# Mechatronic Design and Construction of an Intelligent Mobile Robot for Educational Purposes

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# ABSTRACT

The main aim of this project was to produce a working intelligent mechatronically designed mobile robot, which could be used for educational purposes. A secondary aim was to make the robot as a test-bed to investigate new systems (sensors, control etc.) if possible.

The mechatronic design of the robot was split in to three sections: the chassis, the sensors and the control. The design and construction of the chassis unit was relatively simple and very few problems were encountered. The drive system chosen for the robot was a four-wheeled Mecanum drive. The major advantage of this system is that it allows multiple degrees of freedom while keeping the control and the number of drive motors to a minimum.

The design and construction of the sensors was the main research section. The sensor design evolved around the use of ultrasonic sensors. While a phased array type arrangement was tried with the intention of improving the angular accuracy of the sensors, the use of frequency modulation was used in the end and it proved to be excellent except that the problem of angular accuracy was still not solved.

The entire mechatronic system was completed except for the micro controller programming. It operated well when it was given the correct inputs and performed all of the functions it was designed for.

It is strongly recommended that further work be done on the use of a computer motherboard instead of the current micro controller as this would allow for easier programming, more complex programs and easy implementation of map building.

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# 1 AIM, OBJECTIVES AND CONCEPTUAL IDEAS

## 1.1 Aim

The main aim of this project was to produce a working intelligent mechatronically designed mobile robot, which could be used for educational purposes. A secondary aim was to make the robot as a test-bed to investigate new systems (sensors, control etc.) if possible.

## 1.2 Objectives

The objectives of this project were as follows:

1) Create a working mobile robot.
2) Make the sensor system by means of which the robot can avoid objects in a cluttered room.
3) Give the robot some intelligence so that it can adequately avoid obstacles.
4) Make the robot in such a way that it can be built on in future projects.
5) Make the robot self-navigating (if there is time).
6) Carry out some new research on one or more aspects of the design.

The following sections are about the requirements for each part of the robot and the intended solutions.

## 1.3 Mechanical/drive system

### 1.3.1 Requirements

The requirements for the robots mechanical configuration were that the robot had to be able to manoeuvre in tight spaces. It had to be stable. It had to be able to operate by battery power and it had to be robust.

### 1.3.2 Mechanical complexity

The complexity of the drive configuration decides the mobility and agility of a mobile robot. It was not seen as a major problem because the physical aspects of a mobile robot are relatively easy to build (apart from the space requirements). Also the mechanical design and construction is straight forward although time consuming and as long as everything is built strong and light enough with consideration being taken for the circuitry, navigation etc. there should not be any major problems.

### 1.3.3 Proposed drive configuration

The proposed drive system uses a four-wheeled Mecanum drive. This was chosen because the Mecanum drive has multiple degrees of freedom, which give good mobility and agility. The Mecanum drive also uses very few motors, which keeps the complexity of the programming to a minimum. The Mecanum system is where the wheels have free rotating rollers around their circumference. These rollers are set at 45º to the normal direction of travel. The rollers are also made in such a way as there is at least one roller in contact with the ground at all times.

Figure 1.1 (page 3) shows the types of movements that can be achieved with a four-wheeled Mecanum drive system:

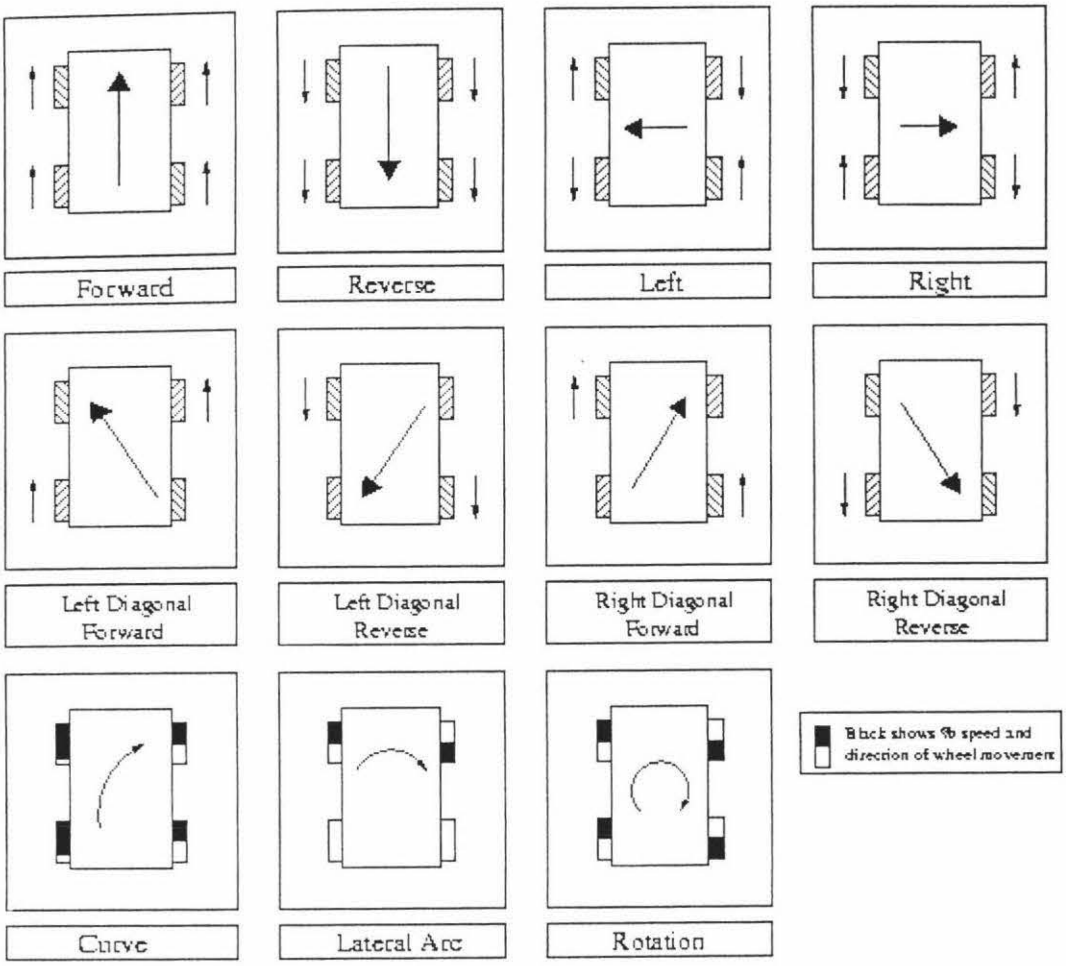



Figure 1.1 Some of the different drive directions possible with a Mecanum drive system. Adapted from [20].

A four wheeled Mecanum drive system requires one motor for each wheel but due to there being no steering of the wheels the only complexity is in the construction of the wheels themselves. It is however believed that the wheels can be constructed relatively easily using the facilities at Massey University. For rigidity and ease of construction it is recommended that the construction of the chassis and wheel units be made from aluminium. Aluminium also has the advantage of being lightweight. For the circuit box it is also recommended that aluminium be used for the same reasons but it will need the use of some insulation material. The rollers on the wheels will need to be made from plastic in order to increase the grip as they only have point contact with the ground.

It was proposed that the use of all of the drive directions shown in Figure 1.1 be implemented except for the curve and lateral arc as these required more difficult control of heading and motor speeds. The remaining drive directions are easy to implement, as they only require three states; forward, reverse and stopped. These can be achieved through the use of motor controller chips.

# 1.4 Control

## 1.4.1 Requirements

The control needs to enable the robot to make a choice about what direction to go in when an obstacle is encountered. It also needs to make sure the robot does not get stuck. This then necessitates a control strategy, which either avoids repetition, or avoids local minima.

## 1.4.2 Electronic Complexity

The complexity of the electronics is not considered to be a serious problem although it will have to be kept to a level, which will be able to be implemented on a small mobile robot and within the time constraints. This of course depends on the complexity of the sensors, the control and the navigation. If the robot creates its own maps or has to store maps the circuitry will of course be more complex because a large memory is required.

## 1.4.3 Difficulty of Programming

The programming can be made easier by splitting the required programming into navigation, sensor control, motor control and robot strategy. The programming could also be done on a higher level programming language but this would involve putting a computer on the robot, which may be a possibility if there is time or it could be the subject of a future project.

## 1.4.4 Proposed control strategy

Firstly it was proposed that a modular system be used for the electronics where extra or different control systems, memory etc. can be put in or swapped at a later date. Also the circuits should be properly designed and etched so as to produce optimal performance, cut down on space and reduce wiring/connection problems.

For the actual control system two micro-controllers should be used. One is for the motor and direction control and the other one is for the navigational control. These micro-controllers will have to work together but by making it a master/slave relationship there should not be any problems. It is also proposed that the two micro-controllers should be able to work separately so that the drive and/or navigation systems can be changed at a later date. Also this should help in the testing stage as it makes each part simpler.

The programming of the motor control should be simple as the instructions given to the motors are simple and there are only a few outputs and inputs. The programming of the navigation system will likely be a lot more difficult as it requires the timing and comparing of several inputs. This is likely to be the most difficult part of the project and initially it is intended to keep it as simple as possible.

# 1.5 Sensors

## 1.5.1 Requirements

The main requirement of the sensors is that they can detect obstacles at a range sufficient enough to avoid obstacles. Secondary requirements are that the sensors should be accurate and be able to detect the majority of common obstacles. If map creation is used then the sensors also need to be accurate in both distance and angle.

## 1.5.2 Complexity

The complexity of the individual sensors is not seen as a significant problem as most sensors come as a package. The operation of the sensors is however more important due to the limited computing power available. The use of the sensors is however considered to be a significant and vital part of the project.

## 1.5.3 Proposed sensor system

The sensor system proposed was to use ultrasonic sensors for detecting the range and angle of obstacles. The sensors would be placed in an arrangement similar to radar where there is one detector on either end of a rotating beam. This beam is horizontal and is rotated at the centre. The transmitter is also fixed at the centre. The system is intended to work in the following way:

1) The transmitter sends out an ultrasonic pulse at intervals. These intervals are sufficiently far apart to allow the previous pulse to return and be recorded before the next one is sent out.
2) The receivers both pick up the returning signal (if there is an object present).
3) The two signals from the sensors are then added together.

4) The resulting signal is then given to a peak detector and when the object is equally distant from both sensors the peak will be at its highest magnitude. This means that the angle can be measured from the angle the beam is at when the peak is at its maximum.

5) The return delay of the signals is also recorded when the maximum peak is reached. This gives the distance measurement of the object.

There was no intention to use any alternative types of sensor because the aim was to try and get the ultrasonic sensing good enough to avoid all obstacles before the robot gets close enough to hit them.

# 1.6 Navigation

## 1.6.1 Requirements

The robot is required to navigate in a room/corridor type environment without bumping into obstacles. A secondary requirement may also be to avoid other moving objects in the environment. It is also considered that the room or corridor may be cluttered and there may be many narrow objects such as chair legs.

## 1.6.2 Complexity

The navigational complexity must be such that the necessary computations can be made by the robot while allowing the robot to move at a reasonable speed. The number of sensors required for the navigation also needs to be kept to a small number to reduce the amount of information processing. The navigation must also be able to handle the majority of situations the robot is faced with and therefore a reasonable complexity will be required to achieve this.

## 1.6.3 Range

The range of the sensors needs to be sufficient to allow the robot to avoid obstacles in the environment. This means that the robot must have enough space to stop in before it hits the obstacle. A secondary requirement is a sufficient range for the robot to be able to see which path is best.

## 1.6.4 Accuracy

The navigation also needs to be relatively accurate so that the robot is able to see the majority of obstacles and doesn't see fake obstacles (phantom obstacles which are caused by reflections etc.). Also if map building is to be used then the navigation needs to be accurate enough to build a meaningful map of the environment.

### 1.6.5 Proposed navigation technique

The proposed navigation technique was to use local mapping where the robot creates its own maps from sensor scans. The map would consist of an array of cells. The cells will each contain a probability that an obstacle exists within the area of the cell. The reason for this was to hopefully overcome one of the major problems with ultrasonic sensing which is that of reflections causing fake obstacles. The reasoning behind this is that as the robot moves the fake obstacles will only be in a particular position at a particular angle. This means that the cells where a fake obstacle is detected will not register that an obstacle is there because the majority of the sensor sweeps will register no obstacle producing a low probability of an obstacle existing in the cell.

As the robot moves the map will also move with it. This means that the robot will always be able to choose the best path through the obstacles around it by consulting the map.

# 2 LITERATURE REVIEW

## 2.1 Introduction

This literature review was carried out in order to obtain a general idea of what has already been done in the various fields of mobile robotics in which this project is involved. The second aim of the literature review was to obtain an understanding of the specific topics that are covered by this project. The final aim of the literature review was to identify new research topics or continuations of research that could be used as a basis for the project.

Throughout the literature review the majority of the emphasis is placed on topics that relate either directly or indirectly to the various sections of the project. This was done so that the aims of the project became more focussed. Another reason was that there is not much point in reviewing literature, which has little or no bearing on the project being undertaken.

Each section of the literature review also has a general discussion of the various characteristics and techniques. Contained within this, there is also a discussion of their advantages and disadvantages with respect to this project.

## 2.2 Configuration

### 2.2.1 Drive Types

The lack of modern literature on this topic (except for non-research literature) indicates that this field has already been thoroughly researched. The exceptions to this are the more unusual drive types and walking robots. Through the process of tracking down literature it was discovered that walking robots are still a highly researched topic but the majority are very complex both mechanically and in the programming. This would make the robot too difficult to construct within the time and budget constraints. For this reason walking robots are not included in the literature review.

## Tricycle Drive

Tricycle drives cause the vehicles centre of gravity to move away from the front wheel on an incline causing loss of traction [3]. Tricycle drives are also often used for AGV applications because of their inherent simplicity [3]. Tricycle and Ackerman steering systems are similar to the steering mechanism on a car [20]. There is however no mention that Ackerman steering is more stable and also more difficult to construct.

## Ackerman Steering

Ackerman steering is used almost exclusively in the automotive industry [3]. Unfortunately there is no supporting statement to say why this is but the assumption would be that it is difficult to implement compared to other robot drive configurations.

## Differential Drive

The differential drive has problems with the drive wheels occasionally loosing contact with the ground [20]. This only occurs in rough terrain and it can be improved by the correct placement of the caster wheels. Miss matches in the motors or drive in the differential drive causes the robot to veer to one side making steering difficult [20].

## Synchro Drive

The Synchro drive has very simple software control [20]. All other literature on this topic points to the same conclusion. The Synchro drive suffers from increased mechanical complexity [20]. There may be errors in wheel alignment for the Synchro drive mechanism [3]. This is mainly caused by the slack in the belts or gears. There may also be problems with friction when the wheels turn [3]. Of the problems mentioned the second problem can easily be overcome by making the turning system more powerful but the first problem may cause friction while the robot is moving and may also introduce errors if Odometry is used [3].

## Tracks

The use of tracks is a special implementation of the differential drive where skid steering is used [3]. Skid steering relies on wheel slippage resulting in poor Odometry measurement. This is why tracked vehicles are generally only used for tale-operated robots [3]. If however the robot relied on a different source of distance measurement then the skidding action would not be important. Tracked vehicles are generally used for surmounting floor discontinuities [3]. Tracked vehicles are definitely better at this than the other types of drive configuration except for walking robots, which can have the ability to step up, down or over discontinuities.

## Multi-Degree-Of-Freedom (MDOF) Vehicles

Multi-Degree-Of-Freedom (MDOF) vehicles display exceptional manoeuvrability in tight quarters in comparison to conventional mobility systems [3]. All other literature read confirms this and it is because the robot does not have to turn corners to get around them i.e. the robot can travel in any direction without turning.

In general it is thought that [20] places too much emphasis on suspension systems where they are not really needed. This is because none of the other text read mentions this and all of the robot systems seen working operate perfectly well without suspension. It may however be important in situations where the drive type requires all wheels touching the ground at all times in order to work.

In general [3] does not reveal much information about the different drive systems when compared to the other sections of the book. This is probably because the drive systems mentioned are all relatively standard and therefore it is considered that enough is already known about them. Also it would take up a lot of time and effort to go into the more unusual drive configurations in any detail.

### 2.2.2 The Mecanum Principle

The Mecanum principle, although it is complicated to construct has the advantage of being Multi-Degree-Of-Freedom (MDOF). Another advantage of the Mecanum principle is that it does not require any turning of the wheels. This cuts out some of the major inaccuracies in steering. The following is a review of the current literature on the Mecanum principle with respect to its use in mobile robotics. It would take six motors to provide the same degrees of freedom as a four wheeled Mecanum drive system using four motors [20]. Another minor point about the Mecanum wheel is that the rollers on the wheel only have point contact with the surface eliminating scuffing [20]. This may also introduce the problem of slipping which reduces the effectiveness of the movement. The Mecanum principle gives a practical way of providing simultaneous vehicle motion in all three directions, longitudinal, lateral and yaw [20]. One of the problems in the construction of a Mecanum drive system is that the wheels have to be orientated correctly and failure to do so results in degradation of the vehicles motion [20]. This however is very simple and is not really a serious problem. The control of a Mecanum wheeled robot is easier and less complex than some of the regular drive configurations [20]. It is similar to the control of a differential drive vehicle, which is very simple, except that there are four wheels to control instead of two. Due to the unrestricted manoeuvrability and simplicity of control, these vehicles are especially adaptable for autonomous or tele-operated operations in tight and cluttered spaces [25]. This is an example of the manoeuvrability of the Mecanum drive system. Any combination of forward, sideways, and rotational movement is possible [26]. Due to the omnidirectional driving concepts this allows the wheelchair to move even within packed indoor environments because of a non-restricted positioning capability [26]. This is another example of the manoeuvrability of the Mecanum drive system. The vehicles presently employed for warehouse and shipboard materials handling operations manoeuvre with precision and operate under low traction conditions, on steep ramps, and over obstacles [25]. This gives a good idea of what a properly constructed Mecanum based system can achieve.

## 2.3 Sensors

In general there is a lot of literature on sensors but most of it is from companies trying to sell their products. There is also a lot of literature on applications of sensors and sensor fusion but this does not mention much about the sensors themselves. This review attempts to use a balance of the two types to get a good picture of what is available and what has been done.

### 2.3.1 Odometry

This section covers sensors that are used for Odometry or Dead Reckoning. Odometry systems are self-contained but on the down side the position error grows without bound unless an external reference is used occasionally, the foremost error in odometry is that any small momentary orientation error will cause a constantly growing lateral position error [3].

There is a good range of different optical encoders and velocity sensors that can be used to measure the motion of a robot [3]. A good description of each, how they work, what they are most suited to, advantages and disadvantages etc. is given by [3]. The description of incremental and absolute optical encoders is particularly informative but unfortunately hardly any information is given on ultrasonic speed sensors except that they work on similar lines to Doppler speed sensors i.e. speed is measured by the compression of sound waves and the corresponding change in frequency is proportional to the speed.

A short description of optical encoders is given by [8] but no detail is given. Shaft encoders are used in all of the Eye-Bot family of robots [5]. The encoders are used via a PI controller to maintain constant wheel speed, keep the robot moving in a straight line and to update vehicle position and orientation [5]. Unfortunately there is no mention as to how efficient or accurate this is.

There is always some differential slippage in the wheels, which can cause pure dead reckoning systems to go awry [15]. This is backed up by the statement that there is positioning error due to wheel slippage or uneven ground [24] and [21]. Also for some drive systems (such as tracked vehicles) the wheel slippage is such that no meaningful information can be obtained from the sensors. Dead reckoning (or Odometry) should be used with some other form of external sensor and compare positions on a map and thus estimating the position [15] and [24]. This would be a good idea as the other sensors or external referencing can be used to nullify the errors in the odometry and vice-versa.

In general from the literature read it seems that Odometry is not a topic, which is currently being researched except in combination with other techniques. It also appears that most scientists do not view Odometry as being very accurate and thus they are looking at more accurate systems and at systems, which give some range information.

## 2.3.2 Heading

This section covers sensors that are used to determine a robots direction. These sensors can be used in compliment with Odometry sensors to give a direction or with range sensors to give a direction (usually in both cases to a point on a map).

Heading sensors are most often used to compensate for the foremost weakness in Odometry, which is from errors due to slippage [3]. The two most common types of heading sensors are gyroscopes and compasses [3]. An extremely good description of the different types of gyroscopes and compasses giving the advantages and disadvantages of each is given by [3]. An indication of the cost is also given and it is stated that some of the more accurate gyroscopes and compasses can be very expensive. A good general description of gyroscopes and how they work is given by [8] but the description does not go into any detail. Offset error leads to continuous drift from changes in temperature over time [22]. This is only for a specific type of gyroscope but other gyroscopes seem to have problems with the offset error as well.

In general apart from [22] there does not seem to be much research being undertaken with heading sensors. This is probably because companies are carrying out most of the research and development in order to produce new types or improvements. Also it is a relatively mature field where a lot of money has to be invested in order to produce only small improvements.

### 2.3.3 Tactile

This section covers sensors that are used for touch sensing. Sensors of this type were not considered as useful for the project as one of the aims was to try and avoid objects rather than reacting when the robot comes in contact with the object.

Most scientific literature and research on mobile robotics also seems to be moving away from the use of tactile sensors except for in legged robots and robotic arms used for pick and place type applications.

### 2.3.4 Range

This section covers sensors that can detect obstacles at a distance from the robot. This section was considered to be very important, as one of the aims was to try and avoid objects, which is what range sensors are used for.

#### Infra-Red

The IR range sensors that were used in the Eye-Bot family due to a number of reasons generate false readings from time to time [5]. This is also consistent with most other IR sensors. The accuracy of an IR range finder is reflectance dependent [21] i.e. errors become significant when the return signal is weak.

## Ultrasonic

Ultrasonic sensors are not good at detecting angle but the range resolution is accurate [24]. Detecting the angle seems to be a common problem with range sensors but this should be able to be overcome by scanning or by using two sensors and triangulating the readings. A good general description of ultrasonic and optical range finders and how they work is given by [8] but it is not covered in any detail.

## Ground based RF beacons and GPS

An entire section is devoted to ground based RF beacons and GPS systems by [3] but both of these systems are well beyond the range of this project in budget. They are also more suited to long range out-door applications.

## Laser Scanners

A good description of a 2-D laser scanner and its application to environment modelling is given by [12]. The complexity of calculations and noise however make this system difficult to implement. The cost of laser systems was also prohibitive for their use in this project.

## 2.3.5 Ultrasonics

The use of ultrasonics seems to be the best option due its low cost and reasonably accurate ranging. It is however not very good with angular accuracy but this should be able to be overcome through the sensor arrangement. The following is a review of the current literature on ultrasonics within the mobile robotics field.

A very good description of the problems associated with obstacle detection using ultrasonic range finders is given by [2]. If a surface is perpendicular to the sensor then most of the energy will be reflected back but if the surface is at right angles only an undetectable amount of energy will be reflected back [2]. A good description of why this occurs is also given. In the situation where most of the energy is reflected away from the sensor there is also a chance that it will then reflect off another obstacle and back to the sensor. In this case the sensor would see a false obstacle (an obstacle which is not where it seems to be) similar to what we see when we look in a mirror.

The amount of reflected sound depends strongly on surface structure of the obstacle and that unfortunately most common indoor objects have a smooth surface, which decreases the amount of reflection [2].

Increasing the frequency (decreasing the wavelength) increases the amount of reflection but increases the energy dissipation [2]. Another side affect of this is that the signal processing required is also much more difficult at high frequencies.

The angle of a smooth surface, which can be detected, can be up to 40-45º if a high receiver gain is used [2]. It is also mentioned that this causes a decrease in directionality and occasional misreading of distance.

The directionality of the transmitters can also cause problems [2]. This is because as the sound spreads out and bounces back, if there is a wide angle of spread we are less likely to know from where it was reflected.

Environmental noise is very likely to occur when more than one robot is operating in the same environment [4]. There is no mention however to noise created by other machinery or whether there are any ambient noise problems. Further reading seems to suggest that ambient noise or noise from machinery is not a significant problem as the frequencies used are not common and are very confined. Cross-talk noise is when one sensor picks up the signal emitted by another sensor on the same robot [4]. Ref. [4] then goes into detail about the methods of rejecting noise and does a good job of explaining how it is achieved.

The main problem with sonar (ultrasonic) sensors is that instead of bouncing back toward the sensor. The sound pulse can hit an obstacle and bounce away from the sensor. Then either the sensor sees nothing or objects, like reflections in a mirror, appear to be much farther away [23]. This is a very good description of what is a major problem in ultrasonic sensing. This is also backed up by [17]. Ref. [23] however does not mention angle or dispersal, which may also cause problems where the angle is also important for determining position.

Ultrasonics do not have any problems with dark or dim conditions, luminosity, colour or transparency because they do not work by optical means [17]. Ultrasonics can however be affected by temperature and humidity [17]. This would be because these change the acoustical properties of the air making sound travel faster or slower. This should not be a severe problem except in extreme conditions and if the accuracy was vital then a temperature sensor could be incorporated and the appropriate adjustments made accordingly.

The minimum step size, which can be taken, is determined by the maximum distance at which the hardest object to detect (an edge) can be detected [11]. The method used by [11] uses the previous statement as its basis and also uses angular detection by rotating the sensor and finding the central peak of any signal, which occurs.

As a consequence of the detection mechanism in the sonar, the depth reading refers to the depth of the nearest reflecting surface [6]. There is no mention as to what happens when the nearest surface gives a much weaker signal than a surface behind it and it would be reasonable to assume that the larger signal would drown out the smaller one. Not much reference is given to this problem in other texts and it may be that the problem is one of different objects being more difficult to detect than others.

Ref. [6] goes on to describe a good method of the use of a rotating ultrasonic device. No reference is given as to how the method overcomes any of the major problems of ultrasonic sensing. This is probably due to the main concentration of the article being on the World Modelling system.

An ingenious method for three-dimensional detection of objects using ultrasonic sensors is described by [7]. The system works by using triangulation of the return signal by three sensors set at the corners of an equilateral triangle. This system gives accuracies of a few millimetres in distance and a few degrees in angle and elevation [7]. This statement is well backed up by the text and shows a reasonable solution to the inherent angular accuracy problem of ultrasonic sensors.

There seems to have been a lot of work in recent years involving ultrasonic sensors but the majority of it seems to be in better use of the information obtained from the sensors. A lot of the work that has been done on the sensors also seems to be theoretical and simulation based rather than practical implementations of sensor systems. Some work has also been done in trying to cut out or eliminate some of the problems associated with ultrasonic sensors and it is obvious that there is still plenty of opportunity for research in this area.

## 2.4 Control

In general the novel and new techniques of control such as Fuzzy Logic, Neural Networks and Genetic Algorithms/Programming seem to be very hot topics at the moment. The regular type control methods now only seem to appear when another topic is being tested in order to cut down on programming difficulty in the available literature.
The following sections only give a small review of the main points.

### 2.4.1 Regular Control

Regular control seems to have been used for almost every application before Fuzzy Logic, Neural Networks and Genetic Algorithms/Programming took over certain applications due to being better able to cope with the situation. Regular control covers such a broad range of applications and types that it would take too much work to cover them all. Also due to them only being mentioned in modern literature where some other research topic is the main topic it seems that research has moved away from this field. For these reasons a review of literature on this field was not included even though regular control was intended to be used for this project.

### 2.4.2 Fuzzy Logic

There are three reasons why Fuzzy controllers are difficult to design [1]:

1) The choice of appropriate inputs to make Fuzzy.
2) The definition of rules, and the possibility to give more importance to rules, or to group several rules.
3) The way to defuzzify outputs of the system.

Ref. [1] proposed an interesting new approach to the design of Fuzzy controllers where it is argued that the global behaviour is the fusion of local behaviours of each physical part, instead of the fusion of high-level behaviours. A good description of Fuzzy control and how it is achieved is also given by [1].

### 2.4.3 Neural Network

A typical approach is to use neural networks for non-linear system modelling [9]. This is because neural networks are very good for approximating complex non-linear functions. A real robotic system is used by [9] for testing the neural network whereas most previous work has been on simulations. The vast majority of neural network research still relies on fixed-architecture networks trained through back-propagation [14]. There are two major problems with this approach [14]:

1) The "appropriate" network architecture varies from application to application but it is difficult to guess this architecture. Also even within the same application functional complexity requirements can vary widely.
2) Back-propagation and other gradient descent techniques tend to converge rather slowly.

The use of flexible cascade neural networks and extended Kalman filtering respectively to solve the two problems is then described by [14].

### 2.4.4 Genetic Algorithm/Programming

Genetic algorithms are search strategies, which use a mechanism analogous to evolution of life in nature [18]. This statement is backed up by most literature on this topic. It is widely recognised that genetic algorithms work even for problems where traditional algorithms cannot find a satisfactory solution within a reasonable amount of time [18]. This is where the real advantage of genetic algorithms is realised but [18] does not state this. Ref. [18] then explains how genetic algorithms can be used for motion planning in time-varying or unknown environments. This is very important for outdoor work where this covers the majority of environments.

## 2.5 Navigation

Navigation in general is a hot topic at the moment with a wide variety of types and applications being discussed. The reason for this is that navigation is extremely difficult to do reliably and quickly with the limited computing power on a mobile robot. Also there are many ways in which it can be achieved with varying degrees of success. There is however no one method that is close to being ideal.

### 2.5.1 Odometry

Dead reckoning is widely used for mobile robot navigation because of its simplicity and easy maintenance [16] and [3]. There is also reference to the low cost of dead reckoning systems. Simplicity, maintenance and cost are all important factors in most applications unless there is a large amount of funding and resources.

Encoder navigation can provide accurate information when the encoder errors are carefully calibrated [16]. This of course depends on the type of drive configuration and environment but no mention is given to this.

Inertial sensors such as gyroscopes and accelerometers can also be used but that these also have problems with errors [16]. While odometry provides good short-term accuracy, the integration of incremental motion information over time leads inevitably to the accumulation of errors [3].

Ref. [3] gives an excellent description of the different odometry errors, the measurement of the errors and techniques to minimise them. Nevertheless odometry or dead reckoning does not seem to be being researched much at the moment. This is most likely because it has been thoroughly researched and that there are a lot of advances taking place in the more complex forms of navigation. Why odometry is commonly used in robot navigation is due to low cost but there now seems to be a trend towards the more complex forms of navigation.

## 2.5.2 Active Beacon Navigation

Active beacons are considered to be at odds with complete robot autonomy but they offer many advantages to counter this [3]. Active beacon navigation is the most common navigation aid on ships and aeroplanes [3]. This gives an example of the range available to this type of system it also gives a relative example of the likely cost. Active beacons can also be detected reliably and provide very accurate positioning information with minimal processing [3]. All of these points are valid and highly desirable. Active beacon navigation systems have very high installation and maintenance costs [3]. This is highly undesirable and in a lot of cases uneconomic.

Accurate placement of beacons is required for accurate positioning [3]. As long as the robot is placed in a position to accurately measure the distances to the beacons at the start of its run then there should not be a problem unless the beacons move which is highly unlikely.

It seems that researchers in general are not looking at active beacon navigation at the moment. This could possibly be because as [3] has stated they are at odds with complete robot autonomy or that they are too expensive. It could also be that there is not much left to research on this topic. Active beacon navigation also has the added disadvantage of being very fixed and inflexible which means that unexpected obstacles need to be avoided by a different method. This therefore means that active beacon navigation really only has a place in extremely structured and non-varying environments.

Active beacon navigation is not being used for this project due to the cost and because the environment types intended to be used for this project are unstructured and dynamic (contain moving objects such as people).

## 2.5.3 Landmark Navigation

Ref. [24] used a system where the basic system uses odometry but the robot uses landmark navigation to keep the odometry measurement accurate. Ref. [24] then proposed the following system for navigation:

1) Find the landmark in the real environment and detect its range and/or direction by using an external sensor embodied with the robot.
2) Estimate robot's position by comparing external sensor data with landmark map, which the robot possesses.
3) Estimate robot's position by odometry.
4) Combine these estimated positions using uncertainty evolution techniques and renew the estimated position.

This type of technique using odometry as the base and landmark navigation to correct the odometry measurements seems to be relatively common and a relatively good description of how the system works is given by [24]. Although [24] does not state it, coming across an unexpected obstacle is a problem with landmark navigation. Ref. [24] does not address this problem as the robot stops when an unexpected obstacle is encountered and waits for it to be removed.

In image based landmark recognition changes in illumination, external clutter and changing geometry affect variability of the landmarks [19]. It is difficult to make use of accurate 3D information in landmark recognition applications [19]. It is not stated why this is but it is presumably because of the previous reasons. A good technique is to have a sequence of images of an object from common viewing angles and to use "visual learning" to teach the robot to recognise objects from these images [19]. An explanation is then given on how this achieved and how to overcome the various problems. This would also presumably use up a lot of memory, which can be a problem on a mobile robot with the space requirements and limited computing power.

Ref. [3] describes landmarks as being distinct features that a robot can recognise from its sensory input. This is a good definition and is much easier to understand than most other definitions given by other authors. Landmarks usually have a fixed and known position and are carefully chosen to be easy to identify [3]. These two conditions would seem to be essential for a landmark recognition technique to work. Ref. [3] describes the typical landmark recognition technique as follows:

1) Acquire sensory information.
2) Detect and segment landmarks.
3) Establish correspondence between sensed data and the stored map.
4) Calculate position.

This is essentially the same as the first two steps outlined by [24]. Most other landmark navigation systems use similar techniques so [3] is correct in stating that it is a typical technique.

Ref. [3] recognises that there are two distinct types of landmarks. These are defined as being natural landmarks and artificial landmarks. Ref. [3] then goes on to discuss the two types of landmarks, the advantages/disadvantages of each and the techniques used for landmark recognition in each case.

Landmark recognition seems to be a good technique for navigation if the landmarks can be detected and identified reliably. It unfortunately requires a large memory to store the images or image segments in and requires complicated visual signal processing to get useful information from the cameras/sensors. This is beyond the scope of this project, as the time required implementing even a basic recognition system would take up the entire project. This is because vision systems require considerable amounts of signal processing and computer power.

### 2.5.4 Map Based Positioning

Ref. [13] proposed the use of local maps as a set of best landmarks used for planning and executing safe motions. This is a good idea because the robot can then concentrate on the local area around it rather than trying to look at the entire global picture. Ref. [13] then goes on to describe a technique of global navigation, which is achieved through the use of a group of local maps linked via uncertainty transforms.

While most researchers have addressed map learning, most have not addressed the ability of maps to be adaptive to changes in the environment [10]. In the real world environments are dynamic and change over time [10]. This means that regular landmark based navigation can be confused by changes in the environment.

Ref. [10] proposed the use of an evidence grid type map where the objects can be changed and the robot will update its long-term map to accommodate the changes because the evidence it gathers suggests that something has changed. This system may have problems if too many objects change at once because the robot will not have enough known landmarks left to localize itself with. It is however a huge improvement on fixed maps. This method is however a very good method and the previous problem could be overcome by having the robot remember where it has previously been.

Although most robots use maps few can create their own maps [23]. Ref. [23] uses maps in a different way where the robot explores its environment and creates its own map. Ref. [13] proposed the use of a technique called frontier exploration where the robot applies the following principle:

*Given what you know about the world, where should you move to gain as much new information as possible?*

Ref. [13] used a grid system where the robot changes the values of the cells depending on whether something is in the grid cell or not. This system is very robust but it would be even better if the cells were treated as an evidence grid such as [10] used.

Map-based positioning is a technique where the robot uses its sensors to create a map of its local environment and then compares it to a global map stored in its memory [3]. There is no reference to systems similar to what [23] uses but this may be due to the technique being a new one. Ref. [3] gives a complete list of the advantages and disadvantages of map-based positioning and also gives a good explanation of the building and matching of the maps. This is then followed by an explanation of the different types of maps (geometric and topographical).

Overall, map based positioning seems to be the best method of positioning, which is in the budget and complexity range of this project. The methods of map production and updating by the robot itself are also very good ideas and are suitable for both unstructured and dynamic environments.

# 3 MECHANICAL DESIGN

## 3.1 Materials and Methods

The mechanical design was relatively easy and straightforward as there was no research and very little development of the design.

It was decided that the chassis and drive system should be solid, well constructed and able to take a variety of sensor types and control systems. The design initially started as being orientated around the wheel design and followed this the whole way through. Sufficient space was also left open for the motors, the control circuitry, the batteries and the sensors.

The reason for the design being orientated around the wheels is because of an interesting wheel design and drive system being chosen. This system operates using the Mecanum principle. The Mecanum principle is described in detail in the section on the Mecanum principle in the Background.
The mechanical design was carried out using Solid Works, which is excellent for this type of design work.

### 3.1.1 Wheels

It started with getting the basic configuration of the wheels to comply with the Mecanum principle. Several different techniques and layouts were tried before the first wheel design was created. The factors considered were:

1) Is the wheel stable.
2) Is the wheel design physically able to be made.
3) Does it conform to the Mecanum principle.

Once a wheel design was decided on a model of the wheel was created to see if it could be constructed using the facilities available. This resulted in several minor changes but the basic idea was kept the same.

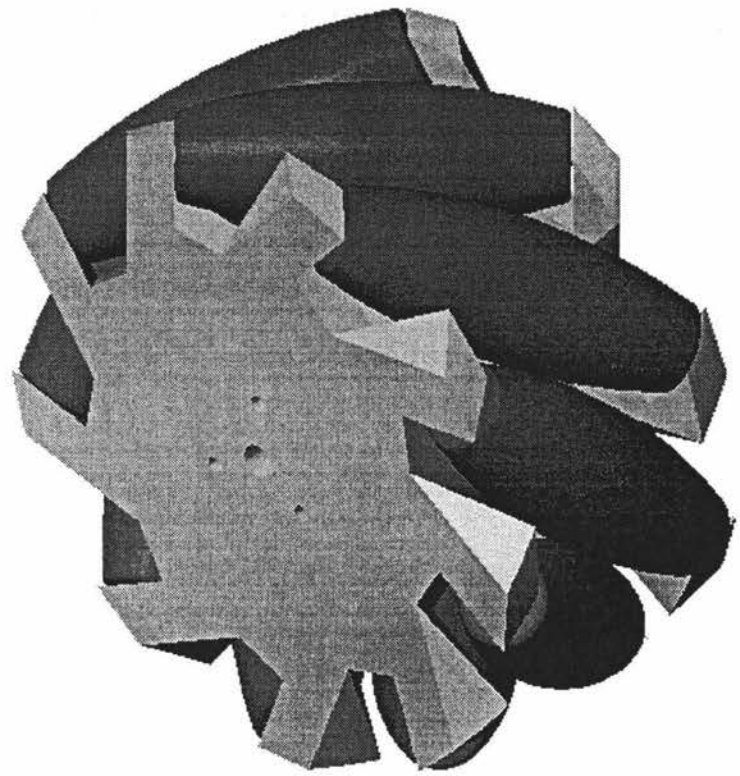


Figure 3.1 Final design of the wheel shown as printed from Solid Works.

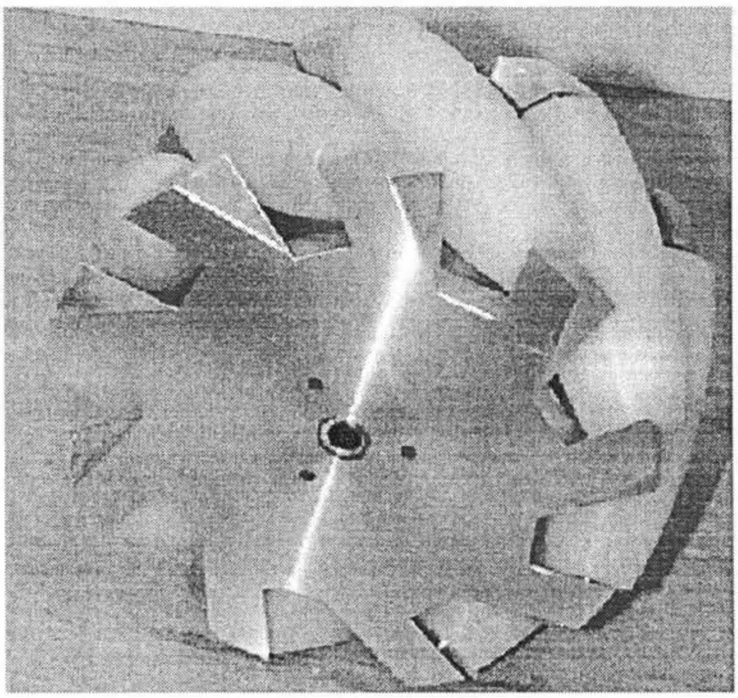


Figure 3.2 Picture of the actual wheel.

The construction of the wheel was relatively time consuming as the parts were difficult to make and all had to be correct or the wheel could not be assembled correctly.

The wheel frame was made from solid Aluminium bar, which was machined to the correct shape. The rollers were made from Nylon and machined in a CNC lathe. The roller shafts, axle and connecting bolts were all made from silver steel.

Spacers were made to fit between the two halves of the wheel frame in order to make the two halves meet. These spacers were made from 3mm aluminium plate. The spacers were made in order to solve the problem of the two halves of the wheel frame not meeting and this is described in the results section.

### 3.1.2 Chassis

The chassis was the next part to be designed as this linked the wheels and the motors together and provides a base for the batteries, the control circuit and the sensors. The chassis was originally designed as a single piece but this was changed when the majority of the literature was read and it all seemed to say that suspension was required because all of the wheels have to be touching the ground at all times for the Mecanum drive system to work correctly.

This required constructing separate sections to the chassis to hold each wheel and motor in such a way that they could rotate and form a suspension system. These sections were remade after it was found that the method of connecting them to the main chassis was not practical.

The chassis was constructed from square Aluminium tube and bar. The cross pieces of the chassis were made from Aluminium channel and the top tray is Aluminium sheet. The whole chassis bolts together, which means that parts can be changed at a later date.

### 3.1.3 Motors and Batteries

The motors were very difficult to obtain, as the drive requires a low speed (around 100rpm) and high torque. Initially small kitset model motors were tried but these were not built strong enough to handle the torque requirements. The next stage was to look at all available motors. This resulted in finding out that there was almost nothing in the range between the kitset motors and industrial type motors. All of the catalogue motor and gearbox sets were in the $300 plus range, which was beyond the project budget.

The only remaining option was to look at motors, which were part of a different application. This resulted in four options:

1) Barbeque rotisserie motors, which had a high torque but were too slow and were noisy.
2) Battery powered drill or screwdriver motors, which were the correct speed and torque but were slightly expensive and difficult to mount.
3) Car windscreen wiper motors, which had plenty of torque and were cheap but were difficult to mount and drew much too high a current.
4) Car electric window motors, which had more than enough torque, were the correct speed and were cheap (when obtained from a car wrecker).

The electric window motors were chosen and turned out to be a good decision except for the high current drain but this was minimised by using relatively modern motors. The motors turned out to be the perfect size for the robot and had a good mounting system. The high current drain unfortunately meant that the batteries go flat quickly and the motor control circuit had to be made more robust.

The batteries were relatively simple to choose as a large storage capacity with high current rating and low cost was required. This meant that the only practical option was a sealed lead-acid battery.

## 3.2 Results

The results of this section are relatively easy to determine. It either works or it doesn't.

The wheels had a few minor problems. The first problem was that it was very difficult to get the holes lined up so that the roller shafts were correctly aligned. This resulted in a few extra holes in the wheels before it was corrected. The second problem was that the rollers did not have enough space between them. This was caused by moving the roller shaft location holes slightly to accommodate some slight changes in the machining.

The assembly of the wheels turned up a number of new problems, which unfortunately could not be solved adequately as all the parts for the wheels had already been made. The main problem was that the holes for the roller shafts had been drilled at slightly the wrong angle, which meant that the two halves of the wheel frame did not meet when the wheel was assembled. A secondary problem was that the holes for the bolts, which held the two halves of the wheels together also did not line up correctly. This could have easily been avoided by drilling the holes after the wheels had been assembled. This however was not thought of before the wheels had been made and therefore more holes had to be drilled after the wheels were assembled.

The production of the chassis also had some problems with it but these were solved eventually without too much time being waisted.
Essentially apart from the time taken to complete the mechanical design it was successful and relatively few changes were made. This is mainly due to a lot of work being done in the design stage, seeking advice from the technicians on the design and when the parts were actually being produced. On the down side it would have taken less time (time that could have been used in research) and resulted in less mistakes if there had been sufficient funding and/or resources to allow all the construction to be done by the technicians.

The pictures below (Figure 3.3 and 3.4) show the real results of the mechanical design:

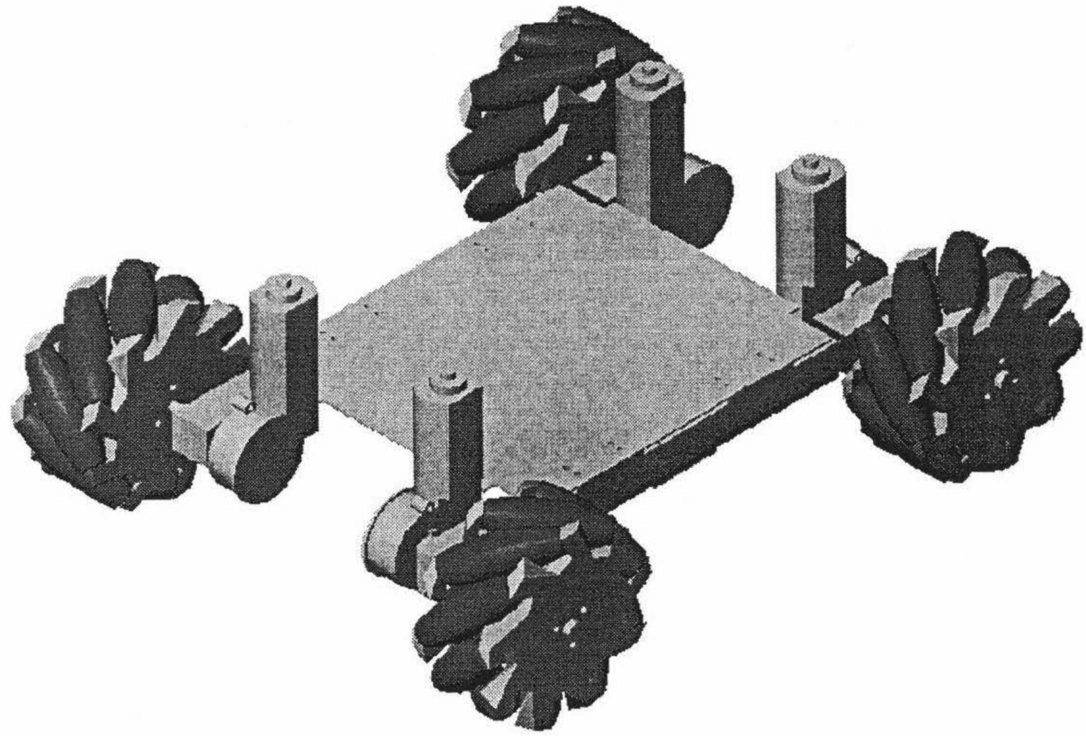


Figure 3.3 Solid Works drawing of the final assembly of the mechanical design.

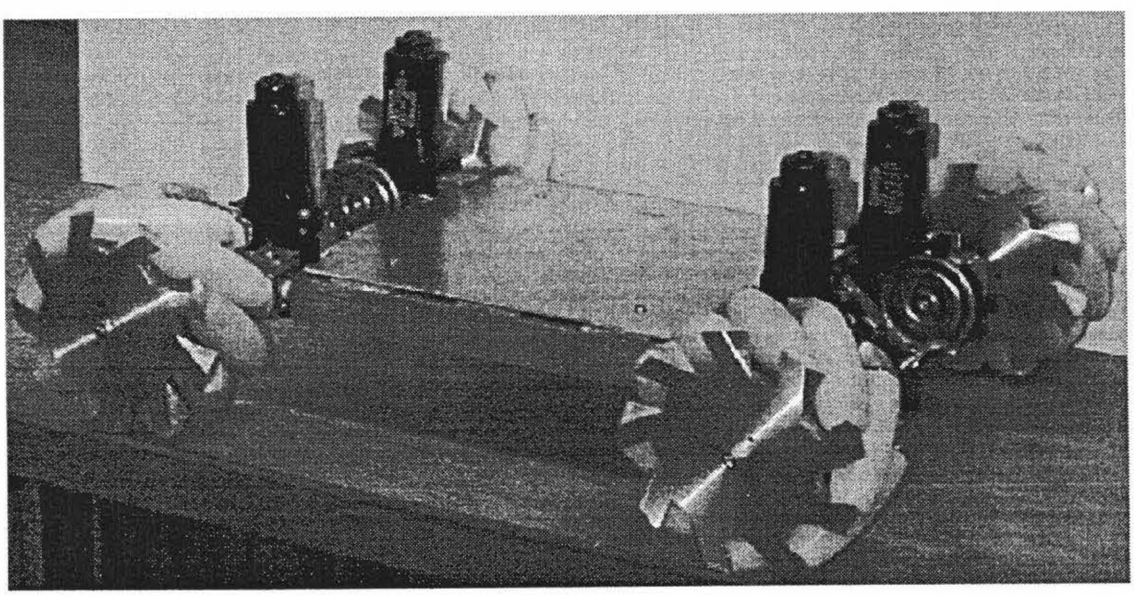


Figure 3.4 Digital photo of the chassis and wheel unit.

More detailed pictures and engineering drawings of the mechanical design and some of its components can also be found in Appendix A.

# 4 SENSOR DESIGN

## 4.1 Ultrasonic Sensing

This section provides some of the fundamentals of ultrasonic sensing and is adapted from [3].
Most of these methods are applicable to ultrasonic sensing and comparisons are given between the different types of range sensing which is also helpful.

## Sensors for Map-Based Positioning

Most sensors used for the purpose of map building involve some kind of distance measurement. There are three basically different approaches to measuring range:

1) Sensors based on measuring the *time of flight* (TOF) of a pulse of emitted energy traveling to a reflecting object, then echoing back to a receiver.
2) The *phase-shift measurement* (or *phase-detectio*n) ranging technique involves continuous wave transmission as opposed to the short-pulsed outputs used in TOF systems.
3) Sensors based on frequency-modulated (FM) radar. This technique is somewhat related to the (amplitude-modulated) phase-shift measurement technique.

### Time-of-Flight Range Sensors

Many of today's range sensors use the *time-of-flight* (TOF) method. The measured pulses typically come from an ultrasonic, RF, or optical energy source. Therefore, the relevant parameters involved in range calculation are the speed of sound in air (roughly 0.3 m/ms — 1 ft/ms), and the speed of light (0.3 m/ns — 1 ft/ns). Using elementary physics, distance is determined by multiplying the velocity of the energy wave by the time required to travel the round-trip distance:

$$d = v\,t \quad (1)$$

where

$d$ = round-trip distance

$v$ = speed of propagation

$t$ = elapsed time.

The measured time is representative of traveling twice the separation distance (i.e., out and back) and must therefore be reduced by half to result in actual range to the target. The advantages of TOF systems arise from the direct nature of their straight-line active sensing. The returned signal follows essentially the same path back to a receiver located coaxially with or in close proximity to the transmitter. In fact, it is possible in some cases for the transmitting and receiving transducers to be the same device. The absolute range to an observed point is directly available as output with no complicated analysis required, and the technique is not based on any assumptions concerning the planar properties or orientation of the target surface. The *missing parts* problem seen in triangulation does not arise because minimal or no offset distance between transducers is needed. Furthermore, TOF sensors maintain range accuracy in a linear fashion as long as reliable echo detection is sustained, while triangulation schemes suffer diminishing accuracy as distance to the target increases.

Potential error sources for TOF systems include the following:

1) Variations in the speed of propagation, particularly in the case of acoustical systems.
2) Uncertainties in determining the exact time of arrival of the reflected pulse.
3) Inaccuracies in the timing circuitry used to measure the round-trip time of flight.
4) Interaction of the incident wave with the target surface.

Each of these areas will be briefly addressed below, and discussed later in more detail.

a. **Propagation Speed** For mobile robotics applications, changes in the propagation speed of electromagnetic energy are for the most part inconsequential and can basically be ignored. This is not the case, however, for acoustically based systems, where the speed of sound is markedly influenced by temperature changes, and to a lesser extent by humidity. (The speed of sound is actually proportional to the square root of temperature in degrees Rankine.) An ambient temperature shift of just 30 F can cause a 0.3meter (1 ft) error at a measured distance of 10 meters (35 ft).

b. **Detection Uncertainties** So-called *time-walk errors* are caused by the wide dynamic range in returned signal strength due to varying reflectivities of target surfaces. These differences in returned signal intensity influence the rise time of the detected pulse, and in the case of fixed-threshold detection will cause the more reflective targets to appear closer. For this reason, *constant* fract ion timing discriminators are typically employed to establish the detector threshold at some specified fraction of the peak value of the received pulse.

c. **Timing Considerations** Due to the relatively slow speed of sound in air, compared to light, acoustically based systems face milder timing demands than their light-based counterparts and as a result are less expensive. Conversely, the propagation speed of electromagnetic energy can place severe requirements on associated control and measurement circuitry in optical or RF implementations. As a result, TOF sensors based on the speed of light require sub-nanosecond timing circuitry to measure distances with a resolution of about a foot. More specifically, a desired resolution of 1 millimeter requires a timing accuracy of 3

Pico seconds (3×10 s). This capability is somewhat expensive to realize and may not be cost effective for certain applications, particularly at close range where high accuracies are required.

d. **Surface Interaction** When light, sound, or radio waves strike an object, any detected echo represents only a small portion of the original signal. The remaining energy reflects in scattered directions and can be absorbed by or pass through the target, depending on surface characteristics and the angle of incidence of the beam. Instances where no return signal is received at all can occur because of specular reflection at the object's surface, especially in the ultrasonic region of the energy spectrum. If the transmission source approach angle meets or exceeds a certain critical value, the reflected energy will be deflected outside of the sensing envelope of the receiver. In cluttered environments sound waves can reflect from (multiple) objects and can then be received by other sensors. This phenomenon is known as crosstalk (see Figure 4.1). To compensate, repeated measurements are often averaged to bring the signal-to-noise ratio within acceptable levels, but at the expense of additional time required to determine a single range value.

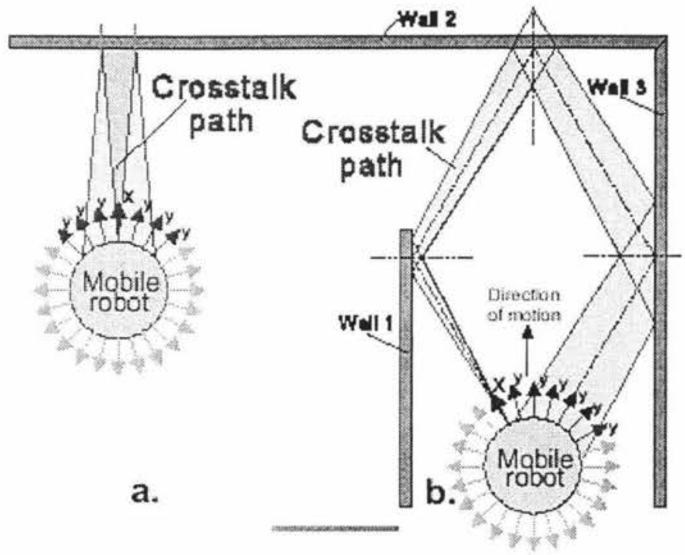



Figure 4.1 Crosstalk is a phenomenon in which one sonar picks up the echo from another. One can distinguish between **a**. direct crosstalk and **b**. indirect crosstalk. [3]

**Ultrasonic TOF Systems**

Ultrasonic TOF ranging is today the most common technique employed on indoor mobile robotics systems, primarily due to the ready availability of low-cost systems and their ease of interface. Over the past decade, much research has been conducted investigating applicability in such areas as world modeling and collision avoidance, position estimation, and motion detection. Several researchers have more recently begun to assess the effectiveness of ultrasonic sensors in exterior settings.

**Phase-Shift Measurement**

The *phase-shift measurement* (or *phase-detectio*n) ranging technique involves continuous wave transmission as opposed to the short-pulsed outputs used in TOF systems. A beam of amplitude-modulated laser, RF, or acoustical energy is directed towards the target. A small portion of this wave (potentially up to six orders of magnitude less in amplitude) is reflected by the object's surface back to the detector along a direct path. The returned energy is compared to a simultaneously generated reference that has been split off from the original signal, and the relative phase shift between the two is measured as illustrated in Figure 4.2 to ascertain the round-trip distance the wave has traveled. For high-frequency RF- or laser-based systems, detection is usually preceded by heterodyning the reference and received signals with an intermediate frequency (while preserving the relative phase shift) to allow the phase detector to operate at a more convenient lower frequency.

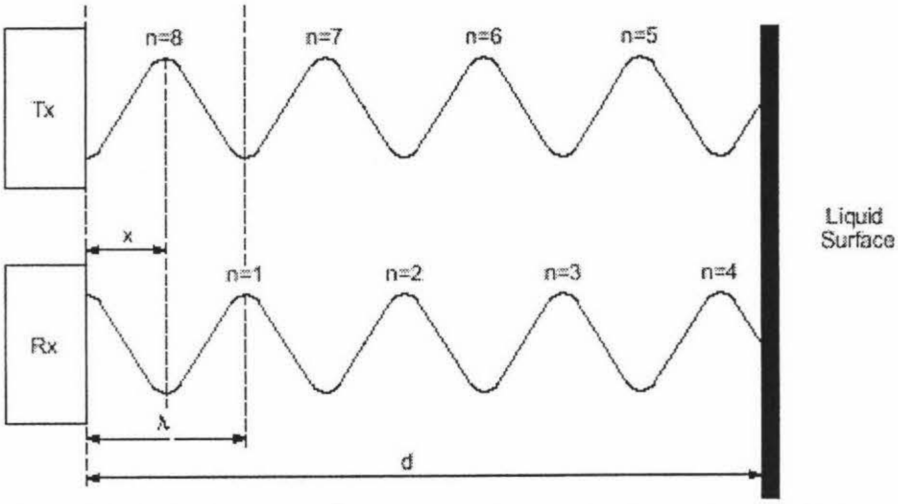



Figure 4.2 Relationship between outgoing and reflected waveforms, where x is the distance corresponding to the differential phase.

The relative phase shift expressed as a function of distance to the reflecting target surface is:

$$\Phi=(4\pi d)/\lambda \qquad (2)$$

Where

$\Phi$ = phase shift
$d$ = distance to target
$\lambda$ = modulation wavelength.

The desired distance to target *d* as a function of the measured phase shift Φ is therefore given by

$$d=(\Phi \lambda)/4\pi = \Phi c/4\pi f \qquad (3)$$

where

$f$ = modulation frequency.

For square-wave modulation at the relatively low frequencies typical of ultrasonic systems (20 to 200 kHz), the phase difference between incoming and outgoing waveforms can be measured with the simple linear circuit shown in Figure 4.3. The output of the *exclusive-or* gate goes high whenever its inputs are at opposite logic levels, generating a voltage across capacitor C that is proportional to the phase shift. For example, when the two signals are in phase (i.e., Φ = 0), the gate output stays low and *V* is zero; maximum output voltage occurs when Φ reaches 180 degrees. While easy to implement, this simplistic approach is limited to low frequencies, and may require frequent calibration to compensate for drifts and offsets due to component aging or changes in ambient conditions.

At higher frequencies, the phase shift between outgoing and reflected sine waves can be measured by multiplying the two signals together in an electronic mixer, then averaging the product over many modulation cycles. This integration process can be relatively time consuming, making it difficult to achieve extremely rapid update rates. The result can be expressed mathematically as follows:

$$\lim_{T \to \infty} \frac{1}{T} \int_0^T \sin\left(\frac{2\pi c}{\lambda} t + \frac{4\pi d}{\lambda}\right) \sin\left(\frac{2\pi c}{\lambda}\right) dt \qquad (4)$$

which reduces to

$$\Phi = A\cos(4\pi d)/\lambda \qquad (5)$$

where

$t$ = time

$T$ = averaging interval

$A$ = amplitude factor from gain of integrating amplifier.

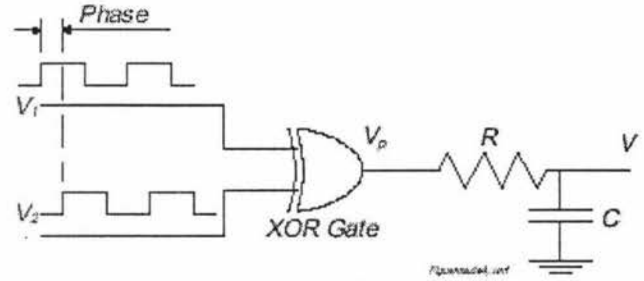



Figure 4.3 At low frequencies typical of ultrasonic systems, a simple phase-detection circuit based on an exclusive-or gate will generate an analog output voltage proportional to the phase difference seen by the inputs [3].

From the earlier expression for $\Phi$, it can be seen that the quantity actually measured is in fact the *cosine* of the phase shift and not the phase shift itself. This situation introduces a so-called *ambiguity interval* for scenarios where the round-trip distance exceeds the modulation wavelength (i.e., the phase measurement becomes ambiguous once $\Phi$ exceeds 360 degrees). This ambiguity interval is the maximum range that allows the phase difference to go through one complete cycle of 360 degrees:

$$R_\alpha = c/2f \qquad (6)$$

where

$R_\alpha$ = ambiguity range interval

$f$ = modulation frequency

$c$ = speed of light.

Referring again to Figure 4.2, it can be seen that the total round-trip distance *2d* is equal to some integer number of wavelengths nλ plus the fractional wavelength distance *x* associated with the phase shift. Since the cosine relationship is not single valued for all of 1, there will be more than one distance *d* corresponding to any given phase shift measurement:

$$\cos\phi = \cos\left(\frac{4\pi d}{\lambda}\right) = \cos\left(\frac{2\pi(x+n\lambda)}{\lambda}\right) \qquad (7)$$

where:

$d = (x + n\lambda)/2$ = true distance to target.

$x$ = distance corresponding to differential phase Φ.

$n$ = number of complete modulation cycles.

The potential for erroneous information as a result of this *ambiguity interval* reduces the appeal of phase-detection schemes. Some applications simply avoid such problems by arranging the optical path so that the maximum possible range is within the ambiguity interval. Alternatively, successive measurements of the same target using two different modulation frequencies can be performed, resulting in two equations with two unknowns, allowing both *x* and *n* to be uniquely determined.

Advantages of continuous-wave systems over pulsed time-of-flight methods include the ability to measure the direction and velocity of a moving target in addition to its range. In 1842, an Austrian by the name of Johann Doppler published a paper describing what has since become known as the *Doppler effect*. This well-known mathematical relationship states that the frequency of an energy wave reflected from an object in motion is a function of the relative velocity between the object and the observer.

As with TOF rangefinders, the paths of the source and the reflected beam are coaxial for phase-shift-measurement systems. This characteristic ensures objects cannot cast shadows when illuminated by the energy source, preventing the *missing parts* problem. Even greater measurement accuracy and overall range can be achieved when cooperative targets are attached to the objects of interest to increase the power density of the return signal.

**Frequency Modulation (also adapted from [3])**

A closely related alternative to the amplitude-modulated phase-shift-measurement ranging scheme is frequency-modulated (FM) radar. This technique involves transmission of a continuous electro-magnetic wave modulated by a periodic triangular signal that adjusts the carrier frequency above and below the mean frequency $f_o$ as shown in Figure 4.4. The transmitter emits a signal that varies in frequency as a linear function of time:

$$f(t) = f_o + at \tag{8}$$

where

$a$ = constant

$t$ = elapsed time.

$f_o$ =mean frequency

This signal is reflected from a target and arrives at the receiver at time $t$ + T.

$$T=2d/c \tag{9}$$

Where

$T$ = round-trip propagation time

$d$ = distance to target

$c$ = speed of light.

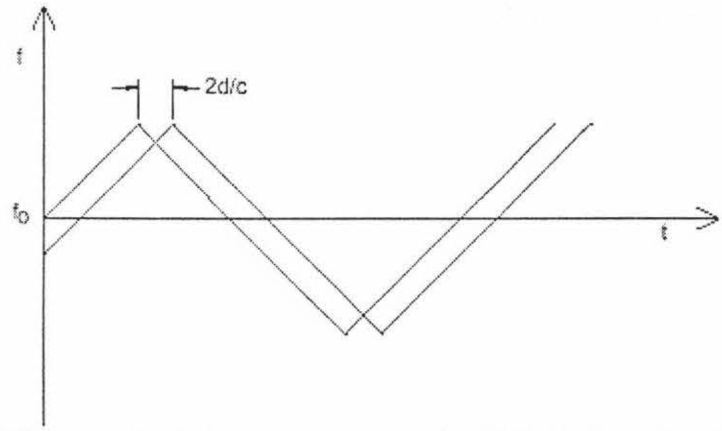



Figure 4.4 The received frequency curve is shifted along the time axis relative to the reference frequency.

The received signal is compared with a reference signal taken directly from the transmitter. The received frequency curve will be displaced along the time axis relative to the reference frequency curve by an amount equal to the time required for wave propagation to the target and back. (There might also be a vertical displacement of the received waveform along the frequency axis, due to the Doppler effect.) These two frequencies when combined in the mixer produce a beat frequency $F_b$:

$$F_b = f(t) - f(T + t) = aT \qquad (10)$$

where
$a$ = constant.

This beat frequency is measured and used to calculate the distance to the object:

$$d=(F_b c)/4(F_r F_d) \qquad (11)$$

where
$d$ = range to target
$c$ = speed of light
$F_b$ = beat frequency

$F_r$ = repetition (modulation) frequency, determined by the measurement distance (longer distance requires a lower modulation frequency).
$F_d$ = total FM frequency deviation, determined by the amplitude of the modulating wave (larger amplitude causes a larger frequency deviation).

Distance measurement is therefore directly proportional to the difference or beat frequency, and as accurate as the linearity of the frequency variation over the counting interval. Advances in wavelength control of laser diodes now permit this radar ranging technique to be used with lasers. The frequency or wavelength of a laser diode can be shifted by varying its temperature. Consider an example where the wavelength of an 850-nanometer laser diode is shifted by 0.05 nanometers in four seconds: the corresponding frequency shift is 5.17 MHz per nanosecond.
This laser beam, when reflected from a surface 1 meter away, would produce a beat frequency of 34.5 MHz. The linearity of the frequency shift controls the accuracy of the system; a frequency linearity of one part in 1000 yards yields an accuracy of 1 millimeter.
The frequency-modulation approach has an advantage over the phase-shift-measurement technique in that a single distance measurement is not ambiguous. (Recall phase-shift systems must perform two or more measurements at different modulation frequencies to be unambiguous.) However, frequency modulation has several disadvantages associated with the required linearity and repeatability of the frequency ramp, as well as the coherence of the laser beam in optical systems. As a consequence, most commercially available FM ranging systems are radar-based, while laser devices tend to favor TOF and phase-detection methods.

# 4.2 Materials and Methods

The sensor design turned out to be the main research section of the project. This is because a novel idea was researched for the use of ultrasonic sensors.

The sensor design started with some experimentation with simple ultrasonic sensors but it was soon discovered that their angular accuracy was almost non-existent. This then lead to some considerable thought about how this could be improved.

The idea of using two sensors with one on either end of a rotating beam was initially tried. The reasoning behind this was that both sensors would pick up the return signal off an object but unless the object was directly in front of the sensors there would be a difference in the time the signal reached each sensor. This is due to the signal having to travel further to one sensor than the other when an object is at an angle. The two signals would be compared and if they were at the same point in time then the signal was considered to be directly in front of the sensors. This result could then be used to determine the angle of the object relative to the robot.

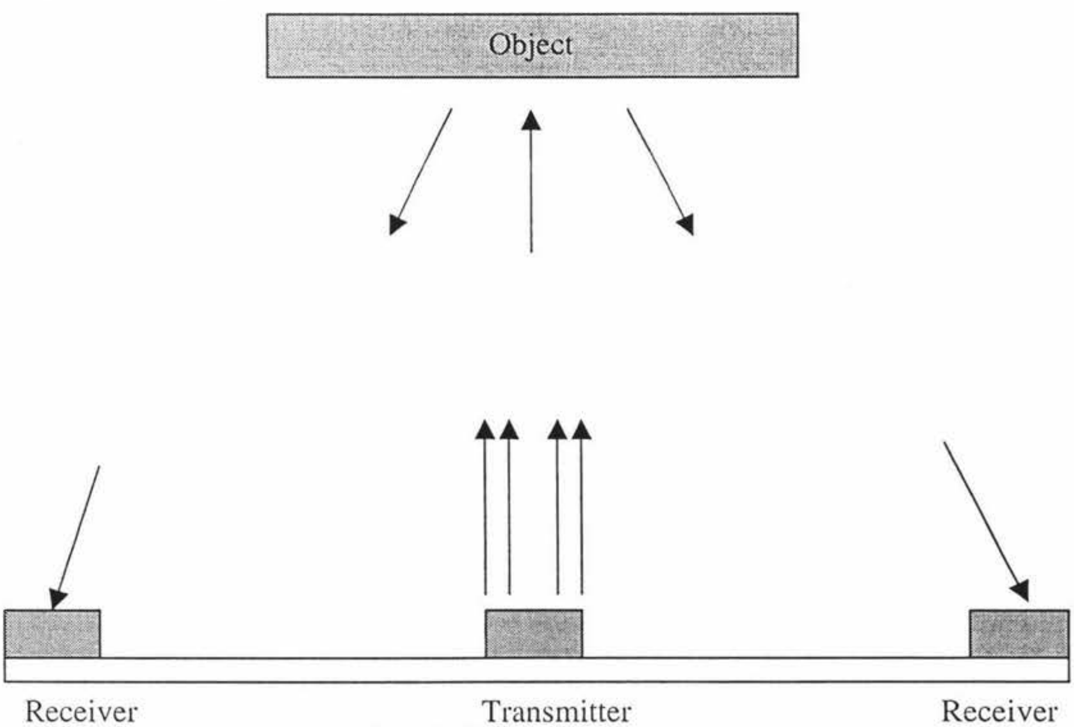



Figure 4.5 Arrangement of the initial sensor layout.

A simulation, which modelled the sensors and their behaviour, was created to test this method. The signal was set up as if it was returning after bouncing off an object. The beam was rotated in steps and the resulting time difference recorded at each step. This was all done in software to avoid constructing a circuit arrangement that in all likelihood would need changing. The simulation essentially used the same program as the program described in the following section except for the number of sensors.

As the results in section 4.3 show the first arrangement did not work particularly well and a different method was tried. This next method still used the rotating beam but instead of using one sensor at each end three sensors were placed on each half of the beam. This arrangement was intended to operate in a similar manner to a phased array antenna. The sensors on one half of the beam have exactly the same spacing as the sensors on the other half of the beam.

To obtain the output, all of the sensor outputs were summed together. As at least one pair of sensors was likely to be out of phase when an object is not directly in front of the sensors the sum of the sensors will only be at a maximum when an object is directly in front. It was hoped that with three sets of sensors there should be some arrangement of spacings where only an object directly in front of the sensors would be detected. Figures 4.6 and 4.7 show the sensor layout and the summing operation.

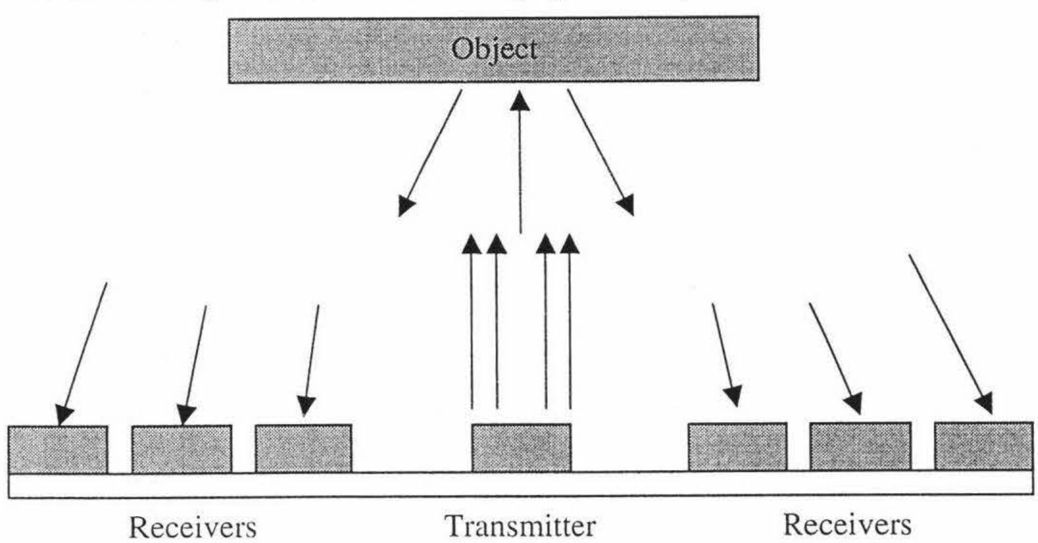



Figure 4.6 Sensor layout for the second method (phased array).

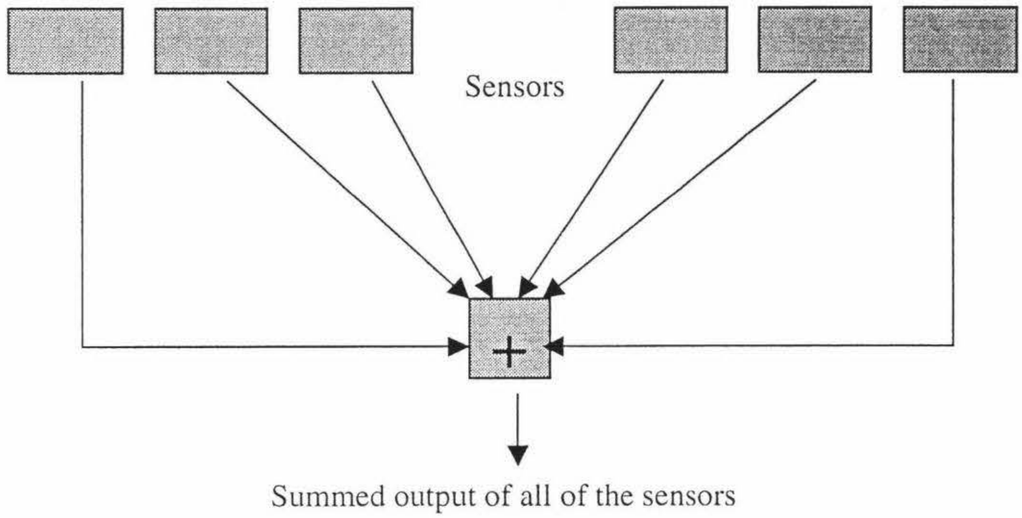



Figure 4.7 Summing operations.

The spacing of the sensors was a big problem as there was no way of knowing what the best spacing arrangement was. It was therefore decided that the best approach was to do a three dimensional optimisation with the three dimensions being the three spacings of the sensors. It was also decided that at least initially the distance of the object should be fixed rather than running each optimisation for all possible distances. This was because with three dimensions each iteration within an optimisation took ten minutes to run. The distance of the object (focal point of the array) was set at two metres because this seemed to be a relatively good distance for detecting an obstacle and reacting to it. The sensors also had to be spaced towards the focal point because unlike in regular phased arrays it cannot be assumed that the focal point is infinitely far away and therefore the signals are parallel. The optimisations were run until they had converged to a local minimum. A new set of starting points was chosen and the next optimisation was run. This process took a number of weeks to complete as there turned out to be a large number of local minima.

The second idea was intended to solve the angular accuracy problem and also to cut out the problem of multiple reflections as it was supposed to only detect obstacles in a very narrow band and any signals outside this would be rejected. Also it was hoped that it would also reduce the effect of corners where the reflections would appear to be at different angles for each sensor.

The first step was to create the program used to test its functionality and find any global minima if they existed. There were only minor changes to this program and these were mainly to make the programming as realistic as possible and also a few changes to make it work correctly.

The program is as follows and contains notes about what each part of the program does there is also a block diagram (Figure 4.8), which shows what each part of the program does:

**Program Notation:**

| | |
|---|---|
| L | Output of the function. |
| x | Input vector of X coordinates. |
| y | Y distance to focal point. |
| Tx | X and Y coordinates of the focal point. |
| Vb | Initial output vector. |
| a | Angle in degrees. |
| r | Angle converted to radians. |
| ang | Current angle (angle is incremented for each iteration). |
| X | X coordinate of the angle on a unit circle. |
| Z | Y coordinate of the angle on a unit circle. |
| A1,2,3 | Reciever distances from signal (focal point). |
| Rx1-6 | X and Y coordinates of the receivers. |
| Txd1-6 | X and Y coordinates of receivers from signal (focal point). |
| d | Time delay for signal to reach sensors. |
| t | Time vector. |
| Y1 | 40kHz sine wave. |
| Y2 | 420Hz envelope (simulates build-up and die-down of signal). |
| Y | Final signal. |
| D1-6 | Time delays to each sensor. |
| f | Step size (resolution). |
| N | Equalising vector (required to get the result vector from each sensor to the same length. |
| n | Vector of zeros N-long. |

T1-6 Vector of sensor results (delay plus signal plus length adjustment).

V Maximum sum of the sensor outputs.

j,g,Va,Vb,Vc Used to obtain an output vector which is updated by adding V onto the end after each iteration.

T Output vector (results).

L1 First 170 results.

L2 Remaining 30 results.

L Ratio used for optimisation (best ratio is the smallest i.e. central peak is much larger than the side lobes).

**Program:**

```
function [L] = phasedarray2(x);
% Produces six outputs delayed by an amount of time determined by an angle
of rotation.
% Each output corresponds to an ultrasonic receiver.
% Outputs are summed together to produce an array type arrangement.

                    %Set initial conditions.

% Set focus point of array.
%y = x(1);
y = 2;
% Set transmitter distance.
Tx = [0,y];

g = 0;
Vb = zeros(1,201);
a = 6;
      % Look at signal at angles from -a to a in a/200 degree steps.

r = (a*(pi/180)); % Convert angle into radians.
ang = -r;
while ang <=0;

  % Set angle coordinates (unit circle). Z is equivalent to Y.
  X = cos(ang);
  Z = sin(ang);

              % Set coordinates and spacing of receivers.

  % Set receiver distances from signal.
  A1 = [(((y.^2)+(x(1).^2)).^0.5)-2];
```

```
A2 = [(((y.^2)+(x(2).^2)).^0.5)-2];
A3 = [(((y.^2)+(x(3).^2)).^0.5)-2];

% Set receivers coordinates.
Rx1 = [-x(1)*X,(x(1)*Z+A1)];
Rx2 = [-x(2)*X,(x(2)*Z+A2)];
Rx3 = [-x(3)*X,(x(3)*Z+A3)];
Rx4 = [x(3)*X,(-x(3)*Z+A3)];
Rx5 = [x(2)*X,(-x(2)*Z+A2)];
Rx6 = [x(1)*X,(-x(1)*Z+A1)];

% Obtain distance from signal of each sensor from sensor coordinates.
Txd1 = [((Rx1).^2 + (Rx1(2)+Tx(2)).^2).^0.5];
Txd2 = [((Rx2).^2 + (Rx2(2)+Tx(2)).^2).^0.5];
Txd3 = [((Rx3).^2 + (Rx3(2)+Tx(2)).^2).^0.5];
Txd4 = [((Rx4).^2 + (Rx4(2)+Tx(2)).^2).^0.5];
Txd5 = [((Rx5).^2 + (Rx5(2)+Tx(2)).^2).^0.5];
Txd6 = [((Rx6).^2 + (Rx6(2)+Tx(2)).^2).^0.5];

% Set delay to minimum possible distance from signal to any sensor.
d = [((Tx(2)-x(1)*(sin(r))).^2+(x(1)*(cos(r))).^2).^0.5];

% Produce signal.
t = 0:.000002:.0012;
Y1 = sin(2*pi*40000*t); % 40kHz wave.
%Y1 = sin(2*pi*43000*t);
%Y1 = sin(2*pi*38000*t);
Y2 = sin(2*pi*420*t);      % envelope.
Y = Y1.*Y2;
%plot(Y')

% Set time delays.
D1 = (0*((0:.000002:(Txd1/343-d/343))'));
D2 = (0*((0:.000002:(Txd2/343-d/343))'));
D3 = (0*((0:.000002:(Txd3/343-d/343))'));
D4 = (0*((0:.000002:(Txd4/343-d/343))'));
D5 = (0*((0:.000002:(Txd5/343-d/343))'));
D6 = (0*((0:.000002:(Txd6/343-d/343))'));

% Set step size for recording signal and length adjustment.
f = .000002;
N = .000002:.000002:f;
n = 0*N;

% Add delay, signal and length adjustment to get complete signal.
T1 = [D1;Y';n'];
T2 = [D2;Y';n'];
T3 = [D3;Y';n'];
T4 = [D4;Y';n'];
T5 = [D5;Y';n'];
```

```
T6 = [D6;Y';n'];

             % Record signal at each receiver and adjust length.

% Receiver 1.
length(T1);
while length(T1)<1200;
  f = f+.000002;
  N = 0.000002:.000002:f;
  n = 0*N;

  length(T1);
  T1 = [D1;Y';n'];
end

% Receiver 2.
f = .000002;
N = .000002:.000002:f;
n = 0*N;
length(T2);
while length(T2)<1200;
  f = f+.000002;
  N = .000002:.000002:f;
  n = 0*N;

  length(T2);
  T2 = [D2;Y';n'];
end

% Receiver 3.
f = .000002;
N = .000002:.000002:f;
n = 0*N;
length(T3);
while length(T3)<1200;
  f = f+.000002;
  N = .000002:.000002:f;
  n = 0*N;

  length(T3);
  T3 = [D3;Y';n'];
end

% Receiver 4.
f = .000002;
N = .000002:.000002:f;
n = 0*N;
length(T4);
while length(T4)<1200;
  f = f+.000002;
```

```
  N = .000002:.000002:f;
  n = 0*N;

  length(T4);
  T4 = [D4;Y';n'];
end

% Receiver 5.
f = .000002;
N = .000002:.000002:f;
n = 0*N;
length(T5);
while length(T5)<1200;
  f = f+.000002;
  N = .000002:.000002:f;
  n = 0*N;

  length(T5);
  T5 = [D5;Y';n'];
end

% Receiver 6.
f = .000002;
N = .000002:.000002:f;
n = 0*N;
length(T6);
while length(T6)<1200;
  f = f+.000002;
  N = .000002:.000002:f;
  n = 0*N;

  length(T6);
  T6 = [D6;Y';n'];
end

                        % Sum the maximum of the outputs.

V = max(T1+T2+T3+T4+T5+T6);

% Add one step to the angle.
ang = (ang+(r/200));

                        % Store outputs in a vector.

j = g+1;
Va = zeros(1,201);
     Va(:,j+1:g+1) = Va(:,j:g);
     Va(:,j) = V;
g = g+1;
Vc = Vb+Va;
```

```
  Vb = Vc;
  j = g+1;
end % repeat until angle =0.


        % compare outputs.

T = Vb;
L1 = max(Vb(1:170)); % largest of the first 170 outputs.
L2 = max(Vb(170:200)); % largest of the last 30 outputs (central signal).
L = L1/L2
plot(T)
```

This program may not be the best or most efficient use of MATLAB but it woks and covers all the variables.

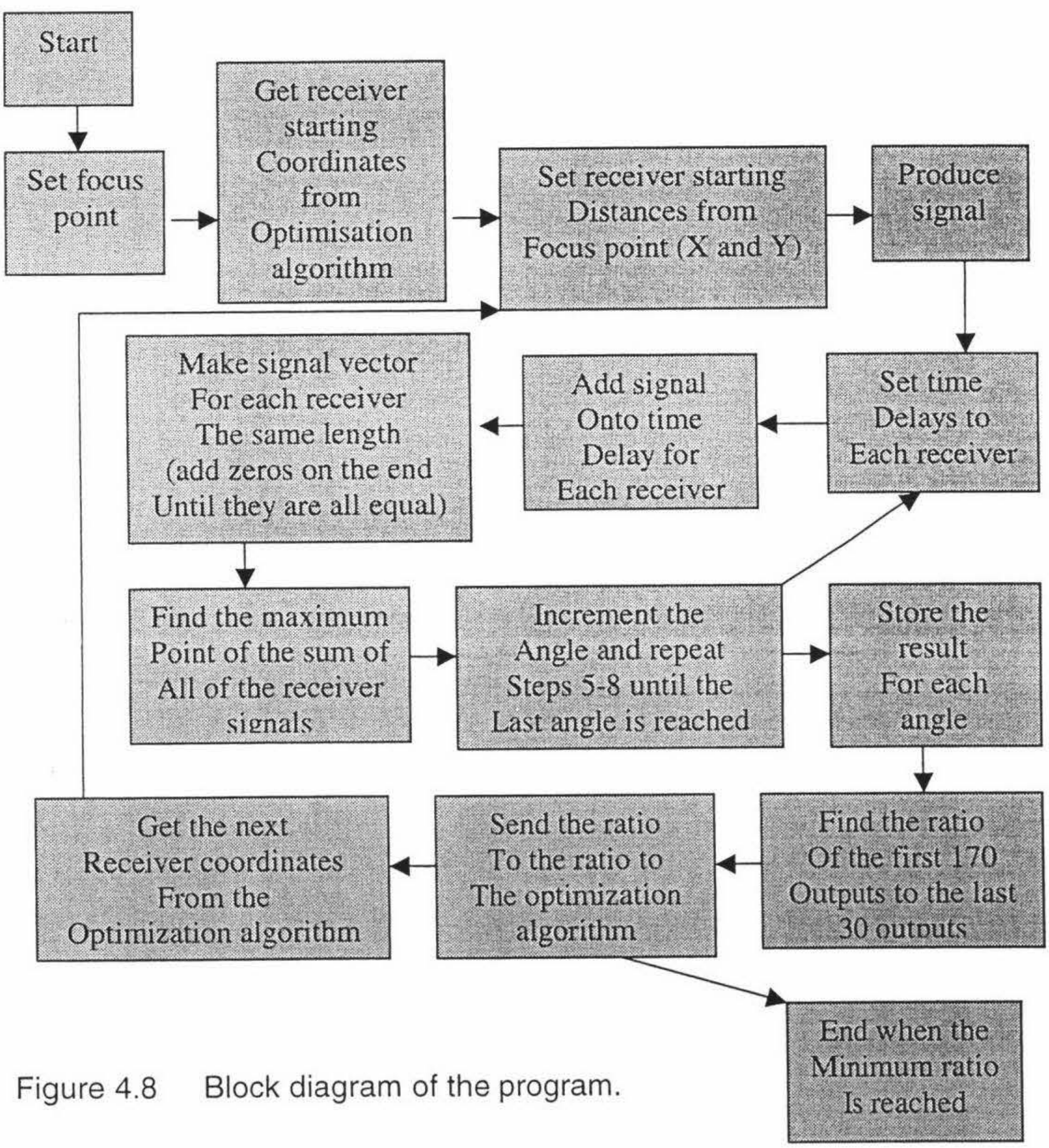



Figure 4.8 Block diagram of the program.

MATLAB was also used for the optimisation. This was achieved by the use of the FMINS function, which uses the Nelder-Mead search algorithm. There may also have been better methods of optimisation but the FMINS function is already in MATLAB and it would have taken considerably longer to program in another algorithm. The local and global minima were obtained by taking the ratio of the central portion (±1°) to the next 5° on either side. The ±1° was thought to be a reasonable angular sensitivity i.e. the any object is within ±1°. The next 5° was to give a reasonable rejection range either side of the detected object (any peaks beyond this can be rejected through the differences in time delays of the signal reaching the sensors). The object of this was to get the ratio as small as possible. This was used to tell if the central ±1° would be received where objects occurring outside this would not be detected.

It was also decided that using different weightings for each set of sensors should be tried. This also involved simulations but the optimisations were six dimensional as there were three extra dimensions for the weightings. Because each of these optimisations took so long to run (about a day each) the number of simulations was limited. Firstly the best five of the previous optimisations were chosen as starting points and then five other starting points were chosen to approximate the likely ranges of values.

As the previous method did not produce any respectable results another method was tried which used thresholding to obtain an output which was digital. This required the insertion of an extra section into the program and the section is as follows:

**Program Notation:**

| | |
|---|---|
| V1-3 | Sum of the maximum output for each pair of sensors. |
| X(5) | Threshold value. |
| Vd-f | Results of the thresholding. |
| V | Multiplication of the three results. |

**Program extension:**

```
V1 = max(T1+T6); %maximum of first pair of sensors.
V2 = max(T2+T5); %maximum of second pair of sensors.
V3 = max(T3+T4); %maximum of third pair of sensors.

% Set threshold at x(5).
if V1 > x(5);
  Vd = 1;
else
  Vd = 0;
end
if V2 > x(5);
  Ve = 1;
else
  Ve = 0;
end
if V3 > x(5);
  Vf = 1;
else
  Vf = 0;
end
V = Vd*Ve*Vf;
```

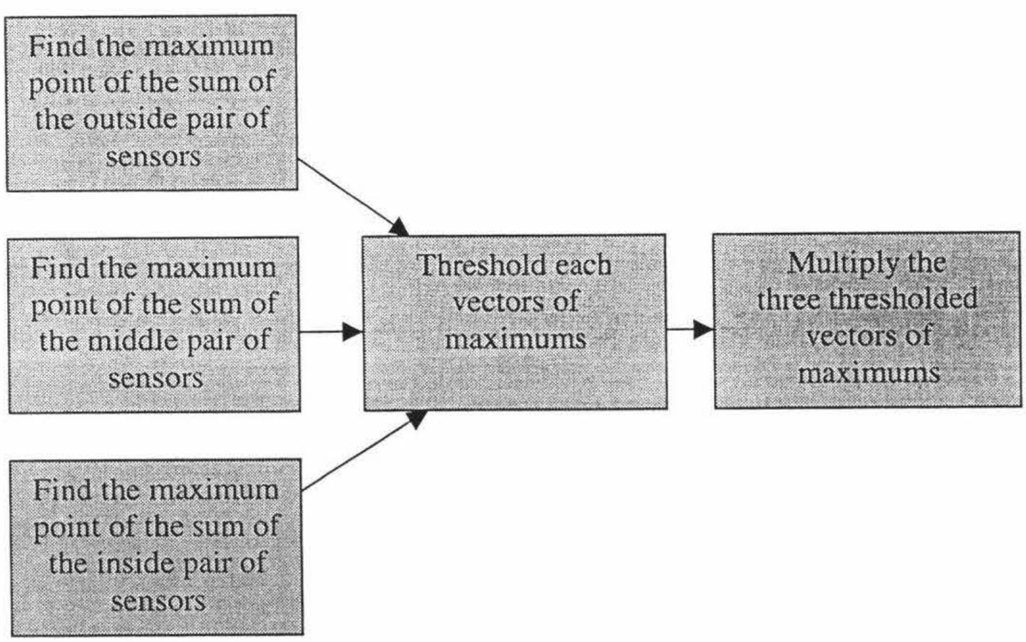



Figure 4.9 Block diagram of the program extension.

This produces thresholding, which means that if the signal is above a certain level it is counted as a one otherwise it is a zero. The two outside sensor signals are added together as are the next pair and the inside pair. These signals are passed through the thresholding after which the resulting signals are multiplied together. This results in a signal which has a value of one only when all of the three resulting signals have a value of one i.e. if any of the signals is zero multiplying will mean that the output will be zero.

As this still did not produce the desired results another small modification was made. This modification involved doing a sensor sweep at three slightly different frequencies. The results for these sweeps were recorded and when the last sweep had been completed they were all summed together. The reasoning behind this was that at the different frequencies the side lobes would be in a slightly different place and therefore when they were added some of the effects of the side lobes would cancel out. This would hopefully enable the use of a lower threshold value.

This produced an output that was not much better than the previous one and it was thought that this would be about the correct time to test if the simulations were accurate before any more significant work was done. A model of the array was therefore created. The spacings of the sensors were all measured and positioned accurately in order to get it as close to the simulated result as possible. The model was then mounted on a dividing head to get the required angular steps and to give a stable base. A flat object (this being the easiest to detect) was placed in front of the array at two metres (the distance of the array focal point). The array was then moved past the object in steps and the distance results recorded. This was then repeated for other distances with the results again being recorded.

### 4.2.1 Frequency Modulation

As the results show the previous method was not practical and another method had to be used. The next idea was to use frequency modulation. It was hoped that this method would be a lot more accurate in the distance measurement. Also it was hoped the angular measurement could be obtained by sweeping past an object and finding the centre point. This would be achieved by recording where the object first occurred and the point at which it disappeared and halving the difference to get the point at which the object actually occurred. This method was also intended to avoid the problems of minimum range and diffuse signals. The minimum range should ideally be zero with this method because there is no need to wait until the signal goes out before the returning signal is detected. Also the problem of diffuse signals becomes less because frequency modulation does not depend on the amplitude of the returning signal. This therefore means that a very weak signal should be able to be detected as easily as a strong signal.

This method was also simulated using Orcad, which was used to create a circuit and test its functionality. This produced good results and therefore a test circuit was produced.

The test circuit was produced by placing the components and wire linkages on Breadboard. Unfortunately the test circuit was difficult to get working due to some points in the circuit having to be tuned exactly right before the circuit would work correctly. Some extra amplification also had to be put in to get strong enough signals. With some parts of the circuit being analog and other parts requiring digital inputs it also meant that Schmitt inverters had to be put in to create appropriate signals.

The Figure 4.10 below shows how the frequency modulation system works:

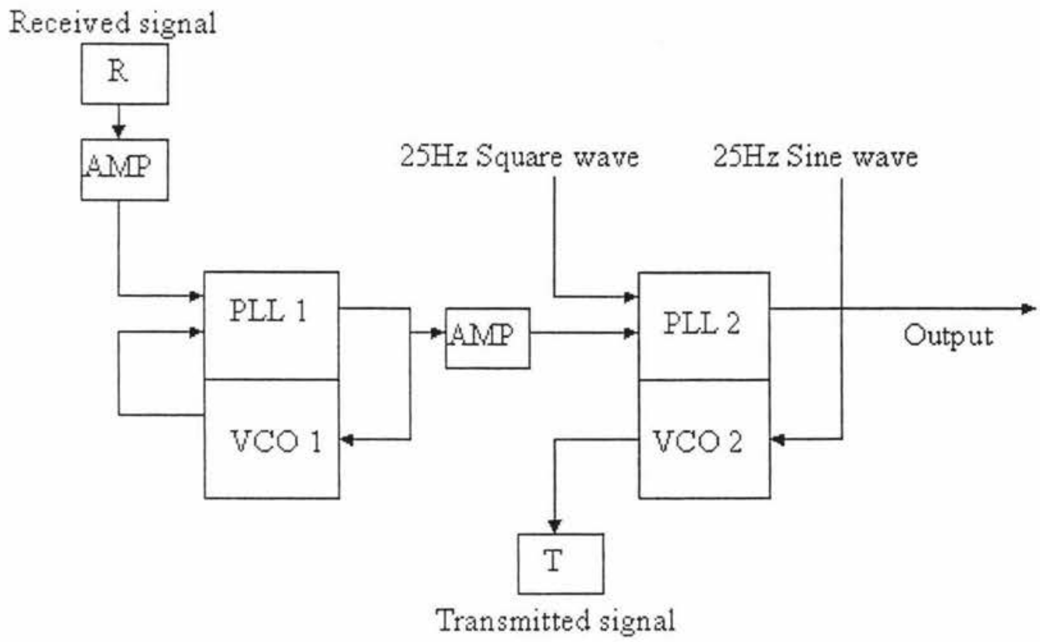



Figure 4.10 Diagram of the frequency modulation/demodulation circuit.

The frequency modulation is produced by sending a sine wave (25Hz) into the voltage input of a VCO (Voltage Controlled Oscillator). The frequency of this signal is the modulating frequency and the amplitude of the signal effects how much the carrier signal (40kHz) will deviate from its central frequency. This modulated signal is then transmitted and the corresponding reflection is received. The received signal is passed through three amplifiers to create a big enough signal and is fed into a PLL (Phased Locked Loop) where it is compared with a 40kHz signal (generated by a VCO set at constant 40kHz oscillation). The output signal from this stage is a 25Hz signal. This signal is amplified and passed into another PLL where it is compared with the original 25Hz signal in a square waveform. The output is a square wave of 25Hz, which has a varying duty cycle (time it spends on compared to time it spends off). The variation in the duty cycle is directly proportional to the distance of the reflecting object (for more detail see Figure 4.11). This output can then be turned into a constant voltage by taking its average and thus the distance is measured.

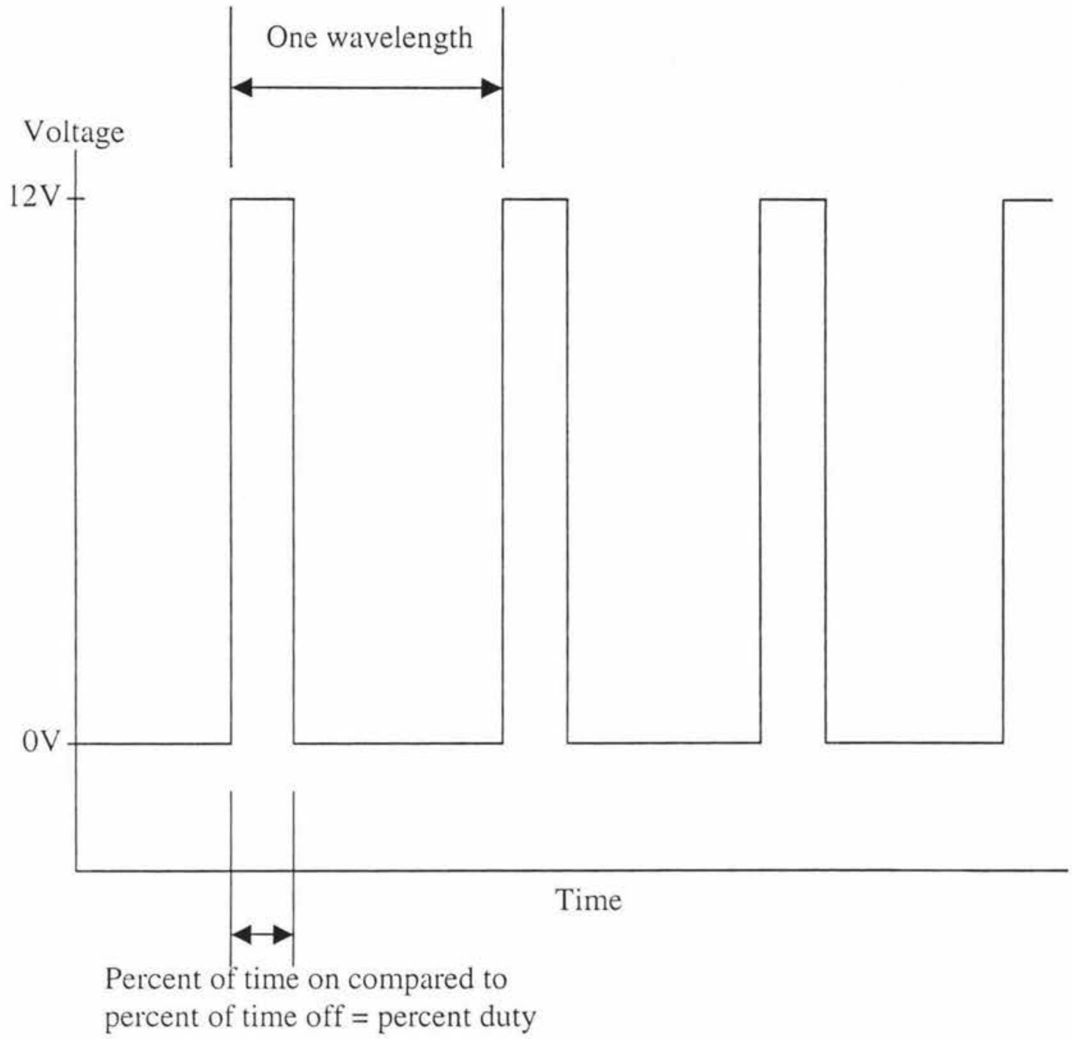



Figure 4.11 Representation of the output.

The circuit was finally completed and tested. The results proved to be as good as the expectations and therefore it was decided that this circuit should be turned into a PCB.

The PCB construction started by modifying the circuit in Orcad to reflect the changes made during the testing phase. The final circuit is shown by the circuit diagrams on the following pages (these were copied directly from Orcad):

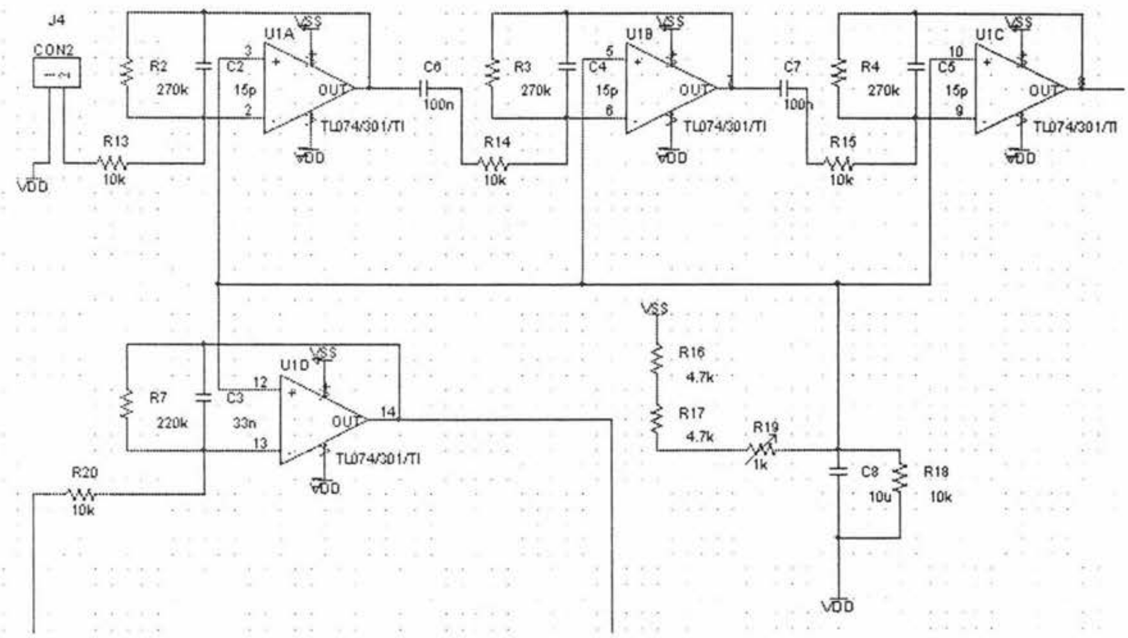



Figure 4.12 The amplifier circuitry.

Three amplifiers were used on the signal pickup in order to produce a signal with a usable strength. Each amplifier was set at maximum giving a combined amplification 19683 times greater than the original signal. This is because the amount of signal reflected even by a good object is much less than the transmitted signal. The conversion back into an electrical signal also reduces it further and the resulting signal is about three orders of magnitude smaller than the transmitted signal. The remaining amplifier was used after the first PLL due to the small output signal.

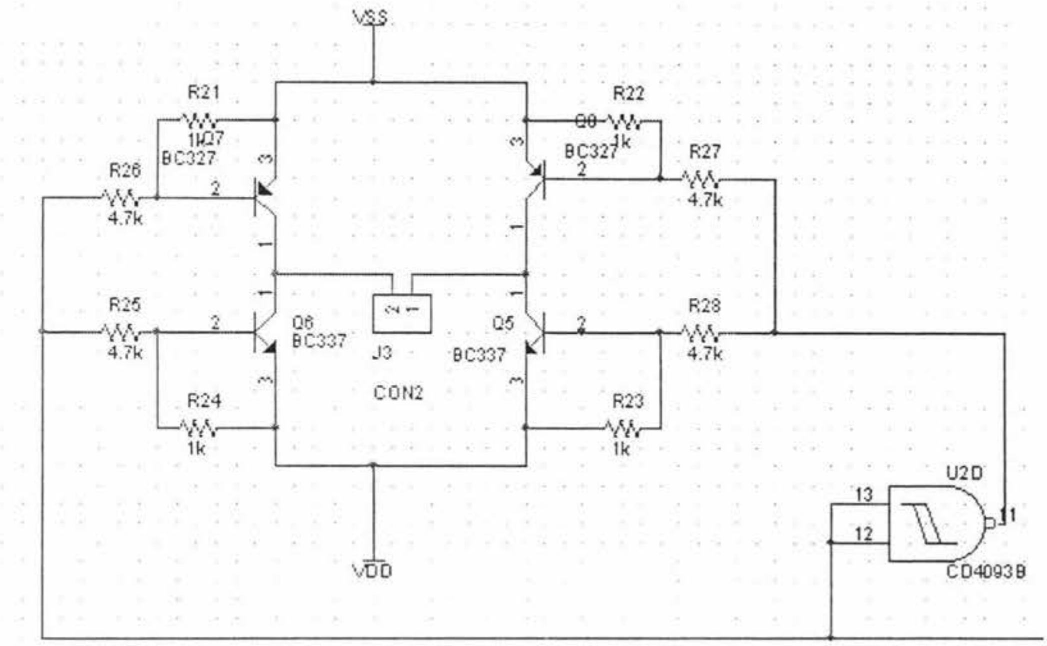



Figure 4.13 H-Bridge circuit used for driving the transmitter.

The H-Bridge circuit drives the transmitter both high and low producing twice the magnitude in the output signal than would otherwise be possible. This produces a much more powerful output giving an increased chance of objects being detected.

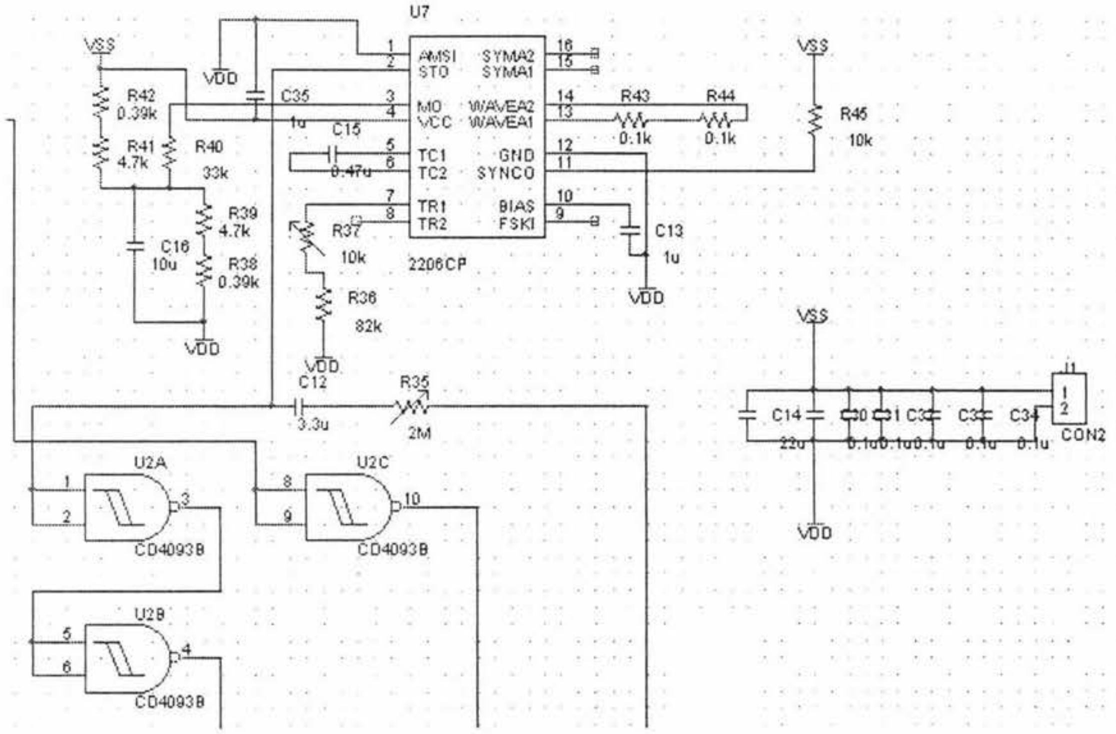


Figure 4.14 Oscillator circuit.

The microchip in this circuit is an oscillator circuit, which is used to produce a 25Hz sine wave. This sine wave is then input into a VCO (Voltage Controlled Oscillator) to provide the frequency modulation. The sine wave provides the modulating wave. Its frequency is 25Hz and this was chosen to give a useful detection range (if the detection distance is more than half a wavelength then a false object will be created close to the robot because this system cannot tell which wave the object occurs on). The amplitude of the sine wave determines the degree of modulation (how much the signal varies above and below 40kHz). If a larger amplitude is used the signal will vary by a greater amount. The amplitude had to be kept below 300mV to produce a signal, which could still be transmitted and received by the ultrasonic transducers.

The three Schmitt Inverters also shown in this circuit are used to produce a square wave from the sine wave produced by the oscillator and one is also used to square the signal from the receiver after it has passed through the amplifier stage.

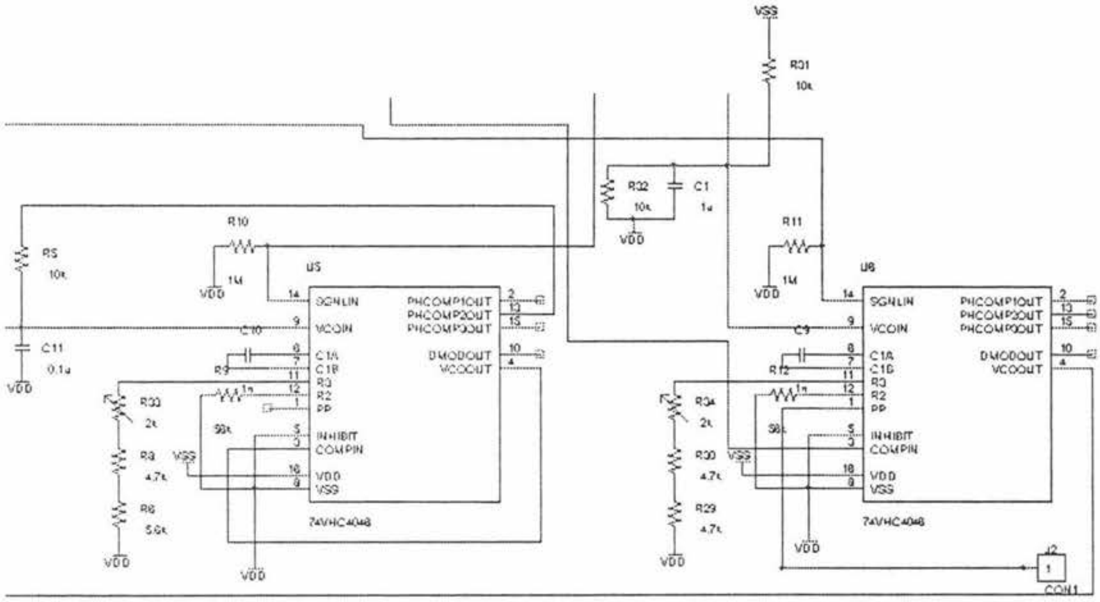


Figure 4.15 VCOs' and PLLs'.

The two microchips on this circuit contain the VCOs' and PLLs' (Phase Locked Loop). These provide the frequency modulation, the demodulation and the comparison of the signals at the end.

Both of the VCOs' oscillate at 40kHz, which produces the modulated waveform. The second VCO is modulated by the 25Hz signal coming from the oscillator circuit. The modulated signal is then sent to the ultrasonic transmitter. The first VCO is demodulated by the output signal from the first PLL. The demodulated signal is then fed back into the first PLL and compared with the signal from the receiver. The output of the first PLL is also sent to the second PLL where it is compared with the original signal from the oscillator circuit. Because the returning signal is delayed the output of the second PLL is a square wave, which has a duty cycle which varies depending on the distance of any reflecting object (a normal square wave is on for half of the time and off for the other half. The duty cycle refers how much time the wave spends on to how much time it spends off).

When the final circuit was completed the design was exported to Layout, which is another section of the Orcad program. Layout is used to position the components on the circuit and link them to each other with tracks.

The following picture (Figure 4.16) is the final design as it appears in Layout:

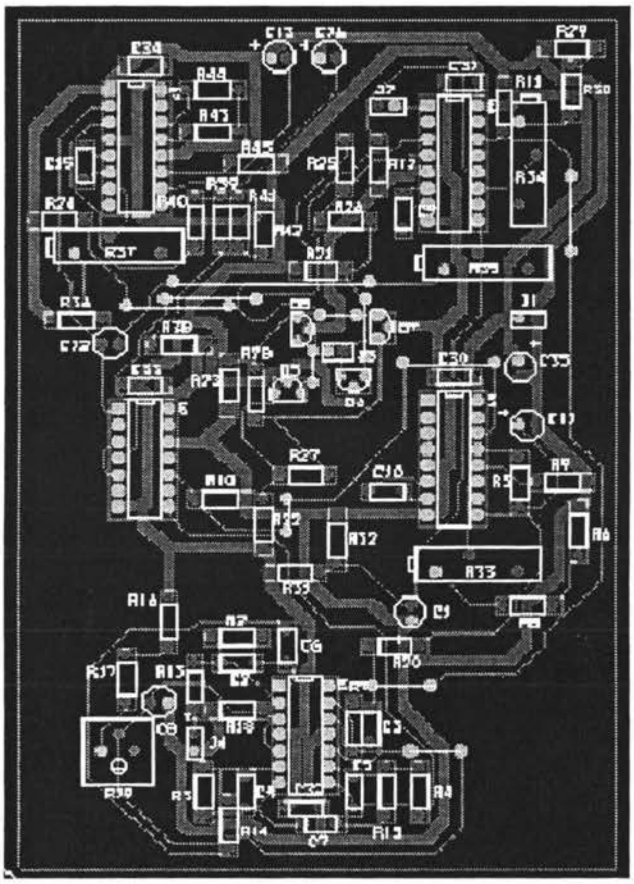


Figure 4.16 The final circuit as it appears in Layout.

This design was then converted into a solder mask, which was saved as a PDF file and sent off to be made into a PCB. The solder mask is shown in the picture (Figure 4.17) on the following page:

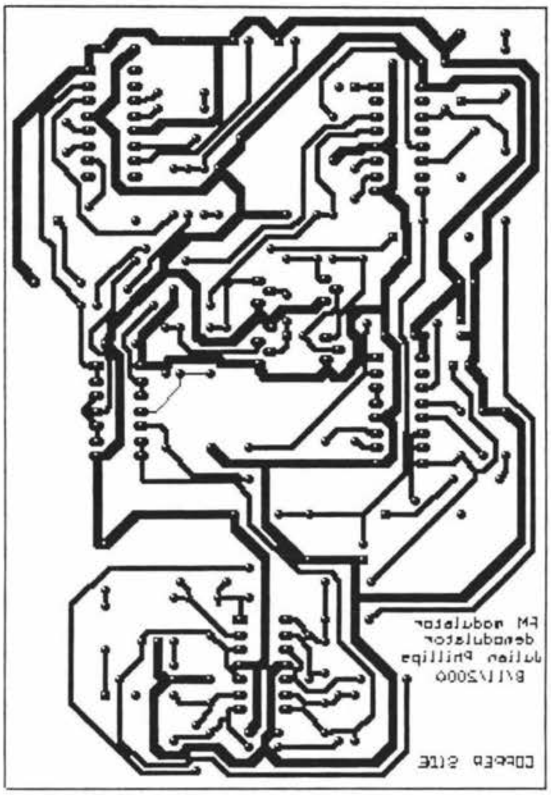


Figure 4.17 Solder mask of the final design. It may be noted that this appears to be back-to-front but this is because it has to go on the bottom of the board.

When the PCB returned the components were inserted and soldered in. The circuit was then tested and the appropriate adjustments made. When this had been done the circuit worked even better than the original testing circuit until the power leads got put on back to front. This resulted in putting a protection diode in and changing two microchips as they were burnt out.

This finally resulted in a working circuit and the sensor design and construction was completed except for mounting the sensors on a rotating platform and connecting the circuitry to the control circuit and power supply.

## 4.3 Results

The results of the sensor design start with the initial testing of the ultrasonic sensors. This showed that there are a few inherent problems with ultrasonic sensing and these are as follows:

1) Ultrasonic waves do not return well from an angled objet because the waves tend to reflect away from the sensors.
2) Ultrasonic sensors have trouble with corners because they involve a double reflection and then return to the sensor giving a false distance reading.
3) There is also a problem with multiple reflections producing phantom objects.
4) The sensor needs time to send a signal out before it can start receiving the signal and therefore the minimum range is limited to about 0.6m. This is because when the transmitter sends out a pulse the receiver must wait until the vibrations of the transmitter have died down enough to avoid detecting a false obstacle at zero distance. The receiver must also wait until the returning signal builds up enough to be sure it is caused by an object and these two time delays equate to about 0.6m.
5) Angular accuracy of the sensors is very poor (around 30°). This is because the ultrasonic transmitters and receivers have an angle of view of about ±15°. This means that for the transmitter as it sends out the signal it will fan out and with the receiver it can detect signals anywhere within the angle.
6) Measuring the actual point at which the signal returns is difficult as it involves a signal, which builds up and dies down and is also different for every object (this produces error in the distance).

With the first idea (using two sensors with one on either end of a rotating beam) it was hoped that the angular accuracy could be increased to about ±3°. The problem was that many combinations of objects produced a result, which looked like there was an object in front when there was an object on either side and no objects in front. Also the problem with multiple reflections became worse and none of the other problems had been dealt with. The ±3° accuracy was also not possible due to the difficulty in determining exactly when a signal arrived back at the sensor. This could have been partially overcome by superimposing one signal over the other and moving them until they lined up but due to the other problems this was not seen as being worthwhile. The idea was however considered worth looking at during a later stage of the project if it was required.

An example of one of the output graphs (Figure 4.18) from the optimisations is shown below:

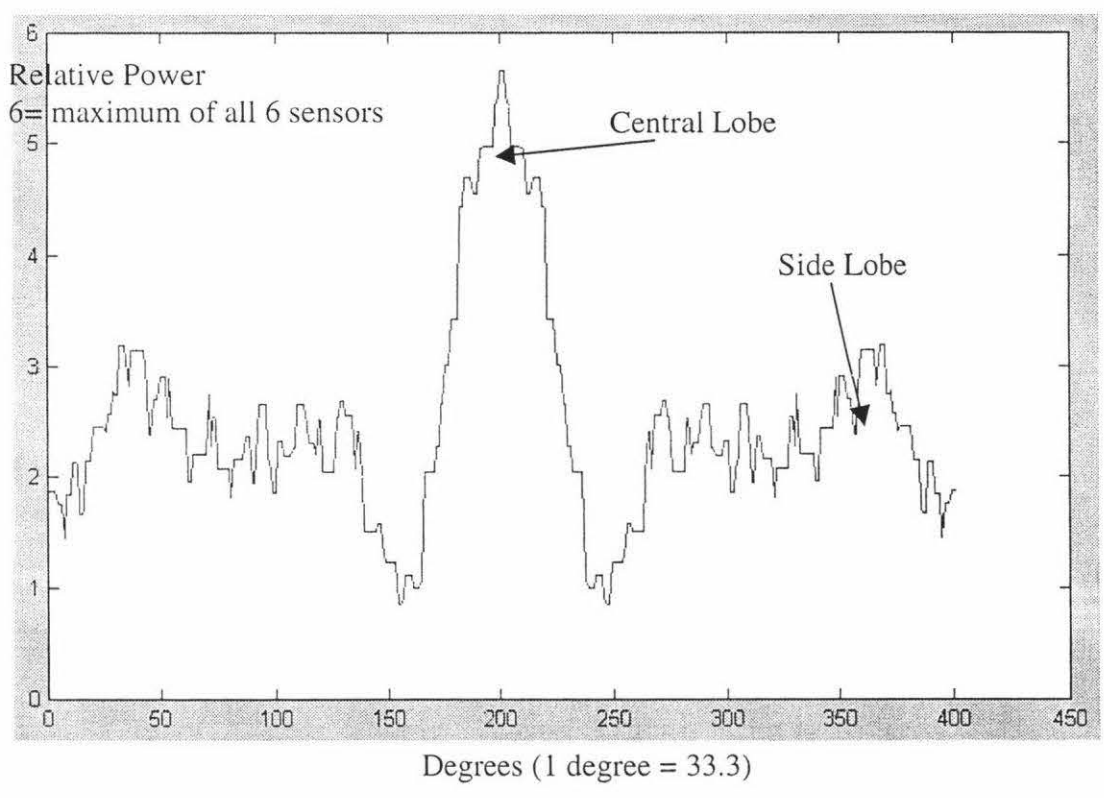



Figure 4.18 Plot of one of the best outputs. The central lobe is what we want (around 200 on the X-axis of the graph). What makes this graph good is that the side lobes are small while the central lobe almost reaches the maximum of six.

The local minima were recorded for each optimisation and these were compiled into a list from which the global minimum was eventually obvious.

From the start it was immediately obvious that there were a lot of local minima as the first simulation converged to a result near the original. The second result also did the same and this was followed for most of the simulations. As the idea was to get the ratio as small as possible the smaller values are better and represent the global minima. Also as there were a lot of optimisations it was decided that the best method of getting the results was to do the optimisations systematically and after all optimisations had been done the best should be refined to see if any better results could be obtained. The table (Table 4.1) below shows the best results of the optimisations:

| X1 Start | X2 Start | X3 Start | X1 Finish | X2 Finish | X3 Finish | Ratio |
|---|---|---|---|---|---|---|
| 140 | 90 | 70 | 147.8 | 87 | 70.2 | 0.5795 |
| 130 | 90 | 60 | 142.5 | 78.3 | 61.4 | 0.5636 |
| 150 | 80 | 70 | 151 | 81.7 | 68.3 | 0.5923 |
| 140 | 80 | 60 | 143.4 | 77.8 | 60.9 | 0.5874 |
| 150 | 90 | 70 | 150.5 | 92.5 | 69.7 | 0.558 |
| 140 | 90 | 60 | 147.1 | 84.6 | 62.4 | 0.5811 |
| 150 | 80 | 60 | 142.8 | 78.2 | 62.9 | 0.5557 |
| 150 | 90 | 60 | 145.1 | 82.1 | 63.3 | 0.5484 |
| 170 | 80 | 70 | 150.3 | 88 | 68.8 | 0.5584 |
| 160 | 80 | 60 | 145.1 | 81.4 | 63 | 0.5484 |
| 170 | 90 | 70 | 152.5 | 94.9 | 73.1 | 0.5874 |
| 160 | 120 | 60 | 187.1 | 137.1 | 52.2 | 0.469 |
| 170 | 90 | 60 | 149 | 88.6 | 69 | 0.5812 |
| 180 | 120 | 70 | 191.2 | 138 | 55.3 | 0.497 |
| 170 | 120 | 60 | 185.8 | 128 | 50.2 | 0.5881 |
| 180 | 130 | 70 | 196.8 | 143 | 58.9 | 0.4693 |
| 170 | 130 | 60 | 189.8 | 134.5 | 53.7 | 0.5296 |
| 180 | 150 | 70 | 196 | 141.1 | 60.2 | 0.4542 |
| 180 | 110 | 60 | 185.7 | 127.2 | 47.5 | 0.5881 |
| 170 | 110 | 50 | 183.5 | 127.2 | 39 | 0.55 |
| 180 | 120 | 60 | 187.4 | 136.3 | 49.4 | 0.5107 |
| 170 | 120 | 50 | 183.7 | 131 | 44 | 0.5711 |
| 180 | 130 | 60 | 187.6 | 136.9 | 52.5 | 0.469 |
| 170 | 140 | 60 | 192.4 | 136.2 | 57.9 | 0.496 |
| 170 | 140 | 50 | 187.3 | 137.1 | 47.7 | 0.5115 |
| 180 | 150 | 60 | 194 | 140.7 | 58.6 | 0.4751 |
| 180 | 110 | 50 | 188.2 | 139 | 45.5 | 0.5181 |
| 180 | 120 | 50 | 185.6 | 127.4 | 45.6 | 0.5881 |
| 180 | 130 | 50 | 186.8 | 127.1 | 49.9 | 0.5653 |
| 180 | 140 | 50 | 187.3 | 137.2 | 49.9 | 0.5107 |
| 180 | 150 | 50 | 194.6 | 146 | 50.5 | 0.5272 |

Table 4.1 Table of best results from the initial three-dimensional sensor optimisations.

In the previous table the starting values (X1,X2,X3start) are the distances in the X direction on which the sensors are placed from the centre of the beam. The remaining three sensors have same values except that they are negative. These starting positions are where the optimisation algorithm starts from. The finish values are the X positions of the sensors when the best result is obtained.

The ratio is what the optimisation algorithm is trying to minimise. The ratio is calculated from the size of the central lobe compared to the size of the side lobes. A small ratio corresponds to a large central lobe and small side lobes. The full table of results is contained in Table B1 of Appendix B.

The second method, which used thresholding, produced outputs, which were in graph form, and the idea was to get only a single peak where the central peak should be and zero everywhere else. This method still did not produce any respectable outputs. They were however better than the initial method. This worked for thresholds of 0.64 or above. Figure 4.19 below shows the best result obtained by using this method with the threshold set at 0.64:

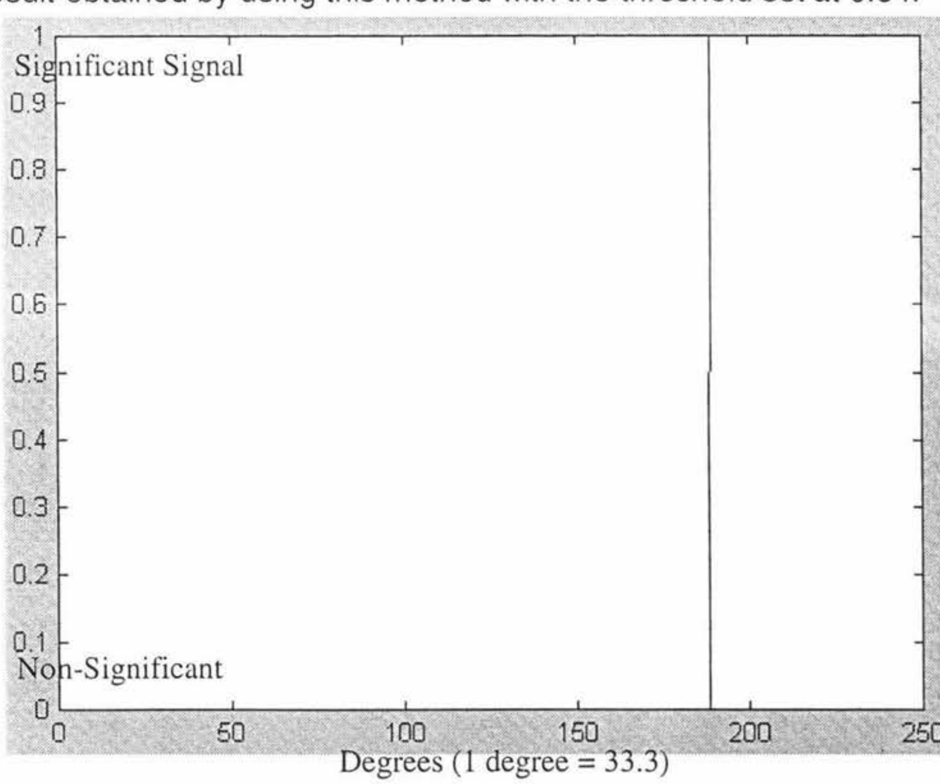
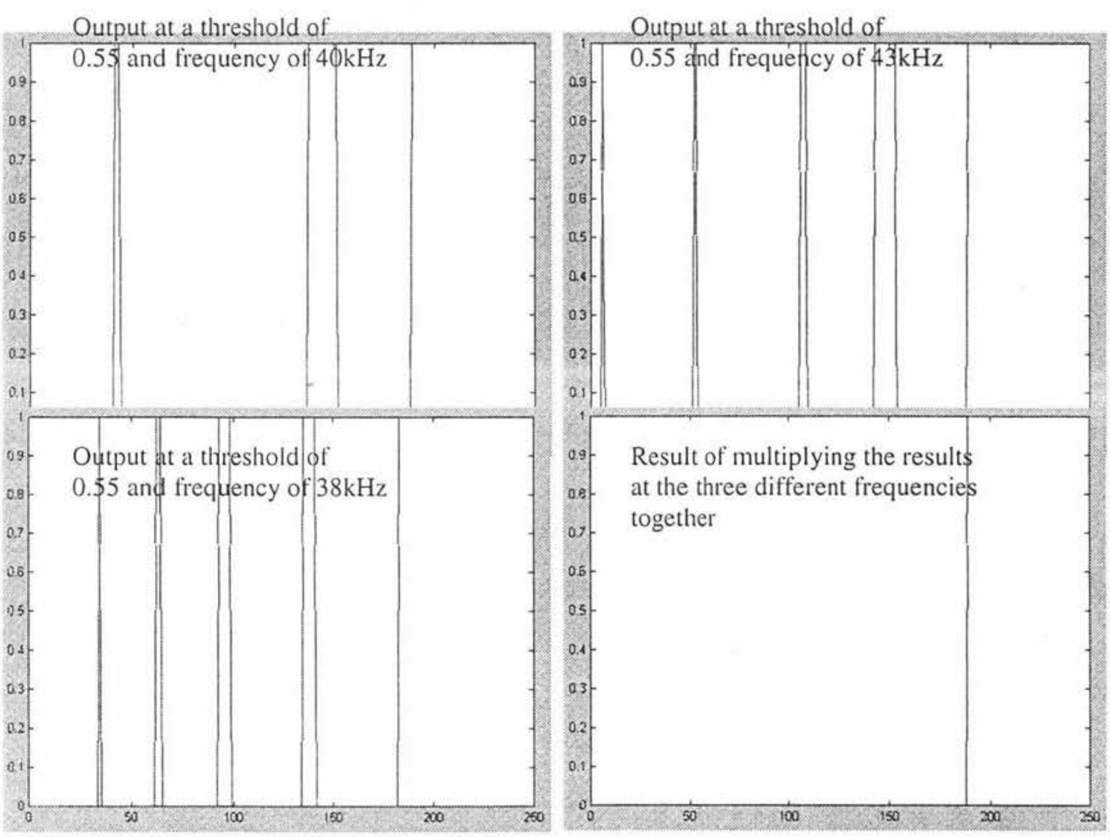



Figure 4.19 Plot from MATLAB of the output signal from the best sensor arrangement with the threshold set at 0.64

One minor change was made to this method to see if any further improvement could be made. This was to do three sweeps each at a slightly different frequency. This would result in the side lobes being in a different place. These three sweeps were then multiplied together in the same way as to get the final result of each sweep. The result was better than the previous method and the threshold was reduced to 0.55 but this was nowhere near enough and it was decided that no further work should be done on this method. To produce a useful result this threshold would need to be around 0.01 due to differences in reflecting surfaces and signal attenuation. The result also has the same problem with only operating well within a very small range centred around two metres (the focal point of the array).

The following graphs (Figures 4.20, 4.21, 4.22 and 4.23) show the results of the three separate frequencies (at a threshold of 0.55) and the final result after multiplying the three results.




Figures 4.20, 4.21, 4.22, 4.23 Output graphs from thresholding. All have X dimensions of 33.3 per degree and Y dimensions of either 1 or 0.

After this method was tried and still did not result in an acceptable outcome it was decided that another method should be tried but also that it was worthwhile testing the arrangement in its simplest form (the original program) to see if what occurred in theory also worked in practice. This was also to see if the programming was correct and no factors had been overlooked.
This was tested and the results (Figure 4.24) are as shown below:

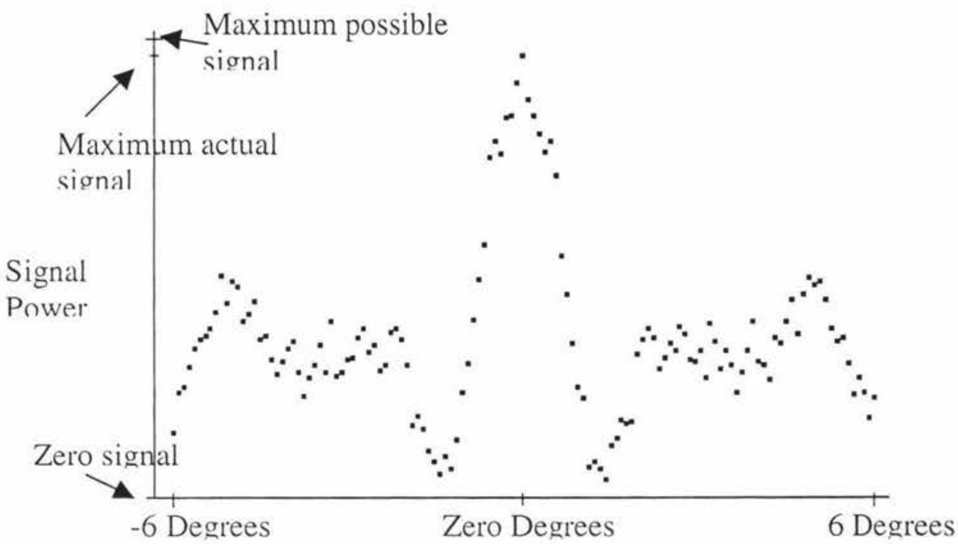



Figure 4.24 Graphical results of the physical test.

These results showed that the simulations had been correct. One advantage that was discovered however was that there was very little cross talk between the sensors and there was almost no pickup directly from the transmitter. A digital photo of the experimental array is shown in Figure B1 of Appendix B.

## 4.3.1 Frequency Modulation

The results of the final sensor design using frequency modulation were very promising. Firstly the initial testing showed that this method would work for any range between zero and around five metres. This overcame the problem of detecting obstacles at short range. It was also obvious that even small objects or objects which produced a weak return signal could still be detected. This resulted in a lot of enthusiasm and meant that a suitable sensor system had been discovered.

Once the circuitry had been correctly tuned it was also noted that more than one object could be picked up at the same time. This was especially evident when a small object was placed in front of a large object such as a wall. Figure 4.25 Shows a histogram where two different objects placed at different distances are both clearly visible. There was unfortunately a downside in that right-angled objects produced only noise and also eliminated the signal (because of the noise) from any other object behind them. This is also a problem with most other ultrasonic sensor systems and was not seen as a big disadvantage. Figure 4.26 Shows the resulting histogram from a right-angled object.

The testing of this system involved hooking the output of the circuit up to a computer and measuring the pulse width over time. The pulse widths were put into a histogram in which the X-axis was distance and the Y-axis was the number of pulses appearing with a particular width. Some small amount of manipulation was required in the number of samples in order to create a stable histogram. Rejection was also used to a minor degree to get rid of any anomalous readings. These anomalous readings were most likely caused by noise in the circuitry and to a small extent from the surroundings. This noise was considerably reduced when the circuit was properly constructed on a PCB, which means that some of it was definitely due to the circuit construction.

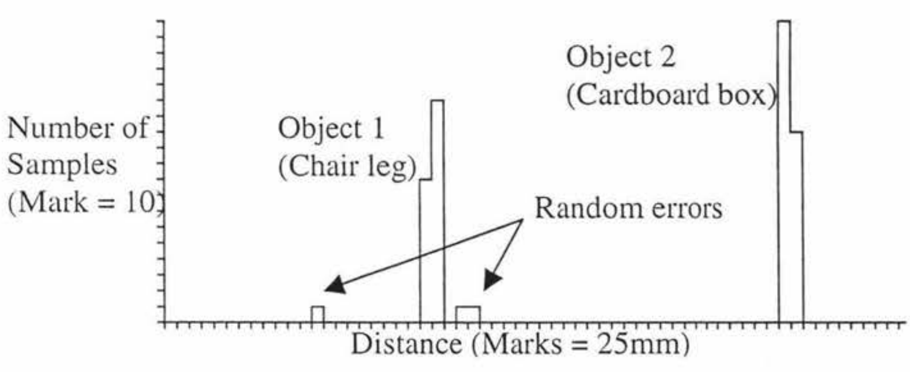



Figure 4.25 Histogram showing two different objects placed at different distances. Chair leg is at 550mm and Cardboard box is at 1300mm.

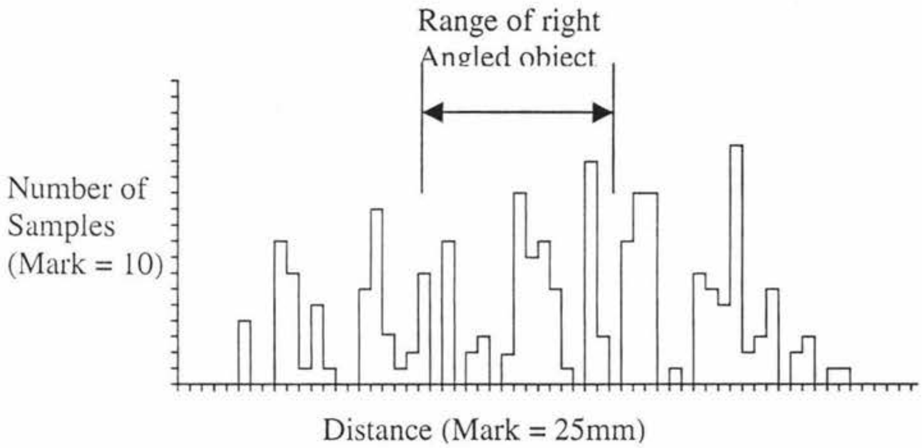



Figure 4.26 Histogram resulting from a right-angled object. Object is one side of a cardboard box and is from 500mm to 900mm.

It can be clearly seen from this graph that a right-angled object is very poorly detected and results in a random signal. The graph (Figure 4.26) is only a snapshot and the peaks shown vary randomly over time.

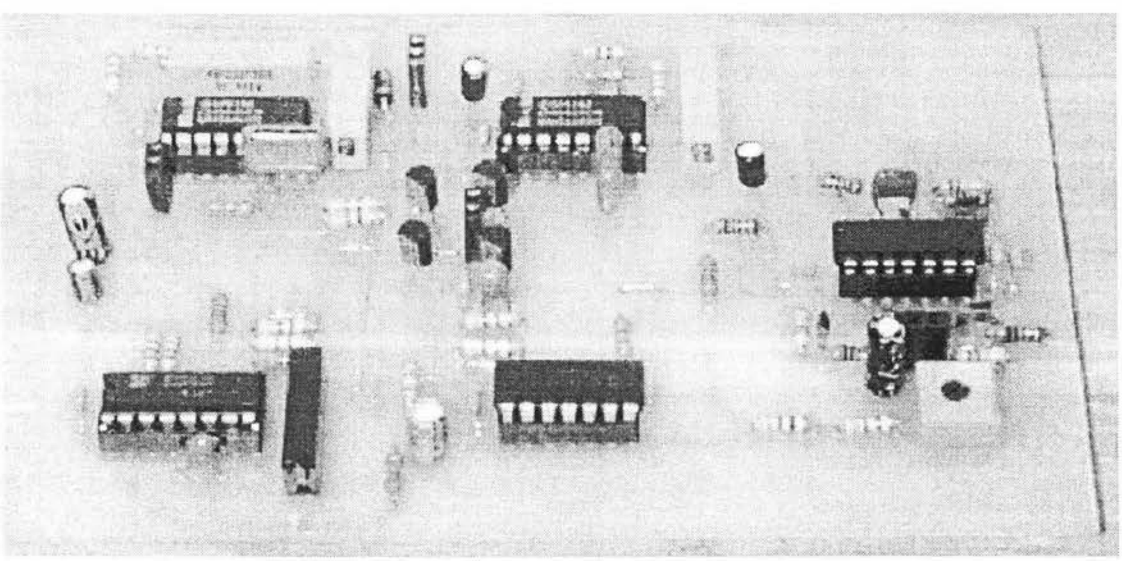


Figure 4.27 Digital photo of the final sensor circuit.

# 5 MOTOR CONTROL AND PROGRAMMING

## 5.1 Materials and Methods

This section covers the control of the robot, the associated circuitry and the programming.

The first part of the control section to be produced was the motor control circuit. This involved creating four H-bridge circuits (one for each motor). The circuit also had to have current protection to stop parts of the circuit overheating if the motors started drawing too much current.

It was discovered after the motors were obtained that they drew too much current for a motor controller chip to handle. This then meant that the H-bridge circuits had to be constructed rather than buying ready-made microchips. This did not pose too much of a problem to start with as the circuitry is not too complicated and the components are easy to obtain. After checking for MOSFETs', which would handle a large enough current it was discovered that NPN versions were cheap but the PNP versions required for the higher side of the H-bridge were very expensive and eight of them were required. This then lead to some lateral thinking which resulted in deciding to use all NPN versions and driving the higher side ones with 24V. This would be achieved by building in a voltage multiplier circuit which would double the 12V supply. The 24V supply would then be passed through a transistor before each of the higher side MOSFETs'. This was required in order to use the logic output to drive the voltage up or down without exceeding the output voltage of the logic chips.

Once this idea had been decided on the circuit was drawn up in Orcad and tested to see if it would work. The diagrams on the following pages show the circuit diagram with associated components as it occurs on Orcad:

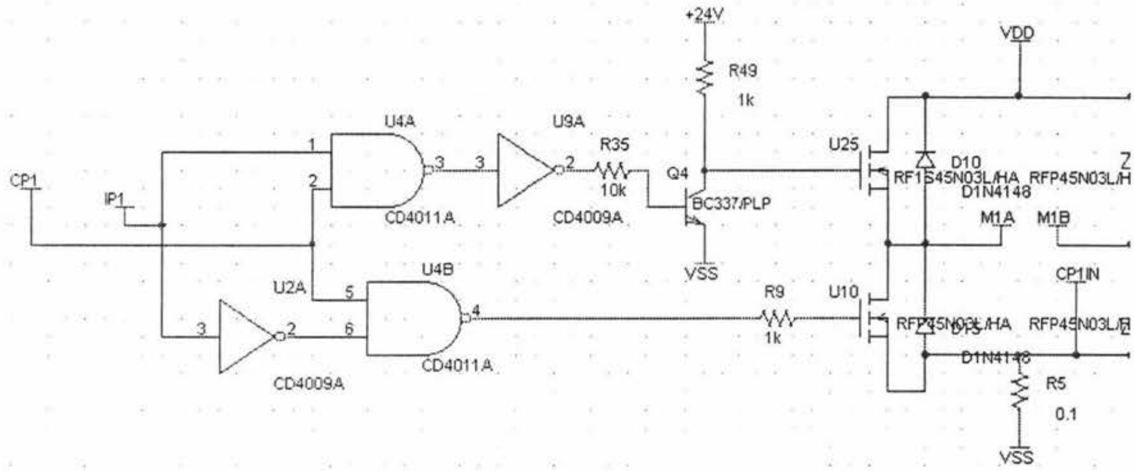



Figure 5.1 Half of the drive circuit for one motor. There are eight altogether with the four motors.

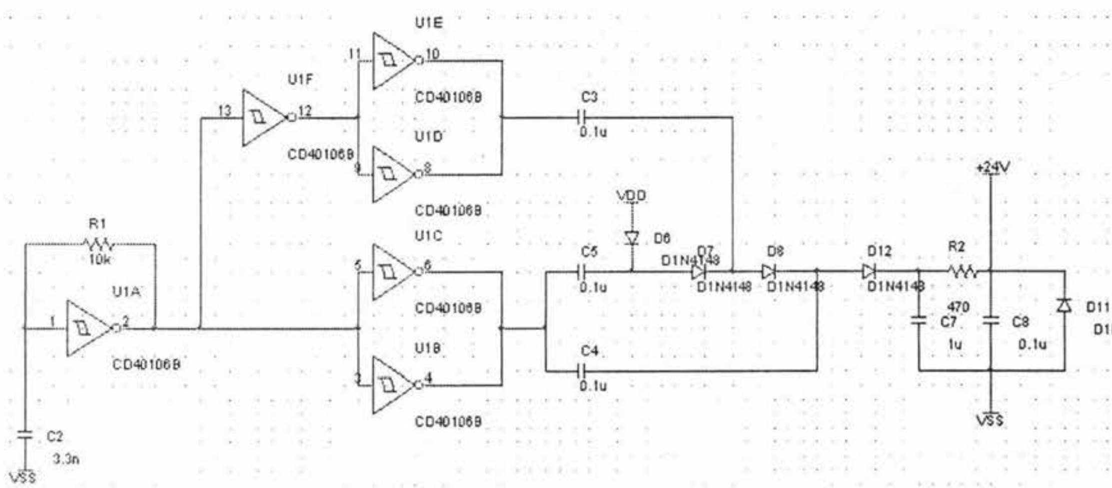



Figure 5.2 The voltage multiplier circuit that is used to create a 24V supply from the battery supply of 12V.

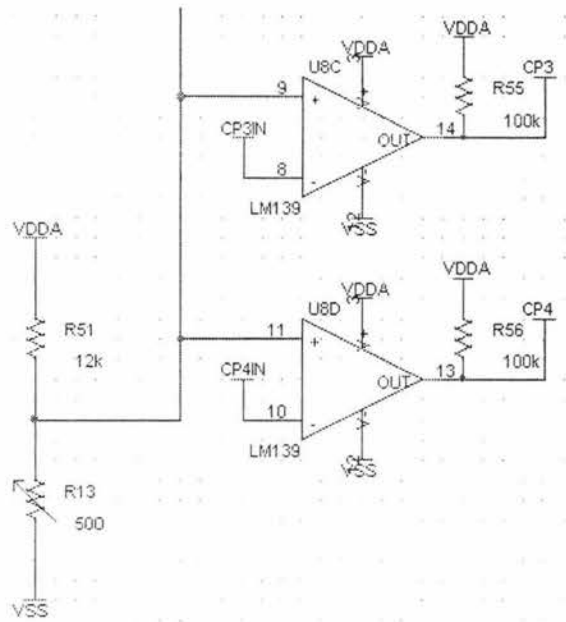



Figure 5.3 The comparator circuit, which is used to switch off each motor if, the current goes over 2A. There are two other comparators above the ones shown to give the current control for the remaining two motors.

The MOSFETs' were also tested to see if they would switch on and off quickly enough. This was important because if the logic was telling them to switch on and off too fast they could get stuck half way and overheat. Also this would be a big problem as not much heat sinking is used on the circuit due to the MOSFETs' running well below what they are capable of.

When this had been completed the circuit was then transferred to Layout and the PCB design was created. This turned out to be a much more difficult problem than the sensor circuit as there were more microchips and less resistors to use for jumping across tracks. There was also the problem of the MOSFETs' being surface mount components, which meant that they had to be flipped upside down. Also a new footprint had to be created for the MOSFETs', as none of the existing footprints in Layout was correct. These problems were finally solved and the PCB design was sent off to be made. The two pictures on the following page show the motor control circuit as it appears in Layout and the final solder mask of the circuit:

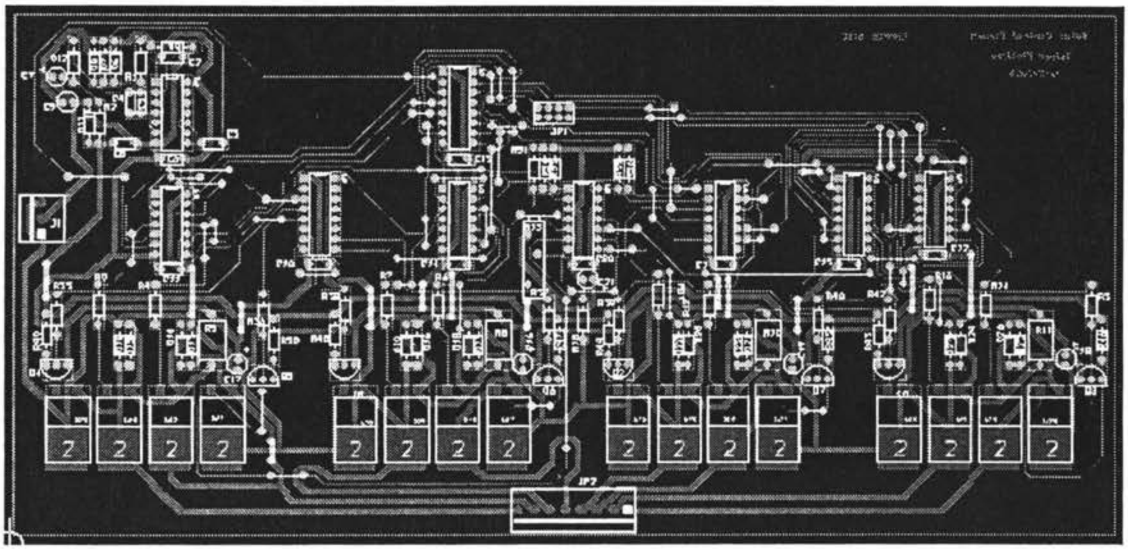


Figure 5.4 The motor control circuit as it appears in layout.

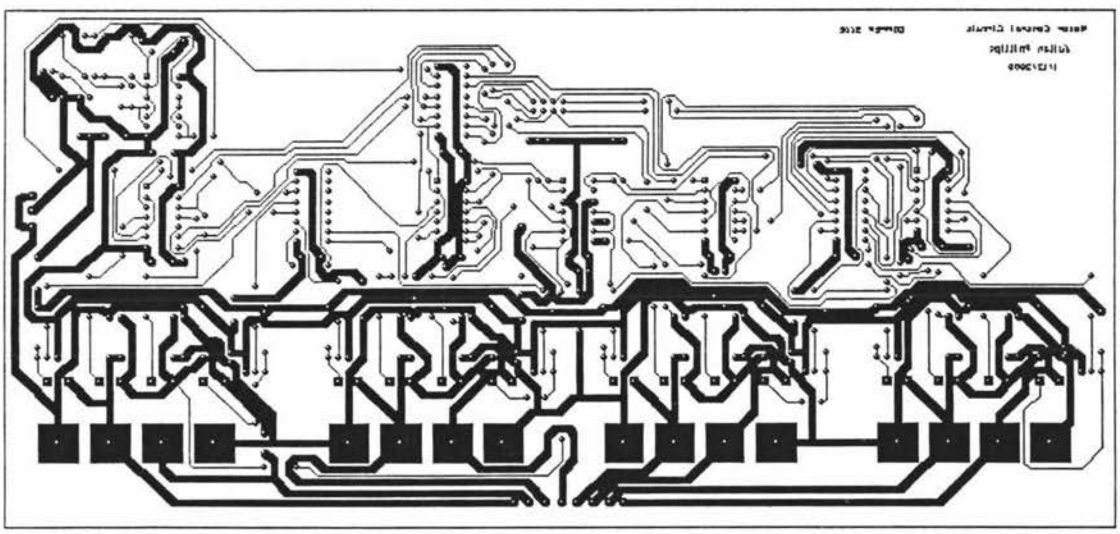


Figure 5.5 Solder mask of the motor control circuit.

The actual control section tuned out to be a big problem as programming a micro controller with a complex set of instructions is very difficult if one has never programmed one before. One alternative that was suggested was to use an old 486-computer motherboard and use a high level programming language. This would also have the advantage of being able to handle the mapping and navigation easier due to having much more memory available and a larger computing power. Also even to use the sensors to detect angle requires the storage processing of data.

It was decided in the end to use a micro controller as time was running out and a lot of time would be required to implement the use of a computer motherboard. This was because all the power supply and interface issues would take considerable time and effort to sort out

.

The micro controller that was decided on was the AT89C2051 and this was because it met all of the output and input requirements while still being relatively simple and inexpensive. As the associated circuitry was standard not much design was required and it was easily assembled. There was however a problem with the power supply as the micro controller required a 5V regulated supply while the supply to the remainder of the robot circuitry was 12V. The obvious solution to this problem was to use a regulator chip. The regulator chip was put onto the micro controller circuit and the entire circuit was kept separated from the remaining circuitry.

## 6.2 Results

The results for the motor control circuit are relatively obvious as the circuitry either performs or it doesn't. The final circuit has eight inputs from the micro controller and these when put through the circuitry tell the motors what to do. The following table shows how each input affects the outputs to the motors:

| Logic Input 1 | Logic Input 2 | Output 1 | Output 2 | Motor 1 |
|---|---|---|---|---|
| 0 | 0 | 0V | 0V | Stopped |
| 0 | 1 | 0V | 12V | Forward |
| 1 | 0 | 12V | 0V | Reverse |

| Logic Input 3 | Logic Input 4 | Output 3 | Output 4 | Motor 2 |
|---|---|---|---|---|
| 0 | 0 | 0V | 0V | Stopped |
| 0 | 1 | 0V | 12V | Forward |
| 1 | 0 | 12V | 0V | Reverse |

| Logic Input 5 | Logic Input 6 | Output 5 | Output 6 | Motor 3 |
|---|---|---|---|---|
| 0 | 0 | 0V | 0V | Stopped |
| 0 | 1 | 0V | 12V | Forward |
| 1 | 0 | 12V | 0V | Reverse |

| Logic Input 7 | Logic Input 8 | Output 7 | Output 8 | Motor 4 |
|---|---|---|---|---|
| 0 | 0 | 0V | 0V | Stopped |
| 0 | 1 | 0V | 12V | Forward |
| 1 | 0 | 12V | 0V | Reverse |

Table 5.1 Table showing how the inputs to the motor control circuit relate to the outputs and the motor directions.

The circuitry all worked as expected and very few faults occurred. This was largely because there was no experimentation involved due to the different parts of the circuitry being well known and relatively standard. The faults, which did occur, were minor and easily fixed. The results from testing the MOSFETs' were good as the switching time was definitely quicker than what was required (required switching time of about 40kHz). The graph (Figure 5.6) on the following page shows the results of testing the MOSFETs':

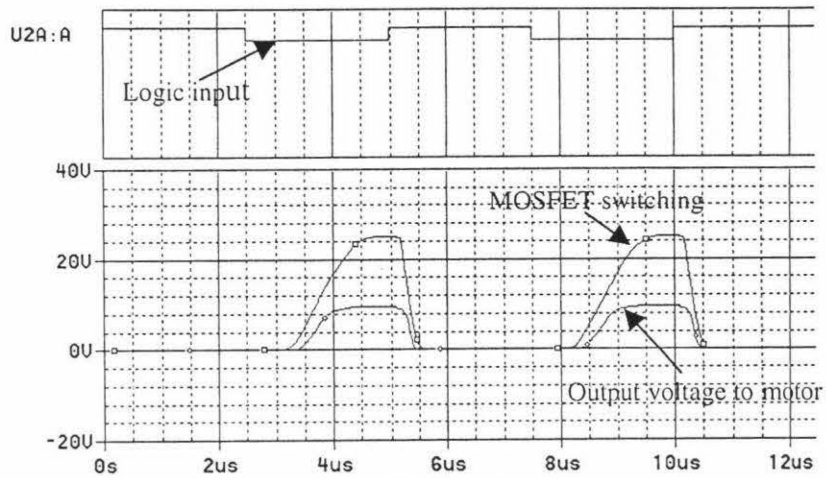



Figure 5.6 Testing results for the MOSFETs'.

Figure 5.7 below shows a digital photo of the final circuit (the MOSFETs' which make up the H-Bridge are underneath the circuit because they are surface mount components):

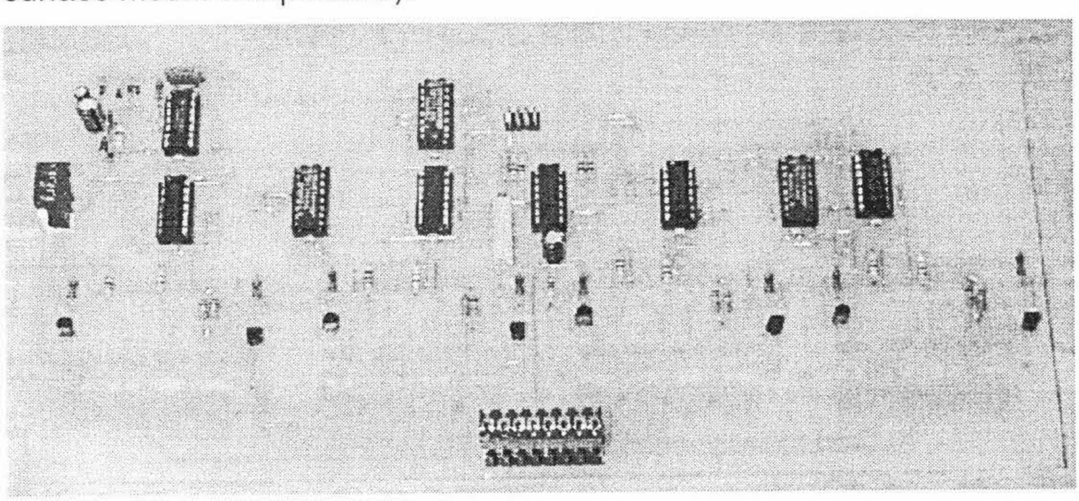


Figure 5.7 Digital photo of the motor control circuit.

The chosen micro controller (AT89C2051) is a standard item with standard circuitry to go with it and therefore the circuitry was virtually guaranteed to work unless components failed. The regulator chip worked well and gave a suitable supply (5V regulated) for the micro controller to run off.

The programming did not progress past the stage of producing an initial program due to running out of time. The program is not included as some major tuning and rewriting is still required before it works well.

# 6 ENTIRE MECHATRONIC SYSTEM

Figure 6.1 to 6.3 show the entire Mechatronic system that is simply the combination of the sensors, the control and the mechanical aspects that produce a working robot. As the programming was not completed the Mechatronic system could not be completed. The system was however assembled as far as it could be and tested without the programming.

The entire system was tested by applying inputs to the motor control circuit. The inputs corresponded to the required robot movements and in an ideal situation would come from the micro controller. The sensor was also rotated and the corresponding output checked. The rotation was achieved by applying an on-off signal to the coils of a stepper motor. This produced a step size of 0.9 degrees per step. This would produce a very good angular sensitivity as long as the sensor itself and the programming can handle the same sensitivity.

Figure 6.1 to Figure 6.3 (Digital Photos of the entire system)

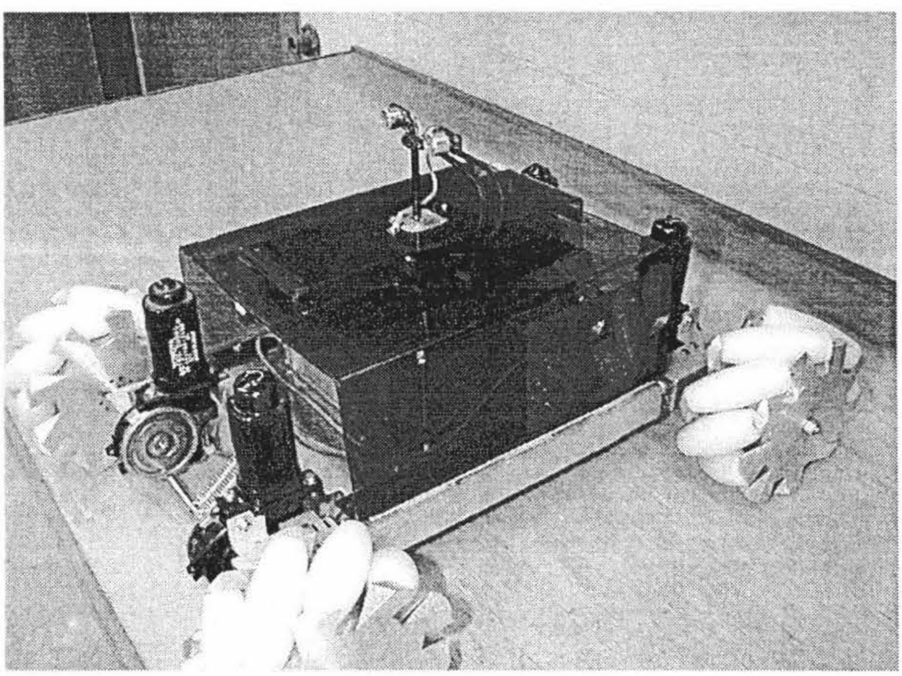


Figure 6.1 Right-hand view of the complete system.

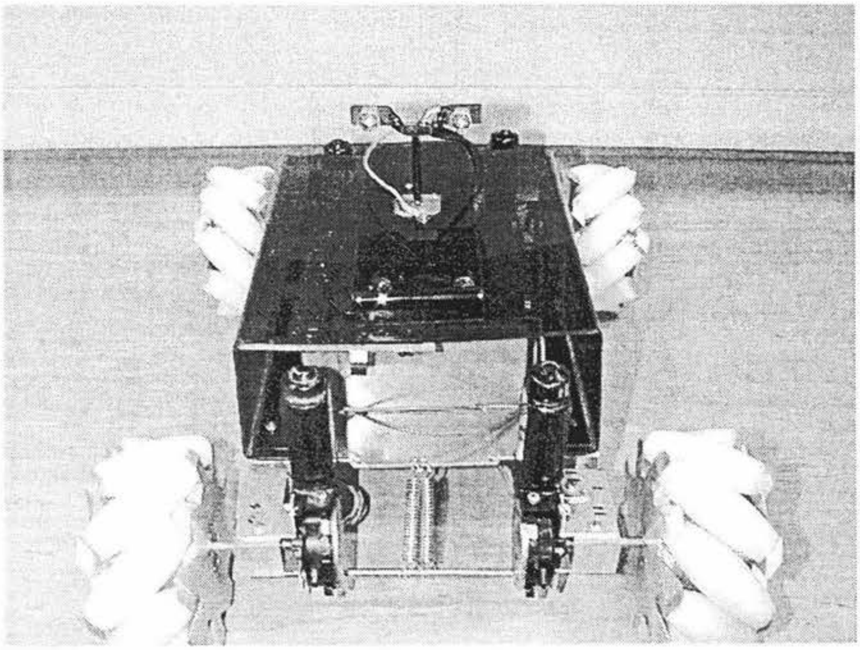


Figure 6.2 Front view of the complete system.

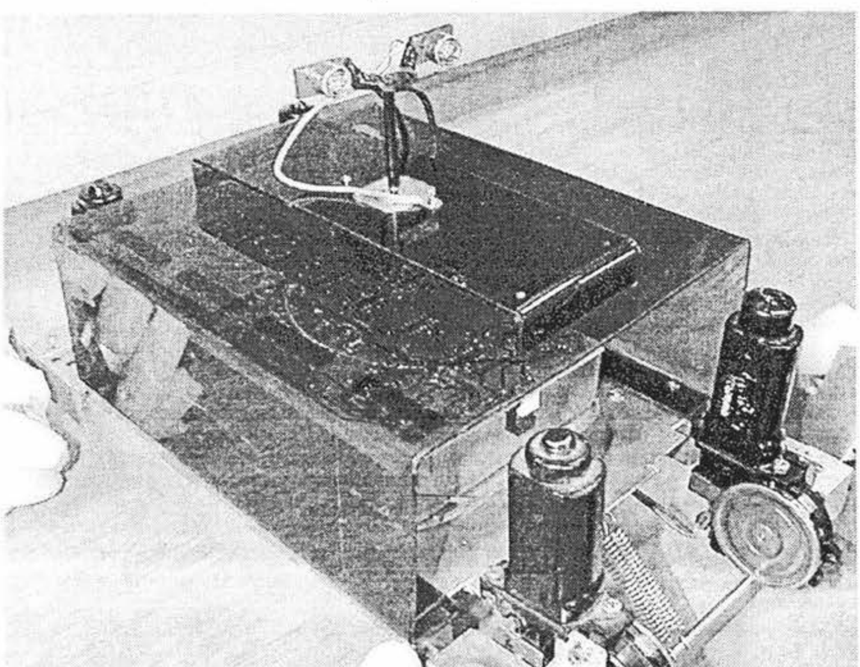


Figure 6.3 Left-hand view of the complete system.

The results of the testing were good and everything performed as expected. The robot movements were all good on carpet but on Lino or concrete some of the movements had a bit of roller slippage, which was expected. The only real problem was some overheating of the motor controller board but this can only be fixed by the production of a new circuit board with more substantial tracks.

# 7 DISCUSSION

This section contains the discussion of the results from each section of the robot construction.

## 7.1 Motor and Chassis Unit

The Mecanum wheel worked almost as planned and provided the robot with several movements, which were useful and impossible for most other types of drive to do. Some multi-degree-of-freedom drives could produce the same movements but would require more motors and higher complexity of programming. With the wheels not needing to be steered the robot also has very good stability.

There was one minor disadvantage and that was that the rollers used on the wheels were made of nylon and while this provided a good bearing surface on the shafts it also meant that the rollers slipped on a smooth floor surface. This reduced the efficiency of the robot movement but all movements could still be implemented.

The motor and chassis unit was produced to a reasonable standard and provides a solid and rigid platform for the batteries and circuitry. The strength of the chassis also allows for further circuitry/sensors etc. to be put on the robot at a later date. The suspension while adequate for the task could be improved at a later date to provide better wheel traction. The motors all work well are robust and provide considerable torque at the correct speed. The motors are therefore perfect for the task and can accommodate any further changes to the robot.

Some small errors were made in the machining and in the practicality of parts of the design. As much was learnt about the practicality of different aspects of design and production this was not seen as being a waste of time.

The actual design stage on Solid Works went very well although it took a long time to complete. The number of errors in the mechanical construction was also cut down at this stage because of advice given by the technicians on what was actually possible and could be made using the current facilities.

Solid Works turned out to be excellent for designing the mechanical parts as it is easy to use, a good idea can be got of the mechanical feasibility of the design and the assembly can be manipulated to see how the entire system will work.

Overall the mechanical design and construction went well with only minor changes being made. This was mainly due to a lot of work being done in the design stage and following up suggestions made by the technicians. There was no research undertaken on the mechanical design and construction except for how well this particular implementation works for the purposes of providing mobility for a mobile robot. It proved to be more than adequate to the task and provides a combination of multiple-degrees-of-freedom with few motors and low programming complexity.

## 7.2 Sensor Design

The sensor design was the main research area of this project and therefore a considerable proportion of the project time was allocated to sensor research. The initial idea was to use ultrasonic sensors in a different way. This idea was carried out with mixed results but unfortunately most of them were negative.

The initial idea was to use two ultrasonic sensors with one being at each end of a rotating beam and a transmitter in the centre. This idea proved to be no better than any previous method because it did not solve any of the existing problems with ultrasonic sensing. Also the problem of angular accuracy, which it was intended to solve, was not improved by much due to the difficulty of finding the actual time when the returning signal reached each sensor. There was also an additional problem where an object on either side of the robot would look like one object directly ahead. For these reasons it was decided to move to a different idea.

Another point of the initial design was that a lot of time was spent getting the MATLAB programming correct. The programming could have been done better and more efficiently by using matrix operations but the difficulty of this was a limited knowledge of programming. Also due to the program working correctly it was initially thought that the current program was sufficient.

The second idea was similar to the first except that there were three sensors on each side of the beam. This idea was an improvement on the first idea and was also intended to solve the angular accuracy problem. The programming for this idea was also similar to the previous idea except that this method required the use of a three dimensional optimisation. The optimisations took a considerable amount of time and computer resources. This could possibly been reduced through modifications to the MATLAB programming or by using a different (more efficient) search algorithm. Both of these would have required a considerable investment of time but due to the length of time the optimisations took in total this may have been worth the effort. If anyone decides to do further work on this idea then it is suggested that the program be rewritten using matrix operations in order to make it run faster in MATLAB. Also there may be justification to program into MATLAB a more efficient optimisation algorithm. An algorithm, which ignores the abundant local minima would also be helpful and should drastically reduce the number of required optimisations.

The problem of local minima turned out to be a major problem with the optimisations as this greatly increased the number of required optimisations. This appears to be a problem with most receiving techniques of this type but usually there is at least one point where a significant global minimum occurs. For this method the global minima turned out to be far less than satisfactory. The most likely reason for this is that for most phased-array applications it can be assumed that the source of the returning signal is infinitely far away. This means that the returning signals can be assumed to be parallel. This cuts out the need for a focal point and the associated problems it causes. One of these problems also seems to be that there is no satisfactory global minimum.

Another major problem that was suspected during the optimisations and proved during the testing was that if an object occurred at a distance further away or closer than the focus distance then the system did not work. On top of these problems was the problem of not having a small enough threshold value (threshold between an amplitude which is detected and one which is not detected). The best threshold value obtained from the optimisations was 0.64 and this would have to be lower than 0.01 in order to be robust enough to use. This is because the maximum reflection of some obstacles is very small and there is also significant signal attenuation over distance. This therefore means that using the threshold value from the simulations either only large objects such as walls would be detected or there would be a huge number of false obstacles detected.

The third idea, which was a minor modification of the second idea, produced a slightly better result (ratio of 0.63) but it still wasn't anywhere near good enough. The use of thresholding produced a much cleaner signal with no side lobes. This was definitely an improvement as it cut out the confusion about whether the side lobes were a secondary (smaller) signal.

As the previous idea was not good enough another improvement was made and this was to use three slightly different frequencies and multiply the results. By using three different frequencies and multiplying them together it was hoped that the ratio would be further reduced. This is because at different frequencies the side lobes are in different places. This means that when the signals are multiplied, due to the thresholding some of the side lobes will completely cancel because they are in different places. This method worked to a limited degree and the ratio was further reduced to 0.55 but the change was nowhere near enough. The main reason for not being able to reduce it further by this method was that the ultrasonic receiver can only pick up signals within a limited range and therefore the frequency could not be varied enough to make much difference.

The physical testing of the second method was relatively successful and confirmed that these methods would not be suitable. It also confirmed that the programming and assumptions were correct. The physical testing also showed that if the method had proved to be practical then there would not have been much problem from self induced noise. This was because the receivers only picked up a very minimal amount of signal directly from the transmitter even without any shielding. This would mean that there was almost no chance of having false obstacles caused by the sensor system itself. The testing also showed that it would be very difficult to determine the exact range of an obstacle due to the return signal being drawn out (took a long time to build up and die down). This means that there would be a lot of error in finding the signal peak, which gives the range.

The system of using a phased array of sensors is therefore concluded to be impractical. It is also recommended that no more work be carried out on the phased array system. This is because the best results obtained are a very long way from what is required and even a large amount of further research is unlikely to reduce the gap by much.

The use of frequency modulation turned out to be a success right from the start and got better as it progressed. The initial results were excellent and showed that the system could be used to detect the majority of obstacles. It also showed that there was no minimum detection range and this is a big advantage over other ultrasonic detection methods. The main problem was the difficulty of tuning the circuitry but this was eventually solved through a lot of effort. The tuning is not ideal however and further work could be done to improve it but the time constraints of the project did not allow it to be done in this project. A minor problem that remains at this stage is that the signal is slightly noisy which results in a lower range resolution than what is possible and this could also be the subject of further research.

The main advantage with the use of frequency modulation seems to be that it has no minimum detection distance but the system, which has been built, also has a significant maximum range (around 5-6m for large objects). This distance is definitely good for mapping purposes, as the robot would not need to go close to a large object to know that it is there. Small objects also seem to be detected well and this is due to the frequency modulation technique not being dependent on signal amplitude. Another advantage that was found after the circuit had been properly constructed and tuned was that more than one object could be detected at the same time. This meant that a small object, which was close to the robot, would not get its signal overpowered by a large obstacle behind it.

Overall the frequency modulation technique was a success and even though it is not an original technique it backs up previous research done by others on this field. The main problem, which still remains is the problem of detecting an angle accurately. This was partially solved in the programming by recording when the signal starts and finishes and then halving the distance between to get the centre. This is far from ideal and it is recommended that further research be done to improve this.

## 7.3 Motor Control and Programming

The motor control was relatively straight forward as no research was being done and no unusual techniques were being used. There was however a problem with the motors drawing too much current for a motor control chip to handle which meant that the circuitry became much more bulky and complicated. The current circuitry works well and there should be no reason to change it if further work is done on the robot.

If further work on the programming results in the use of complex wheel movements where pulse-width-modulation is used there will need to be extra signal inputs on the motor controller circuit. There should however be enough space for this on the existing circuit but a new PCB can easily be produced and the components swapped over if it is required.

The only problem that could occur in the future with the current circuitry is overheating if the motors are run for long periods. The addition of extra heat sinking should alleviate this problem and larger Wattage resistors could also be put in for the current detection. It is concluded that the motor control circuitry was successful and it is recommended that no further work or research be done on this.

The programming turned out to be very difficult which was not unexpected. The difficulty could be removed for further research if a computer motherboard was used for the processing instead of the current micro controller. This would involve considerable work but it should allow for much better and more complicated programs. It would also allow easy implementation of a mapping system due to the larger processing power and much larger memory.

## 7.4 Entire Mechatronic System

The entire mechatronic system worked as well as could be expected. The addition of a micro controller or other form of control would produce an entirely self-contained system. This is desirable and recommended if further work is carried out.

The robot movements were actually slightly better than expected (less slippage of the rollers). This was due to the extra weight of the battery and other components after the testing of the wheel and chassis unit.

The problem of the motor controller board overheating is not serious if the robot is only run for short periods of time. It is however not as good as expected and further work may need to be done on the production of a new circuit board with more substantial tracks.

# 8 CONCLUSIONS AND RECOMMENDATIONS

It is concluded that the Mecanum drive system produced multiple-degrees-of-freedom with a minimum of programming and less motors for the degrees of freedom than alternative drive types. It is recommended that this drive system be kept and experimented on. It is also recommended that the rollers be machined smaller and a rubber coating be put on to increase traction. This may involve considerable effort but the results should be worthwhile.

The system of using a phased array of sensors is concluded to be impractical. It is recommended that no more work be carried out on the phased array system.

It is concluded that the frequency modulation system works well and produces excellent range accuracy. It is concluded that the ability of the system to detect small objects is very good. It is also concluded that the system has show an excellent ability to detect multiple objects at different ranges at the same time. It is recommended that further research be carried out to fine-tune these abilities.

It is concluded that the difficulty of tuning the frequency modulation circuit results in a lower range resolution than is possible and that this can be at least partially remedied by the use of higher quality components. It is also concluded that the current system of detecting angle with the frequency modulation circuit is far from ideal. It is therefore recommended that further research be done to improve the problem of angular accuracy in the frequency modulation sensor circuit.

It is concluded that the motor control circuitry was successful and it is recommended that no further work or research be done on this.

It is concluded that the use of a micro controller is adequate for the basic control of robot movements and sensing. It is also concluded that to introduce a mapping system the use of a computer motherboard (on the actual robot) would be needed due to the amount of processing required and the large storage capacity needed.

It is strongly recommended that further work be done on the use of a computer motherboard instead of a micro controller as this would allow for easier programming, more complex programs and easy implementation of map building.

It is concluded that the motor controller board overheats if the robot is run for any considerable length of time. It is therefore recommended that a new circuit board be constructed with heavier tracks.

# APPENDICES

## Appendix A (Mechanical design)

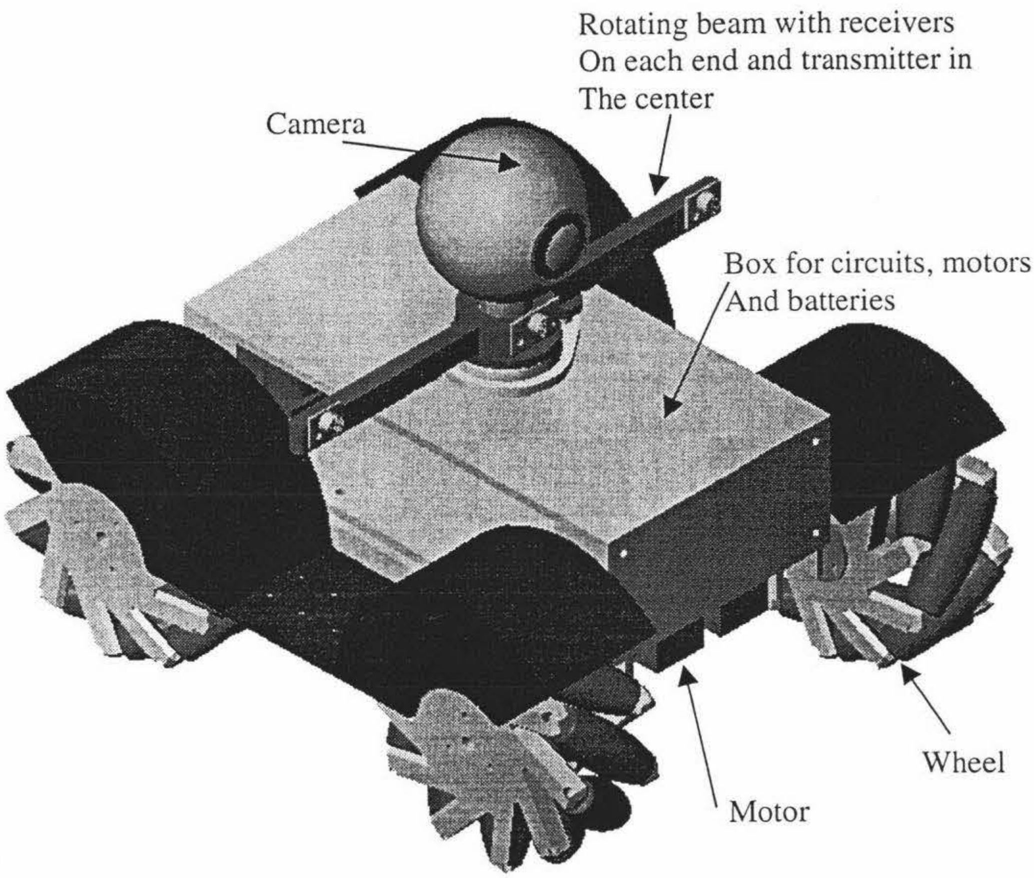



Figure A1 The original concept, which also incorporated a camera as an option. The camera was dropped before the project had really started, as it would require too much signal processing.

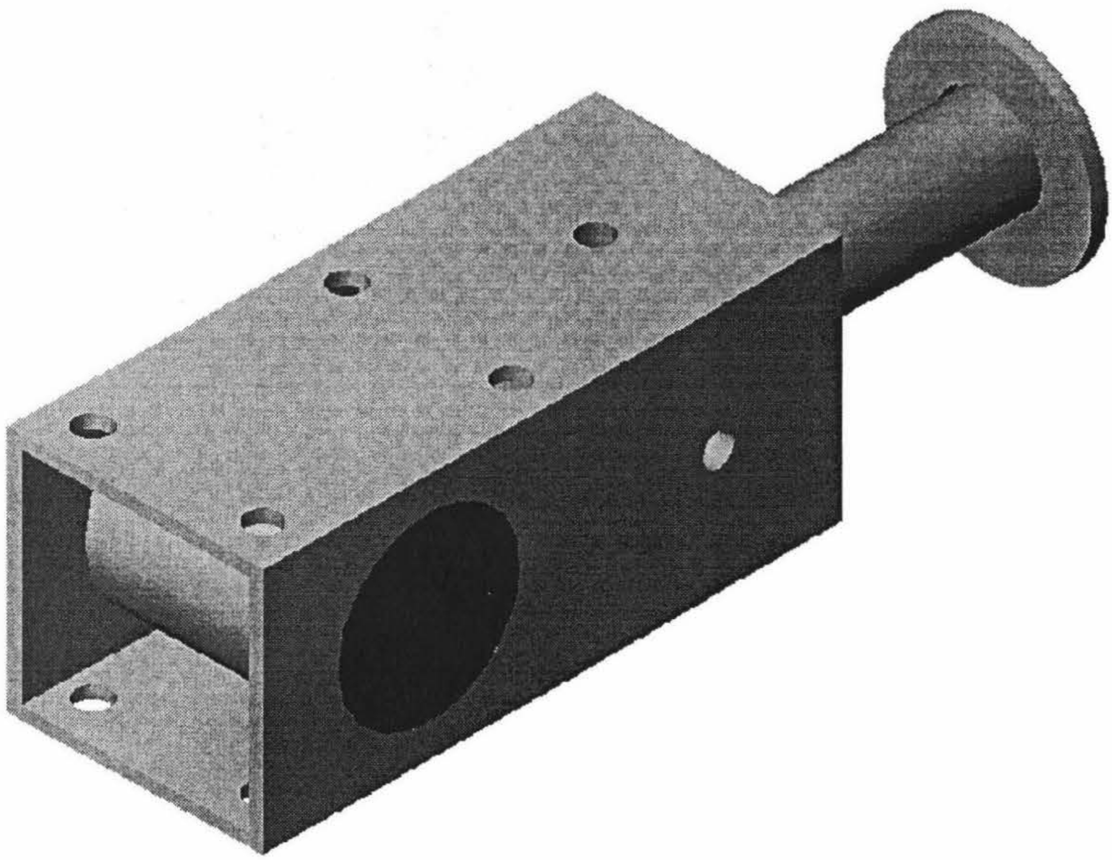


Figure A2 The original design of the chassis extension, which provides suspension and holds the wheel and motor. This design proved to be impractical and was changed.

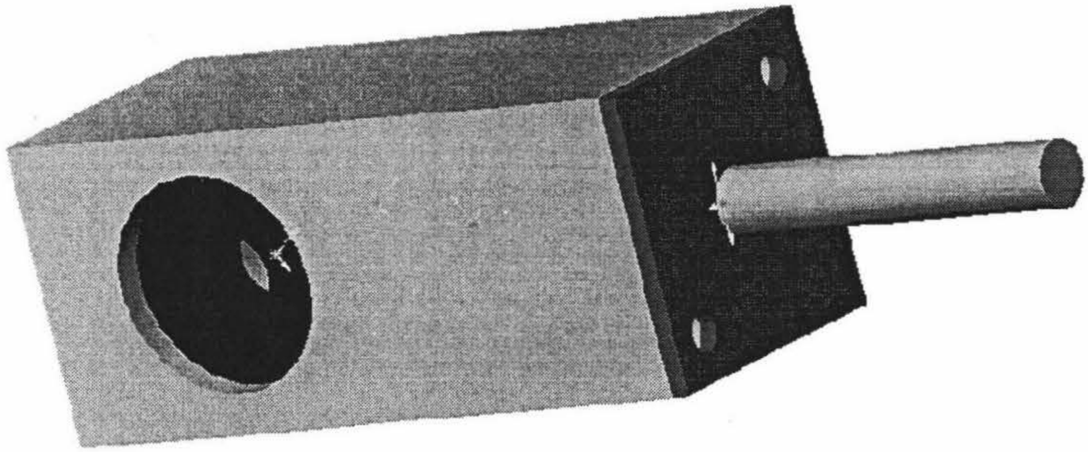


Figure A3 The final design of the chassis extension. The rod at the end is actually a bolt, which screws into the main chassis. The section of the bolt inside this extension acts as a bearing, which allows the extension to rotate independent of the main chassis.

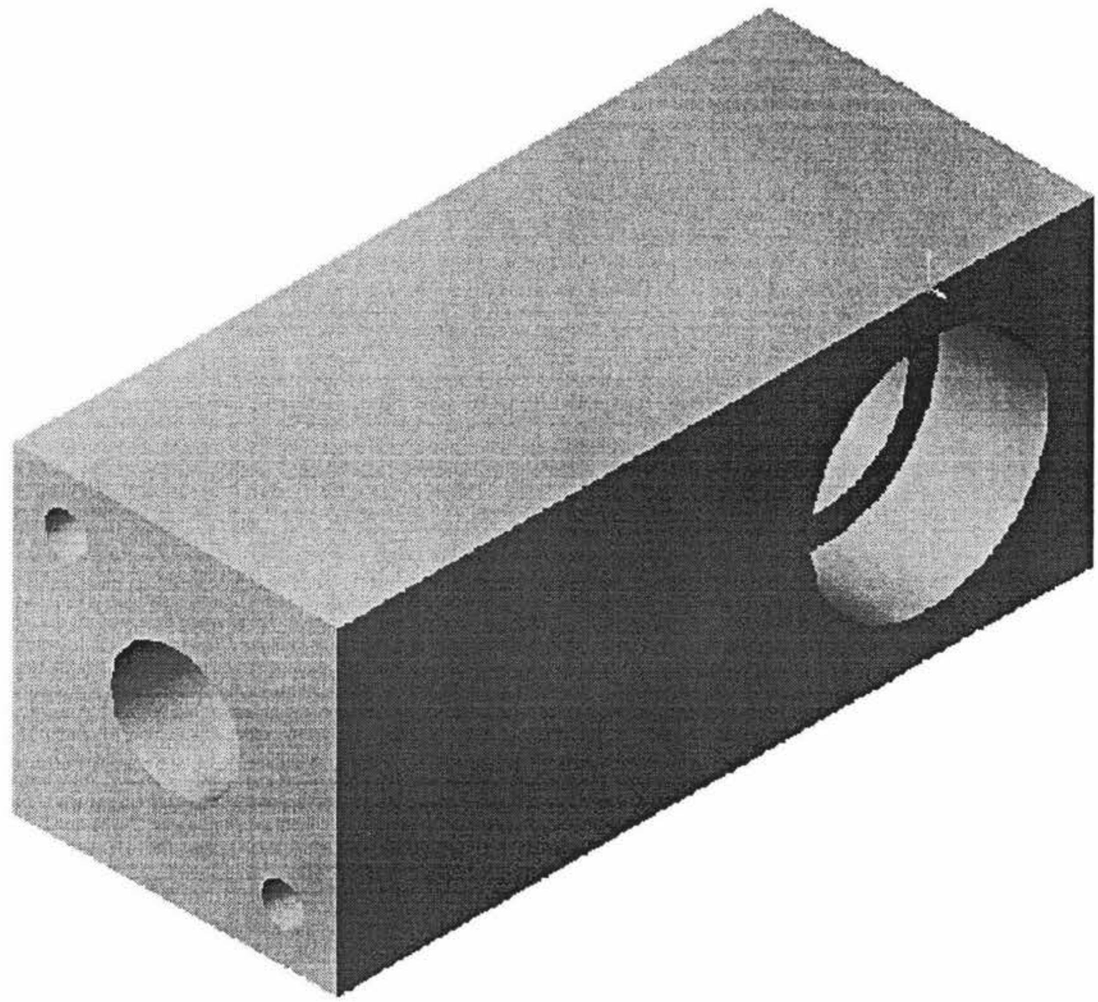


Figure A4 The main block of the chassis extension. A plate screws onto the end to hold the bolt (the part which connects to the main chassis) in place. The bearings for the axle fit into the largest hole and are held in place by split rings.

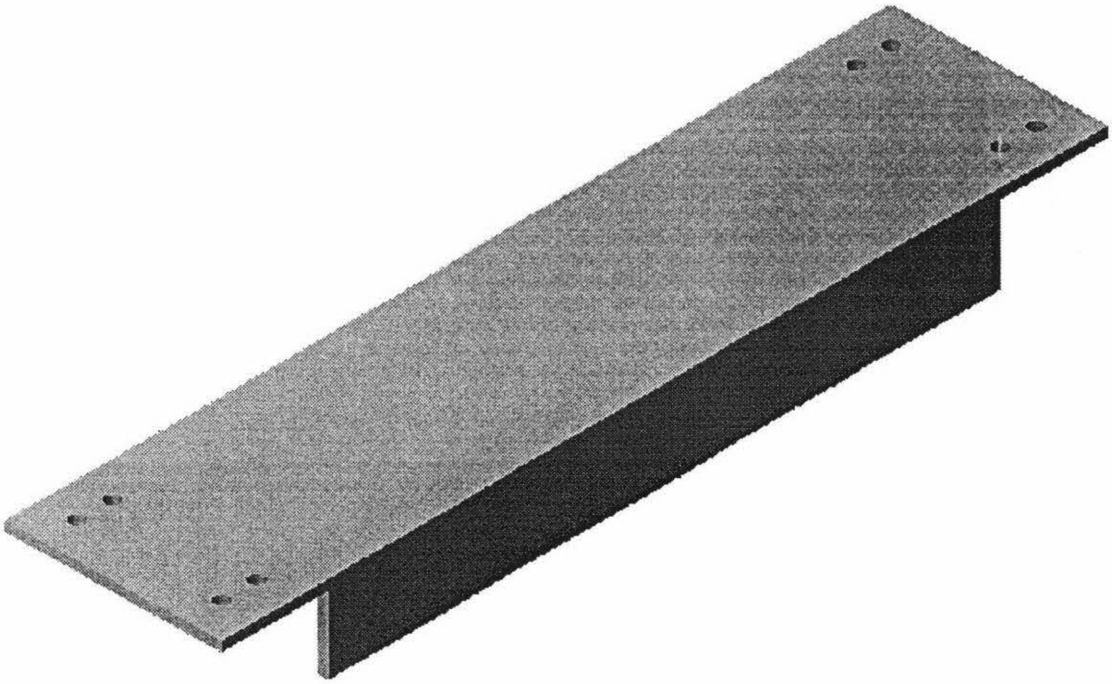


Figure A5 Cross member of the chassis. There are three of these and they give rigidity to the chassis and provide convenient mounting for the batteries.

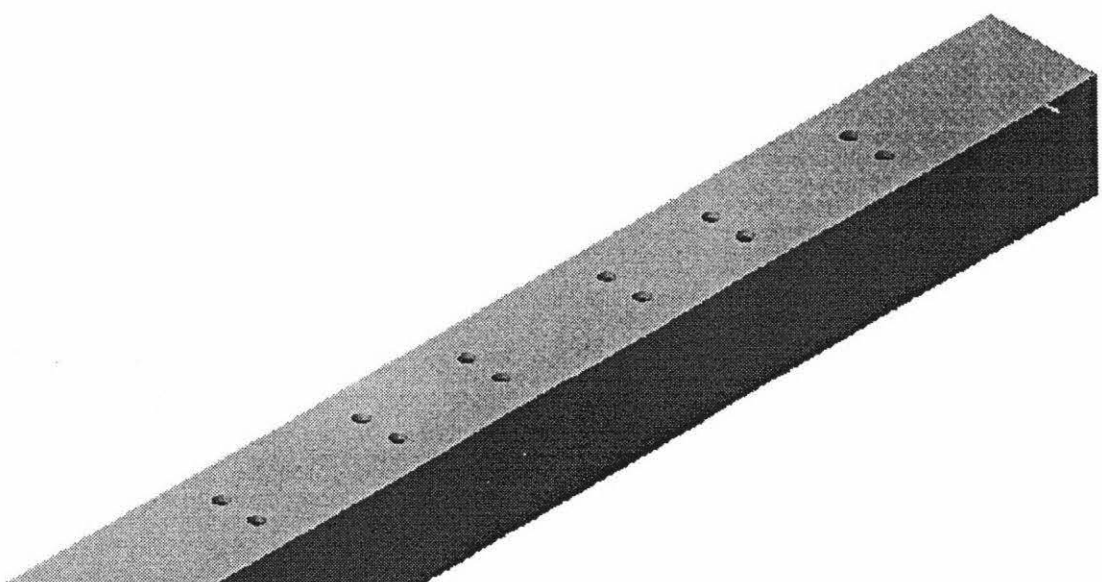


Figure A6 Side member of the chassis. This connects to the wheel extensions and has one at either end.

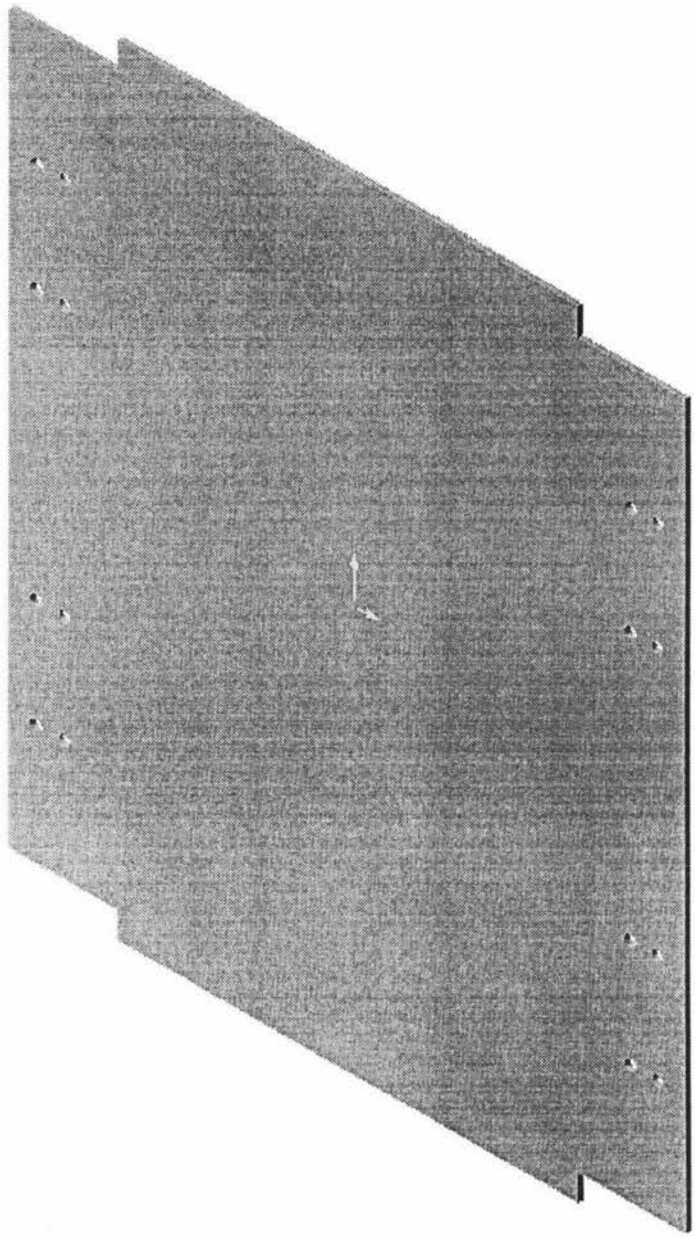


Figure A7 Base plate. This covers the chassis and provides a mounting for the circuitry and the batteries.

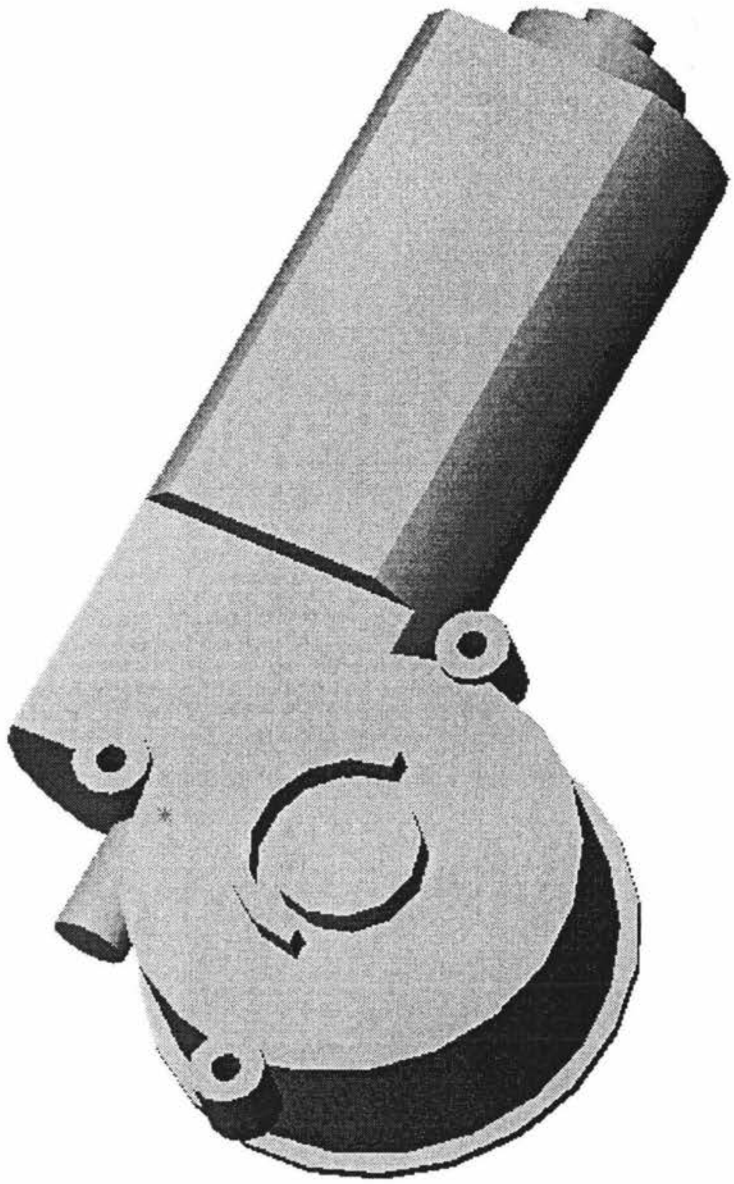
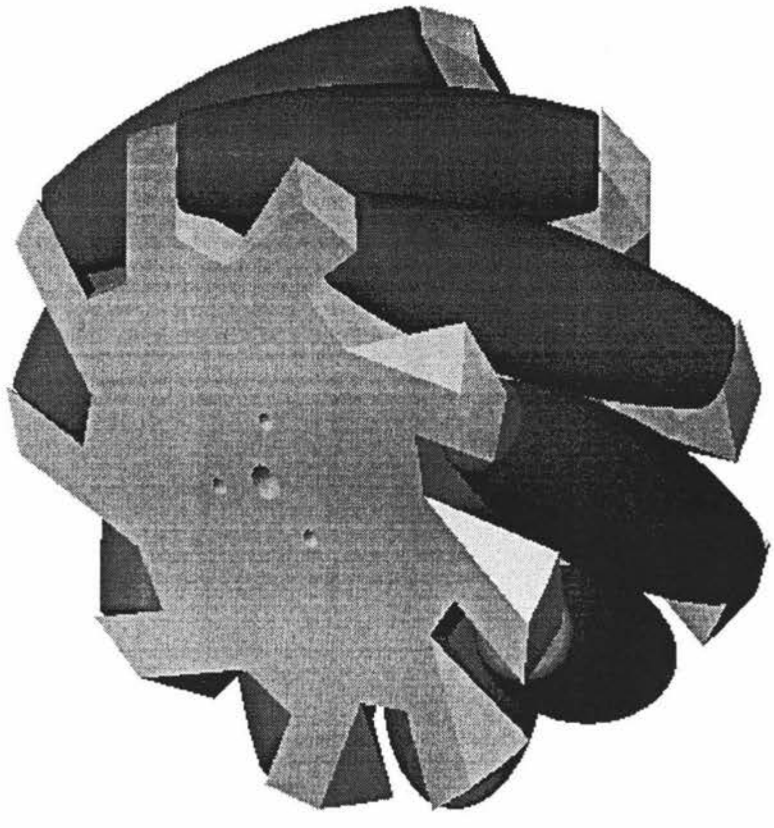


Figure A8 Motor. This is a model drawn in Solid Works to approximate the shape and size of the motor.



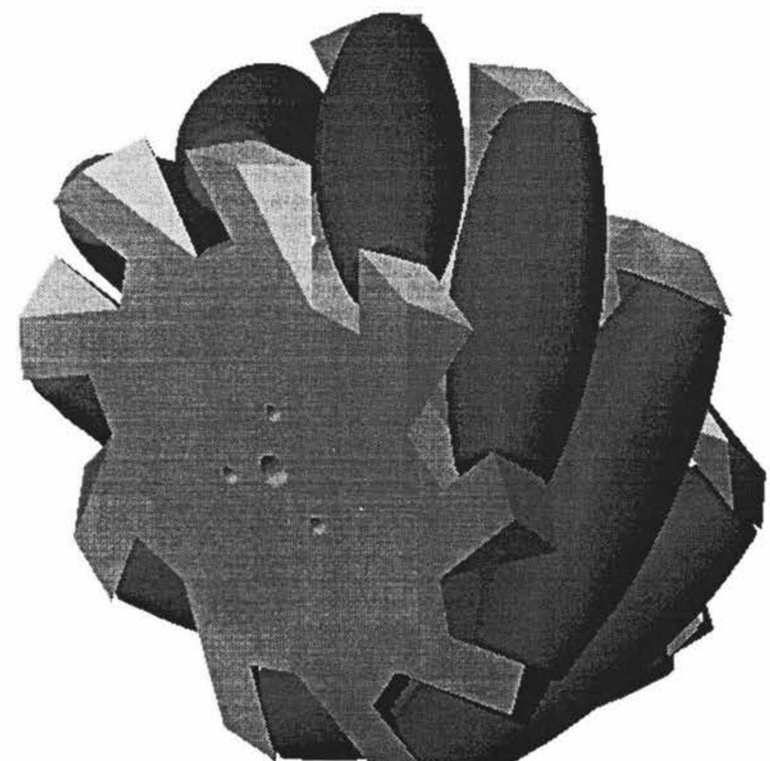


Figure A9 and Figure A10 These two pictures show the two different wheel arrangements. The only difference is the direction in which the rollers point. This arrangement is essential to the function of the Mecanum drive system.

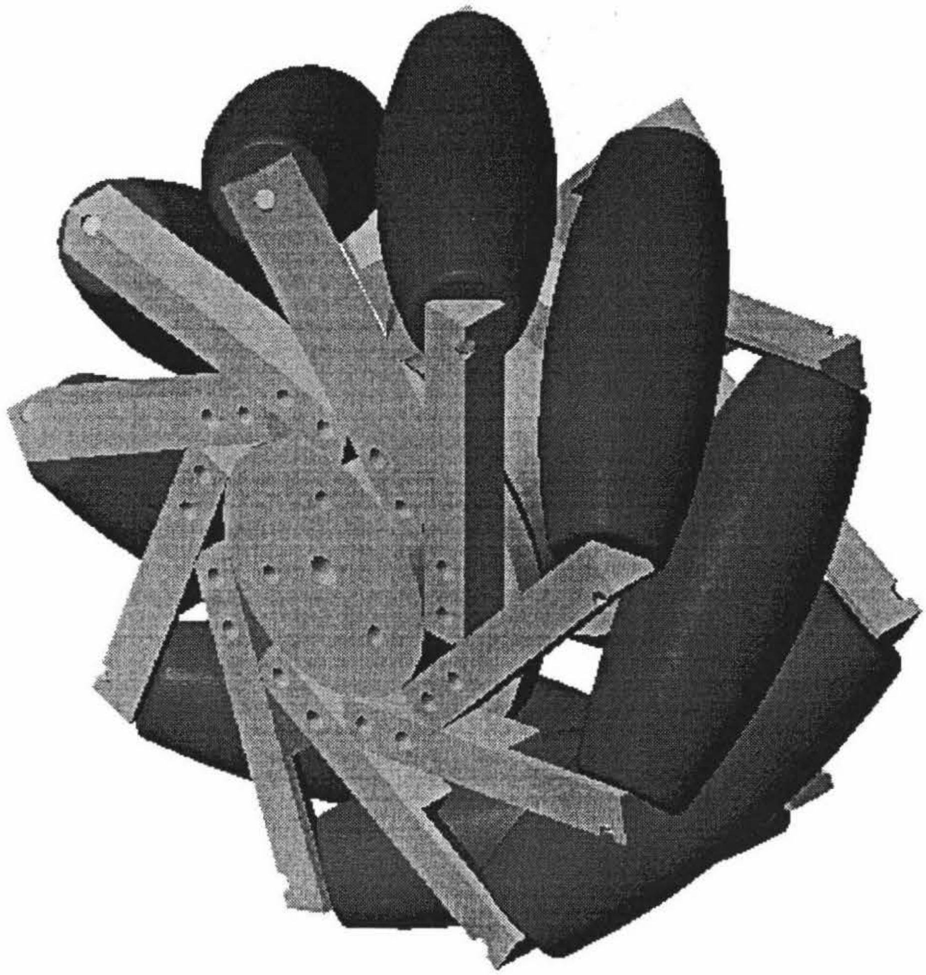


Figure A11 An alternative design to the wheel, which tuned out to be impractical to produce.

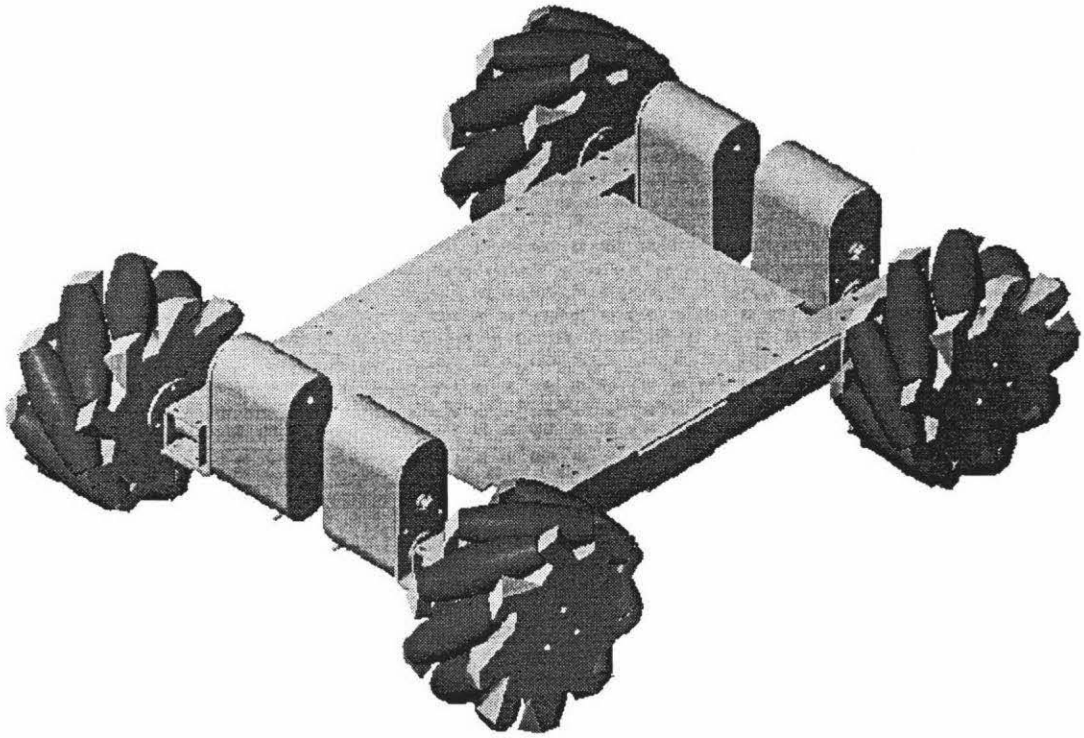


Figure A12 The motor and chassis unit with the idea of using barbeque rotisserie motors. This idea was not implemented and the chassis was further modified after this drawing.

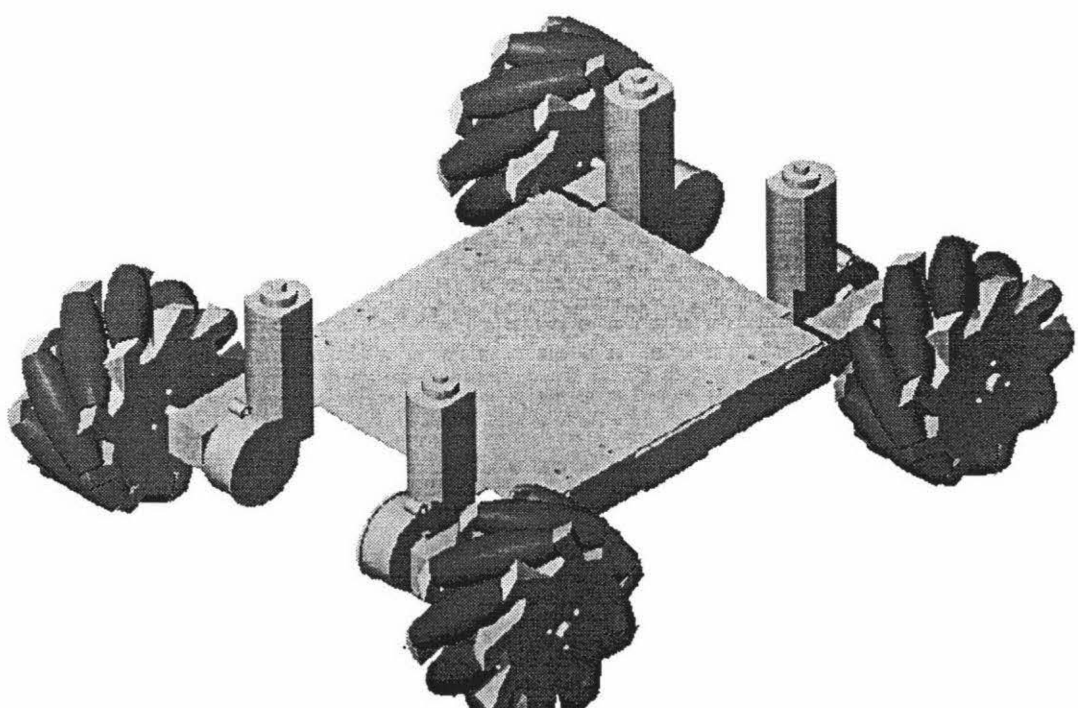


Figure A13 An isometric view of the final design.

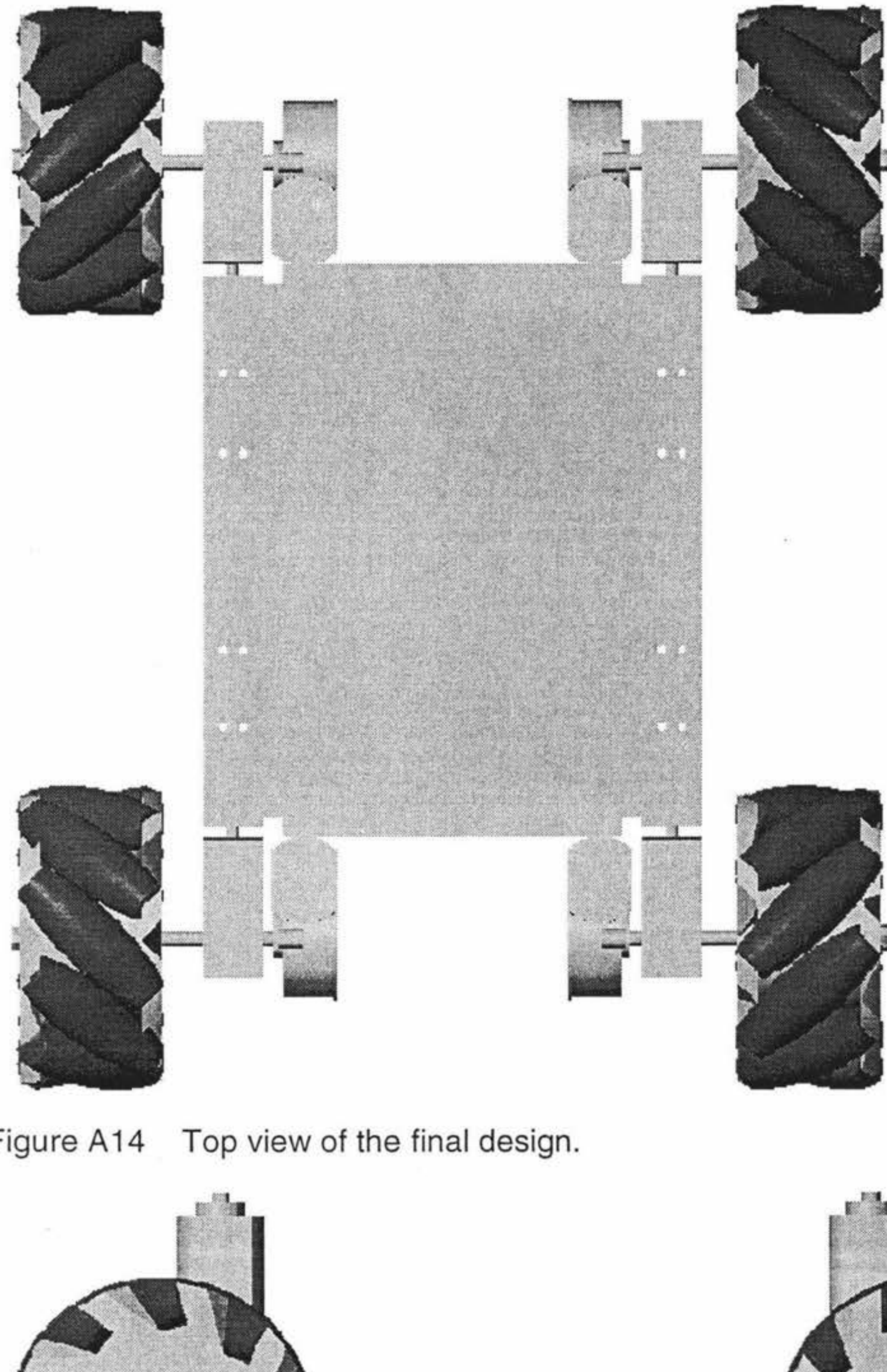


Figure A14 Top view of the final design.

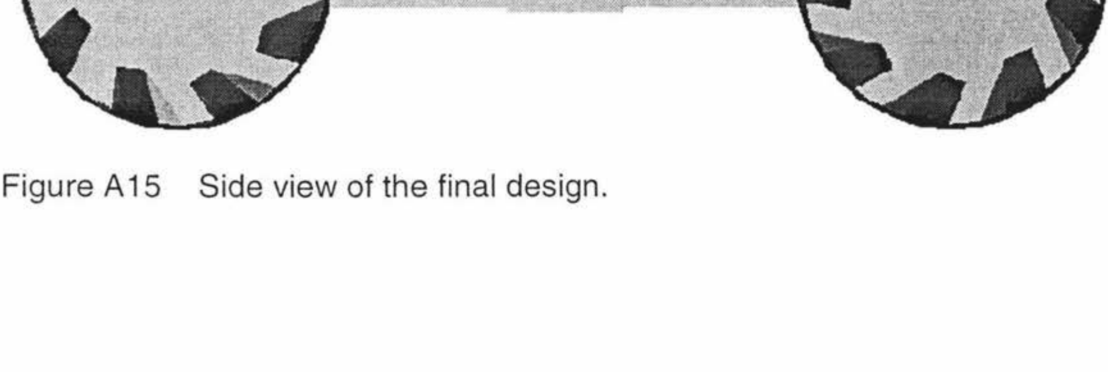


Figure A15 Side view of the final design.

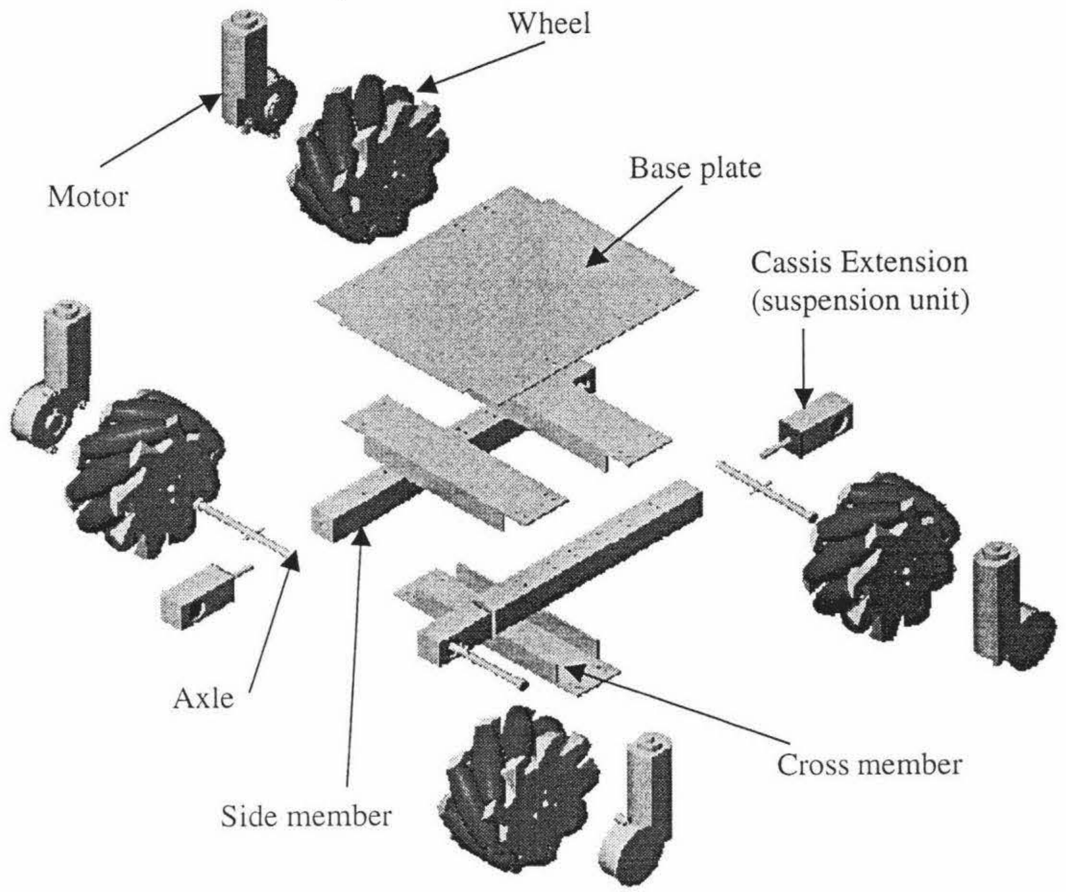



Figure A16 Exploded view of the final design showing the arrangement and associations of the main parts.

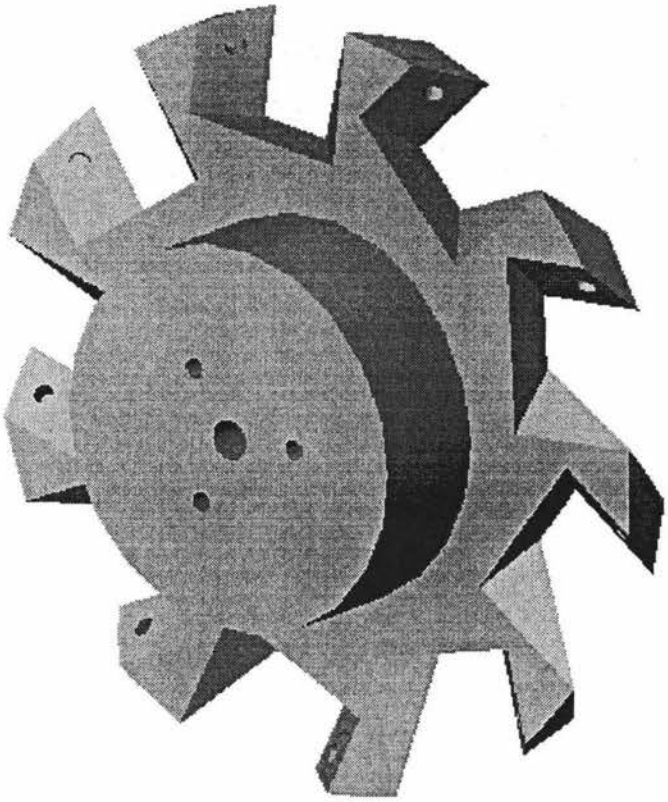


Figure A17 The wheel frame as drawn in Solid Works.

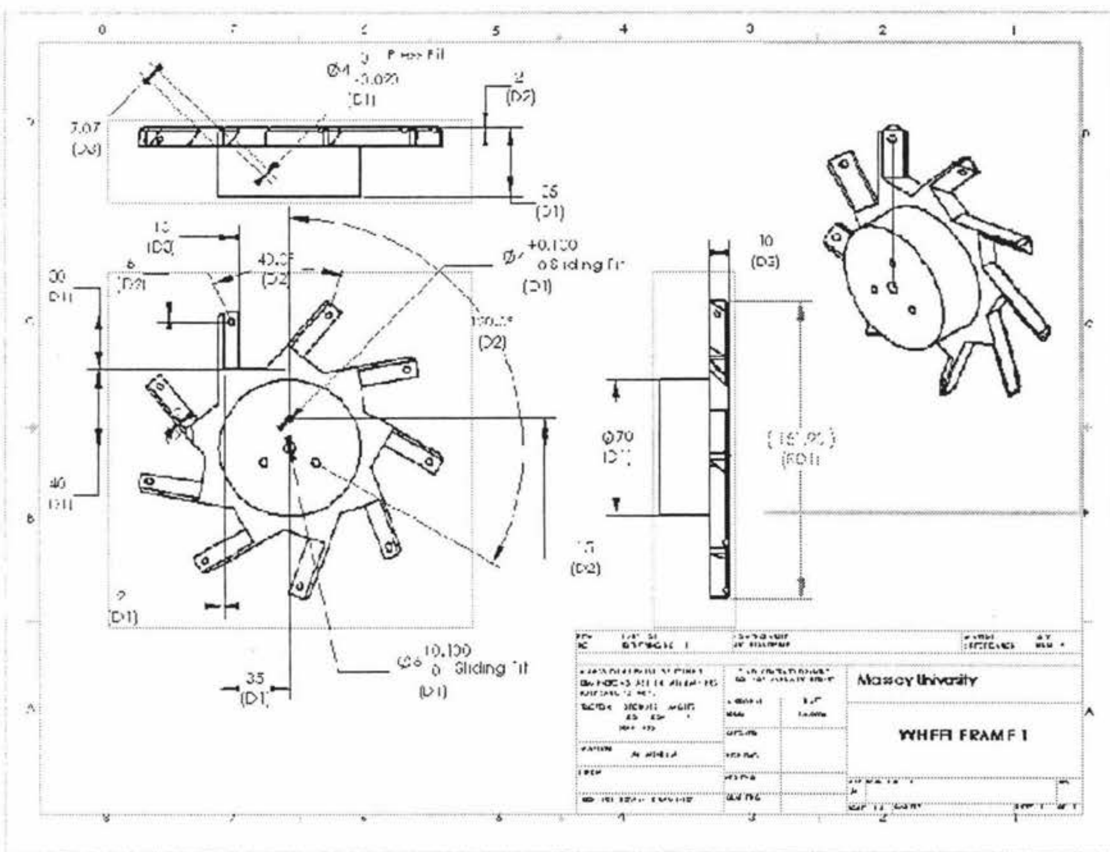



Figure A18 The same wheel frame after it has been converted into an engineering drawing by Solid Works.

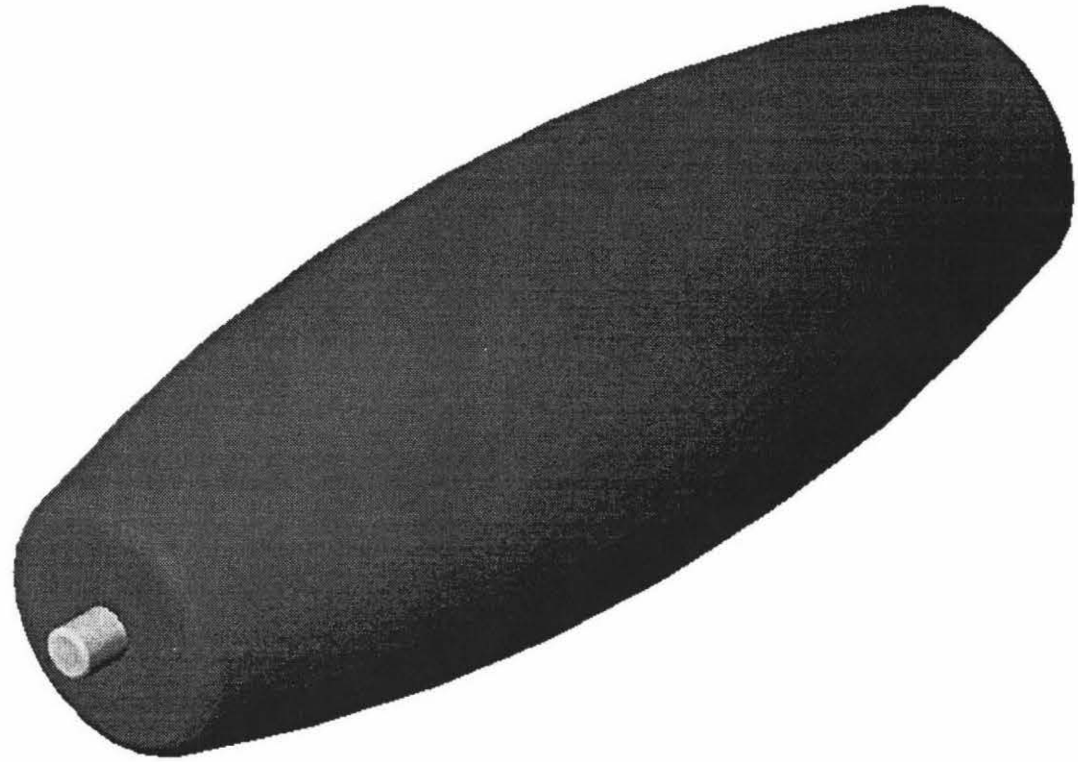


Figure A19 Roller and roller shaft assembly.

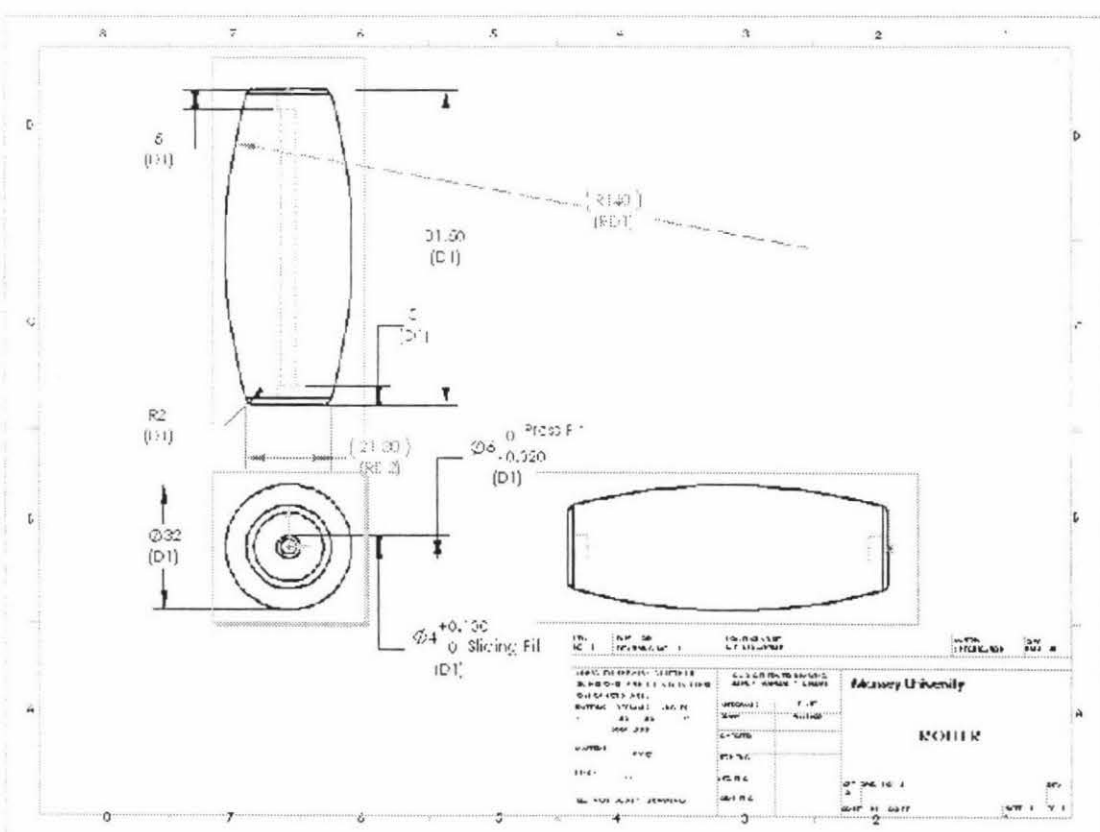



Figure A20 Engineering drawing of the roller.

# Appendix B (Sensors and associated circuitry)

Table B1 The table below gives the results of the initial optimisations. A "*" in the final column indicates that the simulation result was considered to be worth refining, a "%" indicates that the sensors are placed too far apart and a "#" indicates that two or more of the separating distances are too close together (this would make it impossible to mount the sensors correctly).

| X1 Start | X2 Start | X3 Start | X1 Finish | X2 Finish | X3 Finish | Ratio | Indicator |
|---|---|---|---|---|---|---|---|
| 70 | 60 | 50 | 71.7 | 60.3 | 49.9 | 0.895 | |
| 80 | 70 | 60 | 84.4 | 68.1 | 58 | 0.8633 | |
| 90 | 80 | 70 | 94.5 | 80.3 | 67.9 | 0.9237 | |
| 100 | 90 | 80 | 100.1 | 90.2 | 79.8 | 0.8993 | |
| 110 | 100 | 90 | 109.6 | 100.1 | 90.1 | 0.9484 | |
| 120 | 110 | 100 | 123.5 | 109.9 | 100.1 | 0.9205 | |
| 130 | 120 | 110 | 120.4 | 122.5 | 117.5 | 0.9681 | |
| 140 | 130 | 120 | 143.9 | 127.8 | 123.3 | 0.9883 | # |
| 150 | 140 | 130 | 144.8 | 136.6 | 137 | 0.9882 | # |
| 160 | 150 | 140 | 160 | 151.9 | 140 | 0.9667 | |
| 170 | 160 | 150 | 168.6 | 160.1 | 155.5 | 0.952 | # |
| 180 | 170 | 160 | 174.8 | 173.4 | 163.4 | 0.9842 | # |
| 80 | 60 | 50 | 81.7 | 58.2 | 50.9 | 0.8405 | # |
| 90 | 70 | 60 | 93.1 | 69.7 | 59.8 | 0.8606 | |
| 100 | 80 | 70 | 100 | 80.1 | 70 | 0.8675 | |
| 110 | 90 | 80 | 109.7 | 94.4 | 79.9 | 0.9538 | |
| 120 | 100 | 90 | 117.3 | 104.1 | 93.4 | 0.9197 | |
| 130 | 110 | 100 | 129.2 | 117.9 | 101.8 | 0.9193 | |
| 140 | 120 | 110 | 129.6 | 123.6 | 114.3 | 0.9657 | # |
| 150 | 130 | 120 | 145.5 | 132.9 | 121.9 | 0.9711 | |
| 160 | 140 | 130 | 152.9 | 140.5 | 135.4 | 0.9552 | # |
| 170 | 150 | 140 | 152.1 | 154.7 | 146.7 | 0.9951 | # |
| 180 | 160 | 150 | 185.8 | 160.1 | 149.2 | 1.5906 | |
| 80 | 70 | 50 | 86.5 | 71.2 | 47.5 | 0.7483 | |
| 90 | 80 | 60 | 87.3 | 83.7 | 59.8 | 0.8646 | # |
| 100 | 90 | 70 | 99.6 | 92.7 | 70.3 | 0.9074 | # |
| 110 | 100 | 80 | 111.8 | 99.9 | 80.7 | 0.9317 | |
| 120 | 110 | 90 | 118.8 | 107.4 | 95.2 | 0.9205 | |
| 130 | 120 | 100 | 126.4 | 111.7 | 106.7 | 0.9772 | # |
| 140 | 130 | 110 | 139.8 | 130.3 | 113.9 | 0.9033 | |
| 150 | 140 | 120 | 140.7 | 141.7 | 122.1 | 0.9488 | # |
| 160 | 150 | 130 | 146.1 | 133.7 | 147.5 | 0.9538 | # |
| 170 | 160 | 140 | 166.7 | 158.4 | 149 | 0.9443 | # |
| 180 | 170 | 150 | 159.5 | 170.1 | 166.1 | 0.9725 | # |
| 90 | 60 | 50 | 84.6 | 61.8 | 51.7 | 0.8405 | |
| 100 | 70 | 60 | 100 | 70.3 | 61.3 | 1.9728 | # |
| 110 | 80 | 70 | 100.3 | 85.9 | 70.4 | 0.8993 | |
| 120 | 90 | 80 | 104.4 | 94 | 84.1 | 0.8993 | |
| 130 | 100 | 90 | 112.6 | 102.9 | 97.8 | 0.9625 | # |
| 140 | 110 | 100 | 127.8 | 116.4 | 108.6 | 0.9812 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 150 | 120 | 110 | 174.7 | 107.6 | 102.9 | 0.7225# |
| 160 | 130 | 120 | 183.5 | 125.2 | 108 | 0.7747 |
| 170 | 140 | 130 | 177.3 | 134.4 | 128.6 | 0.8884# |
| 180 | 150 | 140 | 187.2 | 145.1 | 136.8 | 0.8453# |
| 90 | 80 | 50 | 87.5 | 77.2 | 52.6 | 0.8644 |
| 100 | 90 | 60 | 99.1 | 79.7 | 62.6 | 0.8597 |
| 110 | 100 | 70 | 104.4 | 88.4 | 78.3 | 0.9109 |
| 120 | 110 | 80 | 111.2 | 107.2 | 84.3 | 0.9407# |
| 130 | 120 | 90 | 114.2 | 122 | 99.8 | 0.9657# |
| 140 | 130 | 100 | 128.4 | 129.3 | 110.4 | 0.9597# |
| 150 | 140 | 110 | 177.4 | 162.5 | 104.8 | 0.7223 |
| 160 | 150 | 120 | 169.3 | 162.4 | 100.1 | 0.7934# |
| 170 | 160 | 130 | 184.6 | 172.7 | 108.5 | 0.7943 |
| 180 | 170 | 140 | 183.9 | 173.2 | 136 | 0.8446 |
| 90 | 70 | 50 | 88.6 | 71.1 | 51 | 0.8086 |
| 100 | 80 | 60 | 99.5 | 80.6 | 61.7 | 0.8597 |
| 110 | 90 | 70 | 103 | 93.3 | 71.2 | 0.8958 |
| 120 | 100 | 80 | 114 | 102.5 | 81.6 | 0.8851 |
| 130 | 110 | 90 | 116.1 | 111.5 | 100.4 | 0.9657# |
| 140 | 120 | 100 | 133.4 | 117 | 106.4 | 0.9196 |
| 150 | 130 | 110 | 141.3 | 128.2 | 118.3 | 0.9711 |
| 160 | 140 | 120 | 184 | 108.9 | 126 | 0.7712 |
| 170 | 150 | 130 | 193.3 | 136.4 | 121.3 | 0.818 |
| 180 | 160 | 140 | 193.6 | 146.1 | 132 | 0.8301 |
| 100 | 60 | 50 | 86.5 | 67.1 | 50.3 | 0.793 |
| 110 | 70 | 60 | 113.3 | 72.4 | 61.5 | 1.9565 |
| 120 | 80 | 70 | 119.4 | 81.4 | 70.6 | 1.8795 |
| 130 | 90 | 80 | 150.5 | 93.4 | 71.2 | 0.616 |
| 140 | 100 | 90 | 153.4 | 96.8 | 85.7 | 0.7456 |
| 150 | 110 | 100 | 167.5 | 107 | 89 | 0.6918 |
| 160 | 120 | 110 | 163.2 | 116.4 | 112.2 | 0.8442# |
| 170 | 130 | 120 | 177 | 129.1 | 114.7 | 0.7999 |
| 180 | 140 | 130 | 180.1 | 144 | 130.2 | 0.8444 |
| 100 | 90 | 50 | 84.4 | 80.1 | 55.8 | 0.9266# |
| 110 | 100 | 60 | 96.6 | 92.5 | 70.9 | 0.8837# |
| 120 | 110 | 70 | 76.8 | 104.1 | 89.9 | 0.9345 |
| 130 | 120 | 80 | 145.1 | 135.3 | 66.3 | 0.704 |
| 140 | 130 | 90 | 159.4 | 144.7 | 74 | 0.6528 |
| 150 | 140 | 100 | 163.1 | 150.9 | 81.6 | 0.77 |
| 160 | 150 | 110 | 173.9 | 162.3 | 105.9 | 0.7503 |
| 170 | 160 | 120 | 178.4 | 160.7 | 118.8 | 0.7821 |
| 180 | 170 | 130 | 188.4 | 176.7 | 119.5 | 0.815 |
| 100 | 80 | 50 | 90.9 | 73.3 | 52.5 | 0.8365 |
| 110 | 90 | 60 | 97.7 | 82.2 | 66.7 | 0.8832 |
| 120 | 100 | 70 | 102.1 | 94.4 | 74.1 | 0.9241# |
| 130 | 110 | 80 | 155.5 | 99.2 | 73.1 | 0.6378 |
| 140 | 120 | 90 | 160.5 | 102.9 | 86.4 | 0.6944 |
| 150 | 130 | 100 | 166.2 | 104.8 | 96.8 | 0.7329# |
| 160 | 140 | 110 | 178.4 | 115.2 | 108.2 | 0.7491# |
| 170 | 150 | 120 | 174.7 | 138 | 117.8 | 0.807 |
| 180 | 160 | 130 | 188.6 | 119.1 | 134.4 | 0.8076 |
| 100 | 70 | 50 | 88.9 | 79.9 | 55.3 | 0.8541 |
| 110 | 80 | 60 | 94.4 | 89 | 67.1 | 0.9074# |
| 120 | 90 | 70 | 99.5 | 98 | 82.2 | 0.9431# |

| | | | | | | |
|---|---|---|---|---|---|---|
| 130 | 100 | 80 | 120.1 | 96.6 | 90.2 | 0.9356# |
| 140 | 110 | 90 | 155.2 | 142.3 | 72.9 | 0.6638 |
| 150 | 120 | 100 | 159.2 | 150.9 | 89.4 | 0.7968# |
| 160 | 130 | 110 | 168 | 158.7 | 95.3 | 0.8337 |
| 170 | 140 | 120 | 174.8 | 155.7 | 114.1 | 0.8633 |
| 180 | 150 | 130 | 174 | 175.8 | 111.2 | 0.8593# |
| 110 | 60 | 50 | 115.1 | 60.3 | 48.6 | 1.6445 |
| 120 | 70 | 60 | 146.4 | 62.6 | 51.7 | 0.7081 |
| 130 | 80 | 70 | 143 | 75.2 | 68.6 | 0.5618# |
| 140 | 90 | 80 | 142.7 | 91.2 | 77.2 | 0.7306 |
| 150 | 100 | 90 | 156.7 | 90.6 | 95.5 | 0.7302# |
| 160 | 110 | 100 | 169.8 | 103.8 | 99.8 | 0.745# |
| 170 | 120 | 110 | 169.9 | 120.9 | 110 | 0.7835 |
| 180 | 130 | 120 | 180.2 | 133.1 | 119.9 | 0.8421 |
| 110 | 100 | 50 | 47.4 | 87 | 69.9 | 0.7378 |
| 120 | 110 | 60 | 124.8 | 109.8 | 59.1 | 1.7751 |
| 130 | 120 | 70 | 140.6 | 129.6 | 60.5 | 0.7723 |
| 140 | 130 | 80 | 151.8 | 138.7 | 72.4 | 0.6679 |
| 150 | 140 | 90 | 153 | 142.6 | 87.4 | 0.7641 |
| 160 | 150 | 100 | 165.5 | 153.9 | 96.3 | 0.8046 |
| 170 | 160 | 110 | 177.1 | 161.3 | 107.3 | 0.7843 |
| 180 | 170 | 120 | 185.4 | 170 | 120 | 0.8263 |
| 110 | 70 | 50 | 115.1 | 70.3 | 48.6 | 1.7304 |
| 120 | 80 | 60 | 123 | 80 | 60 | 1.7346 |
| 130 | 90 | 70 | 147.4 | 89.1 | 66.4 | 0.6263 |
| 140 | 100 | 80 | 150.8 | 96.6 | 78.3 | 0.6612 |
| 150 | 110 | 90 | 162.5 | 102.5 | 90.9 | 0.7212 |
| 160 | 120 | 100 | 167.9 | 119.4 | 97.5 | 0.7787 |
| 170 | 130 | 110 | 170 | 130 | 110 | 0.7881 |
| 180 | 140 | 120 | 183 | 142.3 | 117 | 0.8172 |
| 110 | 80 | 50 | 91.7 | 87.3 | 50.1 | 1.3596 |
| 120 | 90 | 60 | 120 | 90 | 60.7 | 2.0023 |
| 130 | 100 | 70 | 144.7 | 92.2 | 74.8 | 0.6743 |
| 140 | 110 | 80 | 158.5 | 103.3 | 75.6 | 0.6237 |
| 150 | 120 | 90 | 167.7 | 108.2 | 89.5 | 0.6918 |
| 160 | 130 | 100 | 167.1 | 117.1 | 105.5 | 0.7921 |
| 170 | 140 | 110 | 175.2 | 132.6 | 112.6 | 0.8156 |
| 180 | 150 | 120 | 184.5 | 142.5 | 123 | 0.8391 |
| 110 | 90 | 50 | 100.8 | 87.5 | 53.6 | 1.5819 |
| 120 | 100 | 60 | 103.3 | 106.4 | 61.7 | 2.1533# |
| 130 | 110 | 70 | 132.2 | 119.2 | 64.2 | 1.249 |
| 140 | 120 | 80 | 140.6 | 125.6 | 77.8 | 1.2617 |
| 150 | 130 | 90 | 154 | 142.9 | 87.1 | 0.7477 |
| 160 | 140 | 100 | 158.1 | 157.2 | 92.2 | 0.8148# |
| 170 | 150 | 110 | 171.5 | 156.1 | 108.8 | 0.8093 |
| 180 | 160 | 120 | 175 | 167.7 | 120.2 | 0.878# |
| 120 | 60 | 50 | 127.2 | 56.4 | 48.5 | 0.8251# |
| 130 | 70 | 60 | 137.2 | 70.2 | 58 | 0.6858 |
| 140 | 80 | 70 | 144.2 | 75.2 | 72.1 | 0.5732# |
| 150 | 90 | 80 | 149.2 | 92 | 79.3 | 0.6928 |
| 160 | 100 | 90 | 163.1 | 102.3 | 88.9 | 0.7235 |
| 170 | 110 | 100 | 173 | 107.5 | 100.3 | 0.7278# |
| 180 | 120 | 110 | 176.9 | 121.7 | 111.6 | 0.7952 |
| 120 | 110 | 50 | 146.1 | 132.4 | 30.6 | 0.7734 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 130 | 120 | 60 | 139 | 123.3 | 57.8 | 0.7885 |
| 140 | 130 | 70 | 144.6 | 131.9 | 66.8 | 0.6599 |
| 150 | 140 | 80 | 157.6 | 142.6 | 72.6 | 0.6299 |
| 160 | 150 | 90 | 162.1 | 148.9 | 94.1 | 0.7181 |
| 170 | 160 | 100 | 175.1 | 160.1 | 99 | 0.7458 |
| 180 | 170 | 110 | 184.5 | 174.2 | 108.4 | 0.7435 |
| 120 | 70 | 50 | 145.2 | 68.8 | 40.1 | 0.7066 |
| 130 | 80 | 60 | 138.7 | 76.8 | 59.2 | 0.6383 |
| 140 | 90 | 70 | 147.8 | 87 | 70.2 | 0.5795* |
| 150 | 100 | 80 | 153 | 102.2 | 79.7 | 0.6404 |
| 160 | 110 | 90 | 169.2 | 110.3 | 89.6 | 0.6957 |
| 170 | 120 | 100 | 170 | 120 | 102.5 | 0.8112 |
| 180 | 130 | 110 | 185.3 | 129.1 | 109.4 | 0.8055 |
| 120 | 80 | 50 | 135.4 | 71.9 | 48.6 | 0.7134 |
| 130 | 90 | 60 | 142.5 | 78.3 | 61.4 | 0.5636* |
| 140 | 100 | 70 | 147.7 | 92.7 | 70.9 | 0.6095 |
| 150 | 110 | 80 | 155 | 104.3 | 83 | 0.6975 |
| 160 | 120 | 90 | 170.8 | 109 | 96 | 0.711 |
| 170 | 130 | 100 | 178.5 | 117.5 | 105.3 | 0.7709 |
| 180 | 140 | 110 | 185.9 | 129 | 115.7 | 0.794 |
| 120 | 90 | 50 | 119.8 | 90.1 | 51.4 | 2.3655 |
| 130 | 100 | 60 | 142.9 | 86.7 | 67.7 | 0.6436 |
| 140 | 110 | 70 | 140.1 | 110.1 | 71.9 | 1.9987 |
| 150 | 120 | 80 | 143.8 | 128.3 | 79.6 | 1.2121 |
| 160 | 130 | 90 | 148.4 | 142.3 | 91.7 | 0.976# |
| 170 | 140 | 100 | 160.6 | 147.8 | 100.1 | 0.8305 |
| 180 | 150 | 110 | 180 | 151.9 | 111.4 | 2.2303 |
| 120 | 100 | 50 | 123 | 100 | 50 | 2.4748 |
| 130 | 110 | 60 | 137.5 | 128.5 | 48.1 | 0.9075# |
| 140 | 120 | 70 | 140.8 | 127.9 | 66.8 | 0.7389 |
| 150 | 130 | 80 | 148.7 | 141.6 | 73.8 | 0.7076# |
| 160 | 140 | 90 | 157.8 | 149.1 | 85.8 | 0.763# |
| 170 | 150 | 100 | 172.3 | 153.3 | 97.2 | 0.769 |
| 180 | 160 | 110 | 175 | 160.3 | 110.5 | 0.7836 |
| 130 | 60 | 50 | 128.9 | 59 | 51.3 | 0.8007# |
| 140 | 70 | 60 | 140 | 70 | 60.7 | 0.6506 |
| 150 | 80 | 70 | 151 | 81.7 | 68.3 | 0.5923* |
| 160 | 90 | 80 | 157.8 | 97.7 | 70 | 0.6919 |
| 170 | 100 | 90 | 161 | 101.8 | 91.7 | 0.7443 |
| 180 | 110 | 100 | 170.5 | 113.7 | 101.4 | 0.7608 |
| 130 | 120 | 50 | 131.8 | 122.2 | 49.8 | 0.8064# |
| 140 | 130 | 60 | 142.7 | 129.3 | 61.5 | 0.808 |
| 150 | 140 | 70 | 155.2 | 138.9 | 72.6 | 0.6361 |
| 160 | 150 | 80 | 155 | 141.8 | 81.8 | 0.7355 |
| 170 | 160 | 90 | 173.2 | 157.6 | 93.4 | 0.7696 |
| 180 | 170 | 100 | 179.9 | 166.9 | 104.7 | 0.7745 |
| 130 | 70 | 50 | 132.1 | 71.4 | 48.8 | 0.7243 |
| 140 | 80 | 60 | 143.4 | 77.8 | 60.9 | 0.5874* |
| 150 | 90 | 70 | 150.5 | 92.5 | 69.7 | 0.558* |
| 160 | 100 | 80 | 160 | 100 | 80 | 0.7014 |
| 170 | 110 | 90 | 169.5 | 109.9 | 90.2 | 0.696 |
| 180 | 120 | 100 | 179.3 | 120.5 | 102.4 | 0.7747 |
| 130 | 80 | 50 | 138.7 | 71.9 | 54.5 | 0.6564 |
| 140 | 90 | 60 | 147.1 | 84.6 | 62.4 | 0.5811* |

| | | | | | | |
|---|---|---|---|---|---|---|
| 150 | 100 | 70 | 155.1 | 97.6 | 72.1 | 0.6327 |
| 160 | 110 | 80 | 165.8 | 106.6 | 81.1 | 0.7218 |
| 170 | 120 | 90 | 172.9 | 116.6 | 91.7 | 0.7209 |
| 180 | 130 | 100 | 177.7 | 127.4 | 104.4 | 0.7892 |
| 130 | 90 | 50 | 141.4 | 74.8 | 53.5 | 0.676 |
| 140 | 100 | 60 | 152.2 | 82.3 | 62.1 | 0.6194 |
| 150 | 110 | 70 | 156.7 | 99.5 | 72.6 | 0.6455 |
| 160 | 120 | 80 | 167.7 | 107.2 | 83.8 | 0.7101 |
| 170 | 130 | 90 | 174.9 | 116.6 | 94.8 | 0.7226 |
| 180 | 140 | 100 | 182 | 109.7 | 114.1 | 0.7662 |
| 130 | 100 | 50 | 125.3 | 119.5 | 44.2 | 0.8711 |
| 140 | 110 | 60 | 139.8 | 124.7 | 55 | 0.8363 |
| 150 | 120 | 70 | 143.6 | 129.4 | 66.2 | 0.6838 |
| 160 | 130 | 80 | 154 | 140.4 | 79.4 | 0.7125 |
| 170 | 140 | 90 | 150.6 | 151.5 | 92.2 | 0.8027# |
| 180 | 150 | 100 | 173 | 157.7 | 97.7 | 0.7073 |
| 130 | 110 | 50 | 127.4 | 121.4 | 44 | 0.9047# |
| 140 | 120 | 60 | 139.3 | 125.9 | 60.3 | 0.7429 |
| 150 | 130 | 70 | 150.1 | 134 | 69.4 | 0.6573 |
| 160 | 140 | 80 | 158.4 | 146.7 | 80.5 | 0.6783 |
| 170 | 150 | 90 | 170.1 | 153.7 | 90.1 | 0.7395 |
| 180 | 160 | 100 | 178.8 | 162.3 | 101.2 | 0.7543 |
| 140 | 60 | 50 | 130.3 | 61.3 | 51 | 0.7716 |
| 150 | 70 | 60 | 140.5 | 75.4 | 60.8 | 0.6084 |
| 160 | 80 | 70 | 144.9 | 81.6 | 73.4 | 0.628# |
| 170 | 90 | 80 | 154.6 | 104.8 | 84.4 | 0.6865 |
| 180 | 100 | 90 | 164.2 | 108.5 | 90.2 | 0.7225 |
| 140 | 130 | 50 | 145.2 | 127 | 52.2 | 0.8116 |
| 150 | 140 | 60 | 151.9 | 133.5 | 61.9 | 0.7636 |
| 160 | 150 | 70 | 158.5 | 141.3 | 72.9 | 0.6284 |
| 170 | 160 | 80 | 170.9 | 152 | 83.2 | 0.7844 |
| 180 | 170 | 90 | 156.2 | 172.5 | 96.6 | 0.7385 |
| 140 | 70 | 50 | 139.9 | 71.7 | 50 | 0.7168 |
| 150 | 80 | 60 | 142.8 | 78.2 | 62.9 | 0.5557* |
| 160 | 90 | 70 | 157.6 | 93.4 | 67.9 | 0.6323 |
| 170 | 100 | 80 | 166 | 104.1 | 80.6 | 0.7159 |
| 180 | 110 | 90 | 173.7 | 111.1 | 93.7 | 0.7243 |
| 140 | 80 | 50 | 144.4 | 77.5 | 49.8 | 0.6863 |
| 150 | 90 | 60 | 145.1 | 82.1 | 63.3 | 0.5484* |
| 160 | 100 | 70 | 156.5 | 99.1 | 72.1 | 0.642 |
| 170 | 110 | 80 | 167.5 | 107.5 | 83.6 | 0.7101 |
| 180 | 120 | 90 | 175 | 113.3 | 97 | 0.6806 |
| 140 | 90 | 50 | 152.6 | 81.3 | 50.5 | 0.64 |
| 150 | 100 | 60 | 155.3 | 91.2 | 63.8 | 0.6336 |
| 160 | 110 | 70 | 158.8 | 103.9 | 76.2 | 0.6231 |
| 170 | 120 | 80 | 162.6 | 107.7 | 90.1 | 0.7225 |
| 180 | 130 | 90 | 172.7 | 107.7 | 99.3 | 0.7278# |
| 140 | 100 | 50 | 145.2 | 77.5 | 58.3 | 0.6361 |
| 150 | 110 | 60 | 159.4 | 92.8 | 64.7 | 0.6587 |
| 160 | 120 | 70 | 163.2 | 102.4 | 75.9 | 0.6632 |
| 170 | 130 | 80 | 202.2 | 149.7 | 70.8 | 0.5312% |
| 180 | 140 | 90 | 182.4 | 141.7 | 89.2 | 1.6454 |
| 140 | 110 | 50 | 131.1 | 119.5 | 49.7 | 0.8673 |
| 150 | 120 | 60 | 140.4 | 129.5 | 60 | 0.7723 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 160 | 130 | 70 | 151.9 | 136.3 | 68.6 | 0.6821 |
| 170 | 140 | 80 | 165.4 | 148.7 | 79.1 | 0.6967 |
| 180 | 150 | 90 | 196.4 | 151.8 | 87.7 | 0.6853 |
| 140 | 120 | 50 | 137.6 | 123.2 | 49.4 | 0.8572 |
| 150 | 130 | 60 | 147.9 | 133 | 61.6 | 0.77 |
| 160 | 140 | 70 | 157.8 | 141.4 | 71 | 0.6243 |
| 170 | 150 | 80 | 169.7 | 149.8 | 82.1 | 0.7444 |
| 180 | 160 | 90 | 171.1 | 156 | 94.5 | 0.733 |
| 150 | 60 | 50 | 131 | 65.7 | 46.4 | 0.7518 |
| 160 | 70 | 60 | 139.4 | 76.5 | 60.4 | 0.6128 |
| 170 | 80 | 70 | 150.3 | 88 | 68.8 | 0.5584* |
| 180 | 90 | 80 | 194 | 74.6 | 82.5 | 0.8488# |
| 150 | 140 | 50 | 152.1 | 136.3 | 50.9 | 0.9049 |
| 160 | 150 | 60 | 162 | 146.4 | 61.1 | 0.8887 |
| 170 | 160 | 70 | 147.8 | 165.4 | 87.7 | 0.6894 |
| 180 | 170 | 80 | 146.4 | 158.6 | 91 | 0.7633 |
| 150 | 70 | 50 | 142.5 | 73.5 | 48.8 | 0.7028 |
| 160 | 80 | 60 | 145.1 | 81.4 | 63 | 0.5484* |
| 170 | 90 | 70 | 152.5 | 94.9 | 73.1 | 0.5874* |
| 180 | 100 | 80 | 158.4 | 103.7 | 86.3 | 0.6756 |
| 150 | 80 | 50 | 150.4 | 80 | 50.1 | 0.6683 |
| 160 | 90 | 60 | 154.3 | 90.2 | 60.9 | 0.6564 |
| 170 | 100 | 70 | 163.9 | 101.5 | 72.6 | 0.6658 |
| 180 | 110 | 80 | 167.4 | 108.4 | 83 | 0.7101 |
| 150 | 90 | 50 | 152.3 | 85.9 | 53.3 | 0.7199 |
| 160 | 100 | 60 | 157.8 | 93.5 | 67.4 | 0.6051 |
| 170 | 110 | 70 | 159 | 103.6 | 75.3 | 0.6231 |
| 180 | 120 | 80 | 178.9 | 121.4 | 80.1 | 1.6527 |
| 150 | 100 | 50 | 153.2 | 81 | 56.4 | 0.6022 |
| 160 | 110 | 60 | 158.2 | 96.6 | 67.7 | 0.6318 |
| 170 | 120 | 70 | 172.2 | 121.6 | 71 | 1.5335 |
| 180 | 130 | 80 | 191.3 | 132.7 | 74.8 | 0.7336 |
| 150 | 110 | 50 | 131 | 119.9 | 50.7 | 0.8673 |
| 160 | 120 | 60 | 187.1 | 137.1 | 52.2 | 0.469* |
| 170 | 130 | 70 | 172.3 | 134.8 | 69 | 1.3543 |
| 180 | 140 | 80 | 201.6 | 146.8 | 72.1 | 0.5026% |
| 150 | 120 | 50 | 137.5 | 125.4 | 51.2 | 0.8749 |
| 160 | 130 | 60 | 148.1 | 133.7 | 62.3 | 0.8154 |
| 170 | 140 | 70 | 164 | 143.5 | 71.6 | 0.6637 |
| 180 | 150 | 80 | 201.5 | 148.1 | 72.9 | 0.5136% |
| 150 | 130 | 50 | 149.2 | 131 | 50.2 | 0.7981 |
| 160 | 140 | 60 | 155.9 | 135.2 | 62.6 | 0.7713 |
| 170 | 150 | 70 | 167.1 | 150.7 | 72.8 | 0.6678 |
| 180 | 160 | 80 | 203.8 | 149.3 | 77.7 | 0.5363% |
| 160 | 60 | 50 | 132.2 | 67.1 | 51.4 | 0.699 |
| 170 | 70 | 60 | 169.9 | 71.7 | 60.1 | 1.3423 |
| 180 | 80 | 70 | 188.8 | 77.8 | 70.6 | 0.9162# |
| 160 | 150 | 50 | 162.5 | 149.3 | 51 | 0.9582 |
| 170 | 160 | 60 | 165.2 | 149.8 | 64 | 0.8036 |
| 180 | 170 | 70 | 179.3 | 171.5 | 70 | 1.4041# |
| 160 | 70 | 50 | 136.2 | 72.9 | 53.7 | 0.6499 |
| 170 | 80 | 60 | 172.3 | 79.1 | 60.7 | 1.3077 |
| 180 | 90 | 70 | 151.3 | 94 | 72.8 | 0.6083 |
| 160 | 80 | 50 | 152.7 | 80.3 | 51.9 | 0.6804 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 170 | 90 | 60 | 149 | 88.6 | 69 | 0.5812* |
| 180 | 100 | 70 | 158.8 | 103.4 | 74.7 | 0.6237 |
| 160 | 90 | 50 | 152.9 | 82.5 | 55.7 | 0.6022 |
| 170 | 100 | 60 | 151.9 | 92.6 | 69 | 0.6587 |
| 180 | 110 | 70 | 179.8 | 110.1 | 70.1 | 1.2574 |
| 160 | 100 | 50 | 152.6 | 82.1 | 57.1 | 0.6022 |
| 170 | 110 | 60 | 158 | 100.5 | 72.5 | 0.6705 |
| 180 | 120 | 70 | 191.2 | 138 | 55.3 | 0.497* |
| 160 | 110 | 50 | 160 | 112.8 | 50 | 2.0507 |
| 170 | 120 | 60 | 185.8 | 128 | 50.2 | 0.5881* |
| 180 | 130 | 70 | 196.8 | 143 | 58.9 | 0.4693* |
| 160 | 120 | 50 | 161.5 | 119.6 | 50.4 | 1.6711 |
| 170 | 130 | 60 | 189.8 | 134.5 | 53.7 | 0.5296* |
| 180 | 140 | 70 | 200.5 | 143.5 | 63.1 | 0.5119% |
| 160 | 130 | 50 | 147.7 | 132.3 | 52.1 | 0.8902 |
| 170 | 140 | 60 | 169.9 | 143.3 | 60 | 1.4489 |
| 180 | 150 | 70 | 196 | 141.1 | 60.2 | 0.4542* |
| 160 | 140 | 50 | 158 | 143.3 | 49.5 | 0.9638 |
| 170 | 150 | 60 | 163.6 | 151.6 | 62.7 | 0.8351 |
| 180 | 160 | 70 | 180 | 164.1 | 69.9 | 1.3352 |
| 170 | 60 | 50 | 167.4 | 61.7 | 49.5 | 1.1097 |
| 180 | 70 | 60 | 183.1 | 70 | 59.9 | 0.9381 |
| 170 | 160 | 50 | 172.3 | 155.1 | 52.1 | 1.3177 |
| 180 | 170 | 60 | 183.5 | 168.1 | 60.3 | 1.2468 |
| 170 | 70 | 50 | 172.2 | 69.4 | 49.4 | 1.0028 |
| 180 | 80 | 60 | 194.6 | 76 | 57.4 | 0.8951 |
| 170 | 80 | 50 | 172 | 79.1 | 50.7 | 1.0648 |
| 180 | 90 | 60 | 158.9 | 96.6 | 64.3 | 0.6651 |
| 170 | 90 | 50 | 191.3 | 83 | 49.9 | 0.8218 |
| 180 | 100 | 60 | 179.3 | 97.5 | 62.3 | 1.2514 |
| 170 | 100 | 50 | 160.9 | 101.8 | 51.4 | 1.2949 |
| 180 | 110 | 60 | 185.7 | 127.2 | 47.5 | 0.5881* |
| 170 | 110 | 50 | 183.5 | 127.2 | 39 | 0.55* |
| 180 | 120 | 60 | 187.4 | 136.3 | 49.4 | 0.5107* |
| 170 | 120 | 50 | 183.7 | 131 | 44 | 0.5711* |
| 180 | 130 | 60 | 187.6 | 136.9 | 52.5 | 0.469* |
| 170 | 130 | 50 | 185 | 126.2 | 47.7 | 0.6107 |
| 170 | 140 | 60 | 192.4 | 136.2 | 57.9 | 0.496* |
| 170 | 140 | 50 | 187.3 | 137.1 | 47.7 | 0.5115* |
| 180 | 150 | 60 | 194 | 140.7 | 58.6 | 0.4751* |
| 170 | 150 | 50 | 134.6 | 152.9 | 54.7 | 0.855 |
| 180 | 160 | 60 | 179.9 | 164 | 60.1 | 1.3058 |
| 180 | 60 | 50 | 183.1 | 58.5 | 50.8 | 0.894# |
| 180 | 170 | 50 | 183.7 | 167.9 | 50.3 | 1.4043 |
| 180 | 70 | 50 | 183.1 | 68.5 | 50.8 | 0.8515 |
| 180 | 80 | 50 | 188.4 | 77.1 | 48.9 | 0.8327 |
| 180 | 90 | 50 | 179.2 | 91.1 | 50.5 | 1.4023 |
| 180 | 100 | 50 | 176.2 | 100.1 | 51.2 | 2.0497 |
| 180 | 110 | 50 | 188.2 | 139 | 45.5 | 0.5181* |
| 180 | 120 | 50 | 185.6 | 127.4 | 45.6 | 0.5881* |
| 180 | 130 | 50 | 186.8 | 127.1 | 49.9 | 0.5653* |
| 180 | 140 | 50 | 187.3 | 137.2 | 49.9 | 0.5107* |
| 180 | 150 | 50 | 194.6 | 146 | 50.5 | 0.5272* |
| 180 | 160 | 50 | 180 | 160 | 50 | 1.1958 |

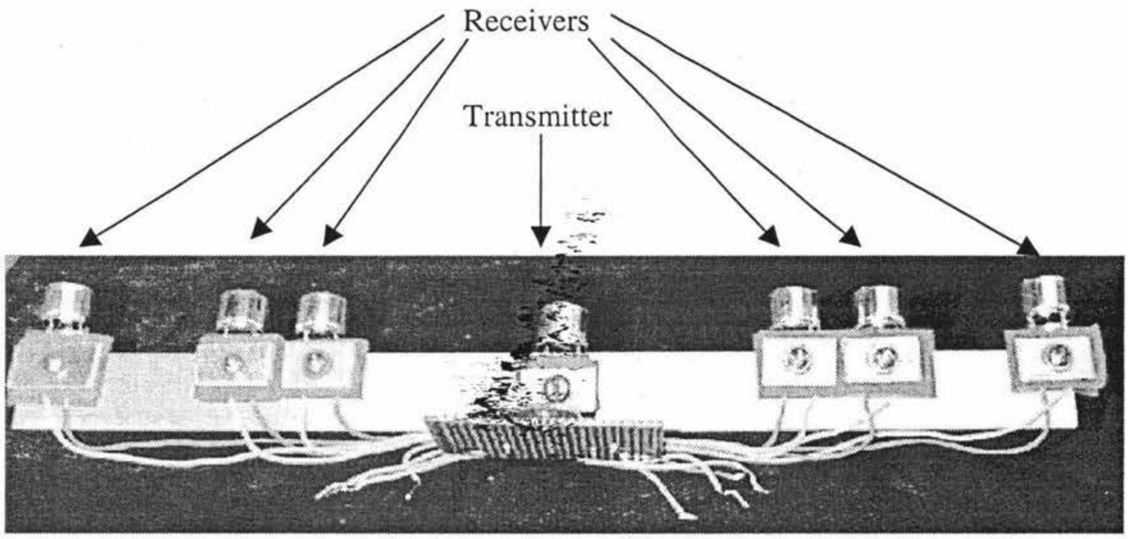



Figure B1: Digital photo of the sensor array looking from the top.

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