only the manual method of entering their location was used. Although the robot does detect obstacles through its distance sensors, these were deemed not reliable enough to rely on for building a map as their data can be noisy and take measurements too often (creating too many points of data). To simplify the avoidance of obstacles and the entering of their position, they are represented as rectangular blocks in the map of the robot's environment. Figure 3-7 shows the graphical representation of the map produced that the operator sees. The brown squares in Figure 3-7 represent the obstacles to avoid in the map and the yellow squares, the RFID tags. Roman numerals are used to give a number to each tag so the operator can refer to them in the program easily. Chapter 5 provides more detailed information about the software system.

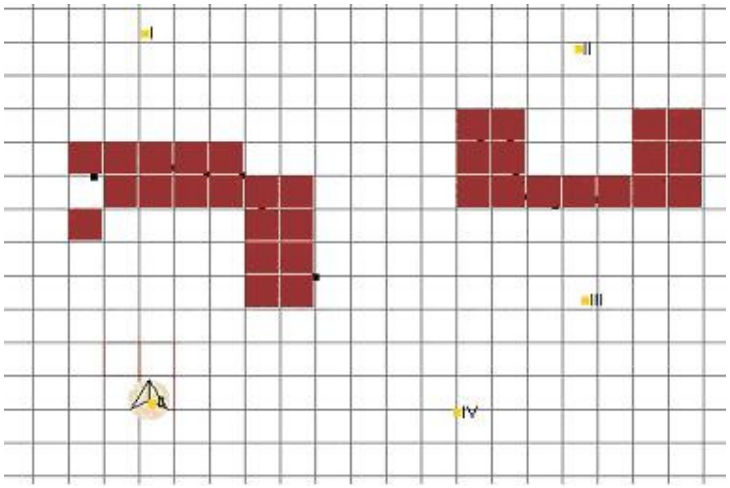


Figure 3-7: Graphical representation of the robot's map. Yellow squares are RFID tags, brown squares are obstacles

The map building software stores the robot's starting position (usually an RFID tag but can be an XY coordinate) as well as its orientation. This position and orientation should be

known and easy for an operator to put the robot in. For example, the robot's starting location may be parallel and at the edge of an object in a room.

The method of localising a mobile robot in an indoor environment has been presented. It uses odometry to estimate the robot's position continuously. Since this is only an estimate and accumulates error as the robot keeps moving, low frequency passive RFID tags placed strategically around the environment are used to update the robot's position and a compass is used to update its orientation. The robot navigates using a map that contains the location of the RFID tags and obstacles that the robot could encounter.

Chapter 4: Component communication

The previous chapter presented a methodology used for navigating a mobile robot within an indoor environment. The map to guide the robot movement can be very large. Processing of sensor data is complex. Complex algorithms are required to determine what the robot should do. As a result, an external PC is used as the central processing unit and map storage place for the mobile robot. This chapter discusses the wireless communication between the PC and the mobile robot, how the microcontrollers on the robot send commands to and receive data from one another, and how the robot's camera sends its video signal to the PC.

4.1 Wireless communication between the host PC and the mobile robot

4.1.1 Role of host PC and mobile robot

The communication standard used for the wireless communication between the PC and the mobile robot and for the serial communication between the two microcontrollers on the robot itself is USART (Universal Synchronous Asynchronous Receiver Transmitter). It is a simple standard for serial communication between two devices. This standard has the benefit of requiring only two pins on each device, a receive pin and transmit pin. Since there is no clock pin, the frequency at which they communicate needs to be programmed to be identical before the devices can communicate. This is realised through the baud rate which is measured in bps (bits per second). The baud rate used was 9600bps. The communication between all these devices is illustrated in Figure 4-1.

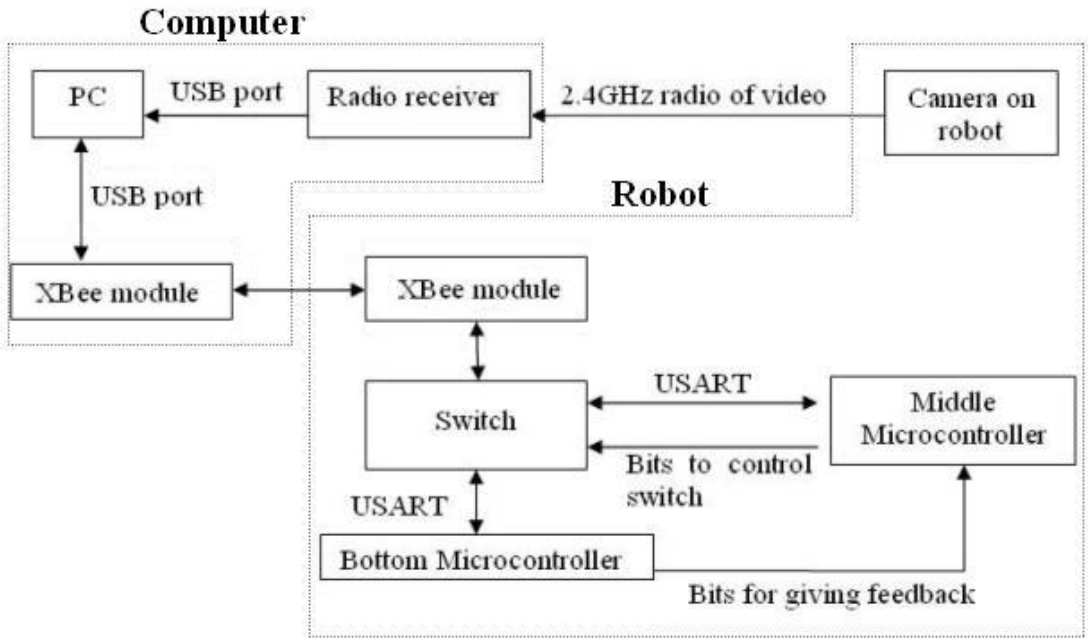


Figure 4-1: Communication between robot and PC using XBee and camera and communication within the robot itself

Figure 4-1 shows two main components, the host computer and the robot. As mentioned above, the host computer does all the processing and calculation for the robot. This includes the following vital tasks:

- Commanding the robot step by step what to do
- Building a map of the RFID tags
- Estimating the robot's current position using odometry
- Localising its location from the detection of RFID tags and the compass
- Deciding which RFID tags should be taken to reach a destination
- Recording the location of detected obstacles
- Deciding when to avoid obstacles

It also provides an interface for a remote operator to:

- monitor the robot estimated position in the map
- see what state it is when moving toward a destination
- control the robot by telling it its destination and manually controlling it if necessary

The mobile robot is the focus of all the work of the PC. Its tasks include:

- Gathering data from the distance sensors, compass, and RFID reader and sending this to the PC
- Executing the commands given by the PC

4.1.2 Wireless communication using XBee modules

The host computer uses two external communication devices in order to communicate with and receive data from the robot: the XBee module and the radio receiver. An XBee module is an embedded device that provides a simple, efficient method of communication via radio communication. This section explains how the XBee module is used to enable the PC to give commands to the robot and to receive data from it.

The XBee module used in this research uses the ZigBee protocol which operates at 2.4GHz. This means that it is able to operate anywhere in the world, coexisting with other wireless protocols including Wi-Fi and Bluetooth (Embedded computing design, 2011). It is ideal for low power applications that do not need to send a lot of information.

XBee modules are designed so that they operate in an exclusive network of devices. In this way, different networks will not interfere with one another. An XBee network requires a network ID, a number that represents an independent group of wireless devices that talk to one another. The XBee modules also need to have the address of the other modules that they communicate with. The configuration of the modules is done through a freely downloadable program called X-CTU from DIGI (a company that deals with wireless communication). The program has a GUI that makes such changes or looks at characteristics very easily using the 'Modem Configuration' tab (Figure 4-2).

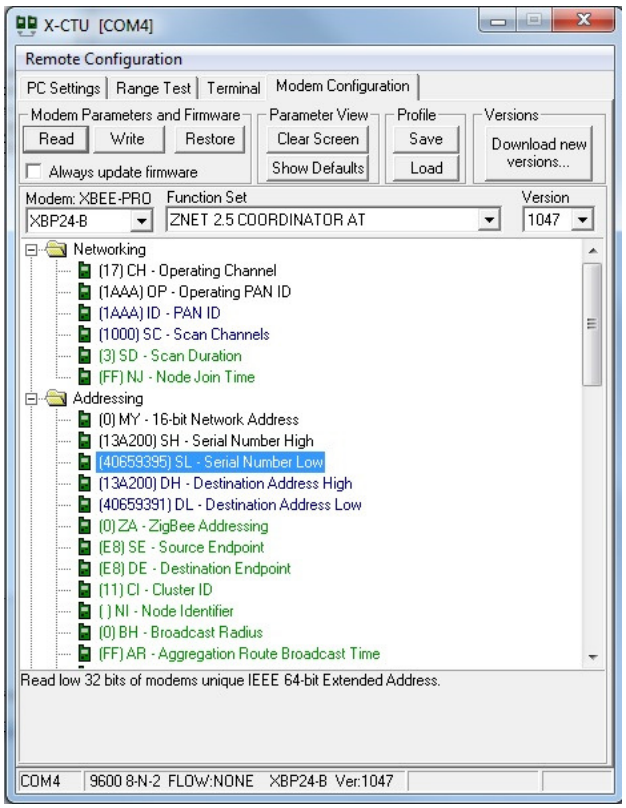


Figure 4-2: Modem configuration for the XBee module

This research uses XBee modules to carry out the communication between the host computer and the mobile robot. The XBee module uses 3.3V as power. The robot uses a DTE (Data Terminal Equipment) serial board (Figure 4-3, left) to connect to the XBee module. This board converts the XBee module's 3.3V to RS232 voltages. This RS232 voltage is then connected to the robot's microcontroller via a chip (the Max 232 dual driver/receiver) that converts between the TTL voltages of the microcontroller and the RS232 voltages of the DTE board. The PC is connected to the wireless module via a USB board (Figure 4-3, right). These two connections are shown in Figure 4-4.

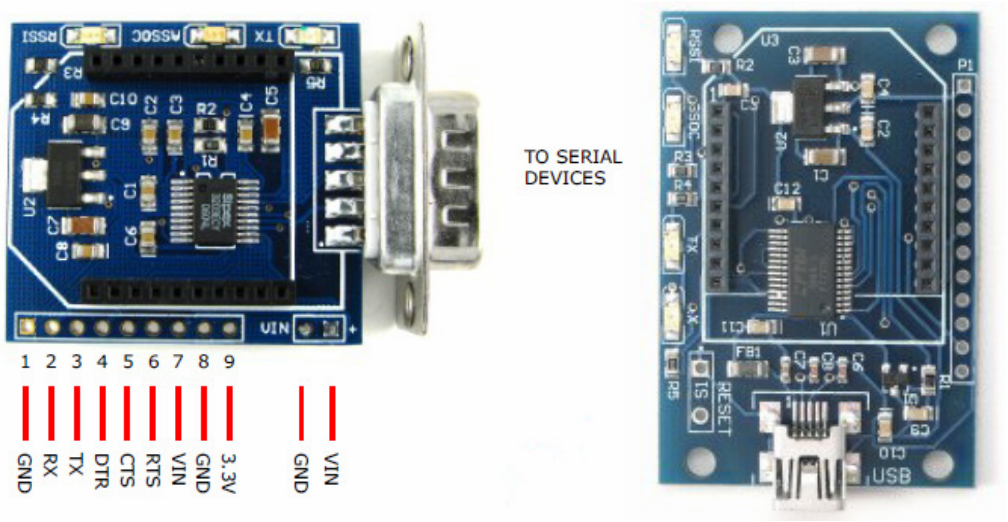


Figure 4-3: Left – XBee DTE serial board; Right – XBee USB board

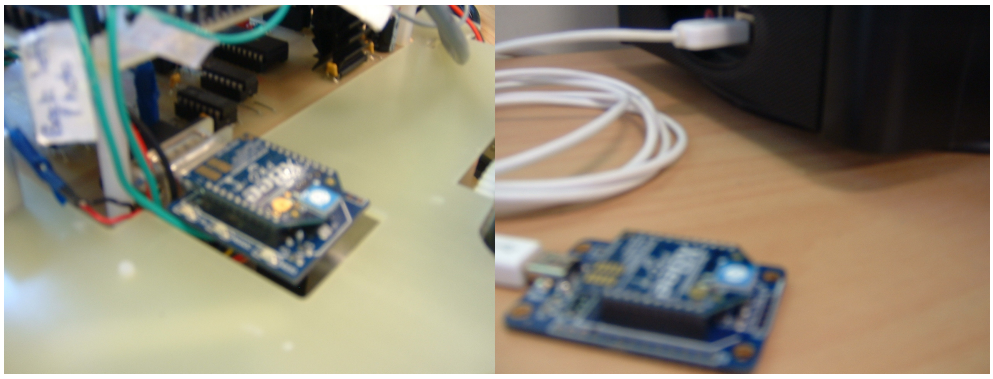


Figure 4-4: Left – DTE serial board connected to mobile robot; Right - USB board connected to PC

A ZigBee network is called a personal area network (PAN). Each network has a PAN ID, a unique identifier that is shared by all devices on the network, and consists of three kinds of devices (Figure 4-5):

- A coordinator that starts a personal network by selecting a PAN ID to use and that can also pass information between devices
- A router, an optional device, that can pass information between devices like a coordinator but cannot start a network
- An end device that cannot pass information to and from devices but has the benefit of being low powered and able to go into sleep mode, where little power is used and where checks on the network to look for activity are made every few seconds

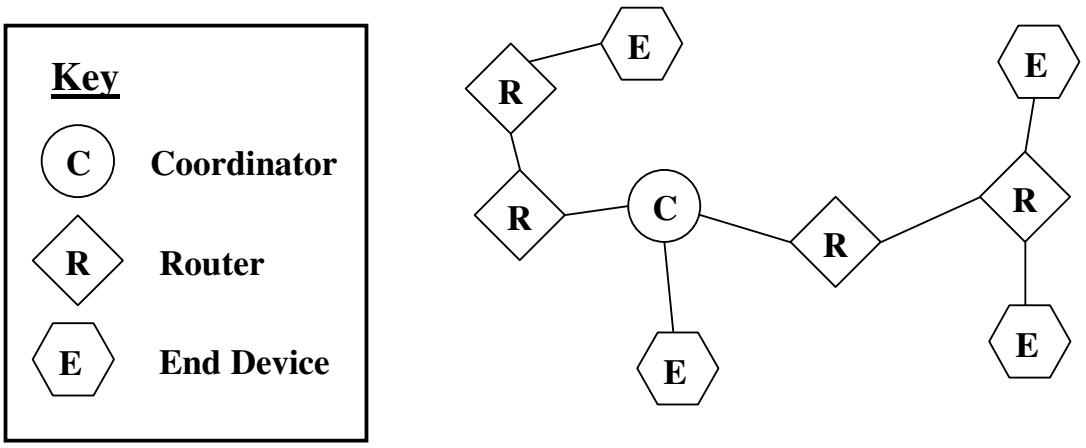


Figure 4-5: Wireless network composed of a coordinator, routers and end devices, (Digi International, 2009, pg. 22)

The PC functions as the coordinator and the robot as the end device. Since the XBee on the microcontroller is in sleep mode it only wakes up every few seconds until it has joined a network from a coordinator. For this reason, it usually takes a few seconds after a signal is sent from the XBee at the PC before communication between the two is established. In order to test the communication between the modules, X-CTU has a terminal program (Figure 4-6) where the developer can send packets easily and see their reply.

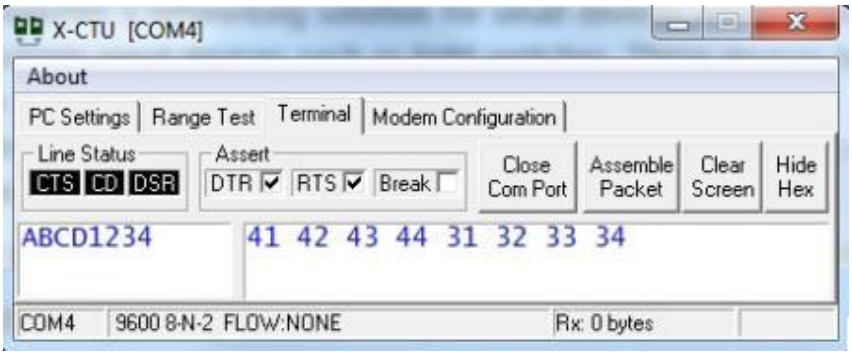


Figure 4-6: Wireless communication with 'Terminal' tab of X-CTU

The PC always sends commands that are only one byte in length. When a command character (8 bits) is sent, the PC waits for an acknowledge byte (which is just an echo of the command) from the mobile robot. If it did not receive this acknowledgement after 100ms then it sends the command again. Appendix B shows this procedure in full.

4.1.3 Receiving data from the sensors

The data from the robot's sensors needs to be received by the PC so that it can localise the robot and avoid obstacles. This section explains the format in which the data is sent over the wireless network. Since the PC controls the mobile robot, the robot will only send its sensor information when asked to by the PC. Sensor data from the robot is not acquired while it is turning since it is unreliable. This is because:

- the distance sensor data is continually changing while the robot is turning
- compass data would be meaningless because it is the result of several averages that are taken at different orientations in the turn

The PC always asks for all of the robot's sensor data at once by using only one command. Each command is represented by an ASCII (American Standard Code for Information Interchange) character. Following is the order the data is sent:

- The two characters 'I' and ':' which the PC looks for so that it knows it is receiving data from the robot's sensors and not anything else
- The six infrared distance sensor's analogue values that represent their distance from objects

- The sonar sensor's analogue value representing its distance detected
- Two bytes representing the compass value
- The left and right encoder bytes
- The state the robot is currently in (moving forward, stopped, etc.)

The last byte indicates the current status of the RFID readers interpreting of an RFID tag's ID. There are seven states used in the program, indicated by different letters of the alphabet, but only three should be sent wirelessly (the rest are internal and are changed in the process of deciphering an RFID signal). The PC usually receives an 'N' indicating that there is no new RFID value read by the mobile robot. If an 'E' is received, that means an unrecognized signal has been received, and it indicates that there is most likely an error.

Sometimes the microcontroller on the robot may not decipher the serial signal sent by the RFID reader correctly. A bit may be missed out or added due to a slight difference in the clock of the RFID reader and mobile robot, something quite rare. This mistake is picked up by analysing the first few bytes of the signal. These bytes differentiate which type of card the reader has picked up (e.g, RFID button, Jaycar flat card, or Farnell clamshell card (see 6.3.2.3. for an explanation of these cards)). If an unrecognised sequence is received, an 'E' will be sent when data is acquired from the robot and the microcontroller will go back into the 'N' state again.

When an RFID tag is read successfully, the status will become 'F' indicating it has just finished a reading. Since a new reading is made, the final part of data sent will be:

- The character 'R', indicating that a new RFID tag has been detected
- A byte indicating the type of RFID card
- Two bytes that represent the unique RFID of the tag

After sending the unique RFID of a new tag detected, the RFID status in the microcontroller is set back to the 'N' status again. In this way the mobile robot sends all the data needed by the robot so the PC can determine where obstacles are in relation to the robot and can localise the robot's orientation and position through the compass and RFID tag data. The PC asks for this data regularly whenever the robot is not turning.

4.2 Communication between the bottom and middle layer microcontrollers

Two ATmega32 microcontrollers are used in the mobile robot used to test the concept of localisation through passive RFID tags (Figure 4-1). Details about this robot are presented in section 6.2 and 6.3. A microcontroller placed on the bottom of the robot mainly controls the robot's motors while another microcontroller placed above it receives data from the robot's sensors and communicates wirelessly with the PC. This section describes how these two microcontrollers communicate. The microcontrollers used each have four ports. Each port has eight pins each and each pin can be configured independently as either input or output.

The middle microcontroller needs to pass on the commands it receives from the PC to the bottom microcontroller. However, the same USART pins are used on the middle microcontroller to communicate wirelessly to the PC and to communicate with the bottom microcontroller. A setup is therefore needed on the middle layer to allow it to switch between the middle layer's serial communication to the bottom layer and its communication to the PC. The position of this switch is illustrated in Figure 4-1.

A two input quad 'AND' gate and a two input quad 'OR' gate are used to carry out this switching. A quad chip has four gates embedded into one chip and so reduces the number of chips needed for an operation. A microcontroller pin is used to turn a particular one of these gates on, allowing the middle microcontroller to communicate with either the PC or bottom microcontroller. Figure 4-7 shows the names of the pins on port D, pins 0 - 3, that are used for the USART communication. D0 is labeled with RXD, meaning it the USART input pin for the middle layer's microcontroller. D1 is the microcontroller's USART output pin and is labeled TXD. As can be seen, if D2 is high, data will be sent and received to and from the XBee wireless module. If D3 is high, data will be sent and received from the bottom microcontroller, which is connected to the middle layer's 2nd ribbon cable port (with labels of M2.8 and M2.9). This ribbon cable joins a port of the middle microcontroller to a port of the bottom one and so is used for communication between them. For this reason, in the code, D2 and D3 are never made high at the same time as then the middle layer's microcontroller would be communicating to both the PC and bottom microcontroller at the same time.

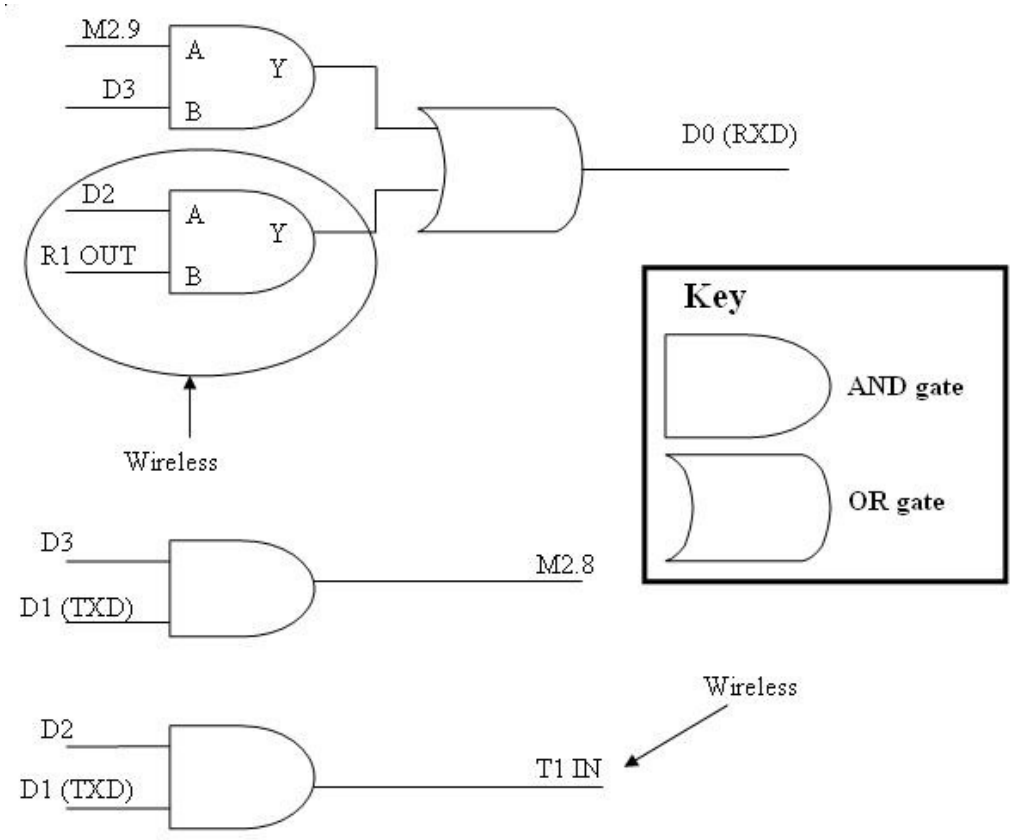


Figure 4-7: AND gates and OR gate used to allow middle layer's microcontroller to switch between wireless module and the bottom layer's microcontroller

This method of communication only takes into account the situation where the middle microcontroller takes the initiative to communicate with the bottom microcontroller. By default, the middle microcontroller has D2 high so that it continuously receives commands from the XBee module. Consequently when the bottom microcontroller wants to give a signal to the middle one while it is connected serially to the PC, it uses several pins (which this research calls COM pins) that are connected between the microcontrollers (in the ribbon cable mentioned above), in order to tell the middle microcontroller something. The two cases that use these pins are explained in the following paragraphs.

First, when a command for the robot to move a certain distance has finished, the bottom microcontroller sends a signal to the middle microcontroller by making a COM pin high. It then waits for a serial confirmation (through USART) to ensure the middle microcontroller receives the signal before making the COM pin low again.

The following C code shows how this confirmation is done.

Code 4-1: Code showing how bottom microcontroller tells the middle one that it has just finished

```
if (movingStatus == 'S') // just finished movement, tell middle micro
{
  PORTC |= 0x08; // tells middle micro that stepping movement is finished.
  if (receivedata == 'S')
  { // if confirmation that middle micro has received signal then turn signal off
    movingStatus = 'N'; // doing nothing at the moment
  }
}
else
{
  PORTC &= ~(0x08); //make the port low if it has not just finished movement (default)
}
```

The bottom microcontroller also uses the same method in the case of an emergency stop. This occurs if the front distance sensor has detected an obstacle too close to be safe twice in a row while the robot is moving forward. Such a method is vital in an emergency situation where communication between the PC and mobile robot is cut off, preventing the PC from being able to tell the mobile robot to stop.

Therefore, this system allows the two microcontrollers to communicate with each other by:

1. The middle microcontroller switching its serial communication between the XBee module and the bottom microcontroller whenever commands are sent from the PC

2. The bottom microcontroller using COM pins to tell the middle microcontroller information it is not asked for.

4.3 Live image data (Camera)

The camera (Figure 4-8, left) is able to record video and sound. Its purpose is to enable the operator to see where the robot is going from the robot's perspective. It also has the capacity of being used in further research involving image processing. This would allow more complex obstacles to be seen from the camera and hence avoided automatically by the robot.

Figure 4-8: Left - Camera used to capture video; Right - Radio receiver that plugs into the PC

Since the camera sends a high volume of data per second and the XBee module is limited in its capacity, it is necessary to send its data to the PC independently. This is done through a radio transmitter on the camera and a radio receiver at the PC. The camera used was a 2.4GHz USB-Funkkamera sold in Germany by Pollin Electronic. The radio receiver (Figure 4-8, right) that receives the video signal is connected to the computer's USB port to allow

fast transmission of its data to the PC. This way it sends data to the PC independently of the XBee module.

Parts of the environment in which the mobile robot operates may be dark so the camera was inserted into a fibreglass frame (Figure 4-9) and three LEDs (Light emitting diodes) were attached to either side of it. The operator can switch them on when necessary to allow manual navigation in a dark environment.

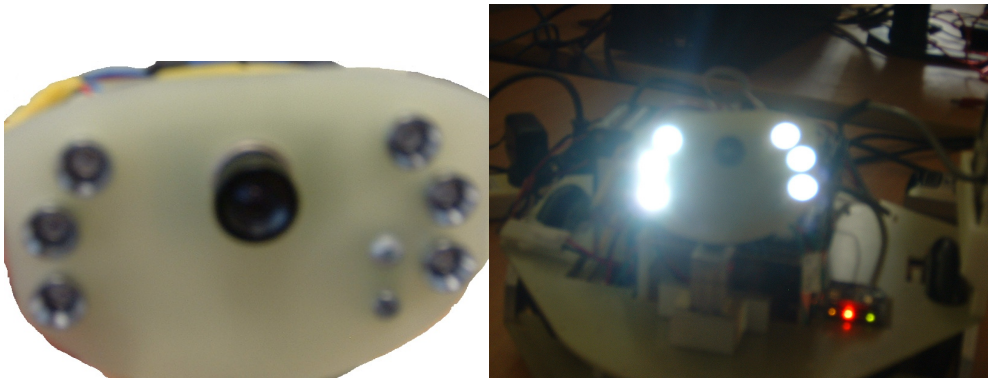


Figure 4-9: Left - Camera with LEDs inserted; Right – Lights shining in a dark room

The quality that this camera produces is seen in Figure 4-10. As can be seen, it is more than sufficient for an operator to see and navigate the robot around a room.

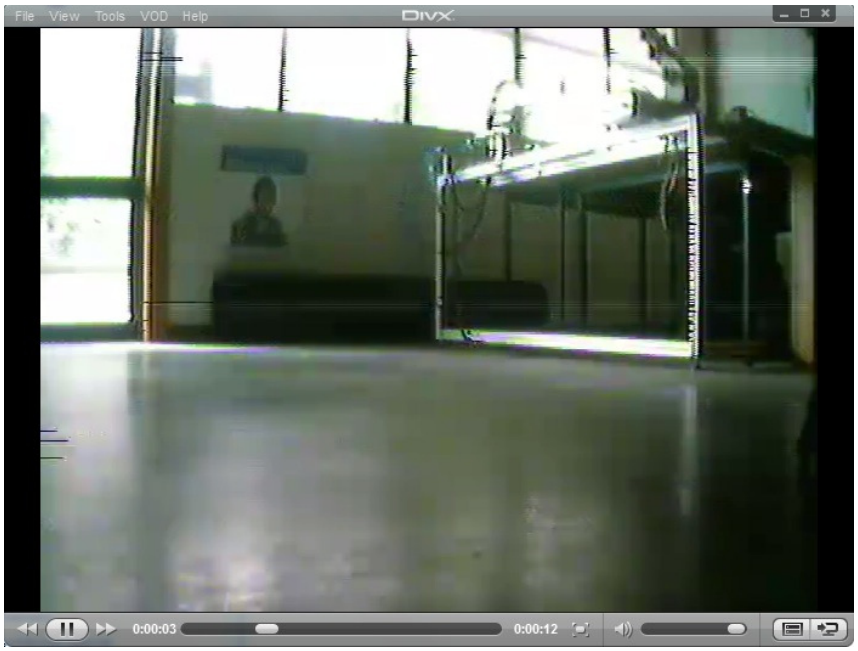


Figure 4-10: Image from a recording taken by the robot's video camera

This chapter has stated how the mobile robot used to test the concept of navigating within an indoor environment communicates between its two microcontrollers using USART and to the PC wirelessly by the use of XBee modules. This allows all the complex processing along with the storage of a map (which could be large) to be done at a PC external to the robot. A camera attached to the robot uses radio communication to transmit its information directly to the PC, allowing an operator to clearly see where the robot is going so that they can manually control it when required.

Chapter 5: Mobile robot software system

With the methodology of localisation using RFID tags and of communicating between the host PC and the robot presented in the previous chapters, there is the need for algorithms to control the path that the robot takes and a program to model the robot's environment so that its position can be estimated continuously and displayed on the PC. This chapter presents the methodologies used to model the robot movement in a real time environment and the software's functionalities.

5.1 Mobile robot navigation algorithms

To control the movement of the mobile robot in different situations, algorithms have to be developed and implemented. These include the algorithms for simply moving from one RFID tag to another and avoiding an obstacle in the robot's path. As a destination usually lies in between several tags, the algorithm for moving a robot between several tags is discussed. Since there are odometry errors that result in the robot being slightly off its intended position, the robot needs to search for the RFID tag it is sent to. An algorithm to do this searching is presented.

5.1.1 Moving from one tag to another

5.1.1.1 Moving straight to the next tag

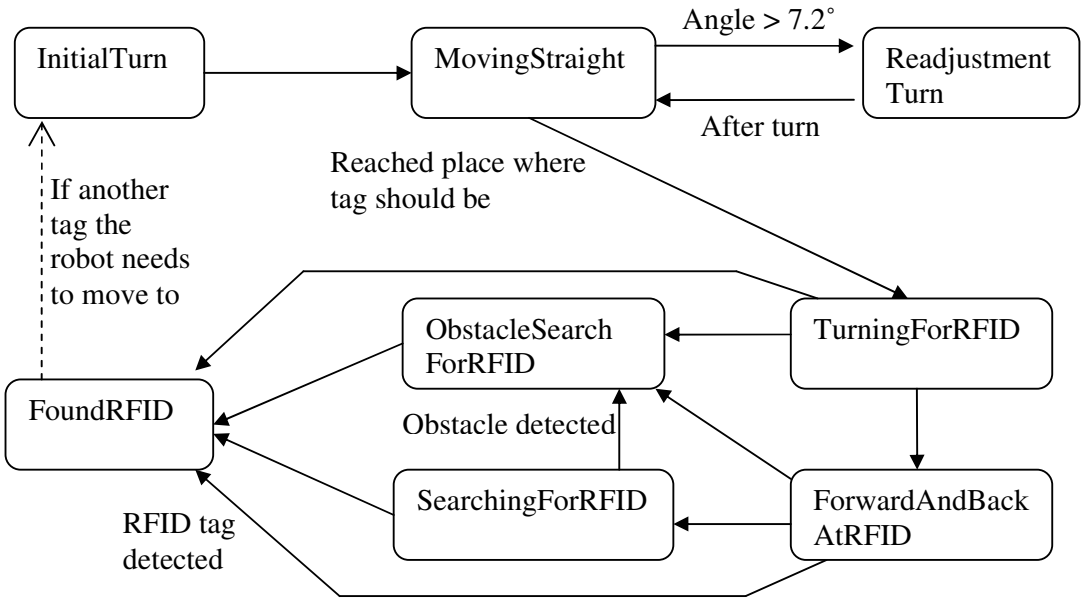
The position of an RFID tag, as recorded in the program, is the best position for the robot to read the tag. Figure 5-1 shows the position the robot should be in order to sense the tag. This

is where the tag would be read on the auto map builder and automatically placed on the map in the program that automatically builds an RFID map (Section 5.3.2).

Figure 5-1: The position where the robot can sense an RIFD tag

In order to move from one tag to another, the robot needs to perform a number of steps. In the C# program used to control and monitor the mobile robot on the host PC, the current state is stored in a variable called 'demoStatus'. These states represent conditions the robot can be in as the robot is guided from one RFID tag to another. As soon as the robot detects an RFID tag, no matter what state it is in, the robot will stop as the aim of all the states is to find an RFID tag. If the robot needs to pass several tags before reaching its final destination, the next tag on the path to the final destination will be the next target for the robot to detect, and the robot will start from the first state, the 'InitialTurn' state again as described below.

The states used by the control program to move the robot from one RFID tag to another are shown in the state diagram below:



State diagram of the states of the control program for moving between RFID tags

Following is a description of these states:

- InitialTurn - Rotate the robot to face the target.
- MovingStraight - Move the robot straight to the next RFID tag. In this state, every three seconds, the angle is checked to see whether the robot is off from the one that should be used to get to the next RFID tag by 7.2 degrees or more. If it is then the robot will rotate to correct the angle in the ReAdjustmentTurn state.
- ReAdjustmentTurn - Make an adjustment turn toward the target. This state is entered from the previous state when its angle is slightly off from directly facing the target. After this turn, the robot will continue by calculating the distance to travel to the next RFID tag and returning to the MovingStraight state.
- TurningForRFID - Turn the robot 90 degrees four times in order to detect the RFID tag at any orientation around the robot. This algorithm copes with the situation when

the robot reaches the place where the RFID tag should be detected by the robot's reader and the RFID reader is not directly facing the tag, for example, when the RFID reader is perpendicular to the RFID tag. One situation where this would occur is when the robot moves directly to the RFID tag it would need to turn 90 degrees to detect the RFID tag as illustrated in Figure 5-2. The state is entered whenever the robot reaches the RFID tag.

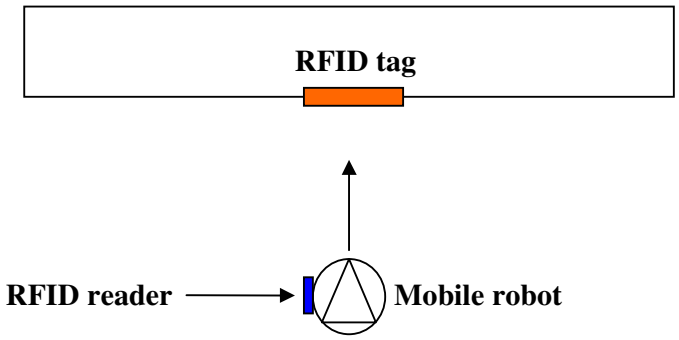


Figure 5-2: Robot moving towards an RFID tag needing to turn to detect the RFID tag

- ForwardAndBackAtRFID - Move the robot forward, turn around and then reverse to the place where the map says the tag should be detected. This function is designed for the cases where the control program underestimates the actual distance to the next RFID tag. After the TurningForRFID state, this state is entered and will enable the robot to detect an RFID tag slightly in front of the area the tag was estimated to be detected.

- SearchingForRFID - Move the robot in a spiral shape in order to search for the RFID tag as explained in section 5.1.3. This is carried out after the ForwardAndBackAtRFID state.

- ObstacleSearchForRFID - Move the robot around the place where the tag was meant to be detected in an environment where obstacles have been detected as explained in section 5.1.1.2. This state is only entered when an obstacle is detected while the robot is close to where it intends to detect the RFID tag.
- FoundRFID – Stop the robot as the RFID detector has found an RFID tag. If the robot is currently moving between several tags toward a final destination, the program will immediately tell the robot to start moving to the next RFID tag and return to the InitialTurn state mentioned as the first state in this list. Otherwise, the robot will simply stop and wait until the operator gives it another command.

5.1.1.2 Obstacle avoidance

5.1.1.2.1 Deciding whether an obstacle is in the robot's way

The locations of obstacles are stored in an array whose elements correspond to 1cm squares in the environment. When checking for obstacles, a simpler array is used whose elements correspond to 25cm squares. A simpler array makes it much easier and faster to search for obstacles however it also limits the precision of recording an obstacle's location. For example, if an obstacle is detected on the far left side of a 25cm square, the robot would consider the entire square as an obstacle. This size is sufficiently small as the robot itself is 30cm in diameter. Figure 5-3 illustrates this problem.

This lack of looking at the exact location of obstacles causes problems when a robot needs to move close to obstacles to detect RFID tags due to the substantial difference between one side and the other of a square of the grid square.

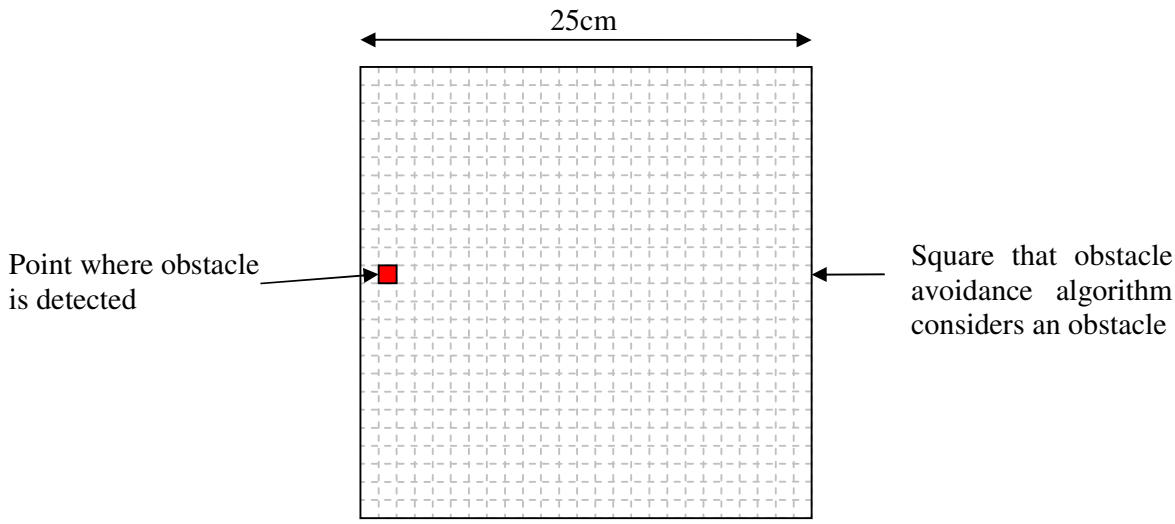


Figure 5-3: An obstacle detected in a certain spot being considered as covering a large part of a grid

The software used by the operator to monitor and control the robot uses a panel that is divided into squares 25px wide to display the estimated position of the mobile robot, obstacles, and RFID tags. When the scale of the environment is 1cm/px, these panel squares correspond exactly to the 25cm squares used for checking obstacles. The operator can define how many 25cm squares ahead of the robot to check for an obstacle to avoid and they see an approximation of the area checked on the squares of the programs panel. Figure 5-4 shows the checkboxes used to make this choice in the software produced. The 25cm squares the robot can check to avoid are:

- Where Robot is – The square the center of the mobile robot currently is on the map
- Where Robot is(L) – A square slightly ahead of the robot toward its left
- Where Robot is(R) – A square slightly ahead of the robot towards its right
- Ahead Robot – A square ahead of the robot

- Ahead Robot(L) - A square ahead of the robot toward its left
- Ahead Robot(R) – A square ahead of the robot toward its right
- Further ahead Rob – A square even further ahead of the robot

This choice allows the robot to change its sensitivity is necessary to change the robot's sensitivity to different environments. For example, if the mobile robot is required to be careful, not having obstacles on either side of itself, then the 'Ahead Robot(L)' and 'Ahead Robot(R)' could be turned on to indicate to stop for obstacles that are ahead of the robot on its left or right side. However, when the robot is travelling parallel to obstacles on its left or right side, this option would need to be turned off. Otherwise, the robot would move away from the obstacle on its side.

To maintain a proper appearance, the grid shown to the operator always has squares that are the same size (i.e., 25 pixels on the computer screen). The borders of these grids are red if they are currently being investigated for an obstacle. If there are enough obstacles in any of the squares being investigated then the obstacle avoidance routine will start.

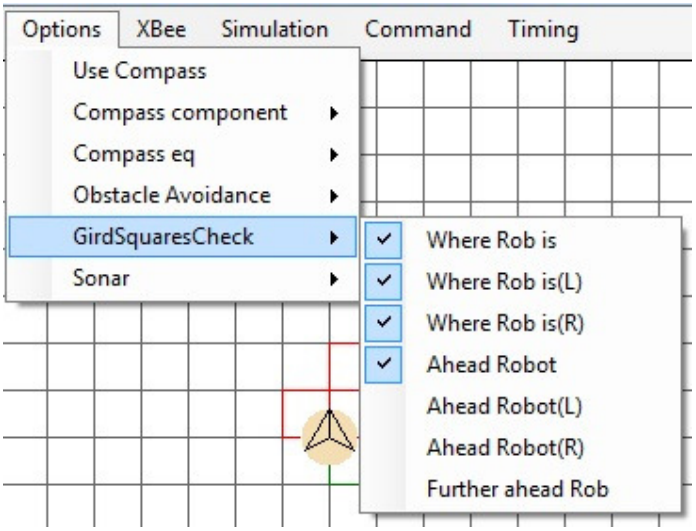


Figure 5-4: Checkboxes that determine which squares ahead of the robot to check for an obstacle

Obstacles are considered more hazardous when they have been detected more recently. Since there is an error in the robot's estimated position that accumulates over time, the reliability of previous distance measurements also becomes less and less as time progresses. Therefore, after a certain period of time, measurements taken previously are counted as having no significance and so are erased from the map memory.

Since the array that stores the obstacle locations is currently divided into a grid of 1cm wide squares, as the map gets larger the array produced does so too. Therefore, in large environments, methods of obstacle storage such as the Quad Tree or Linked List (section 2.3.1) could be used to minimize the size of the map in the computer's memory.

5.1.1.2.2 Moving automatically around an obstacle's right and left side

If an obstacle is detected and is in the range of the robot's avoidance path, it is firstly checked to see whether an obstacle is truly there. This checking involves waiting for 1.3 seconds and

then rechecking if the obstacle is still there. A check is done because there can be error in the distance sensors measurements. If the obstacle is detected again, three steps are made to avoid the obstacle.

In the first step, the robot will step to the right three times, each time turning to look in the direction it was originally going in. If the robot still detects the obstacle after three steps, the robot will try the same thing around the left of the obstacle. Otherwise, if the robot senses the area is free once moving to the side of the obstacle it will move forward by 32cm and then recalculate the angle to move back to the robots destination.

If the robot does not find a free path in its searching around the right and left side of the robot, the program will give a message (see Figure 5-6) to the user that they need to manually move around the obstacle. These steps in obstacle avoidance are shown briefly in Figure 5-5.

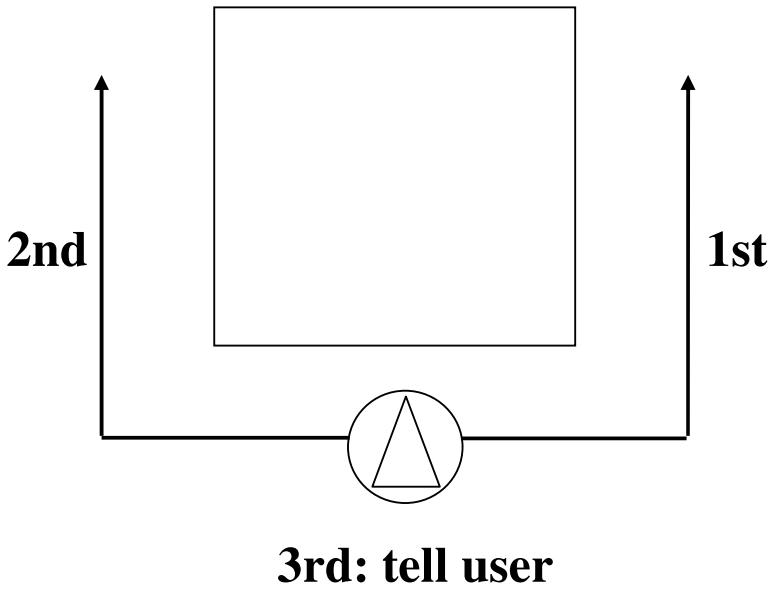


Figure 5-5: Steps for robot to avoid an obstacle by firstly moving to the right, then to the left and finally by notifying the user so they can avoid it

5.1.1.2.3 Manual obstacle avoidance by the operator

When the program has given up trying to avoid an obstacle, it will send a signal to the operator that it needs help. At this point, the operator needs to move the robot manually either through giving it commands from the PC or picking the robot up and placing it at an RFID tag. The program will not give any commands to the robot automatically until the operator indicates they have finished avoiding the obstacle. In this situation, the camera would become useful as the user could see video from the perspective of the robot. Figure 5-6 shows what the program does when the user is meant to manually move the robot pass the obstacle. First, a message box appears, notifying the user that they need to avoid the robot's obstacle through giving commands to the robot themselves. Then, once this is done, control can be handed

back to program through clicking on the orange ‘Continue Auto Movement’ in the bottom right corner of the screen.

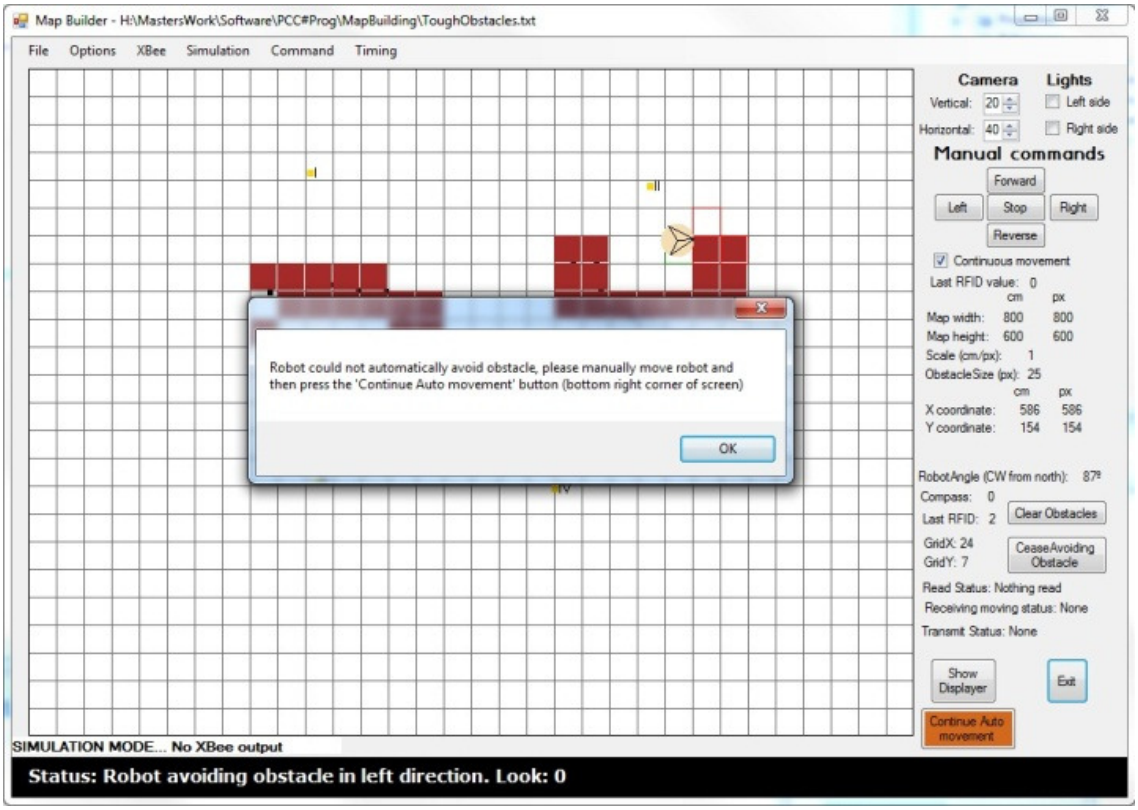


Figure 5-6: Demonstration program showing the message given to the user when the robot cannot avoid an obstacle and the orange continue auto movement button in the form’s bottom-right corner

5.1.2 Moving between many tags

5.1.2.1 Define the best path

When moving a mobile robot in a room, the best way to travel is not necessarily the straightest obstacle free path to the destination. Since error accumulates over time (due to wheel slippage and miscommunication between PC and robot) the sooner an update of position occurs from the detection of an RFID tag, the better. For this reason the best path for

the robot to travel is the one that not has merely the least distance to travel but also has the least distance between tags on the way towards its destination. A method to do this is shown in 5.1.2.3.

5.1.2.2 Calculation of all possible paths

A recursive function (main part of the code is shown in Appendix F) is used that goes through every possible combination of RFID tags beginning from the current tag and ending with the destination. In the case of there being more than five RFID tags, the total number of possible paths becomes too large for an array to store them all. Therefore, for more than five RFID tags, the total number of paths is limited so that only specific combinations of tags are tried in order to find the best path. These limitations are discussed in the following paragraph and shown in Table 5-1.

When an environment has more than five RFID tags, paths are limited to only include RFID tags that are between the start and the end tag along the X axis. This inclusion of specific tags narrows the number of possible paths and is illustrated in Figure 5-7. This method does not always include the very best path but should find a reasonable one to reach its destination. After the first 1000 tags, the paths are narrowed to include only tags between the start and end RFID tag in both the X and Y axis.

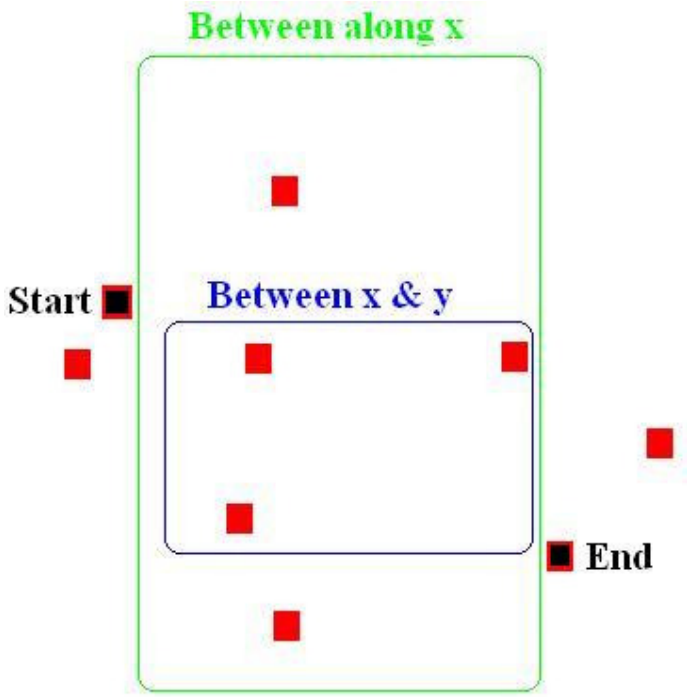


Figure 5-7: Showing the space between the start and end RFID tag in the X coordinates (green rectangle) and with the space between them limited by both the X and Y coordinates (blue rectangle)

Table 5-2: Showing the tags included in the possible paths from the start RFID tag to the last one

Condition	**Tags to include in possible paths**
5 or less tags in the map	All tags in the map
More than 5 tags in the map, 1st 1000 paths	All tags between start and end in the x axis
More than 5 tags in the map, after the 1st 1000 paths	All tags between start and end in the x and y axis

5.1.2.3 Least distance between tags

The 'Least distance between tags' algorithm goes through all the paths and finds the 1st, 2nd, and 3rd maximum distance between any two tags in each path. The purpose of finding the maximum distance is to find the path with the smallest maximum distances between any two tags. Since the robot has its position localised whenever a RFID tag is met, the path should make use of as many RFID tags as possible on the way to its destination to minimize the

distance between any two tags. A path with a small maximum distance must make use of RFID tags on the way toward its destination in order to have minimized its maximum distance. Figure 5-8 shows how the maximum distance between two tags decreases as more RFID tags are used.

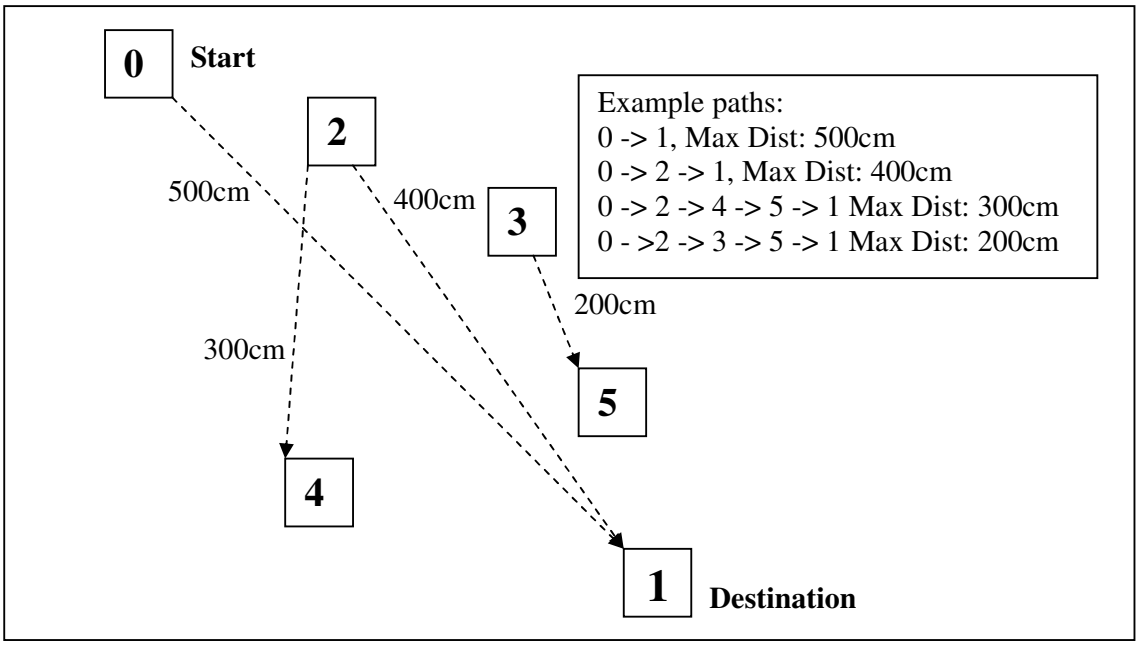


Figure 5-8: Showing how using the least maximum distance among the paths results in the best path for the robot to take (Not drawn to scale)

The paths that have the smallest maximum distance are put into an array and their 2nd smallest max distance is found. The reason for this is that with more RFID tags, it is likely many paths will share the same 1st maximum distance as they all may share in common two tags that are close to one another. Out of the ones with the same 2nd smallest max, the 3rd smallest max distance is found. Currently only 3 levels of maximums are found. If the algorithm were perfect, it would keep looking at the next highest distances until only one path

is shown to be better than the others. For a small number of paths though, this is not necessary as there are not that many paths with the same number of maximums.

This algorithm maximises the use of localising the mobile robot through using RFID tags which therefore minimizes the accumulated error the robot picks up as it moves towards its destination.

5.1.2.4 Notifying the user

The operator tells the PC to calculate a new destination to travel to by changing the value in the 'Long term destination' combo box as shown in Figure 5-9. Once the best path has been calculated a message box appears showing the best path calculated and the maximum distances (maximum, second maximum, third maximum) between nodes. In this way, the operator will know which path the robot has decided to take. The best path includes the current RFID tag the mobile robot is at and the destination chosen by the operator. The maximum distances between nodes is shown to indicate to the user the maximum distance the mobile robot should need to travel between any two tags. In the example in Figure 5-9, the first maximum distance says '301' which indicates that the most the robot should have to move between any two RFID tags is 301cm. Based on this knowledge, the operator should know whether it is likely to move such a distance without drifting too far away from an RFID tag due to odometry errors.

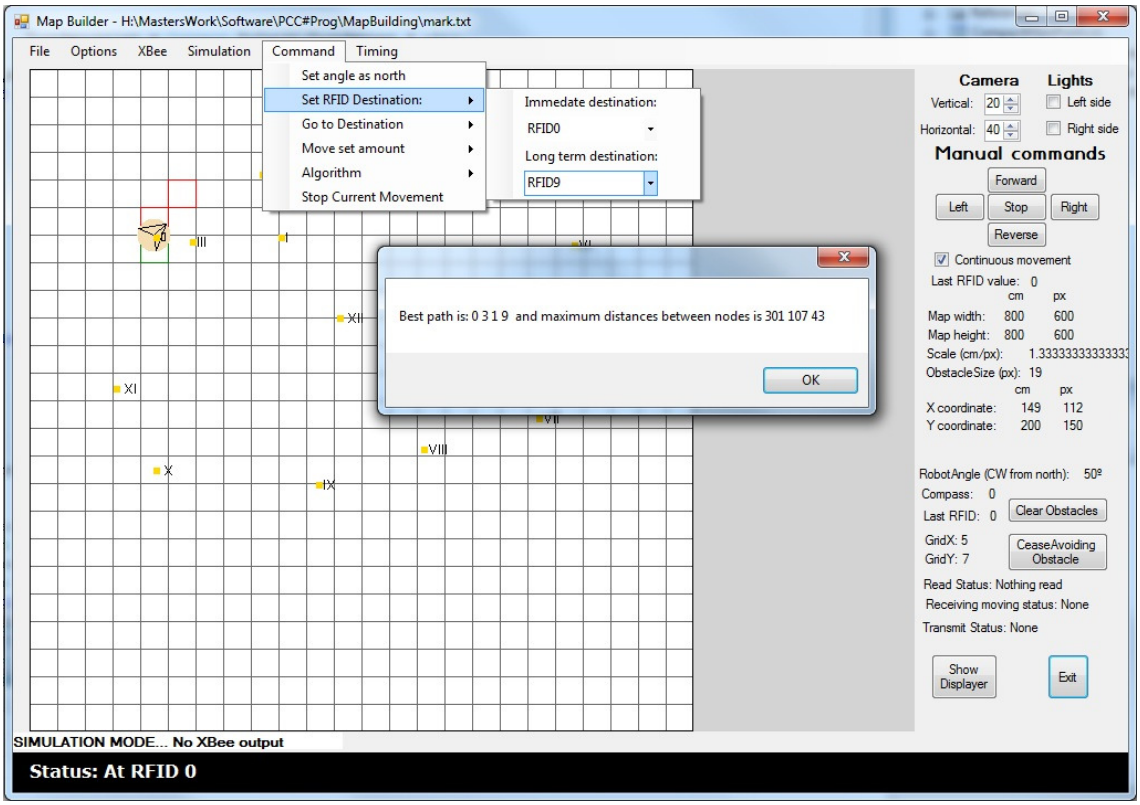


Figure 5-9: Program showing the result of the best path method

5.1.3 Searching for the nearest tag

Like Kriechbaum's 'Uncertain Bug algorithm' (2006), the algorithms presented previously are an attempt to move to the destination with acceptable uncertainty. The robot accumulates uncertainty in its position as it moves toward its destination and this uncertainty is reset to a particular area around the RFID tag whenever one is detected. The greater a distance a tag is from another, and the more obstacles there are in between tags, the greater the uncertainty about the position that the robot is in there will be. Therefore, the robot needs to search for the tag when it has travelled to the place where it theoretically should be as it is likely it will not be close enough to the tag due to odometry errors. This section describes in detail the states ForwardAndBackAtRFID, ObstacleSearchForRFID, and SearchingForRFID mentioned above.

When the robot reaches the position a tag is meant to be at, it will explore its immediate surroundings in order to find the tag. As soon as the robot reaches a tag, it will stop executing its current movement command and stop. On the robot panel on the PC, the robot teleports to the position of the tag detected. This is how the localisation occurs. Then, if there is another tag to travel to, it will start moving to that. Due to this, if the robot was in the process of turning when it detects an obstacle, it will immediately stop.

The steps involved in this exploration procedure are:

- Turn 90 degrees four times
- Move forward 40cm
- Turn 360 degrees
- Reverse 40cm
- Start spiral search

Since the RFID reader is only on one side, when the robot reaches the position where a tag is meant to be the robot will turn around on the spot 90 degrees four times so that, if the reader is close by, it will sense the tag.

Once the robot has turned four times, it will move forward a small distance, turn 360 degrees to look for the tag, and then reverse back to its previous position. The reason for this is that the calculated distance to travel to reach the tag may be slightly less than it should be. This can easily occur due to there being a region in which the robot can detect a tag and the robot

may detect the previous tag slightly before the intended position. Figure 5-10 describes how this can occur. After this, the robot will search around the tag's expected position in a square shaped spiral (see Figure 5-11) in order to look for the tag.

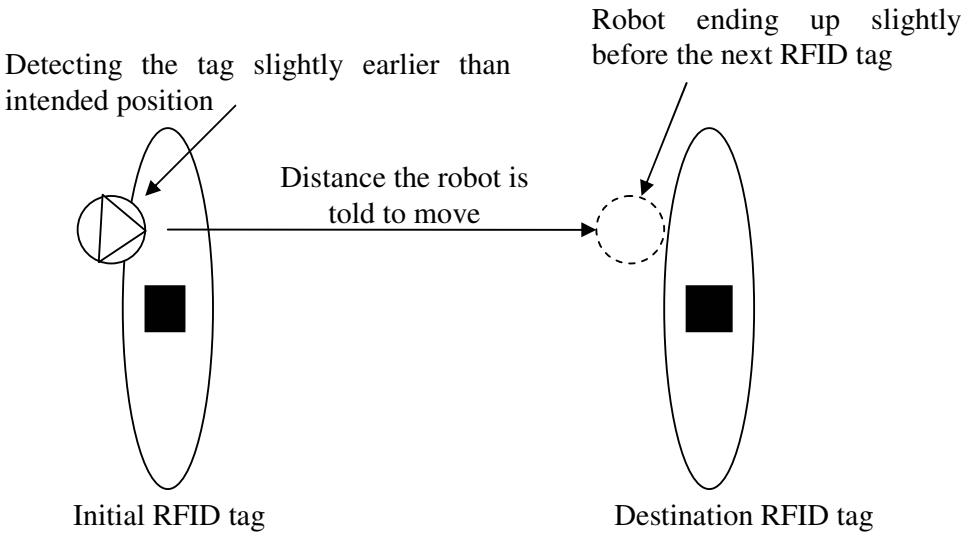


Figure 5-10: Showing how the robot can be told to move just before the place where the RFID tag can be detected

5.1.3.1 Spiral search without obstacles

The aim of the spiral search is to search around the robot's current position in such a way that the RFID reader's detection range will cover every part of a certain area. The robot will first rotate 90 degrees and then move forward 20cm. The robot continues to turn right and move forward again and again so that it moves in a spiral. The distance the robot moves forward is referred to as 'DM'. DM increases by 20cm every time the robot makes two movements (each movement comprising of rotating the robot 90 degrees and moving it forward). The reason why the distance is incremented 20cm each time is that testing shows that the reader

has a detection distance of approximately 20cm with the clamshell cards used, when the reader is directly facing the RFID tag.

The robot continues to move in a spiral shape until DM reaches a certain value. This value is currently 140cm but this can be easily changed in the software. It is referred to as 'SD', since this value will estimate the diameter of a circle that the algorithm will search around the current area. In the program, the function is given an amount that is half of this, i.e., 70cm. This distance indicates the search radius. Figure 5-11 shows the path the robot takes when moving according to this algorithm. The blue line in the diagram shows the path that the robot will travel whereas the green line accompanying it shows the approximate area where the RFID reader can detect a tag (as the RFID reader is on the left side of the robot).

The basic algorithm of the spiral search in pseudocode is shown in Code 1 below.

Code 1: Pseudocode showing loop used in the spiral search algorithm

```
Beginning of loop
  For I = 1 to 2
    Turn right
    Move the robot forward by DM cm
  Next I
  Increase DM by 20cm
Loop until DM is greater than SD
```

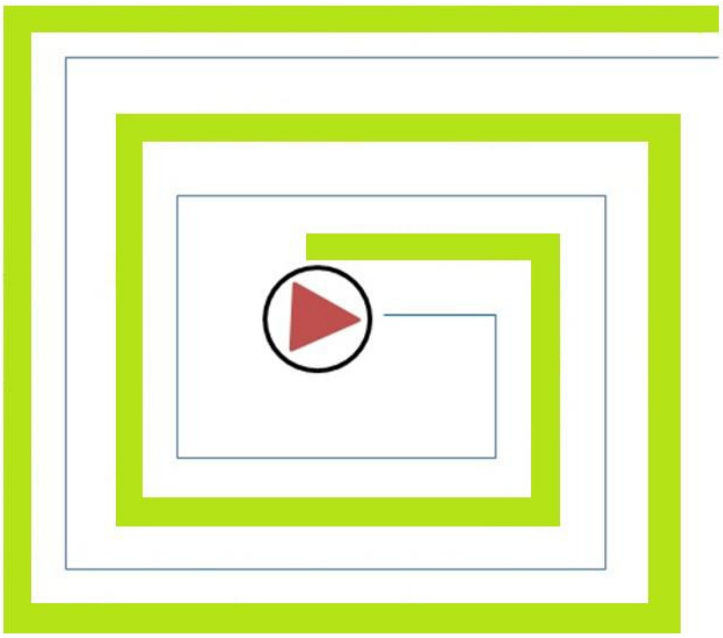


Figure 5-11: Robot spiral search

5.1.3.2 Searching in an environment with obstacles

If the robot is within fifty cm of the destination RFID tag and senses an obstacle it will make a decision what to do depending on the situation. The pseudocode showing all the various states the robot can be in and what it does is shown in Appendix A.

If an obstacle is detected while the robot is moving forward and back at the RFID tag's expected position or is doing a spiral search for it then it will enter into a state where it will check for indexes around the tag. Each index represents a location that the robot will attempt to move to. If the robot detects an obstacle on the way to an index then it will turn around in an attempt to search for the RFID (the reason for this is that the RFID tag may be mounted on the obstacle that was just detected). After that the robot will try to go to the next index and so on until it travels or attempts to travel to each index. The robot starts at index '1' and moves

in ascending order until it reaches index 8. The index locations are shown in Figure 5-12. The figure shows the expected tag's position in the middle and the locations of the indexes the robot attempts to move to. The arrows show the position the robot will intend to move at each position.

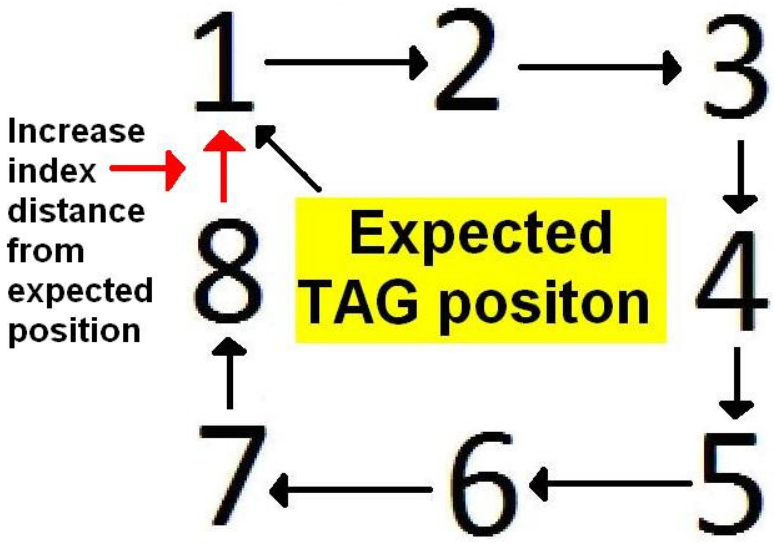


Figure 5-12: Index locations for robot to search

The indexes are initially twenty cm away from the tag. After searching through the eight index locations, the index location is increased by twenty cm further from the expected tag's position (as detection distance is 20cm) and the robot moves around the index locations again, starting from index 1. The robot does this until it has moved the search radius, the same distance as the spiral algorithm would move to.

An array in the program stores the details about the index positions. This includes their coordinates and status. The status indicates whether the index has been travelled to or not or

whether obstacles have prevented the robot from reaching it. A structure called 'SearchLocation' was formed in order to do this. The structure is as follows:

Code 5-2: C# code for 'SearchLocation' structure used to store position and status of the index locations

```
/// <summary>
/// Locations where the robot will search around an RFID
/// </summary>
struct SearchLocation
{
    /// <summary>
    /// Position in cm where the the search point is
    /// </summary>
    public Point Location;
    /// <summary>
    /// Indicates whether the location has been searched already or not able to be searched
    /// due to an obstacle being there.
    /// <para>
    /// 'N' Not been there; 'S' Searched already; 'O' Obstacle in the way
    /// </para>
    /// </summary>
    public char Status;
}
```

When an obstacle is detected that is in front of the robot while it travels to an index location, the robot will spin 360 degrees to allow its RFID reader the chance to detect the RFID tag if it is on or near the obstacle. If however, the robot has moved less than 16cm before detecting an obstacle it will not spin around. The reason for this is that at a position less than 16cm away from the previous one, it is unlikely that the tag could be detected as the robot has already turned to look for the tag a short distance away. After making a 360 degree turn the software will mark that index position as 'Obstacle in the way' in its status and attempt to move to the next index. In this way the mobile robot can search around the environment while ignoring moving to any place that has obstacles.

This algorithm would work well for simple environments but with obstacles that come out to just one side of the area being searched, the robot will be unable to cover all the possible index locations. An example of a situation where this would occur is shown in Figure 5-13. In this figure, the robot would find itself not being able to reach index 6 directly from index 3 due to an obstacle at index location 4 and 5.

Figure 5-13: Showing the problem with index search in that the robot is unable to move directly to index 6 due to the obstacle at index location 4 and 5

In order to get out of such a situation, a smarter algorithm would be needed. One possibility would be to move back to the previous index and then try the other indexes. In this example that would mean that after trying to move directly to index 6, the robot would move back to index 2 and then try to move to 6. This approach would help the robot to detect RFID tags more easily when they are inserted among obstacles.

5.2 Mobile robot navigation simulation

This section discusses the program used to model the mobile robot and its environment. This simulation program has been used to test and evaluate the various navigation algorithms made in the previous section, prior to testing them using the actual mobile robot itself, which is much harder.

Collet, MacDonald, & Gerkey (2005) discuss the development of free robot control and simulation software. They mention that "The availability of flexible, reliable, and reusable tools for robot programming is crucial to the research community." (Collet, et al., 2005, p. 1) For this specific application, it was easier to construct an independent program since algorithms specific to moving a mobile robot among RFID tags are required and the control of the robot is linked to the simulation of its movement. Although this simulation software was not built using reusable robot tools and does not provide tools that could be used generically in a library in many kinds of environments, it is hoped that it could provide help to others working in the same endeavour of simulating a mobile robot using a PC.

5.2.1 Simulation of the robot's environment

Information about the indoor environment in which the mobile robot moves was displayed to the operator by a panel on the program's form. Figure 5-14 shows this panel. The panel is divided up by many squares that divide the map up so that it is easier to see relatively how far apart things are from one another. A red border around a square indicates that it is where the robot is currently searching for obstacles to avoid. Two of these red borders can be see at the

squares directly in front of the mobile robot in Figure 5-13. The details of how these squares are searched to find obstacles and how these obstacles are stored are explained in section 5.1.1.2.

When the robot detects an obstacle from its sensors it places a 1px point in the panel to represent its position. The colour of the point determines how likely it is that it represents an obstacle that needs avoiding. A list of colours relating to the number of points is shown in Appendix G. If many points are detected within a 25cm wide grid square, a square will be shown on the panel proportional to its size. Appendix G mentions the details of when these are shown. Figure 5-13 shows such squares representing obstacles in the robot's environment. These obstacles were set in the map by the manual map builder program explained in section 5.3.

An array is used to store the RFID tags used in the map. They are displayed on the panel as yellow squares with a Roman numeral beside them. These Roman numerals are not the complex unique RFIDs of the tags (which are 10 ASCII characters long) but are used simply for the operator to easily distinguish between tags. The operator uses these numbers when telling the robot where to move within the environment.

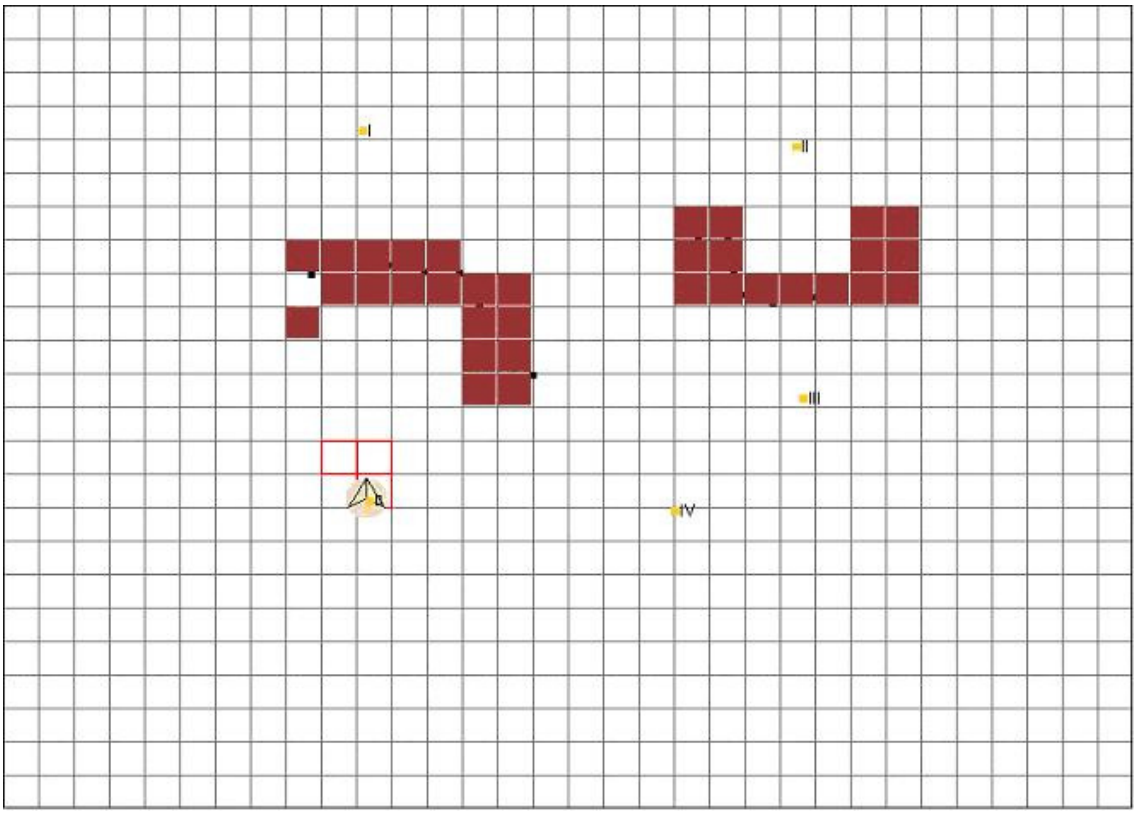


Figure 5-14: Panel on which movement of the robot is simulated

By default, the width of a map is 800cm and the height 600cm, having equal amount of centimetres as pixels used to show the map to the operator. This means that the scale factor is 1cm/px. If a different size is required, an operator can define a certain width and height of the map in cm as shown in Figure 5-15 which is part of the map builder program shown in Figure 5-18. The scale of the number of cm per pixel is automatically calculated at this time.

Figure 5-15: The dimension height and width dimension textboxes that the user can modify together with the scale that automatically changes to suit them

With a scale of 1cm/px, the size the robot is shown is approximately in scale with the robot's actual size in the environment. However, when the scale changes, the size of the robot does not, as that would make the robot harder to see in large environments. Only the speed the robot apparently moves on the panel changes as each pixel represents a different number of centimetres (more or less than 1).

5.2.2 Simulating the robot

After simulating the environment in which the robot navigates, the robot itself must be simulated so that the PC can correctly estimate the robot's position and give the correct commands to the robot to tell it what to do. A picture of the robot is displayed to the operator on a panel in the control program they use. Without accurate measurements about the size of the robot and the speed it travels, mistakes about the estimated position of the robot would be made. Since the position of the robot is updated by the RFID tags and its orientation by the compass, measurements do not need to be perfect. They only need to be good enough to allow the robot to effectively move between RFID tags. With good enough measurements, the distance the robot moves can be estimated based upon how far it has been told to move.

To estimate this distance the speed of the robot was measured. The speed of the robot moving in the PC and shown to the operator had to approximate the speed of the mobile robot in the real world. This is hard to do perfectly due to the time the robot takes to accelerate being hard to estimate and there being small delays in communication between the robot and the PC. Therefore, although the user can tell the robot to move continuously without any limit of how much to move, it is preferred to tell the robot a set distance to move and then wait for it to do so before giving another command. Therefore, when a command is given to move the robot to a RFID tag, the commands to the robot are always to move a set distance and then have it wait for the next command. Also, the program that commands the robot waits for approximately one second after its simulation has completed a movement command to ensure that the mobile robot has definitely moved the distance it has been told to before giving it another command.

For example, suppose the robot needs to turn 90 degrees and then move forward 20cm. The PC would first tell the robot to move 90 degrees. Then it would simulate it moving 90 degrees by its estimation of the robot's speed. After the simulation has completed the turn, it will wait for about 1 second and then tell the robot to move 20cm. After the robot's simulation on the PC has moved 20cm, it will again wait a second before giving any further commands.

In order for the robot to effectively plot where the obstacles that the distances sensors pick up are the program needs to know:

- The size of the robot
- The position of its sensors

- The actual distance an object is from the detecting sensors

The robot can be approximated by a circle that has a diameter of 30cm. Six infrared distance sensors are placed at different angles around the robot and a sonar distance sensor is placed at its front. The dimensions and angles used to model the robot in the program are shown in Figure 5-16. The red circles represent the approximate location of the infrared distance sensors on the robot, the angle is the orientation when moving clockwise from the front of the robot, and the green circle represents the location of the robot's sonar sensor.

The location of an obstacle detected by a distance sensor can be plotted by taking into account the sensors' position and orientation. The distance for the infrared distance and sonar sensor from the centre of the robot is approximately 14cm and 19cm respectively. This distance is added to the distance determined by the sensor itself to determine how far an obstacle is from the robot's centre. Then by using the orientation where the sensor is placed, the coordinate of the obstacle can be recorded in the obstacle map based on the robot's coordinate. This calculation stores the location of the obstacle in an array that records the number of times each square centimetre in the environment has been detected. The way this data is used has been explained in section 5.2.1.

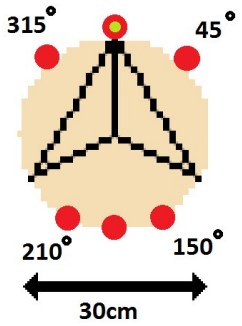


Figure 5-16: Dimensions and angles of sensors on the robot. Red circles - infrared distance sensors; Angles - from north; Green circle – Sonar sensor

This approximation, even if made as accurately as possible, is only an estimate. When turning or moving forward the robot can slip, creating an error between the actual position and orientation and the simulated one. These errors accumulate over time. Therefore periodical localisation is necessary to eliminate the errors accumulated between the actual position and orientation and the simulated ones.

5.2.3 Testing and evaluating navigation algorithms

A simulation program has been created that allows the user to test navigation algorithms. Currently, to create a new algorithm for the robot to follow, a program written in C# is required and the programmer has to know how the program operates. To make this easier, functions have been made that carry out all the small commands needed when giving a command to the robot such as the process of sending a command to the robot. This means that a person can test a new algorithm without needing to use too much code since they can utilise all the functions already created within the program to do the basic robot commands (such as move forward, turn, check for obstacles, etc).

The program that simulates the robot's movement can be run in pure simulation mode, meaning that no signal is actually sent wirelessly to a mobile robot but all the functions just move the robot's model around the panel in the program. This simulation mode enabled all the details of the various algorithms to be tested. Without such a mode, testing all the aspects of the algorithms would be unnecessarily tedious and time consuming as the robot would need to be placed in an environment that matches the one the algorithm is testing. The robot was put into such environments to test that the algorithms worked to control the robot however only after they were properly tested under the pure simulation mode.

Often, it is necessary to know the current state that the program is in while simulating or controlling the robot. A separate form is used for this that the operator may choose to display above the main control form. It is shown in Figure 5-17.

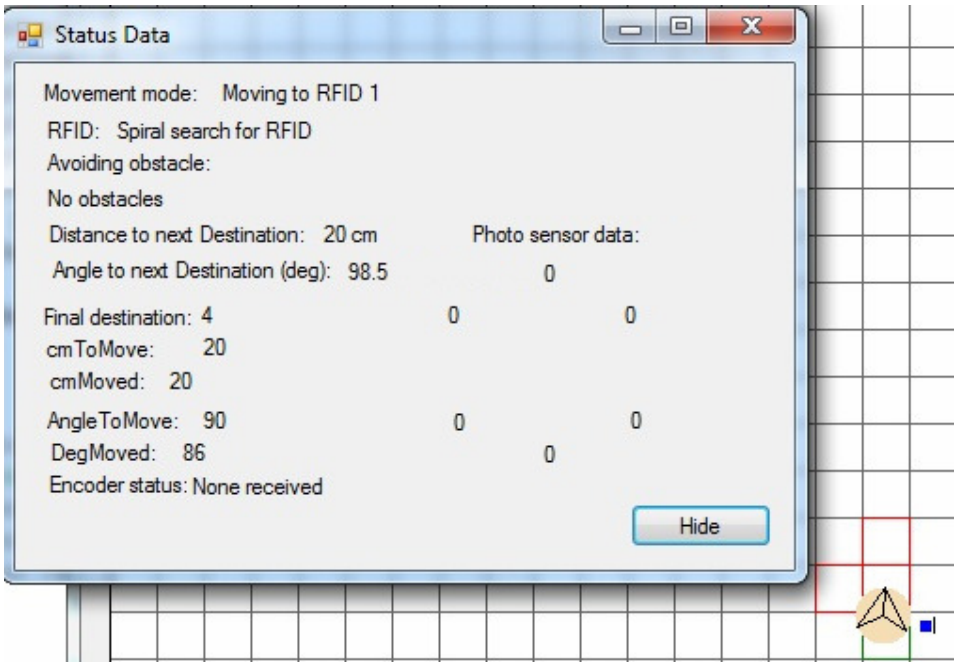


Figure 5-17: Status data showing the moving status of the robot

The meaning of the labels in Figure 5-17 is described below:

- ‘Movement mode’ (top label) shows which RFID tag the robot is currently trying to reach
- ‘RFID’ shows the method used to find the next RFID tag which currently is a spiral search for obstacles (see section 8.3.1)
- ‘Avoiding obstacle’ shows the current status of the robot related to avoiding an obstacle
- ‘Distance to next Destination’ and ‘Angle to next destination’ show the linear distance the robot needs to move and the angle the robot needs to turn respectively in order to move straight toward the RFID tag it is currently moving toward
- ‘Final destination’ shows the numeral representing the RFID tag that the robot is currently trying to reach
- ‘cmMoved’ shows the modelled robot has completed the 20cm it was told to move to as is seen in the ‘cmToMove’ label above it
- ‘DegMoved’ shows the simulated robot has currently moved 86 degrees out of the angle it has been told to move (shown at the ‘AngleToMove’ above it) which is 90 degrees
- The six zeros under ‘Photo sensor data’ show the distance data from the infrared distance sensors and are placed according to what their position on the robot is when the robot is facing north (e.g., the top ‘0’ is the distance detected by the front sensor and the bottom ‘0’ is the distance detected by the rear sensor). Since this image was

taken while the robot is in simulation mode, there are no readings from the distance sensors and so they all say a distance of '0'cm

- 'Encoder status' refers to the state the robot should be in as determined by the encoders on the robot's wheels. Since the robot is in simulation mode, nothing is received

By using this data, the operator can understand what stage of movement the robot is in and therefore determine whether the algorithm created is working as it is intended to.

In summary, a program useful for simulating and controlling a mobile robot has been developed. This uses a model of the robot itself and its environment and simulates its movement so that the operator can see an estimated position of the robot on the screen all the time. The program has been useful for testing all the algorithms the mobile robot uses and gives clear indication of the state the robot is in as it carries out its commands.

5.3 Environment map building

In this section, the way to build a map of the environment is discussed. A map is simply an array containing the position of the RFID tags used and obstacles that need avoiding. Two ways to construct such a map have been developed and are presented in this section. The first is to build a map by manually entering the coordinates of RFID tags and obstacles by either clicking on where the relative position is on the map or typing in their co-ordinates in a textbox. The second way is through the teaching mode, that is by guiding the robot step by step around the RFID tags while the simulation updates its position as the robot moves and the software automatically places the coordinates of RFID tags as they are detected.

The coordinates of the RFID tags do not represent the physical location of the RFID tag, but rather the optimal position where the robot should move so that it can detect it (as the tags are placed on objects that are obstacles to the robot). The map is displayed on a panel that is 600px high and 800px wide. The default is to have a scale of 1cm to 1px but this is easily changed through changing the number of cm for the map's width and height in the program made as explained in section 5.2.1.

It is expected that an environment will have the robot start at an RFID tag and from there move to other tags as RFID tags are this research's unique method of knowing a certain location in the map. Therefore, a specific variable called 'StartPosIndex' is used to store the starting RFID tag. However, if the starting position is somewhere other than an RFID tag, the operator can still manually define a coordinate in the map for the robot to start at and leave the 'StartPosIndex' as '-1' which indicates to the program that the robot is not starting at a tag. Once a map has been completely configured, it is saved in a text file. Appendix D shows an example of a map created by the map building software.

5.3.1 Manual map building

A room with RFID tags can be measured manually using a ruler and then built using a program made in this research called 'MapBuilder'. This program allows the coordinates of the environment's obstacles, the robot's starting location and of the RFID tags to be entered (either in cm or px) and then saved into a map that can be later read by a program that monitors and controls the mobile robot.

There are two methods for placing objects on the map, a quick method or an accurate one. The quick and estimated method of placing objects at a position in the environment is done through hovering the mouse over the map panel and observing its position (cm and px) shown on the left of it (Figure 5-18, under 'Mouse Position'). For example, in Figure 5-18, the cross hairs represent the mouse's current position and the figure's left side says its coordinates are 163 cm in x and 237 cm in y. By clicking on the panel, an object can be placed there. This is useful for when the exact measurements of an object is unknown. This method allows an object to be visually placed depending on where it should be in relation to other objects.

The accurate method of placing an object can be done by manually changing the values of the set position variable in either pixel or cm textbox under the 'Set Position' section of the form and then clicking on the 'Place Item' button. This allows a quick way of entering the position of objects whose coordinates are known.

Figure 5-18 shows the coordinates with the top-left corner of the panel as the reference point. This default reference point is easily changed, through an option in the software, to any of the four corners of the panel to suit the operator's method of referencing coordinates in a map.

In order for the user to have a visual idea of how big the robot is in relation to the rest of the map, a circle at the bottom left corner of the form is used to show how big the robot would actually be on the panel. This size changes when the scale is changed by the operator specifying a map with different dimensions than the default ones. If the picture of the robot itself that moved on the map actually got smaller as the map got bigger, it would make it

difficult to see so a constant size is used for the robot on the map and a separate panel gives a visual indication of the robot's size compared to the environment.

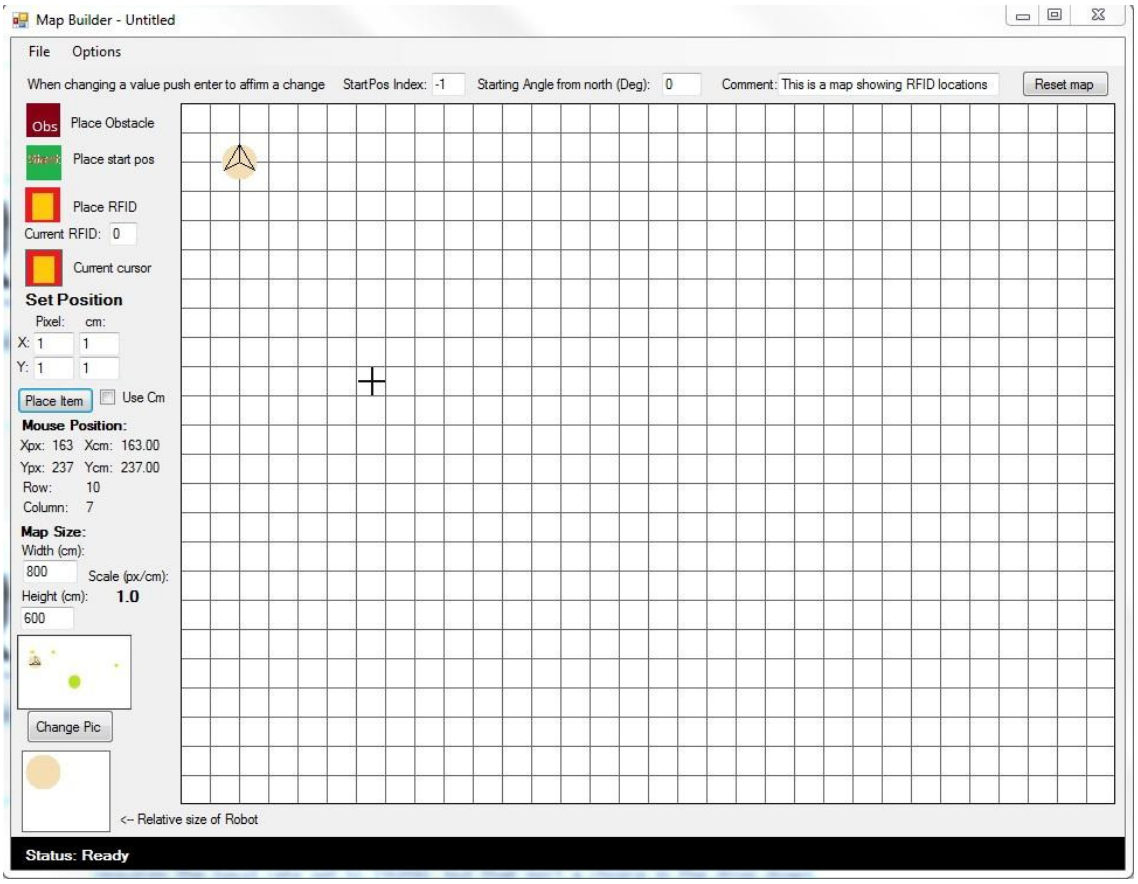


Figure 5-18: Manual map builder program

This program further allows a comment and a picture to be added which are shown when the map is loaded in the demonstration program. This provides a description of the environment that can be used to point out to someone loading the map any necessary details about it.

5.3.2 Auto-map building through detecting RFID tags

The simplest and fastest method to construct a map is to use the 'AutoMapBuilderViaDetection' program as shown in Figure 5-21. The robot's position in the

map (in pixels) can be set through typing in the co-ordinates and pressing the 'Set Coord' button (see Figure 5-19). This should be done just at the beginning of the map building process as the robot will automatically move on the panel in correspondence to where it is moving in real life.

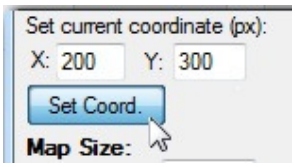


Figure 5-19: Showing how the user can set the robot's starting position

Once placed, the robot is wirelessly controlled by the user to move between the places where the RFID tags are detected. When the RFID reader detects a tag, it automatically puts its number on the map and this coordinate is recorded in the map. This occurs automatically when the robot first detects an RFID tag. Usually, this first detection point will not be the best place for the robot to aim to move toward in order to sense the tag. It is likely that it first senses the tag at a position that is to the side of the best place to sense it (see Figure 5-20). Therefore, the best method is to move the robot to the best position and then click on the 'Place now' button. This will place the tag at the robot's current coordinates. When an RFID tag is detected, the current tag's number is automatically updated so the user only needs to be concerning with driving the robot to the right position to detect the tag and then click the 'Place now' button.

Figure 5-20: The place where the robot first detects the RFID tag versus the best place for the robot to move to in order to detect it.

Since the speed of the robot is not exactly the same as how the robot moves in the panel, it is safest to use set distances to move the robot around (see section 5.2.2). This ensures the robot and the panel's estimated position of it are at the same position at each step that is made.

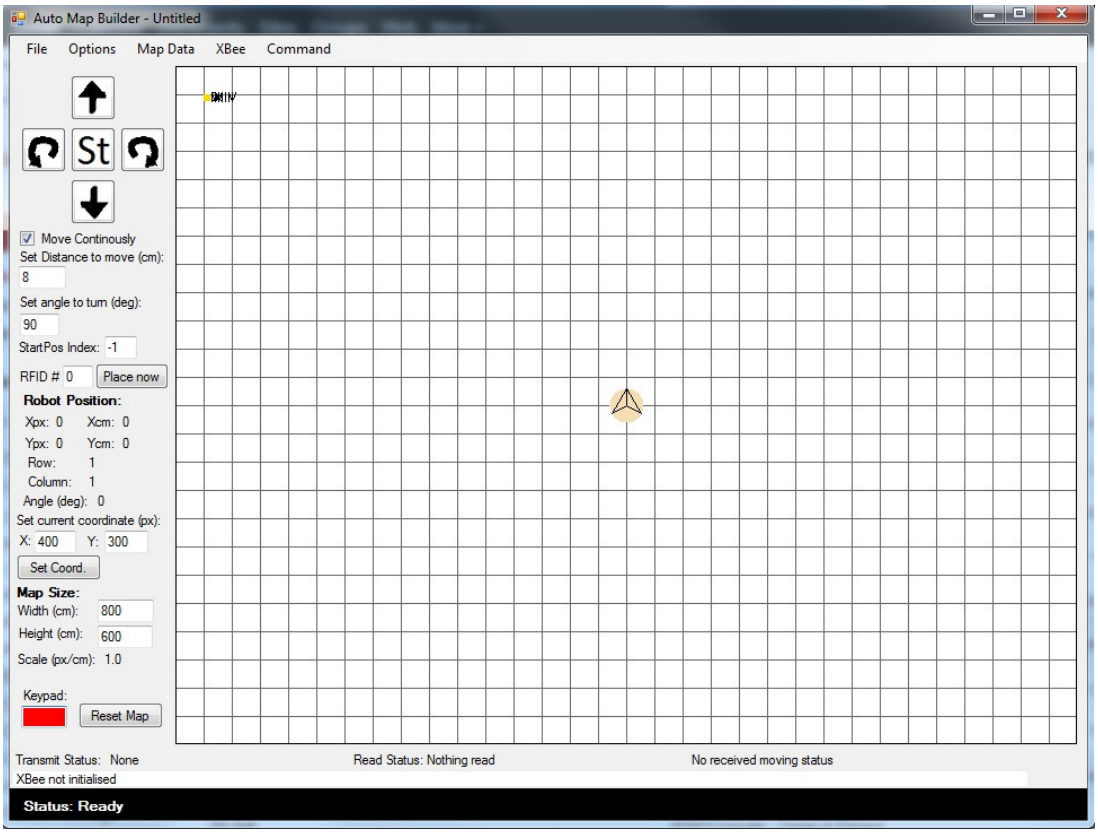


Figure 5-21: AutoMapBuilderViaDetection program that is used to build maps automatically while driving the robot

Due to the robot's slipping at different angles, the robot should be manually observed while building the map and its angle manually corrected whenever it is off where it should be. If the compass is working adequately it will automatically convey the off angle to the PC, making the actual robot angle and the PC the same. This would make the building of a map faster. If the compass is not working correctly when a slippage occurs, an easy method is for the user to manually pick the robot up and place it at the intended angle. For this reason, it is best to tell the robot to move only simple angles when building the map. For example, if an angle of 90 degrees is used and the robot slips slightly resulting in the robot being at the wrong orientation it is intended for, the robot could be manually picked up and carefully placed at the correct orientation.

This method of building a map by moving the robot around only loads the map with the RFID tags positions. The same map would need to be opened again in the 'ManualMapBuilder' program if obstacles needed to be placed on it. This is because the detection of obstacles from the infrared sensors and sonar sensor is deemed not reliable enough to use as data representing a permanent obstacle in a map. However, this method has proven to be able to successfully build a map holding the RFID tag positions in their correct position and saving much time from building a map manually.

Through either the manual or automatic method a map can be created that can be loaded by an operator within an indoor environment. This map contains the coordinates of the correct positions to detect RFID tags, obstacles to avoid and where the robot will start. It is used to model the robot's environment and the robot itself by a program created in this research so

that the robot can navigate within an indoor environment. This navigation is accomplished through the use of specific algorithms that cater for various situations the robot may encounter.

Chapter 6: Testing localisation methodology

This chapter describes the kind of environment in which this methodology is tested and the constraints for the robot in planning a path between two RFID tags and in avoiding obstacles in between them. It further lays out some of the mechanical designs that can be used for mobile robots and describes the basic structure of the mobile robot used in this research. With this as a base, the motors and sensors used as well as the motor selection, control, powering and testing are then considered and three tests made on the robot are shown by discussing their testing environment and demonstrating their outcome.

6.1 Indoor mobile service robot design considerations

This section presents the specific requirements and constraints this research takes into account for an indoor mobile robot. First, the robot's environment in which it moves and its own basic functions are discussed. Then, the constraints defining the particular robot used in this research are explained, followed by the requirements and characteristics for planning a path between two locations. Finally, the constraints of obstacle avoidance are discussed and the purpose of a robot with such constraints is explained.

6.1.1 Constraints of the Robot's environment

In mobile robot design, the environment that the mobile robot is required to effectively navigate in has to be first considered. The mobile robot must be in continual communication with the PC since the PC collects all the data, makes the decisions and guides the robot step by step as to what to do. Since the robot is being controlled remotely by a PC, the

environment in which the robot works should be conducive to reliable communication. If the environment did not allow the robot to be in continual communication with a remote PC, a different method of mobile robot control would need to be considered.

For this research, a small mobile robot will be designed and built to test the methodologies. In order to keep the cost low, simple microcontrollers and sensors were used. A simple inexpensive radio transmitter was used to capture video for the robot. As this transmitter has a limited communication range, the sustained continuous wireless communication environment defined for the mobile robot is a round area with a 5-meter radius from the host PC. As the communication range is fairly small, it is also required that the area be free of any tall and obtrusive obstacles as these will significantly obstruct the wireless communication between the controlling PC and the mobile robot.

The floor of the environment should be a flat surface to minimize errors in estimating the robot's position using odometry. The obstacles in the environment should be of a reasonable size and without any thin protruding parts so that they are definitely detected by the robot. The reason for this is that the robot's distance sensors that detect obstacles are only placed at set angles around the robot and do not cover the full span of the area ahead of robot.

6.1.2 Path planning

Path planning means determining the way to travel between two co-ordinates while avoiding obstacles in between them (Kim, 2004). The current research is constrained in the path planning algorithms designed. The planning for paths between two points in an environment should not require detailed data about the obstacles or expect the exact location of the robot

to be known. The reason for this is that the robot is constrained to having only simple obstacles' sensors, and odometry does not provide an accurate estimate of the robot's location at all times. Therefore algorithms such as Optim bug algorithm mentioned in section 2.3.4.2 that assumes no odometry errors cannot be used. The plan should also aim to move the robot to its destination as quickly and safely as possible so the algorithms should strive to cause the robot to take a direct route to its destination. For example, if the robot moves back and forth too much to find information about its obstacles (as Optim bug would) without localising itself, it is likely to accumulate more odometry errors and have difficulty reaching its destination within an acceptable amount of uncertainty. As there is likely to be high odometry errors due to an imperfect, inexpensive mechanical and electrical design, the position and orientation of the robot should be regularly updated. This will ensure the robot is kept on the correct track as it heads towards its goal.

6.1.3 Obstacle avoidance

Abiyev, Ibrahim, & Erin (2010) stated that obstacle avoidance can use two main types of navigation. They are:

- global navigation - where a path avoiding the obstacle is selected upon prior knowledge of the environment
- local navigation - where the environment is unknown and sensors are used to detect obstacles and change the robot's path upon detection of obstacles

This research will use local navigation to avoid obstacles. Even when permanent obstacles are recorded on the map before the mobile robot needs to detect them, the algorithm used to

move the robot carries out the obstacle avoidance when the robot reaches them instead of creating a path that will avoid it before reaching them. This is due to the constraint of only using simple algorithms and also the fact that the system has errors accumulated in its position estimation so planning a path before reaching an obstacle could incorrectly avoid the obstacle.

Since this research is merely to test the concept of localising using RFID tags, the memory size and speed of the microcontrollers does not need to be great, and high accuracy, high speed sensors such as lasers are unnecessary. For example, the Hokuyo URG-04LX-UG01 from Acroname Robotics (Acroname robotics, 2011) laser costs $1150 US yet can read at a range of 240 degrees, with 0.36 degree resolution and would provide a lot of data as can be seen by the red lines on Figure 6-1. However, its cost is too high, and the current microcontroller used would not be able to process this much data or send it wirelessly to a computer.

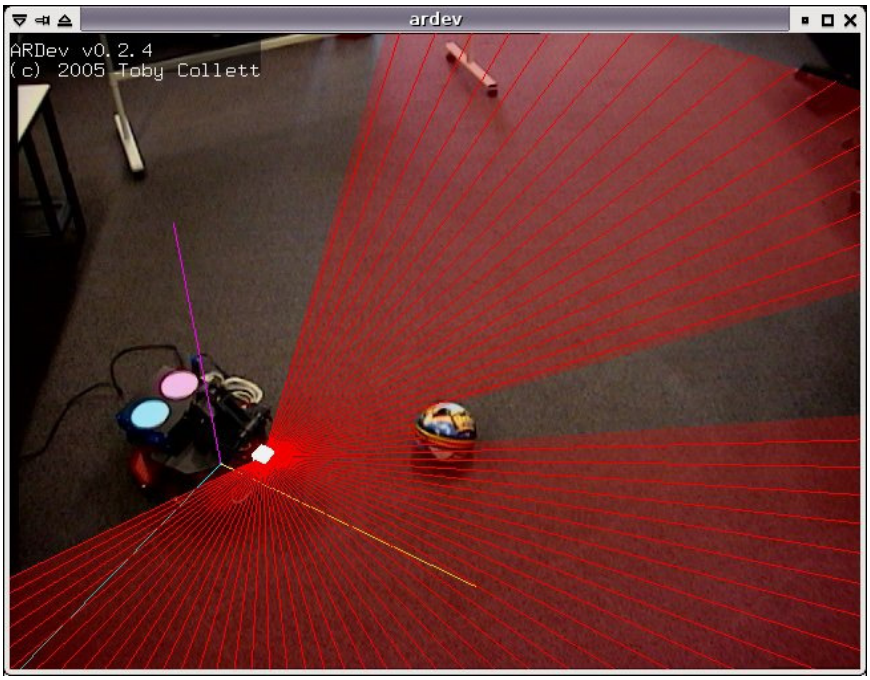


Figure 6-1: The simulated beam of the Hokuyo URG laser mounted on a robot, (Collet, Macdonald, & Gerkey, 2005, pg. 5)

6.1.4 The usefulness of the designed mobile robot

A robot that is inexpensive, can avoid only simple obstacles, moves in a limited range from the controller, and uses simple algorithms to get to its destination would not be reliable enough to be directly useful for industries or households requiring mobile robots in an indoor environment. However, this research provides a base for further research and development of more reliable mobile robots that could perform tasks such as making observations (using their cameras) or transporting goods from one part of a factory to another.

An operator could choose between several mobile robots that could transport goods around a factory. This would require additional methods of loading inventory from a factory onto the robot. With improvement made to the reliability of obstacle detection the robot may be able

to operate in environments with moving obstacles such as an office environment. A doctor in a hospital could check up on his patients remotely through using such a robot. To do this, the main thing that would be changed would be the robot's height so that the robot could show a doctor's patients in their bed and the equipment in their room.

6.2 Mobile robot mechanical system design

This section opens up the various mechanical configurations that can be used to move a robot around and then talks about the specific mechanical design used in this research.

6.2.1 Mechanical system configurations

There are many configurations for the movement of mobile robots. These include omniwheels (a group of wheels that co-ordinate to allow movement in any direction without needing to turn around), two wheeled robots (where balancing would be required to keep the robot upright), three wheeled robots with either one or two driving wheels, four-wheeled vehicles, and robots with legs (that can be thinner and that could step up and down steps).

As the number of wheels increases (from two to four), so does the stability (Disabled world, 2009). Three wheeled robots are able to remain upright. They can be designed to be smaller than a four wheeled robot and can also rotate easily. This makes a three wheeled robot more flexible to move around than a four wheeled one. An increased mobility means the robot is more able to avoid obstacles successfully (Shih, Chen, Chou, 2010). Of course, if small obstacles need to be avoided or a robot needs to travel in spaces with confined space, a bipedal robot, one with two legs, would be better, as the entire robot itself can be thinner (Manoonpong, 2009).

The movement of the robot is controlled by motors. In order for the robot to use odometry to estimate its position, the motor should allow the robot to easily calculate how far the motor

has turned and hence how far the robot has travelled. Steppers and servo motors enable the amount the robot has been told to move to be determined.

A stepper motor is composed of a static part (called the stator) that does not move and a gear shaped piece of iron (called the rotor) that is connected to the motors shaft. The stator has many teeth-shaped electromagnets and is on the outside of the motor. These electromagnets pull the rotor's iron teeth to cause it to turn. By turning on and off various electromagnets on the stator, the motor shaft turns in small increments called 'steps'. An external electrical circuit powers the outer electrical magnets and causes the rotor's teeth to be aligned to the outer teeth on the electromagnet. At each step, the teeth on the rotor are misaligned slightly to the next electromagnet's tooth on the stator making a small step each time the next electromagnet is energised. A stepper motor is usually 'open loop', that is, it provides no feedback so that an operator could know how far it has actually moved. Due to this, the stepper motors chosen should be capable of handling much more load than what they actually handle so that there is confidence that no steps are missed.

A servo motor is a closed loop device and so does not require over-specification like a stepper motor. This compensates for its price being much higher than stepper motors. There are different types of servo motors. Some servos use a variable resistor connected to the motor for sensing feedback and are designed for moving a motor back and forth to different angles but not to move continuously. These can be modified so that they move continuously but then they lose their ability to provide feedback.

A stepper motor was chosen for the mobile robot in this research as it can provide the information for estimating the robot position even with open loop control. The benefit of open loop control is that the mechanical system is simplified making the robot less complicated and less expensive.

6.2.2 Mobile robot platform design

This section describes the particular robot built to test the concept in this research.

6.2.2.1 Platform layers

The platform of the mobile robot was designed with two stepper motors at the back of the platform and one flexible omniwheel at the front of the robot to balance it. The front wheel is not driven but simply goes along with the two stepper motors. As the weight of the robot is a concern and a cheap fibreglass plate was obtainable, it was decided to use a fibreglass plate as the basic structure of the mobile robot to hold the circuit boards, sensors, and motors. Fibreglass is a light yet strong material. Using Fibreglass as opposed to steel significantly reduces the weight of the mobile robot and gives a strong and solid base to hold other components. The main structure of the robot consists of two layers. In between these two layers is a component (Figure 6-2) that holds the wheel bearings used to hold the shaft turned by the motor. The motor itself is on the other side of the wheel and is bolted to the bottom layer. With this arrangement the robot's wheel is held in place yet its shaft is still free to rotate. Nylon spacers are used to hold up a stand under which the front wheel is supported. Figure 6-3 shows the layout of the bottom layer. The three main holes shown in this figure provide room for the robot's three motors to pass through.

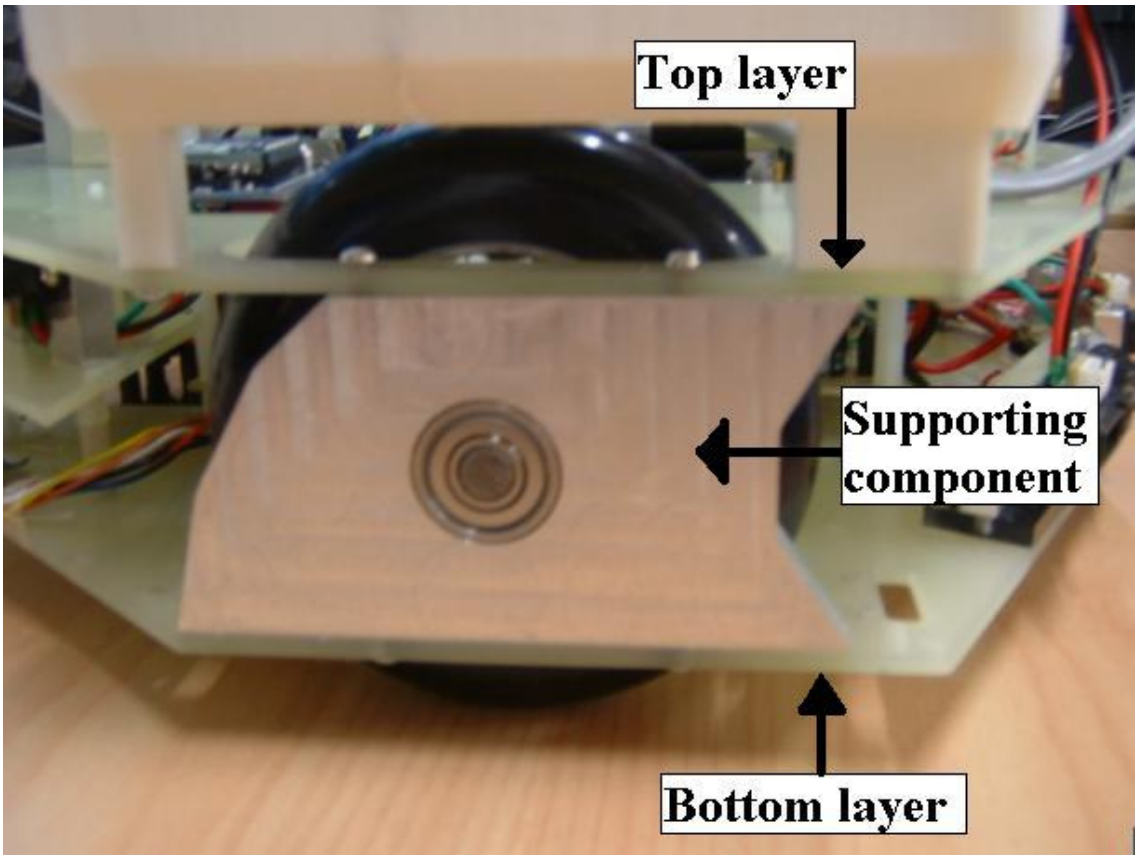


Figure 6-2: Wheel supported by a component in between the two fibreglass layers

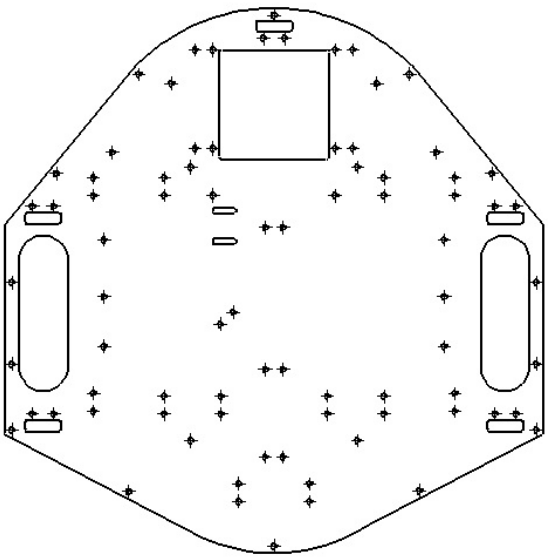


Figure 6-3: The layout of the bottom layer

Three circuit boards are used which are stacked up directly above one another and spaced apart with Nylon spacers. The bottom circuit board was attached to the bottom fibreglass layer via nylon spacers that allow the circuit to be slightly raised above the fibreglass layer. This circuit board contains the microcontroller that controls the stepper motors used to move the robot. The middle circuit board is responsible for the communication between the PC and the XBee module. As the height of this circuit board stack is larger than the distance between the two fibreglass platforms, rectangular holes were made in the middle of the top fibreglass plate as shown in Figure 6-4. The top circuit board has many connections for the sensors of the mobile robot to connect to.

The top fibreglass plate also has a wireless communication module, an RFID sensor, a stand for the camera, a compass, and a battery holder. These components were all bolted in through holes made in the top fibreglass plate.

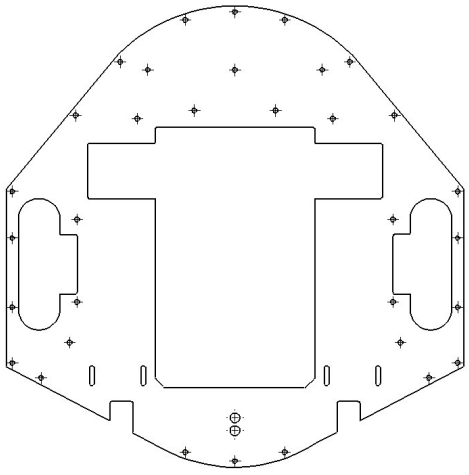


Figure 6-4: The layout of the top fibreglass plate

6.2.2.2 Wheel selection

Wheel arrangement and selection greatly affect the behaviour of the mobile robot. The wheel selection for this robot mainly considers a wheel that has a low level of slippage, that is easy to manoeuvre around and has a low cost. Initially, a castor wheel shown in Figure 6-5(left) was used as the front wheel. As this wheel has to bear some of the robot's weight, testing showed that it was very easy for the robot to slip and hence cause an error in estimation of the robot's position. It was also noticed that, when the robot started to move, if the castor wheel was turned to be perpendicular to the direction the robot needed to move in, the motors would struggle to align it to the right direction. This meant that a 'move forward' command would often cause the robot to turn a tiny a bit and then move straight forward. This resulted in the robot accumulating a larger and larger difference between where it should be, based upon what it has been told, and where it actually is.

The second approach was to replace the castor wheel with an omni-directional wheel shown in Figure 6-5 (right) that could move freely in any direction. This omniwheel consisted of a spherical ball placed on three shafts packaged in a height adjustable plastic stand. Testing proved that this change greatly helped prevent wheel slippage.

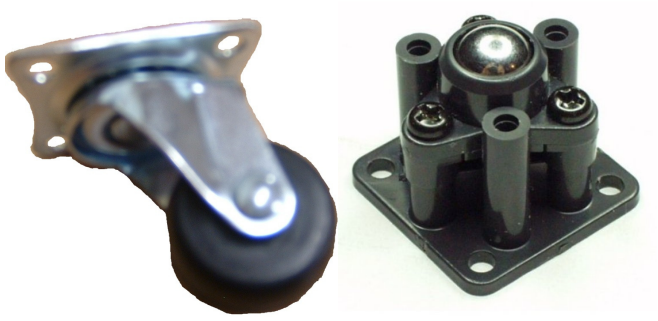


Figure 6-5: Left – The castor wheel originally used to support the robot; Right – The omniwheel finally installed

The two axles of the driven wheels were connected to the two stepper motors via gears. The gear ratio was 3.125 teeth on the wheel per tooth on the stepper motor. This arrangement is shown in Figure 6-6. This gear ratio makes the robot slower but increases its torque, making it more powerful. The torque power relationship for the motor used is shown in Figure 6-7 with the black line (representing torque) being greater when the speed on the x axis is smaller. This extra torque is necessary to insure the robot does not slip.

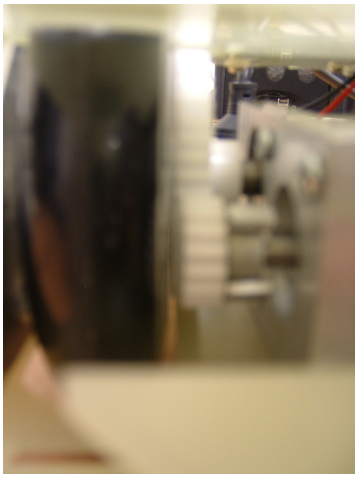


Figure 6-6: Gears connecting the motor shaft to wheel axle to increase torque

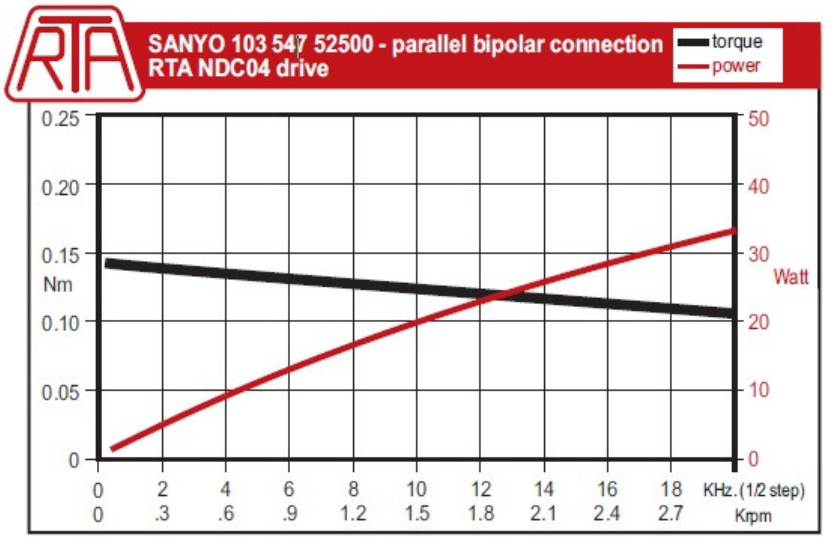


Figure 6-7: Torque versus speed relationship for this research's motor, (RTA PDF Catalogue, n.d., pg. 15).

The robot's speed was not calculated based upon physical characteristics such as the torque and power of the robot mentioned above. It was considered too complicated since many factors affected it such as the frequency the microcontroller gave steps to the motor controller, the current the batteries were able to give to the motors, and the static friction for the wheels to overcome in order to start moving. It was found that empirical measurements were the most effective way of finding the best approximations for the robot's real speed.

6.3 Control system design

This section explains the control system for the robot. A robot's control system should have input from data about its surroundings and output that controls the robot's actions. The input for this robot is the data from all the robot's sensors and the output is the motors that move the robot around. Therefore this section explains how the motors and sensors operate and how they were used.

6.3.1 Motor controller, power supply and testing

6.3.1.1 Motor controller and driver

The motors used for this research were Sanyo Denki stepper motors. Each motor had four wires and a 1.8 degree step resolution meaning that the motor moves 1.8 degrees each step. The half step mode is used meaning that the motor will turn in half step increments, i.e., 0.9 degrees per turn of the motor. It does this through turning on two magnets in between each step, which moves the robot half way between a matching tooth on each electromagnet on the stator. This not only increases the stepping resolution, but since two electromagnets are energised at one time during a half-step, it also increases the torque. An increase in torque will increase the amount of current used but will in turn make the wheel connected to the motor less susceptible to errors resulting from slipping since it is less likely for a greater torque to slip.

An L297 stepper motor controller was used to provide the control signal needed to control the stepper motors. All it needs is the direction to move (clockwise or anticlockwise), mode (full step or half step), and a falling edge to indicate when another step should be taken. This

relieves the microcontroller from performing any hard calculation work. The L297 receives low TTL voltages (0V and 5V) from the microcontroller and does all the calculations required for controlling the four wires in the mode selected by the microcontroller. Then it sends its control signals to the L298 dual full bridge driver (see Figure 6-8). The L298 is used to drive the current across the four wires for each motor. Hence, it needs to handle a lot of current. The L298 is designed for high voltages and currents, handling a supply voltage of up to 46V and a DC current of up to 4A. Therefore it was more than sufficient for this application which used approximately 10V and 0.8A to drive the motors. A large heat sink (Figure 6-9) is used to dissipate the heat from the two L298s.

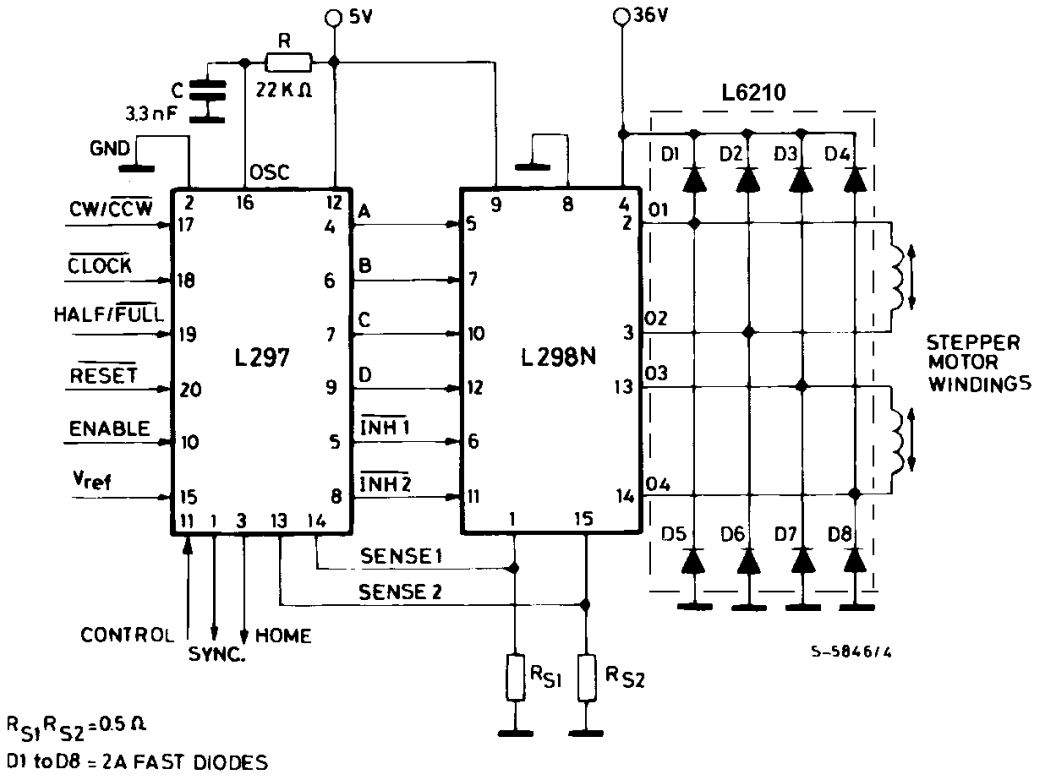


Figure 6-8: Circuit diagram for L297 and L298

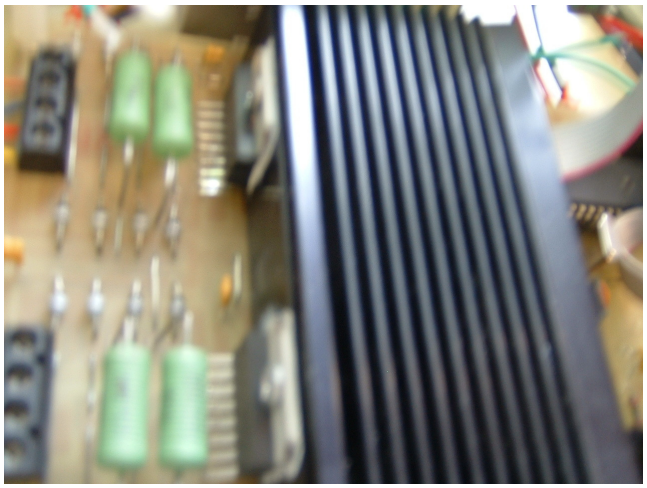


Figure 6-9: Heat sink used to dissipate the two motor drivers' excessive heat

Eight Zener diodes were used in front of the L298 to allow the motors to be driven forward and backward at any speed by limiting the voltage that can be given to the power supply and ground. The bottom circuit board that holds all the components for driving the motor was designed to hold all these components to drive and control the motors. The PCB board of the bottom circuit board is shown in Figure 6-10.

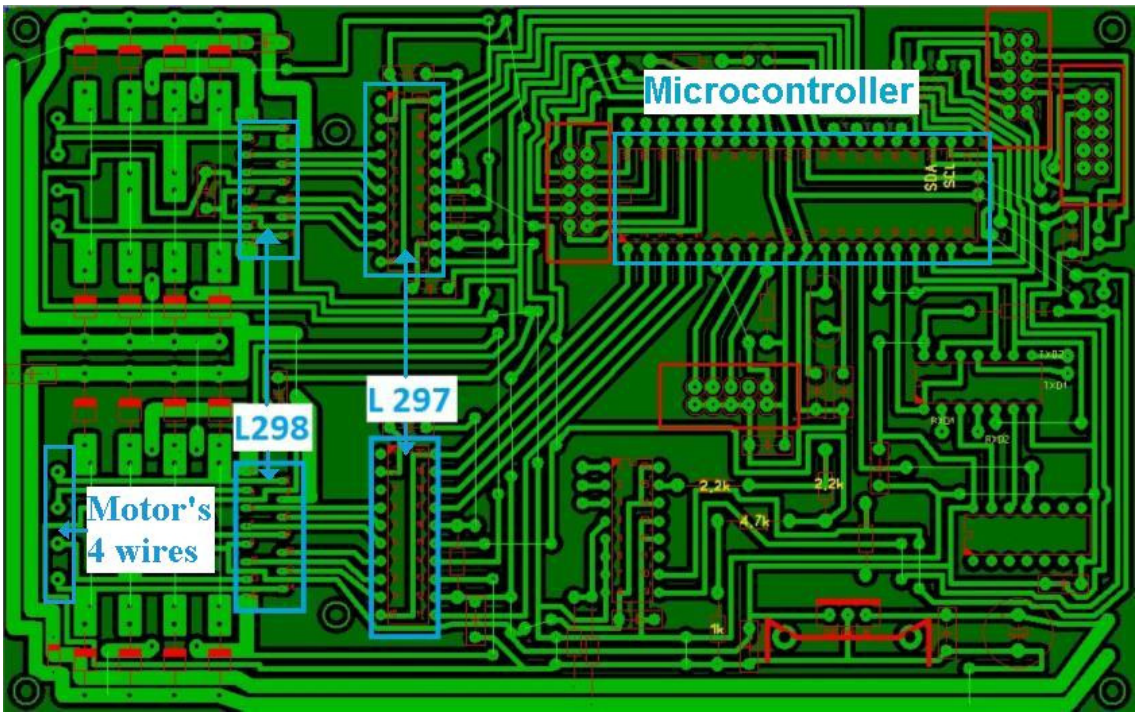


Figure 6-10: The bottom circuit board showing motor control circuitry on the left side

6.3.1.2 Power supply

The funding for the robot's parts was limited so to test the concept, many small batteries were connected in parallel in order to power the robot. Sixteen rechargeable 1.2V Ni-MH AA batteries (see Figure 6-11, left) were used in order to power robot. These batteries were high capacity, having a typical power usage of 2500mAh so that they could power for a longer time. Eight batteries in series yielded the correct voltage required to drive the motors, approximately 10V. However, with all the sensors added, the batteries could not supply enough current to power everything. Therefore, two sets of eight batteries were connected in parallel to double the current. This extra current enabled all the components of the robot to have sufficient current. In the future, it would be better to use a single high capacity battery to power the robot as this would be easier to recharge (as the other batteries need to be put into several chargers) and would allow the robot to run for longer.

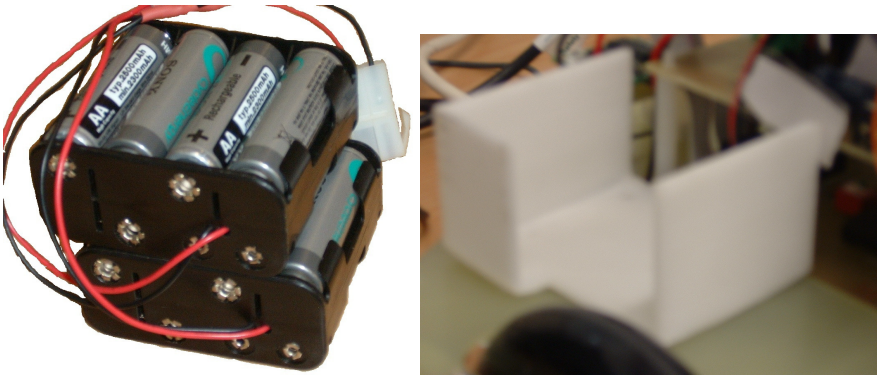


Figure 6-11: Left - Sixteen batteries used to power the robot; Right - Holder for batteries

A battery holder (Figure 6-11, right) was made out of nylon plastic to hold the sixteen batteries. It was made to exactly fit the two black battery packs using a rapid prototyping machine. A rapid prototyping machine converts a 3D drawing on a computer into a physical object. It does this by building it up layer by layer with melted plastic that quickly solidifies after being inserted onto a platform. This machine allows precise, particular shapes to be made effortlessly.

Each circuit board has a 5 volt voltage regulator that is used to provide a 5V power supply from the approximately 10V input from the robot's batteries. The 78T05TC chip was used for this. Only the bottom circuit board needed a voltage higher than five volts in order to drive the motors and it got this directly from the 10V power supply. All other chips, such as the L297 stepper motor controller and the microcontrollers, ran on 5V and so relied upon the 5V voltage regulator.

6.3.1.3 Motor driver circuit testing

The motor drive circuit was tested by varying the peak current the motor can use and varying the speed of the motor through changing the frequency of the square wave to the motor controllers (see section 6.3.1.1). This section briefly describes these tests.

The L297 motor controller has a voltage reference pin whose analogue voltage controls the maximum current the motor can use. This pin was set through the PCF8591P ADC DAC converter. This device is necessary since the ATMega32 microcontroller used in this research has no DAC on it and so can only output digital information. This DAC was given its analogue voltage via two wire interface (TWI) communication. TWI uses only two pins to provide serial communication, SCL (Serial clock) and SDA (Serial data). It works on the basis of having a master that selects a slave and either gives it information or asks for information from it. The master sets the clock for the slaves to use. This method of I2C communication makes it very easy to test different voltages by changing only one parameter in a piece of code instead of changing some electronic physical components as would be needed if a voltage divider were made with resistors in order to set the voltage.

Figure 6-12 shows the relationship between the serial values given to the DAC through I2C versus the motor current draw detected by a power supply. As can be seen, the relationship is linear. Such a relationship makes it easy to change the maximum current the motors can use.

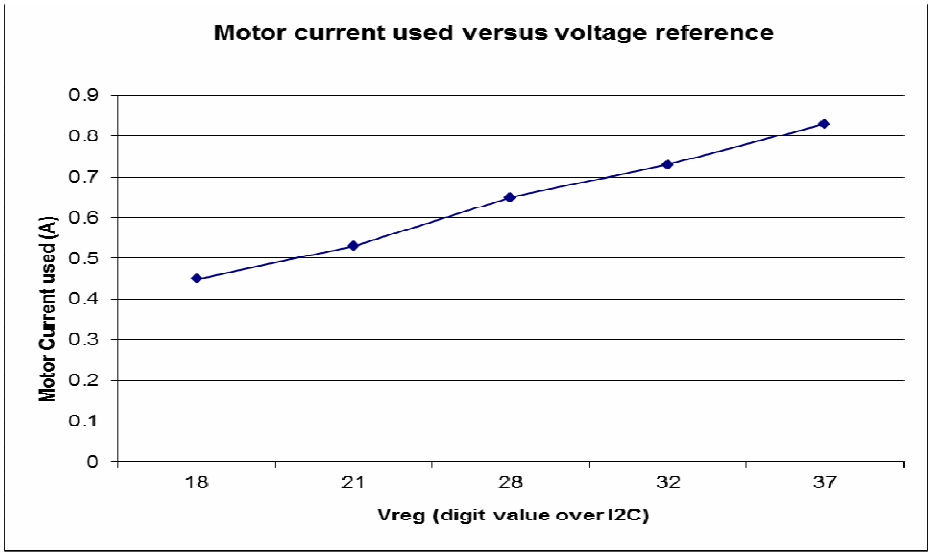


Figure 6-12: Motor current used versus voltage reference

The value used to run the motors needed to have enough power to run the motors properly yet not take too much current from the batteries. Eventually, a current of approximately 0.73A was chosen, represented by the serial value of 32.

The speed the stepper motors ran at was also tested. This was changed through varying the frequency of a square wave sent from the microcontroller to the motor controller. Whenever the motor controllers CLOCK input (see Figure 6-8) was made low it would turn the stepper motor one step (or a half a step depending on the mode). If the motors were run too fast or too slow, it would make strange sounds and not turn smoothly. Eventually, a speed of approximately one step per 960 micro seconds was chosen. This worked out to be approximately 30cm per second.

6.3.1.4 Synchronizing motor movement in real time with the simulation's movement

Initially, when testing the robot, the robot was told to move in a certain direction continuously until it was told to stop again. After trying to get the simulation of the robot on the computer to exactly match its real position, it was realised that it was very hard to have the robot and the simulation at exactly the same speed and location all the time. Therefore the PC tells the robot to move only a certain distance at a time and then waits before giving it another command. This was done simply by counting the number of steps the stepper motors had been told to move and stopping the motors after this count equalled the number of steps desired. The PC would wait for a short time after its simulation had reached the point it was told to move to ensure the robot had also reached the end of its movement before giving the next command.

To move a certain distance or turn a specific angle, the program had to figure out how many steps were needed. The actual counter was incremented whenever a change in the signal to the motor controller was made. Since the signal to the motor controller is a square wave and only moves the motor on a downward pulse, each 'increment' from the counter is only half a motor step. After testing it was realised that it takes time (or a number of steps) for the motor to reach the speed at which it is told to move. This speed versus increments relationship for turning the robot is shown in Figure 6-13.

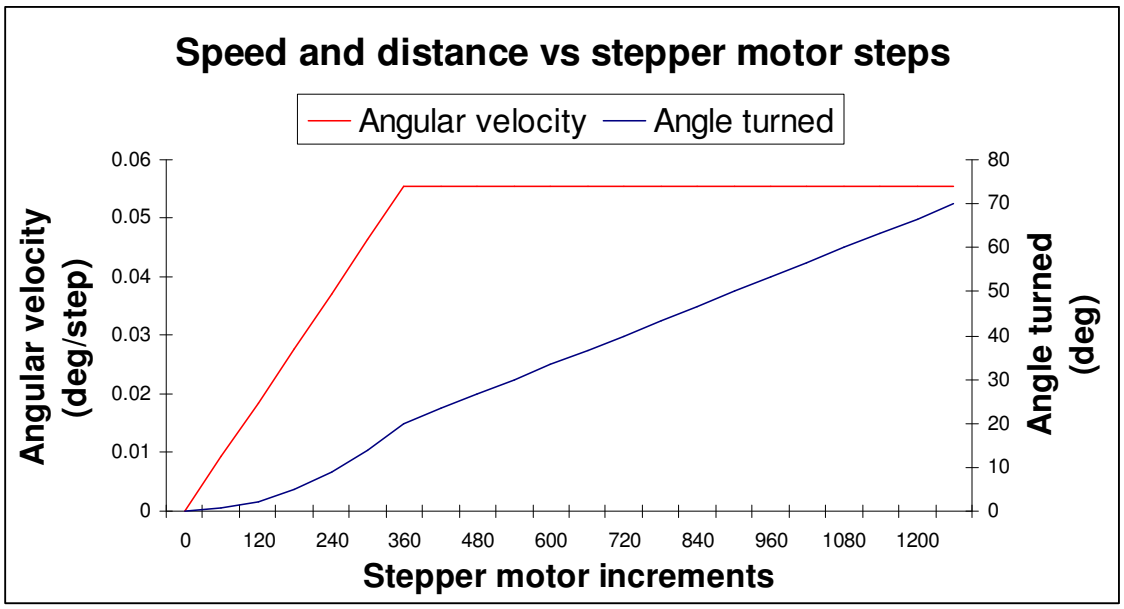


Figure 6-13: Speed and distance of robot versus stepper motor increments

The equation for modelling the behaviour of the robot from the number of steps given can be calculated from just two trials where both the number of increments and the distance moved or angled turned is known. The calculation of equations to model the distance or angle a robot used using this data is shown below.

The speed at which the motors move can be approximated by an initial constant acceleration and then a constant speed. Although the robot is given steps to move at a constant rate from the beginning, it still takes time for it to come up to speed. Therefore, the steps mentioned here are not the actual number of steps moved by the stepper motor but the number of steps the motor controller has been told to move. There is a difference between the two because it takes time for the motor to reach a certain speed. The purpose of this appendix is to show how the equation to find how many steps to give the stepper motor to move it a set distance can be obtained, through using this approximation.

Although the robot takes time to accelerate it does not take time to decelerate as the stepper motors have a good braking mechanism. This can be seen by the jerk that occurs when the robot stops. The velocity is shown in Figure 6-14. In this figure, S_A represents the number of steps the robot has been told to move until it has accelerated to its constant speed and S_C represents the number of steps the robot has moved at its constant speed.

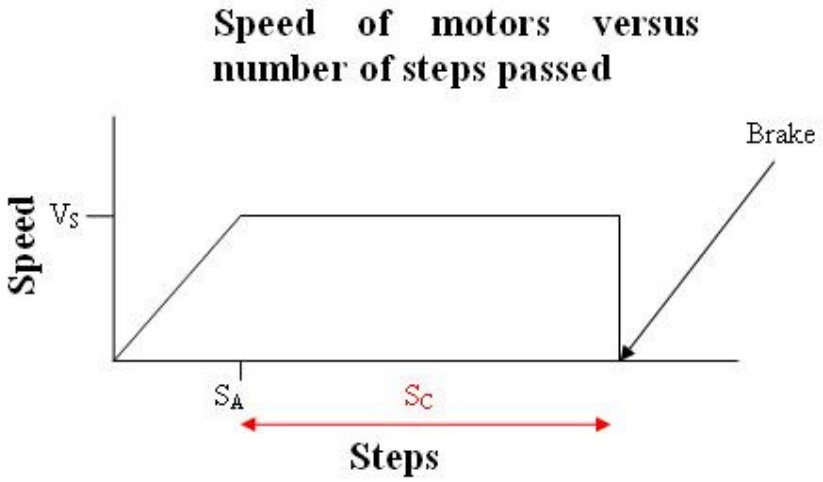


Figure 6-14: Speed of stepper motors versus number of steps passed

The integral of the above shape gives the distance the robot has traveled. This calculation of this integral is shown in Equation 6-1.

Equation 6-1: Distance robot has travelled depending on how many steps have been given by the microcontroller

$$D = \tfrac{1}{2} S_A \times V_S + S_C \times V_S$$

If two tests are done with a known number of steps and a measured distance, the parameters S_A, S_C and V_S can be calculated. With these values equations to calculate how many steps to give the stepper motor can be calculated. Through rearranging two equations the number of steps to accelerate the motor to constant speed can be as shown in Equation 6-2.

Equation 6-2: Calculation of the number of steps required to accelerate to constant speed

$$S_A = \frac{(Dist2 \times NumStep1 - Dist1 \times NumStep2)}{(-1/2 \times Dist1 + 1/2 \times Dist2)}$$

In Equation 6-2, Dist1 & Dist2 refers to the physical distance of the test for test 1 and 2 respectively. NumStep1 and NumStep2 refer to the total number of steps the microcontroller has told the program to move in each test. Since the total number of steps will already be known, as the microcontroller counts how many times it changes the output to the motor controller, S_C can be easily found by subtracting S_A from the total number of steps. V_S can also be easily found from S_A using Equation 6-3.

Equation 6-3: Calculation of constant speed's value once accelerated

$$Vs = Dist1 / (-0.5 \times S_A + NumStep1)$$

Then, with these values the number of steps to move a certain distance can be calculated by considering Figure 6-14. If the number of steps is too small for the robot to reach V_S then the equation will be as is shown in Equation 6-4.

Equation 6-4: Number of steps to move when distance is less than the distance required to reach constant velocity

$$NumStep = 2 \times Dist / Vs$$

Otherwise, if the number of steps is large enough so that the robot will reach Vs, the number of steps will be as calculated from Equation 6-5.

Equation 6-5: Number of steps to move when distance is greater than that required to reach constant velocity

$$NumStep = Dist / Vs + \frac{1}{2} \times S_A$$

In order to know which equation to use, simply multiply V_S by ½ S_A to get the distance the robot will move before it will start moving at a constant speed. This distance is referred to as D_A. If the distance for the robot to move is less than D_A then use Equation 6-4, otherwise use Equation 6-5.

After testing the robot using the previous algorithms two Equations were formed to model the number of steps to rotate the robot and move it linearly. Equation 6-6 shows the number of steps to give the motor to turn the robot before its constant velocity is reached and Equation 6-7 shows what this is afterwards, where D represents the distance the robot rotates in steps of 3 degrees. It can be seen that the number of steps to give the robot can be easily calculated.

Equation 6-6: Number of steps required to rotate the robot before its constant velocity is reached

$$NumStep = 6 \times D$$

Equation 6-7: Number of steps to rotate the robot after its constant velocity is reached

$$NumStep = 10 + 3 \times D$$

6.3.2 Sensing implementation

This section covers how the particular sensors used in this research were chosen out of a range of available sensors, how the sensor data was processed so that it could be used by the computer to make decisions, and how the sensors were implemented on the robot.

6.3.2.1 Selection of sensors

Initially, many sensors were looked at in order to be able to cancel out odometry errors and detect obstacles. These included:

- Proximity sensors, that turn on or off when an obstacle is detected close by.
- Infrared distance sensors, that measure the time for light to travel to an object and reflect back to calculate distance.
- Sonar sensors, that measure the time for a sound wave to bounce off an object.
- Doppler speed sensors, that measure the speed a robot is moving by sending a high frequency signal and measuring the frequency change due to the robot's movement.
- Hall Effect sensors that detect a magnetic field. If magnets are placed on the wheels the Hall Effect sensor will have a change in output and therefore an approximation of the wheel's speed.
- Accelerometers, that measure the acceleration of the object they are on.

- Gyroscopes, that measure the angular change of an object and therefore the acceleration.
- Compasses, that use the earth's magnetic field to output their current orientation.
- RFID (radio frequency identification) tags; both active, that require their own power source to run, and passive, that have their current induced by the reader. These tags can store a unique ID and be placed around a map so that a robot detecting them can localise itself.

Acceleration sensors were deemed unnecessary for this research as acceleration to a fixed speed takes a very short amount of time, the processing of the microcontroller is limited, and their reliability for such small distances questionable. Such sensors would be only useful if they could detect unexpected movements or in the case of slipping, the robot not moving when it should. It is unlikely that processing would enable such a small difference in acceleration, from what was intended to what actually happened, to be monitored. In the same manner, Doppler sensors measuring speed would not be useful in this research as the speed would mainly be either still or one speed and slippage of wheels would only cause a minor change that would not be easily noticed.

Proximity sensors are useful for stopping a robot when it is too close to an object and other methods have failed to stop the robot. These were considered and plan to be implemented on the robot in the future to increase safety.

A sonar sensor was installed on the robot. The sonar sensor chosen was the MB1300 from MaxSonar. Although it is more expensive than some more basic ones, it has automatic calibration for changes in voltage, temperature, and electrical noise and has no time needed for calibration when first powered up, as some devices require. These features make it less prone to error and able to operate immediately upon starting of the robot.

The short range Sharp GP2D120 infrared distance sensor was used to detect obstacles that are close to the robot. The sensor is able to sense from 4 – 30cm. It has less influence from the colour of objects it detects as other infrared sensors may. This feature is a necessity for the mobile robot to be useful in practical applications that have different coloured obstacles. It also requires no external circuitry making it much easier to use.

The CMPS03 compass used is said to be designed specifically for use in robots as an aid to navigation. It uses two magnetic field sensors sensitive enough to detect the earth's magnetic field to calculate the current angle of the object it is placed on. The PWM (Pulse width modulated) signal on it was used to obtain the angle.

RFID sensors were also implemented on the robot. A reader to read passive RFID tags with a frequency of 125kHz (the lowest frequency for RFID tags) was chosen. Having a lower frequency decreases the detection distance range but this is not a problem as the tags are only meant to be read when the mobile robot is near them. Passive tags have the benefit of being inexpensive, simple, and having no need of a power source. The tags are credit card shaped and can be easily attached or detached to walls or other objects in an indoor environment. This allows that the indoor environment in which the robot moves to be easily rearranged as

opposed to using AGVs (Automated guided vehicles) which may require lines to be put on a floor or wires to be installed underground. This ease of change is important in a changing working environment where new products are produced more often than before, meaning that the working environment may need to be rearranged and hence the path of a robot changed to fit in with it. This method of passive RFID tags allows the creation of new paths for mobile robots to take to be created quickly.

6.3.2.2 Processing and testing of sensor data

This section describes how the data from the sensors was processed so that the PC could use the data and make the right decision for the robot.

6.3.2.2.1 Infrared distance sensor

The GP2D120 photodiode sensor (see Appendix I) was used due to its simplicity to use, availability, and reasonable price as the distance sensor to detect objects around the mobile robot.

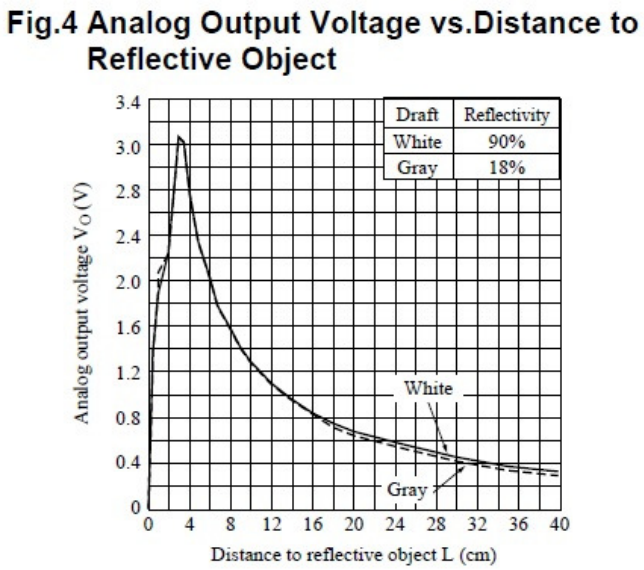


Figure 6-15: Infrared distance sensors' analogue output versus obstacle distance for a grey and white object

The relationship between analogue voltage and distance from the sensor used is a power-law function (as seen in Figure 6-15) with the power being negative as distance increases. The sharp sensor's analogue voltage was tested versus distance and Figure 6-16 was produced, confirming the datasheet's results.

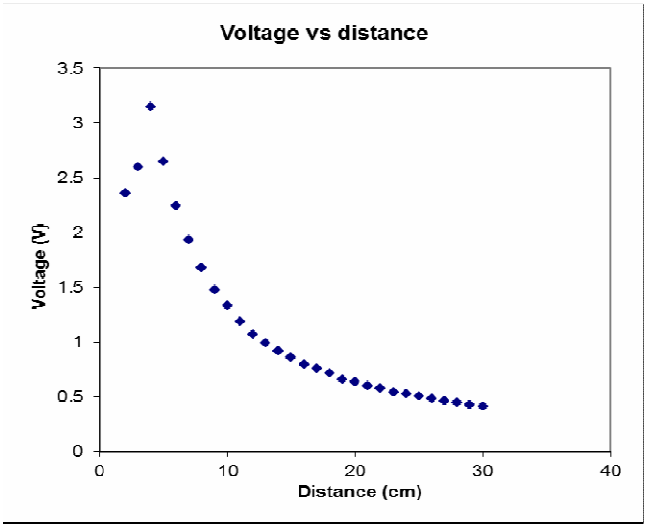


Figure 6-16: Voltage of infrared distance sensor versus distance from object

The voltage was read using an oscilloscope and the distance, through a ruler. A brown object was used and tests confirmed that the color of the object did not make a difference. This voltage was then converted to a bit value to mimic what the ADC would read in the microcontroller and Figure 6-17 was produced.

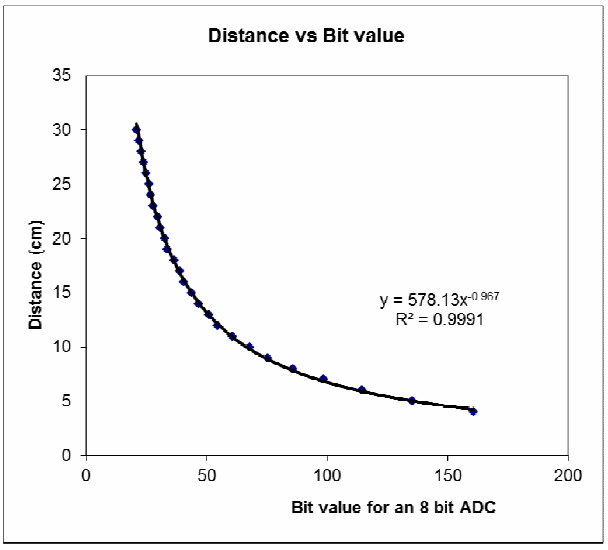


Figure 6-17: Object's distance from infrared sensor versus the 8 bit representation on the microcontroller

Although the microcontroller uses a 10 bit ADC, the lowest 2 significant bits are not necessary to get the accuracy needed so only the top 8 bits are used. This equation of the line is then used in the PC, to obtain an accurate distance value from the analogue voltages read and transmitted onto the PC.

6.3.2.2.2 Sonar

The MB1300 sonar sensor yielded an analogue voltage proportional to the distance in cm after the minimum detection distance of 20cm. The datasheet said that the analogue voltage was approximately 0.49mV per cm at a supply voltage of 5V. The robots regulated supply voltage is slightly less than 5V so it would be expected that the gradient is slightly less. Tests showed it having a relationship of approximately 0.47mV per cm as can be seen in Figure 6-18.

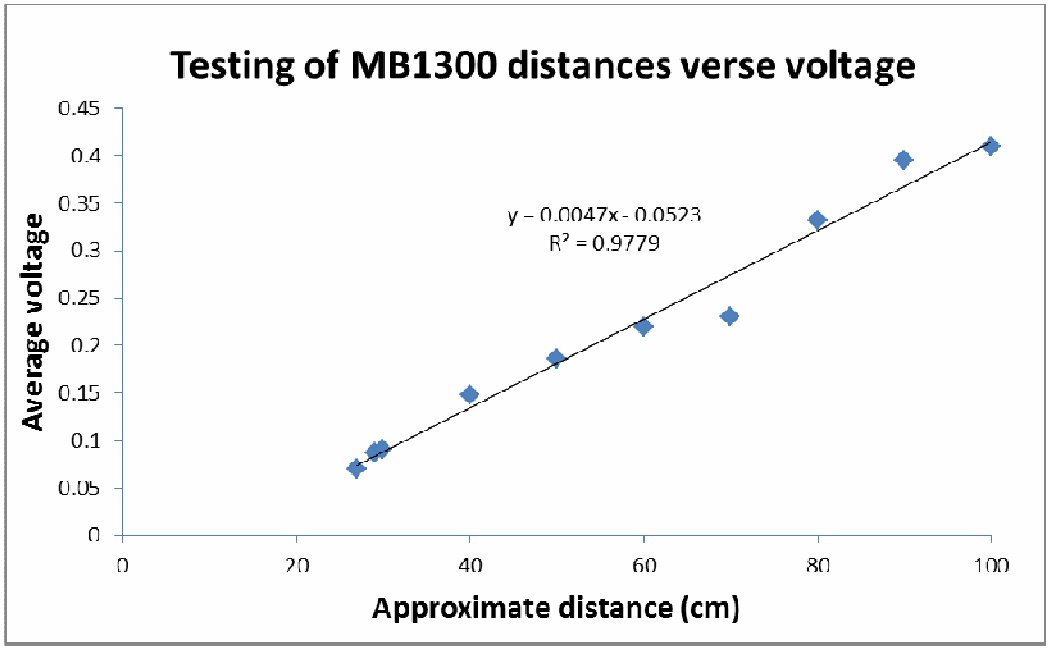


Figure 6-18: Relationship of analogue voltage of sonar sensor versus the approximate distance from it

Although the robot's tests were good, they were carried out with the robot sitting on the desk with empty space below the sonar's view. After experiencing some expected readings from the sonar sensor when the robot was placed on the ground, it was figured that the sonar sensor must be reflecting off the ground. Although the sensor does not point toward the ground, the

width of the sonar's signal would disperse more and more as the signal travels. Eventually this would mean that the signal touches the ground and indicates an obstacle is there. This makes the robot too sensitive to obstacles and so the sonar was not used for long range obstacle detection. Since the sonar sensor yielded a fixed voltage up to 20cm, this voltage was used to indicate whether an obstacle was close to the front of the robot or not.

6.3.2.2.3 Compass

According to the data sheet and initial tests, before connecting the compass to the robot, the angle to pulse width was perfectly linear as can be seen in Figure 6-19.

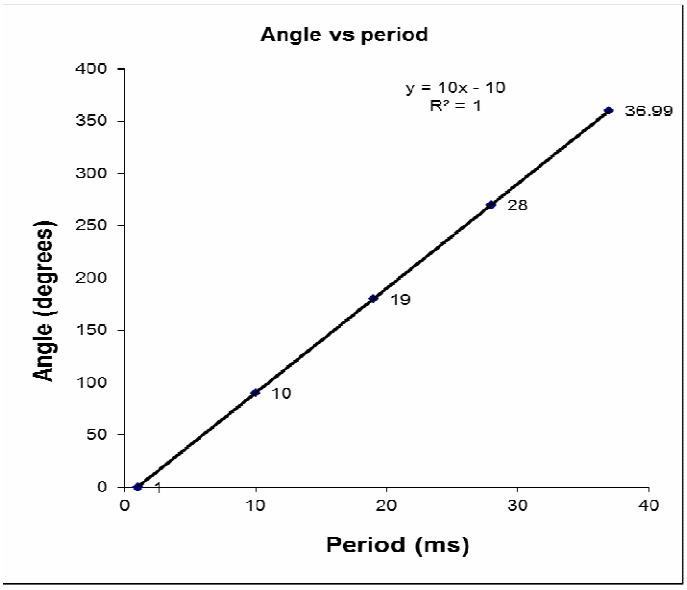


Figure 6-19: Initial robot angle versus compass value

After connecting it to the robot, however, it was better modelled with two lines as can be seen in Figure 6-20. This would have been caused by magnetic interference from the robot's own motors and electronics on the robot and in the robot's test environment.

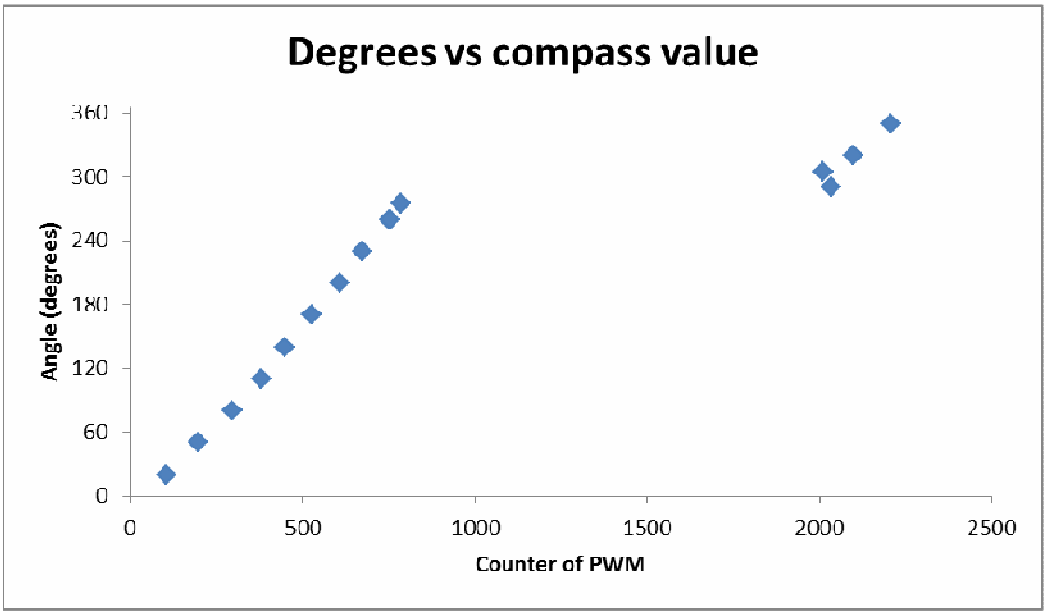


Figure 6-20: Compass value after fitted to the robot

Figure 6-20 mentions the 'counter of PWM'. Since the output was a PWM, the microcontroller incremented a counter every 8 microseconds from the time of the pulse start until it finished. Hence, the counter was directly proportional to the pulse width. Since the compass values seems to jump to a different line when reaching a certain value, two equations are used when interpreting the angle from the counter in the PC. The equation used depends on the counter value. As mentioned previously, the reason for this strange behaviour is external magnetic fields interfering with the compass' signal.

6.3.2.2.4 Encoder

In order to provide a secondary method for knowing how much distance has been travelled, three magnets were placed on each wheel. The SS490 Hall Effect sensor was placed near the magnets in order to detect the change in magnetic field strength as the magnets went past it. This Hall Effect sensor yields 2.5V at 0 gauss (as seen in Figure 6-21) and goes either below

or above that depending on the direction of the magnetic field. Therefore, a differential amplifier was used to amplify the difference from 2.5V.

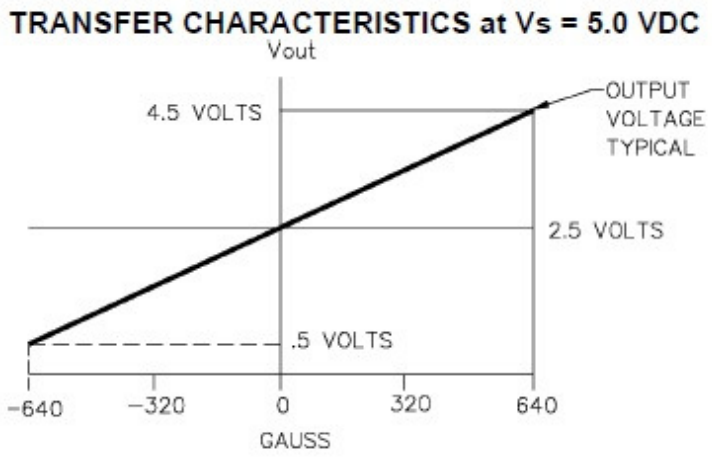


Figure 6-21: Hall effect output from datasheet, (Honeywell, n.d., pg. 2)

Figure 6-22 shows the circuit built to amplify the difference the signal had from 2.5V. Equation 6-8 shows the model describing the amplification and Figure 6-22, the differential op-amp circuit. As seen in the equation and Figure 6-22, V_2 was set as 2.5V so that any magnetic field with strength greater than 0 Gauss yielded a positive voltage whereas no magnetic field yielded zero volts. Using the appropriate resistors, this positive voltage was boosted so that it was recognized as a digital high by the microcontroller.

Equation 6-8: Differential amplifier output based on resistor values, (Mancini, 2002, pg. 22)

$$V_{OUT} = V_1 \frac{R_2}{R_1 + R_2}\left(\frac{R_3 + R_4}{R_3}\right) - V_2 \frac{R_4}{R_3}$$

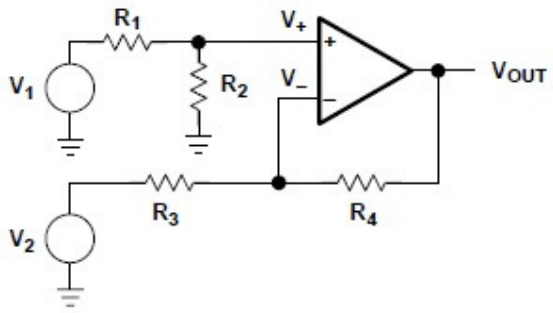


Figure 6-22: Differential amplifier Op Amp circuit, (Mancini, 2002, pg. 22)

Figure 6-23 shows the schematic made in Altium designer in order to make a PCB (Printed circuit board) to contain the components needed to amplify the signal. The PCB was bolted to the fibreglass bottom layer with nylon bolts and the Hall Effect sensor held close to the magnets on the motor's gear.

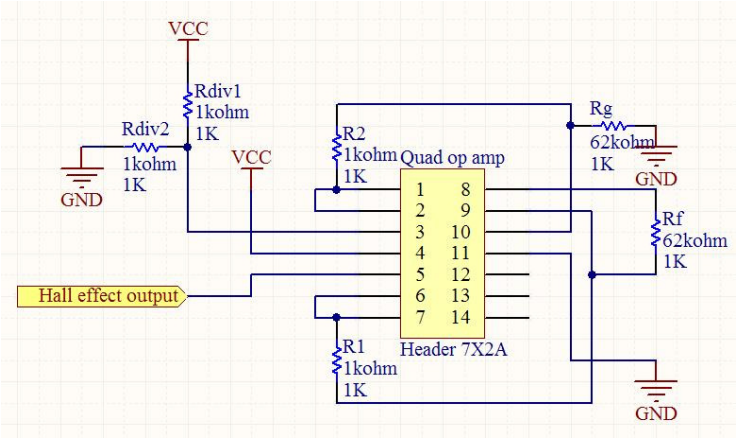


Figure 6-23: Schematic of resistor used for Hall Effect sensor

6.3.2.2.5 RFID

An ID-40 RFID reader (see Appendix L) was used since it was readily available at the workspace and provided the right frequency to use for this robot. The RFID reader outputs a RS232 format serial signal that carries the unique data of the RFID tag. Since the USART on the microcontroller is already used to communicate with the XBee and the bottom microcontroller, this serial signal had to be analysed by polling a bit using timers. Polling a bit means simply to keep checking the status of the bit. In this case, it meant checking the status of the bit and recording it approximately 9600 times per second, as that was the bit rate that the RFID reader used.

Figure 6-24 shows the bits an RS232 signal uses. As can be seen, it always has a start bit to indicate the start of the data byte and two stop bits to indicate the end of the byte. A parity bit can be used as error correction to ensure that the data sent does not have any errors. The parity bit can be either even or odd parity. If it is even parity, the value of the bit will be made either high or low in order that all the bits that are high in the byte plus the parity bit equal an even number of bits. For example, there are an odd number of high bits, '1's, then the parity bit will be '1' to make the total number of high's even. Therefore, if one bit is changed due to errors while transmitting the data, the receiver will detect this (as there will be an odd number of high bits) and be able to ask for the byte again. However, the signal from the RFID reader used in this research was simpler than the one shown in the figure and did not use a parity bit.

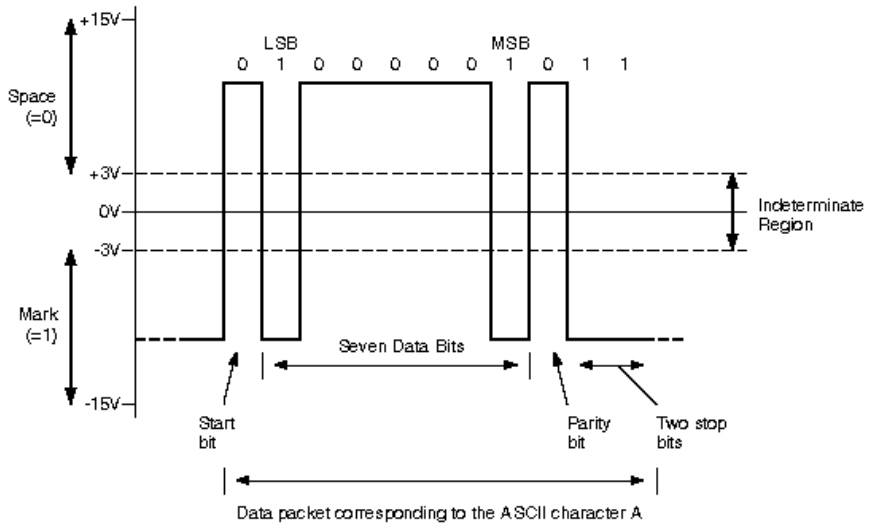


Figure 6-24: An illustration of an asynchronous RS232 Byte (ARC Electronics, n.d., section 13)

In order to get the timer overflow occurring at the same point of the byte, when a high is detected on the pin connected to the RFID reader, indicating that the reader has a read from an RFID tag and is sending data, the timer is temporarily turned off until a low is detected on the pin. This is a very useful point to have as it indicates an exact point in the serial bit sequence. At this point, the timer is reset after 50 micro seconds. This process is shown in Figure 6-25 and the C code is shown in Appendix C.

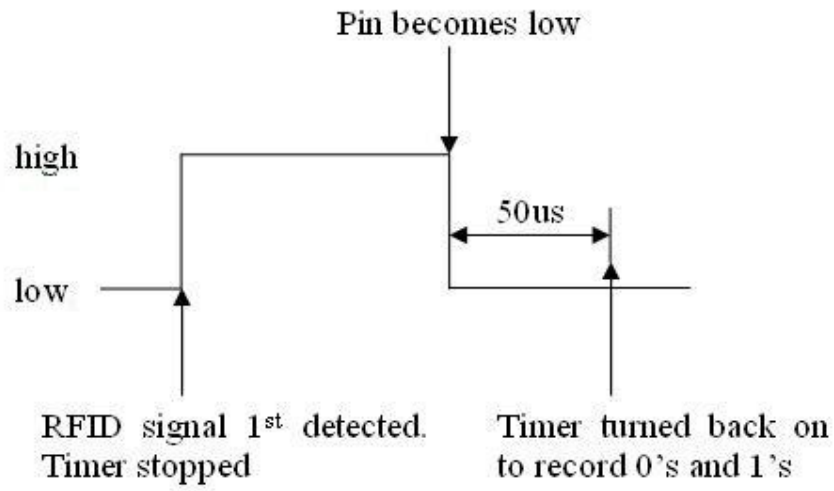


Figure 6-25: Stop and start timer to pin point the start of recording the bit sequence

This resetting of the timer at this point ensures the bits read are the same every time the same RFID tag is read. Initially, without doing this, the timer overflow was not exactly 9600 bits per second and slightly different bit sequences were produced each time the same RFID tag was read. However, with the starting point to read the 0's and 1's being the same each time, the bit sequence is exactly the same every time the same RFID tag is read. This enables the robot to distinguish which tag has been detected reliably.

6.3.2.3 Sensor implementation

This section explains how the various sensors including the RFID tags were implemented in the navigation system of a mobile robot to detect RFID tags and avoid obstacles.

6.3.2.3.1 Light sensors

For a robot to know its environment, a simple real time information system is developed. The real time data contains the location of the robot and the information of its surroundings.

GP2D120 infrared distance sensors as seen in Figure 6-26 were used to scan for obstacles and provide information to build a real time map of the environment.

In testing this concept, only six of these sensors are placed around the robot to cover a nearly full circle around the robot at one time. Of course, to have the full range covered, more sensors have to be installed or sensors would need to be rotated and measurements taken at different angles.

Figure 6-26: GP2D120 Infrared distance sensor used for detecting obstacles

After testing, it was realised that the information received from these sensors is only reliable when the robot is not turning as only when the robot is not currently in the middle of a turn will the orientation be clearly known. Due to this fact, the robot's current position was only an estimate based on odometry feedback. Since the current position was merely an estimate, the distance data was deemed not reliable enough to build a permanent map unless the same location had its point measured many times and the position of its measurement was known for certain. Therefore, each obstacle sensed has its time of detection recorded and disappears in the map after a certain period of time unless that particular spot in the map is detected again. This is a kind of real time or live map which can provide more reliable and relevant information of the environment to the controlling PC.

After testing the robot around an environment, it was realised that the back sensors are not so necessary. Originally, it was hoped that the distance information could allow a permanent map of the objects in the room to be formed and hence, the more information about the surroundings of the robot, the quicker a map could be built up. However, through the testing, it was discovered that the distance data is not reliable enough to form a permanent map and since the robot hardly reverses, only the front sensor information is really useful. Therefore the distance sensors were not used to help the PC build a permanent map yet helped the robot to avoid immediate obstacles in its path or obstacles that it would soon encounter.

6.3.2.3.2 Sonar sensor

The MaxSonar MB1300 sensor shown in Figure 6-27 detects much further distance than the light sensors and is used at the front of the robot to detect far away objects. According to the data sheet its resolution is 1cm and it can reach up to more than 7.5 metres. However the beam spreads out as the distance from the sonar sensors increases (see Appendix K). If an object is closer than 20cm then the range is read as 20cm. This short distance range is used for detecting whether obstacles are close to the robot though how close is not known from this data.

This sensor was found to be useful as a reliable method of picking up obstacles at a short range and was used to avoid the obstacle in the test discussed in section 6.4.2.

Figure 6-27: Sonar sensor used to detect distances far away

6.3.2.3.3 Compass

The CMPS03 compass module shown in Figure 6-28 (see Appendix J) is used to get the absolute angle of the robot. The compass is useful to correct against errors in the orientation caused by slippage in the wheels. The more the robot turns, the more error accumulates in the angle of the robot's orientation. Having a slight error in the orientation causes an accumulation of distance error as the robot moves forward. Hence, it is very important to have a device to correct this.

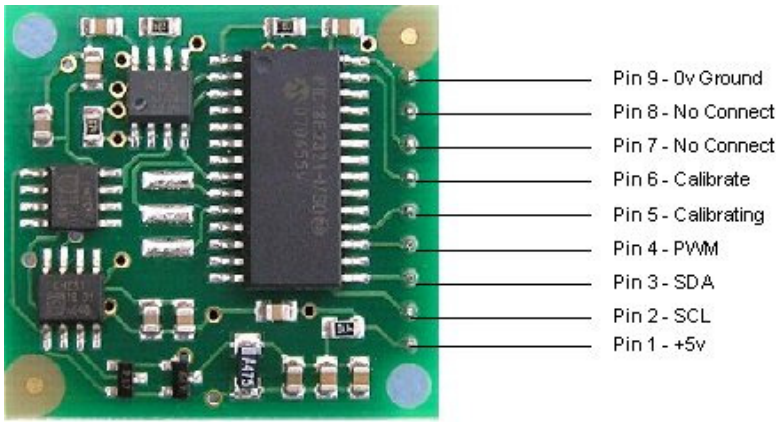


Figure 6-28: CMP03 compass used to get the angle the robot is facing

When the compass is in the right environment (having no external magnets that are great enough to interfere with the reading of the earth's magnetic field) it can give a consistent output that can be used to judge the direction the robot is facing. The compass succeeded in localising the robot in the environment shown in section 6.4.1.

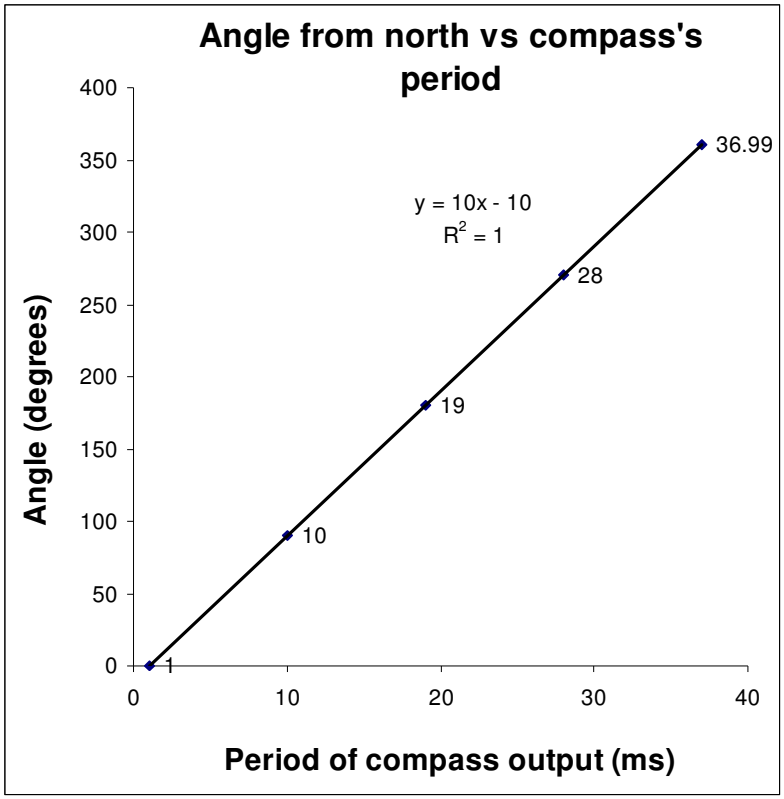


Figure 6-29 CMP03 signal in a good environment with no sources of significant magnetic interference

6.3.2.3.4 RFID

An ID40 RFID reader (see Figure 6-30, left) from ID-innovations (see Appendix L) was used to read the RFID signal from the RFID tag. This made a beep sound when an RFID tag was detected and provided a RS232 signal down a signal line. The distance an RFID reader can detect a passive tag mainly depends on the size of the coil inside the reader and inside the tag

being detected. For this reason, readers that detect larger distances need to be larger. This reader uses a frequency of 125 kHz.

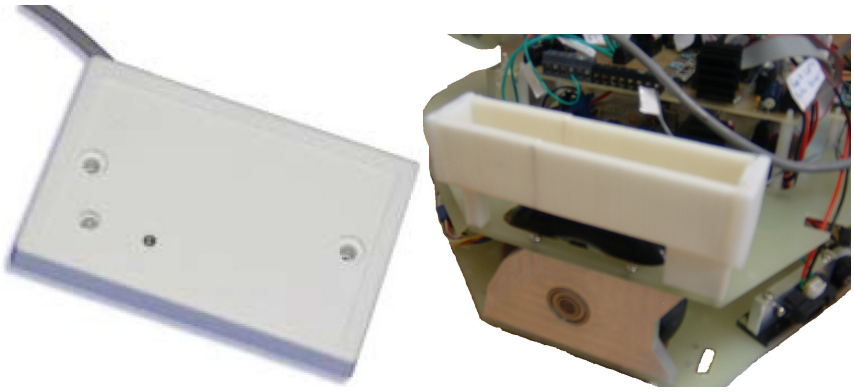


Figure 6-30: Left - RFID reader used to detect RFID tags (ID Innovations, n.d., pg. 1); Right - Robot showing RFID reader holder

In order to hold the reader, a holder was made out of plastic using the rapid prototyping machine (Figure 6-30, right). Initially, RFID buttons (Figure 6-31, left) were used because they were small and therefore able to be placed in many locations. However, it was found that they only had a detection distance of up to 6 cm when facing the reader, a distance too small to be useful in navigating a robot that is 30cm in diameter.

Figure 6-31: Left - RFID laundry tag; Centre: Clamshell RFID card; Right - Flat Sparkfun RFID card

Therefore, tags that were the size of credit cards were used. After testing the difference between a flat card like Sparkfun's and a Clamshell card, it was proved that the Clamshells thicker durable cards provided the longest detection range (up to 20cm when facing directly).

ID-innovations long range card is specified to be able to read up to 40 cm. Therefore, for the test model, Clamshell cards were used as they are available in NZ and can be easily obtained.

6.3.2.3.5 Sensor connection

The distance sensors were connected to the bottom layer microcontroller through a ribbon cable connector on the top layer. The rest of the sensors, the RFID reader and the compass were connected to the middle microcontroller through the top layer. The connection of all the sensors on the top layer is shown in Appendix D.

6.4 Mobile service robot prototype system testing

This section presents three tests that were used to test different functionalities of the robot. All tests reached their goal successfully although there was a slight error in where their actual position ended up to be compared to what it should have been. The three tests shows:

- The robot's basic moving from one tag to another using the compass
- The robot's avoiding a simple geometric obstacle that was not previously recorded in the map
- The robot's moving between several tags in order to reach a destination

6.4.1 Test one – Proving compass

In the first test, the robot was told to move from one tag to another manually at each point, unlike the third test where the robot is just told the destination and it automatically calculated the path to travel. The compass worked sufficiently in this environment so was used to continuously update the robot's actual orientation whenever the sensor data was read. The environment used to test the robot is seen in Figure 6-32.

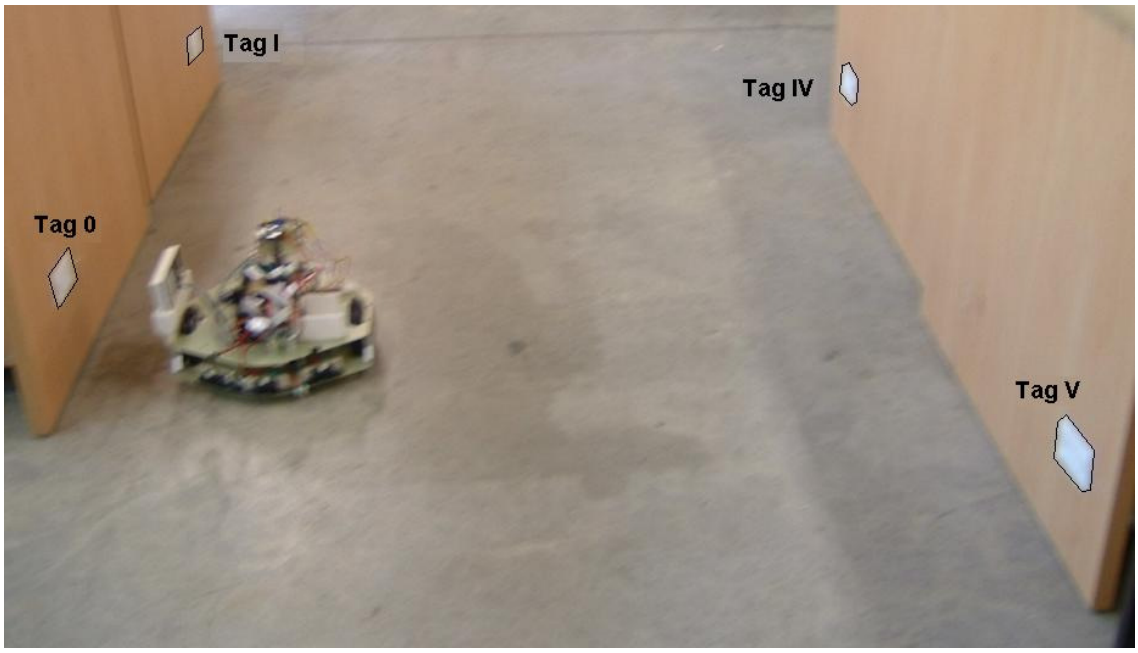


Figure 6-32: Lab where the robot moving between several tags with compass correction was tested

The outcome of this test was successful as can be seen by the approximate path shown in Figure 6-33. This figure is not the simulated version on the PC as the simulated movement is shown to be perfect and does not recognize errors. Hence, the figure was drawn to approximate the path the robot actually moved.

Moving straight from one tag to another is a very simple process. However, when the robot has to make a turn, a slight slippage in the wheels or slight miscalculation of the angle from the compass causes an ever growing error as the robot travels forward. This error can be seen when the robot made its last movement. The robot turned clockwise slightly too much and so did not travel in the right direction in order to move in a straight line to the tag. The compass's resolution was not strong enough to pick up this difference and give indication that the robot was off course. If it did, the algorithm (see section 5.1) that checks the robot's

current angle as it is moving toward the destination would have picked this up and turned the robot slightly anticlockwise.

The accuracy of the compass is not so fine due to the interference of magnetic objects around the room. In the FAQ for the CMP03 compass, they clearly demonstrated that this compass is affected by other magnetic fields, such as motors, magnets, and ferrous objects (Coe, n.d.).

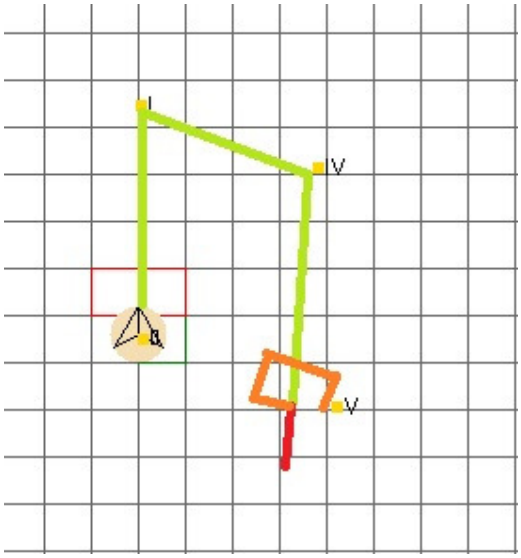


Figure 6-33: Approximate path of where robot actually travelled: Green - Path moving directly to RFID tag; Red - Moving forward and back path; Orange - Spiral search for RFID

In the diagram, the red line indicates the robot's moving forward and back to look for the RFID. This is done in case the robot has moved too small a distance so is slightly before the RFID tag. Then the orange line shows the algorithm that moves the robot in a spiral to search for the tag. This spiral search algorithm enabled the robot to reach the tag and detect at which approximate location the robot really is and so update the simulation position on the PC.

In summary, the need for a high resolution, better compass is illustrated in this test and the usefulness of algorithms such as the spiral search algorithm demonstrated.

6.4.2 Test two – Avoiding obstacle

The second test involved avoiding a simple geometric object that was not already mapped in the program. The object was a blue rectangular box as shown in Figure 6-34. In this environment, the compass could not be used as it was not yielding consistent outputs at the same angle. This must be due to interference from significant external magnetic fields. The aim was for the robot to move straight from one tag to the next, avoiding the obstacle in its path.

Figure 6-34: Lab showing the obstacle that the robot avoided

The outcome was successful as shown by Figure 6-35. The robot first moved until it detected the obstacle. Then the obstacle avoidance routine started so it moved towards the right of the obstacle 32cm, turned back 90 degrees toward the next tag and looked to see if it could move there. The algorithm tries to do this move to the side and look up to three times if the obstacle is detected as still being there (see section 5.1.1.2.2 for more details). On the second look, no obstacles were detected so the robot moved 32cm past the obstacle. After this, the path to the next tag, tag one was calculated and the robot continued in that movement.

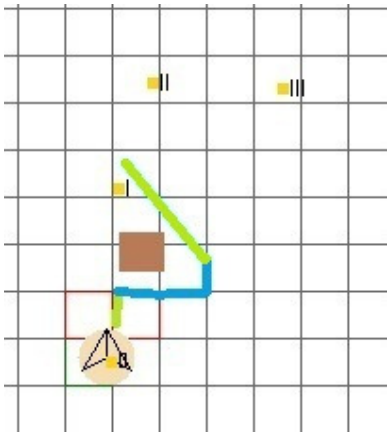


Figure 6-35: Approximate path of the robot avoiding an obstacle: Green – Path of robot moving directly to tag; Blue – path of robot while avoiding the obstacle

As can be seen by the final green line the robot moved slightly above the RFID tag's position. This miscalculation must have occurred due to odometry errors. However, the tag was still detected at this position. This small error though shows how error can accumulate over time, thus requiring methods of localisation such as using RFID tags for position and the compass for orientation.

6.4.3 Test three – Moving through best path

The third test involved telling the robot to move to a destination which was in between other tags. As in test two, the compass did not work adequately in this environment due to external magnetic inference so its data was not used to localise the robot. The path to travel was an 'L' shape, meaning the robot needed to turn a 90 degree corner to reach its destination. The environment is shown in Figure 6-36.

Figure 6-36: Lab showing the corner of the best path the robot is travelling between two tags

The 'Least path accumulated error' algorithm was used to calculate the best path to travel. This algorithm calculates the path to travel between tags that will result in the least possible distance between any two tags in the path. Essentially, this algorithm moves the robot toward the destination by passing through as many tags as would be useful to localise the robot as it travels.

The robot was successful in calculating the path to take. In order to move from tag one to tag four (as seen on Figure 6-37), the robot should move to tags two and three which it calculated

it needed to do and then did so. In Figure 6-37, only a green path is shown. This indicates that only the algorithm to travel between tags was needed. Since the tags were at simple positions to find, no searching algorithms were needed.

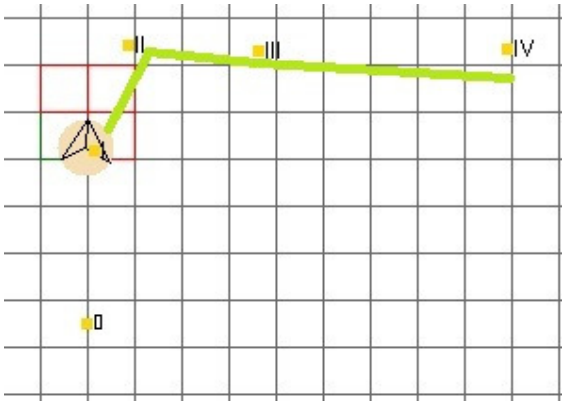


Figure 6-37: Path of the robot between tag 1 and 4; Green – path of the robot when it is on its best path algorithm

This test demonstrated the effectiveness of the 'best path' algorithm in determining which tags to move to in order to reach the destination with as much localisation as possible.

In conclusion, these three tests showed the need for:

- Localising a robot using RFID tags and the compass
- Searching algorithms to look for a tag when it is not picked up at its intended position
- Algorithms to find the best path to travel between RFID tags in order to utilise them

Chapter 7: Future improvements

The robot built in this research merely tests the concept of navigating a mobile robot in an indoor environment using passive RFID tags. Hence, in order to produce a robot to be used in industry many improvements are needed. This chapter mentions the improvements that could be made to the mobile robot in order to make it more able to detect obstacles, easier to detect RFID tags, less likely to make odometry errors, and have a faster communication speed. Some of these improvements would increase the cost and complexity of the robot so they may not necessarily make the end product better.

To detect more complex obstacles a servo motor holding an infrared distance sensor could be used. The servo could then be turned to discrete angles and the distance value read at this angle. By turning back and forth a broader and more detailed range of looking for obstacles could be made. Also, using just one sensor at the front would prevent the current need to change between the different analogue pins to read the analogue value from each distance sensor (see connections on Appendix E). This would make the program for reading the analogue data simpler, relieving the need for the microcontroller to keep changing which pin it is taking its measurement from.

Another method of detecting more complex obstacles would be to process the image received from the robot's camera. This data is already received through the camera's radio waves so all that would be needed is the algorithms to interpret obstacles from the image and approximate their distance from the robot. If the camera were correctly modified it could also provide the approximate distance of the objects it sees from the robot's camera (Xiaoming,

Tian, Wanchun, 2010). If this could be successfully carried out, the height and shape of obstacles could be determined. This would require a different method of mapping the obstacles unless the data was simplified to be a 2D representation.

The detection of the RFID tags that localise the robot could also be improved in a number of ways. Presently, the robot used in this research only has a RFID reader on its left side. To make detection of obstacles easier, another reader should be placed on its right side so that RFID tags to the right of the robot can be detected without needing the robot to turn around. Also, higher frequencies of RFID could be looked at as they have a greater distance of detection range. Some have even used high frequencies with long enough ranges so that the mobile robot can detect three RFID tags at one time and use the power of these signals to estimate the robots current location (Oktem & Aydin, 2010). Such a method could be investigated to improve the robot's localisation.

The robot's error in odometry could be minimized through using a compass less affected by external magnetic fields. The current compass used had many problems due to external magnetic fields as it does not have any protection against them. Due to this it could not be used to accurately correct the robot's error in orientation in an environment with significant magnetic fields. The robot's odometry error could also be minimised by having a bigger omniwheel at the front of the robot. Currently, the wheel is 10mm in diameter. This is small considering the size of the rest of the robot. Having a larger diameter would allow the wheel to properly touch the ground on uneven surfaces, making the robot less likely to slip in environments with slight dents or grooves on their surface.

The speed of the wireless communication greatly affects the amount and frequency of the data that is sent to the computer about the robot's surroundings. Increasing the baud rate from the current value of 9600bps to higher value may help to increase the speed. Other wireless protocols like Wi-Fi could also be considered as Wi-Fi can communicate information at a much faster speed than XBee can. Faster communication would allow more data about the robot's environment to be obtained at a faster speed, allowing better decisions to be made about how to control the robot.

The reliability of the robot also needs to be increased to ensure that its movement does not harm itself or others, and that there is no chance of a serious fault occurring when some unexpected situation arises. Safety and fault-preventing features would need to be implemented on this research's robot before it could be used as a commercial or industrial product. This may include more emergency stop features like push buttons on the side of the robot to ensure the robot stops if it touches an obstacle.

Chapter 8: Summary and Conclusions

8.1 Summary

This research has firstly shown a brief history of the development of mobile robots from the Chinese development of a mechanical warrior in 1023-957bc to the development of microcontrollers allowing more complex tasks to be done. The various interoperating methods in place to help navigate a robot to a certain destination have been discussed. These were:

- guiding the robot by using a map
- using odometry to estimate the robot's current position
- using localisation techniques to reset odometry's accumulated errors
- using an algorithm to determine how the robot travels in order to reach its goal
- using sensors so that the robot can avoid damaging itself or others

Mobile robots are essential for developing the modern world as they are increasing in ability and have a vast range of applications.

The environment used in this research is defined as:

- small, so that wireless communication can be continuous
- flat so that the robot's position can be determined most accurately using odometry
- free from obstacles that have thin parts on them hard to detect

The robot itself is constrained to be one that is inexpensive and simple. This would allow others to replicate its concept and improve it. Its mechanical system is a three-wheeled robot with two stepper motors moving the robot and a third to balance it. Using three wheels is more stable than two and allows the robot to turn around while changing only the orientation, not the linear position. Stepper motors allow the robot to move set known distances so that the robot's position can be estimated using odometry. Fibreglass, a light yet strong material, has been used as the basic structure that holds the robot's sensors, circuit boards, and motors. An omniwheel, composed of a spherical ball resting on three shafts, was used at the front of the robot to follow the movement of the other two wheels. Using such a ball enabled the robot to be turned and moved with full freedom, as opposed to the resistance created by a swivel wheel.

The stepper motors used were powered by two electromagnets, driven by a L298 dual full-bridge driver that takes in control signals from a L297 stepper motor controller. These two ICs allowed the motor to be controlled by a simple square wave from the microcontroller. An external DAC was used to control the peak current of the motors through giving an analogue value to the L297 motor controller. Infrared and sonar sensors were chosen for the robot and their data processed to detect obstacles blocking the robot's path. The compass and the RFID reader proved to be useful in localising the robot.

An XBee module at the PC and the robot allows transmission of the PC commands to the robot and the sensors' data back to the computer. The camera's radio transmitter enables live video from the robot to be captured and recorded on the PC.

Two ways of map building have been presented. The first is for a user to manually measure RFID tags' distances from one another, determine their positions on a map, and then put this position information manually onto the mapping software. The second is to build a map automatically through controlling a mobile robot, having the program simulate its position in the environment, and placing RFID tags on the map as it detects them.

Algorithms that use the maps made to navigate the robot made have been presented. These algorithms enable the robot to avoid obstacles in its path, plan how to move between several tags in order to more accurately reach a destination, and search around to find a tag when the robot has arrived at the position it expects it to be. The algorithms made have been tested by the program made on the computer. This program is able to simulate the robots movement and uses this simulation to decide how the robot should move. Three tests of these algorithms in the designed robot have been demonstrated that illustrate the need of an accurate, stable compass to correct the robot's orientation, the problem occurring from wheel slippage, and the benefit of using searching algorithms that make up for inaccuracies in robot movement.

The mobile robot made has shown that the method of localising a robot using passive RFID tags within an indoor environment works successfully.

8.2 Conclusions

To conclude, this research has shown:

- A mobile robot can be effectively located through using passive RFID tags around an indoor environment
- Using passive RFID tags can mean an environment can be quickly created with little expense
- An RFID map can be built accurately and quickly through automatically detecting the tags as the robot moves past them
- Intelligent searching algorithms can help a robot overcome position problems caused by the accumulated error resulting from odometry
- It is not safe to use a low resolution of distance data to build a permanent map due to the mere estimation of position using odometry
- Back sensors are not useful as their distance measurement is not reliable enough (due to position error) to be kept in the long term

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Appendix A: Obstacle avoidance decision algorithm

Obstacles are only regarded as necessary for some change in the robot's action if the robot is moving forward (reversing the robot would need to consider obstacles but this is only used once and straight after moving the robot forward). An operator may also turn the obstacle avoidance off if they do not want the robot to try to avoid obstacles.

When the robot detects an obstacle, what it does depends on the state it is in as shown in the pseudocode below.

Obstacle avoidance pseudocode

If the distance to the next RFID tag is more than 50cm away and the status is not:
  Moving forward and back @ RFID
  Doing a spiral search for RFID
  Doing an index search (when obstacle detected) around RFID
    If the robot is not already avoiding an obstacle
      Start performing the algorithm to try to move around the side of the obstacle. (The 1st step of this algorithm is to pause and recheck if there is really an obstacle in front of the robot to worry about).
    Else if it is then cause the obstacle avoidance routine to progress to the next stage (either avoiding on left side or complain to the operator).
Else if the robot is less than 50cm away:
  If the robot is moving straight to the RFID tag:
    If the distance from the front sensor is currently more than 15cm away and front-left & right sensors more than 20cm away then creep toward the RFID tag (that is more 8cm forward toward it).
    Else start turning around to search for the RFID tag since close enough to it
  Else if the robot is already creeping:
    If the front distance is less than 15cm then start turning around to search for the RFID tag since close enough to it.
  Else if the creep movement has finished and still more than 15cm away then creep forward again
  Else if the robot is doing a 'spiral search' or is 'moving forward and back @ RFID' then:
    Start the search using indexes around the RFID
  Else if the robot is already doing an index search:
    Mark that location as an obstacle and try to move to the next index

Appendix B: PC wireless communication procedure

Wait until all data is received from the robot before sending a command

Read all existing data in the wireless buffer.

Send the command to the robot wirelessly

Wait for one millisecond

Try to read the character from the wireless module and store it in ‘ack’ (acknowledgement) variable

Wait until a character is received (at most 100ms)

If the acknowledgement is equal to the command sent, then it must be correctly received so:

    If the command changed the direction of the robot, make the change to the robot moving on the PC

    Inform user the command has been read

    Exit procedure

Else

    Send the same command to the robot wirelessly

    Wait for one millisecond

    Try to read the character from the wireless module and store it in ‘ack’ (acknowledgement) variable

    Wait until a character is received (at most 100ms)

    If there is nothing received after 100ms then

        Inform user

Exit procedure

Else if the acknowledgement equals to the command sent:

If the command changed the direction of the robot, make the change to the robot moving on the PC

Inform user the command has been read

Exit procedure

Else

Inform user the command acknowledgment not read and say what has been read instead

Appendix C: C code for reading a serial bit signal manually

```
// For reading RFID signal at 9600 bps
void baud9600(void)
{
	//PORTC ^= 0x10; // toggle C4 for testing baud rate. 104us between transitions
	//		corresponds to 9600bps
	// byte format is: Start (1), Data (8), Stop (1), Idle(1)

	// when port initially becomes high we have a signal
	if ( ( (PINA & 0x20) == 0x20) && (RFIDStatus == 'N') )
	{
		// start of reading process
		// At very beginning of reading process. Wait until 1st low
		cli(); // clear any interruptions
		while ( (PINA & 0x20) == 0x20); // wait until the pin is low
		_delay_us(50); // wait until the middle of the bit
		sei(); // set global interrupts again
		RFIDStatus = 'S'; // start of reading process
		serialBitCount = 2; // set counter at 3rd bit of signal
		remainderBit = 2;
	}
	else {
		remainderBit = (serialBitCount % 11); // find out which part of data byte
program is at
	}
	if (remainderBit == 0)
	{
		statusByte = 0x00; // reset statusByte each for each byte of data
	}

	if ( (RFIDStatus != 'N' ) && (remainderBit < 9) && (remainderBit > 0) )
	// anything but not reading and within the data bit then add to status bit
	{
		remainderBit -= 1; // decrement to make shifting operation work
		if ( (PINA & 0x20) == 0x20)
		{
			// status byte will have a zero since signal is inverted

			//statusByte &= !( 1 << remainderBit); // make particular bit low
		}
		else
		{ // pin is low, representing digiatal '1'
			statusByte |= (1 << remainderBit);
		}
	}

	// Record the bit value for the 1st 30 values read from the signal
	/* Does not work as intended anymore
```

```
	if (serialBitCount < 30)
	{
		if ( (PINA & 0x20) == 0x20)
		{
			serialBits[serialBitCount] = '1';
		}
		else
		{
			serialBits[serialBitCount] = '0';
		}

	}
	*/

	TCNT0 = 1; // reset the time after reading the value

	// Put this in once you have a sure knowledge of what SerialBitCount 20 will give

	if ( (serialBitCount == 20) && (RFIDStatus == 'S') )
	{ // In correct mode and just read 1st byte
		if (statusByte == '4') // all RIFDs buttons will have this number at this position
		{ // correct this corresponds to a RFID button
			typeOfCard = 'B';
			RFIDStatus = '1'; // read 1st byte
		}
		else if (statusByte == '1') // all Jaycar RIFDs will have this number at this
position
		{ // correct this corresponds to a Jaycar Lanyard card
			typeOfCard = 'J';
			RFIDStatus = '1'; // read 1st byte
		}
		else if (statusByte == '0') // all Farnell RFIDs will have this number at this pos
		{
			typeOfCard = 'F';
			RFIDStatus = '1';
		}
		else
		{ // bad measurement
			RFIDStatus = 'E'; // error
		}
	}



	// Put the following in if you don't know what the format will be
	/*
	if (RFIDStatus == 'S')
	{
		RFIDStatus = '1';
	}
```

```
        */

        if ( (serialBitCount == 109) && (RFIDStatus == '1') )          // 109
        {
                uniqueIDA = statusByte;
                RFIDStatus = '2'; // read second byte
        }

        if ( (serialBitCount == 120) && (RFIDStatus == '2') )
        {
                uniqueIDB = statusByte;
                RFIDStatus = 'W'; // wait till end of byte
        }

        if ( (serialBitCount == 170) && (RFIDStatus == 'W') ) // end of text
        {
                RFIDStatus = 'F'; // Finish status
        }


        if ( (remainderBit == 10) && ( (serialBitCount / 11) < 20 ) ) // At end of character
        {
                serialBits[(serialBitCount / 11)] = statusByte;
        }


        serialBitCount++;

}
```

Appendix D: Example map holding RFID tags and obstacles

The format of the map is shown below:

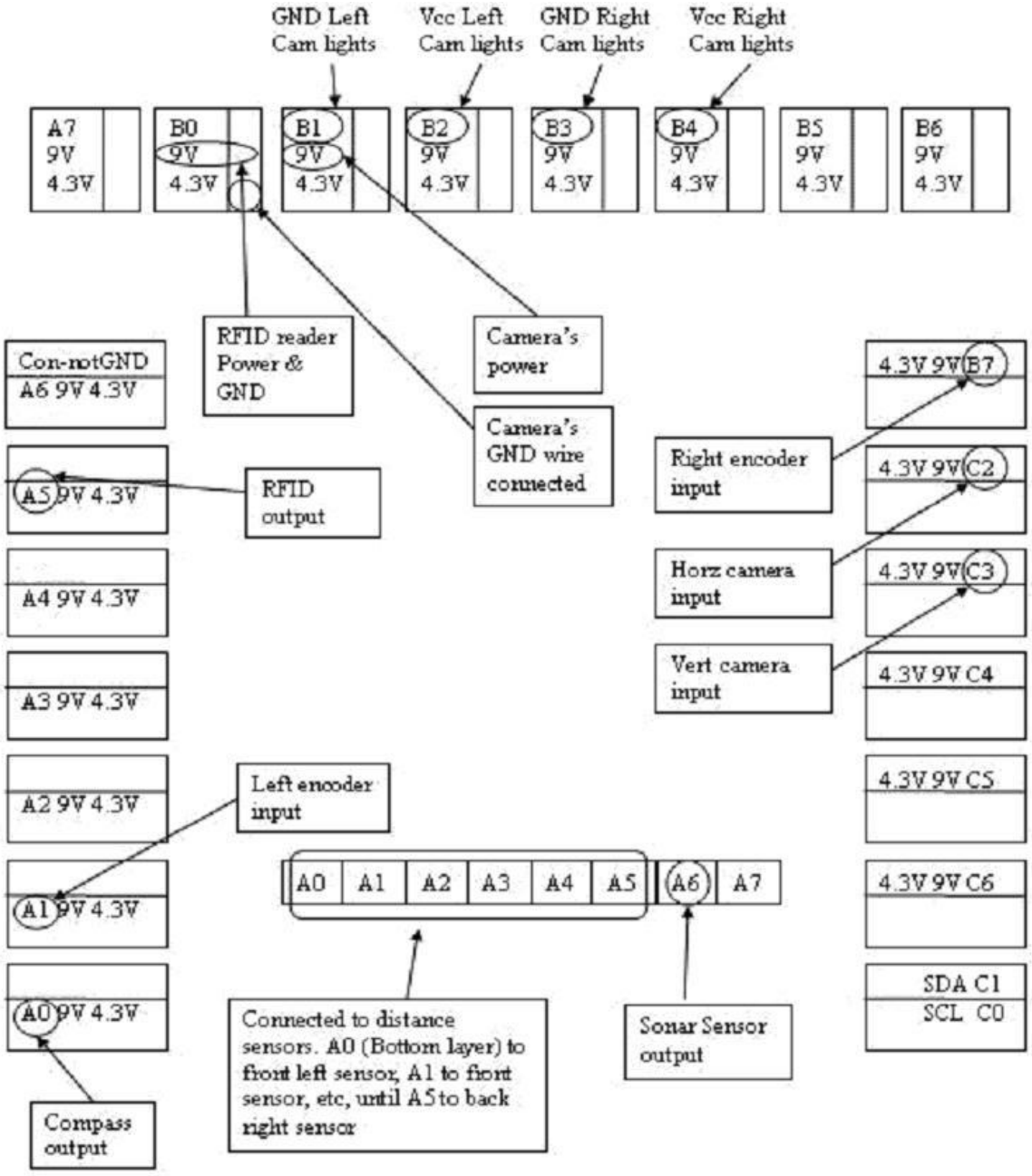
Width
{Width in cm}
Height
{Height in cm}
StartXPos
{Starting x pos in cm}
StartYPos
{Starting y pos in cm}
StartAngle
{Starting angle in degrees}
NumRFIDs
{NUM of RFID tags}
RFID0
{X coordinate of 1st RFID}
{Y coordinate of 1st RFID}
RFID1
{X coordinate of 2nd RFID}
{Y coordinate of 2nd RFID}
RFID2
{X coordinate of 3rd RFID}
{Y coordinate of 3rd RFID}
RFID3
{X coordinate of 4th RFID}
{Y coordinate of 4th RFID}
RFID4
{X coordinate of 5th RFID}
{Y coordinate of 5th RFID}
NumObstacles
{NUM of obstacles}
OBSTACLE0
{X coordinate of 1st obstacle}
{Y coordinate of 1st obstacle}
OBSTACLE1
{X coordinate of 2nd obstacle}
{Y coordinate of 2nd obstacle}
OBSTACLE2
{X coordinate of 3rd obstacle}
{Y coordinate of 3rd obstacle}
…Any more of obstacles
Comment
{Comment shown when map is loaded}
{Picture file shown when map is loaded or 'No Picture Selected'}
RobotStartIndex
{RFID tag the robot starts at. If -1 then use StartXPos, StartYPos}

An example of such a format is shown below:

```
Width
800
Height
600
StartXPos
50
StartYPos
50
StartAngle
0
NumRFIDs
8
RFID0
310
191
RFID1
519
132
RFID2
650
235
RFID3
715
407
RFID4
604
541
RFID5
507
321
RFID6
114
511
RFID7
279
379
NumObstacles
0
Comment
This is a map showing RFID locations
H:\MastersWork\Software\PCC#Prog\MapBuilding\Pictures\map3.jpg
RobotStartIndex
1
```

Appendix E: Connection of all the sensors to the robot

The following diagram shows how the mobile robot's sensors were connected to sockets on the robot's top circuit board.



Appendix F: Recursive function for finding possible paths among RFID tags

Following code written in C#

```
private void completePath(int currentPathIndex, int currentStopIndex, string currentPath, int
destination)
{
        string RepCurrentPath;
        RepCurrentPath = currentPath; // needed because 'currentPath' acted like pointer
        int newpathIndex = 0; // receives the globalPathIndex
        for (int i = 0; i < DemoMap.RFIDCount; i++)
        {
           if ((NumberInPathString(currentPath, Convert.ToChar(i)) == false) && i !=
destination && movingTowardPath(currentPath, i, destination)) // if the number is not in the
path, a new number then go there
           {
              globalPathIndex++; // new path
              newpathIndex = globalPathIndex;
              RobotPaths[newpathIndex].RobotPath = RepCurrentPath;
              RobotPaths[newpathIndex].RobotPath += Convert.ToChar(i); // add on next stop
              completePath(newpathIndex, currentStopIndex + 1,
RobotPaths[newpathIndex].RobotPath, destination);
           }
           else if (i == destination)
           {   // Horray! Complete another path
              RobotPaths[currentPathIndex].RobotPath = RepCurrentPath;
              RobotPaths[currentPathIndex].RobotPath += Convert.ToChar(destination);
           }
        }
}
```

Note:
An array is used to store all the paths. Each path is represented as a string of characters in the 'RobotPaths' array as can be seen by the 'Convert.ToChar' function above.
This algorithm basically starts at the current RFID index position and then goes from 0, the lowest RFID number to the total number of RFID tags there are and goes through every possible combination. The index 'i' represents the current tag being looked at. The possible combinations never include the exact same sequence of numbers twice in their path. Otherwise there would be no end in the number of paths. Whenever the destination is reached, that path is completed and added to the array of paths (called 'RobotPaths').

Appendix G: Obstacle colours depending on the number of points within a grid

Individual obstacle pixel table

Number of points	Time elapsed less than	Colour of square drawn	Width of square drawn
1	2	Red	2
2-4	n.a	Light Blue	2
5-9	n.a	Blue	2
10-99	n.a	Dark Blue	3
100+	n.a	Black	5

Obstacle points within a 25cm grid

Number of points	Time elapsed less than	Colour of square drawn	Width of square drawn
14	5	Light Green	Grid size -1
40	n.a	Brown	Grid size -1

Notes:

The grid size depends on the scale factor of px to cm i\n the map created. For a scale-factor of 2.5cm/px, the grid size will be 25cm / 2.5, which is 10px. The width of the square drawn will therefore be 9px.

Appendix H: AT mega 32

The AVR AT mega 32 microcontroller created by Atmel has 4 ports (A to D) that each have 8 pins. That makes a total of 32 pins to be used for receiving and sending digital data. The way these ports are set out is shown in Figure H-1. The pins in each port can be configured independently from one another. For example port A could have 3 input pins and 5 output pins. Each of the pins also has a special function that can be used to perform useful operations. For example, port A has 8 ADC pins that allow the microcontroller to interpret up to 8 different analogue signals.

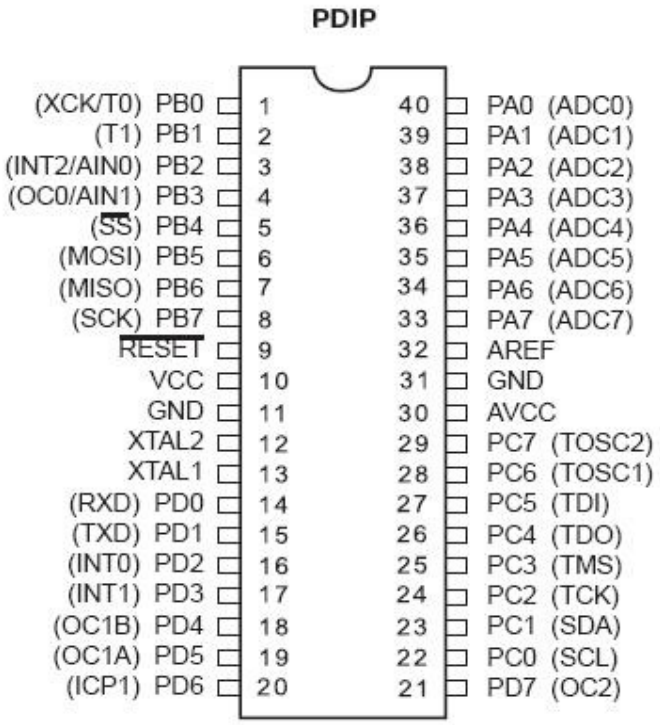


Figure H-1: Pins for AT mega 32 microcontroller (Atmel, 2009, pg. 2)

The microcontroller uses the efficient architecture designed by Atmel to perform 1 MIPS at 1MHZ. That means that when a 1MHz crystal is connected, it is able to perform 1 million instructions per second. It is a low-powered device, using approximately 1.75mA supply

current for a supply voltage of 5V when the frequency is 1MHz. The current versus frequency characteristics for different voltages is shown in Figure H-2.

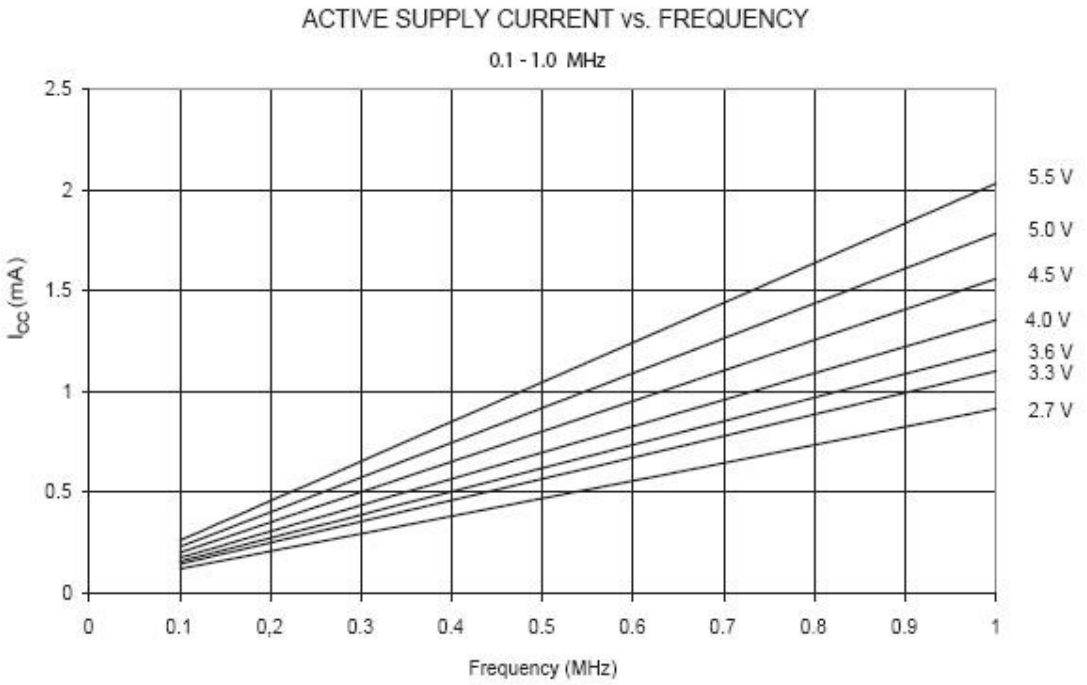


Figure H-2: Supply current of AT mega 32 versus oscillator frequency, (Atmel, 2009, pg. 296)

The AT mega 32's features (Atmel, 2009) include:

- Storage of up to 32 K Bytes of programmable Flash data that can be retained for 100 years at 25 degree's Celsius.
- Two 8-bit timers and one 16-bit timer
- Four PWM channels to produce PWM signals
- An 8 channel, 10 bit ADC
- A simple Two-Wire Serial Interface to communicate with TWI devices
- A serial USART

Appendix I: GP2D120 Infrared distance sensor

The GP2D120 is a an infrared distance sensor that detects objects from 4-30 cm away from itself and outputs an analogue voltage that can be used to find the distance it has detected. As can be seen from Figure I-1, the voltage values before 4cm can be mistaken for those after 4cm. However from 4 to 30cm a steady curve is shown. Therefore, this device is not able to handle objects that are less than 4cm to it.

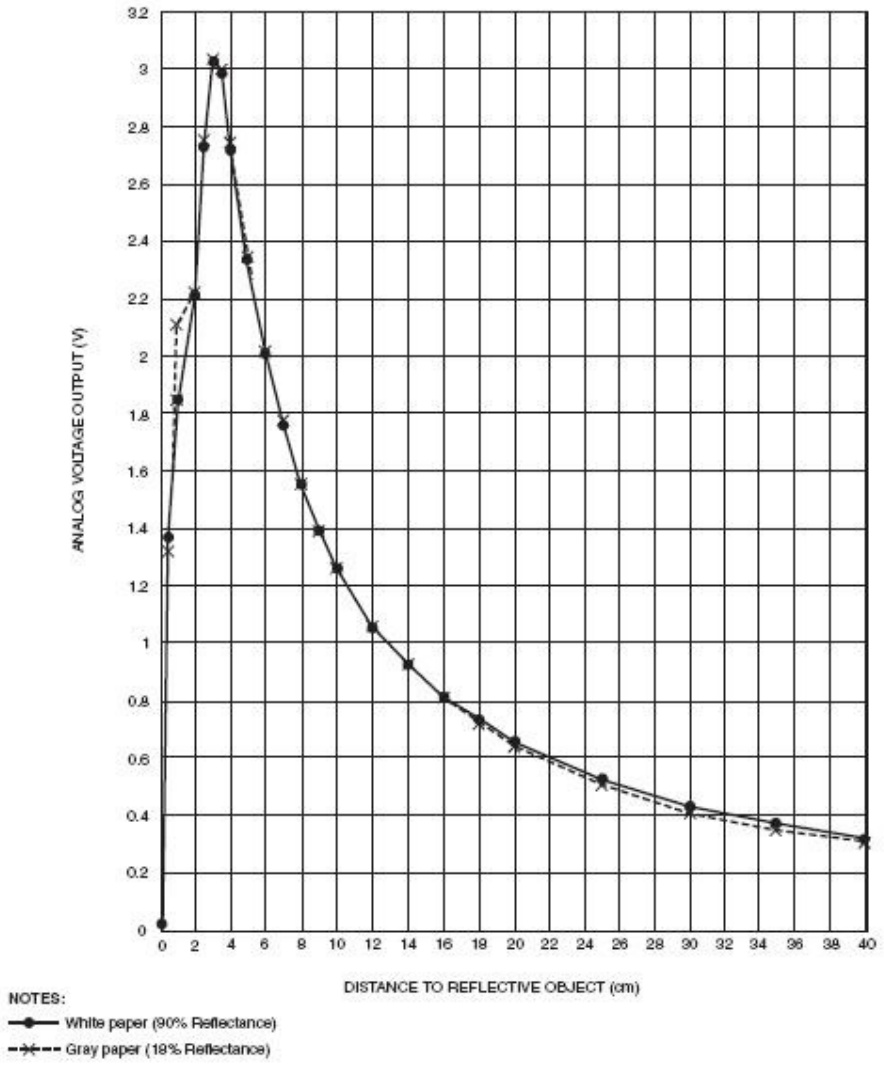


Figure I-1: Analogue output voltage for GP2D120 sensor versus its distance to an object, (Sharp Corporation, 2006, pg. 4)

The dotted line on Figure I-1 represents the detection of grey paper. This nearly perfectly overlaps the solid line showing that the sensor is affected very little by differences in the reflectance level of an object. The sensor has inbuilt processing which alleviates the need of any devices to process the signal before it is read by a microcontroller. The block diagram of how it works is shown in Figure I-2.

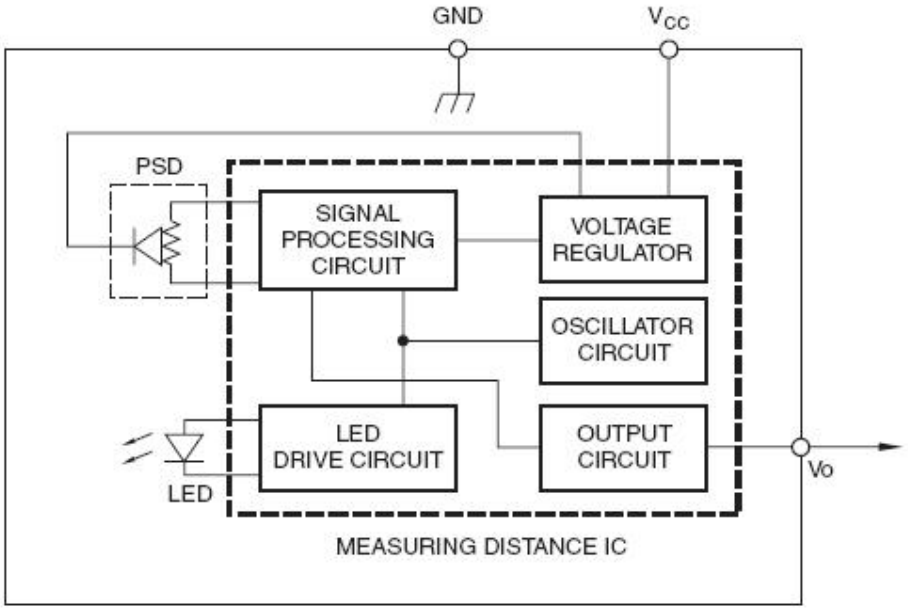


Figure I-2: Block diagram for GP2D120 Sharp sensor, (Sharp Corporation, 2006, pg. 1)

Appendix J: Compass CMP03

The CMP03 compass is designed for use in assisting robots in navigation. The output from two Philips KMZ51 magnetic field sensors placed at right angles to one another is used to generate a unique number that represents the angle the robot is facing. This number is represented on the compass by two signals that can be easily read by a microcontroller. The first signal is a wave with pulses that vary from 1ms to 36.99ms to represent an angle from 0° to 359.9°. The second is using an I2C signal to get a serial representation of the angles by using the SDA and SCL pins on the circuit. The top view of the CMP03 compass is shown in Figure J-1.

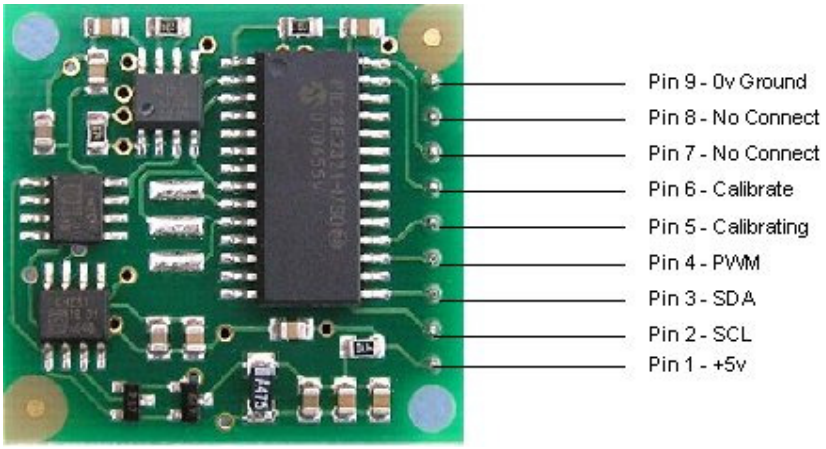


Figure J-1: Top view of CMP03 compass, (Robot Electronics, 2007, pg. 1)

Appendix K: Sonar sensor MB1300

The MB1300 shown in Figure K-1 is a sonar distance sensor. It adjusts itself automatically for changes in temperature, voltage and electrical noise to ensure a reliable distance reading every time it is used. Objects from 0.1cm to 20cm are detected but their distance is just displayed as 20cm. Therefore, it is not able to distinguish how close objects are when they are too close. The sonar sensor gives distance readings up to 765cm with 1cm resolution. However its signal width increases as its distance increases, as Figure K-2 shows. The outputs it has include a real-time analogue voltage envelope, an analogue voltage output and a serial digital output.

Figure K-1: MB1300 sonar sensor, (MaxSonar, 2011, pg. 1)

Figure K-2 shows the spreading of the beam characteristics of the MB1300. Dowels of 3 diameters (6.1mm, 2.54cm, and 8.89cm) were used to produce the 3 detection patterns shown. The grid in Figure K-2 is 30cm for each square. By observing it is obvious that the sensor will detect the ground when placed low down on a robot after a as the distance from the sensor increases.

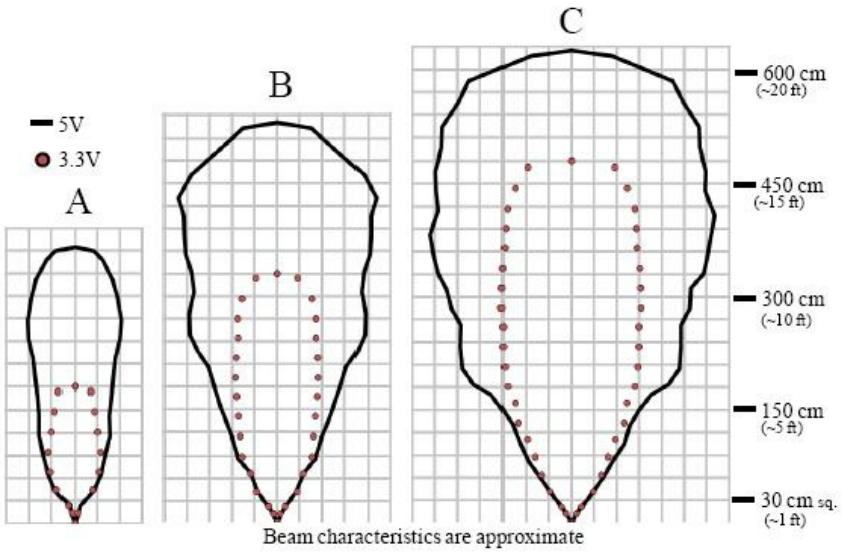


Figure K-2: Beam characteristics of MB1300, (MaxSonar, 2011, pg. 3)

Appendix L: ID 40 RFID range reader

The ID-40 RFID range reader shown in Figure L-1 is designed to read passive RFID tags at a frequency of 125kHz. With ID-Innovations long range card, the reader is able to detect tags at a typical range of 25cm. It is encapsulated within a hard plastic container to protect it from the environment. Digital Signal Processing is used to eliminate noise in the signal received. The output is either:

- A chain of ASCII characters
- Wiegand 26
- Magnetic ABA track 2

Figure L-1: ID-40 RFID range reader, (ID Innovations, n.d, pg. 1)