University of Southern Queensland
Faculty of Engineering and Surveying

Upon the construction of a remote controlled tracked reconnaissance vehicle

A project dissertation submitted by

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Abstract

The aim of this project is to investigate, construct and evaluate a radio controlled tracked reconnaissance and inspection vehicle. It is envisaged that this project would implement a series of wireless web cams or video cameras to transmit a video feed back to a remote portable location to allow for the inspection of hazardous and inaccessible locations.

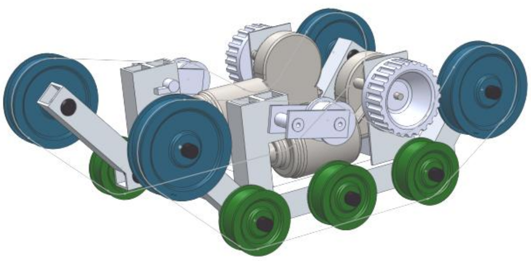
The concept of having mobile robots that are able to control themselves in either an autonomous or semiautonomous operational mode is not at all new. Over the years there have been many different attempts at constructing robots capable of this feat. Generally, most robots of this nature are designed primarily for military use. Under military use, these robots are often deployed for bomb diffusion and bomb placement as well as general reconnaissance.

The primary objectives of this project were to construct a remote controlled semi-autonomous robotic tracked inspection vehicle for the inspection of hazardous and inaccessible locations. It was also necessary that this vehicle be highly stable, and easily adaptable to form the basis for further developments of suitable attachments such as grapplers or robotic manipulators such as arms and hands.

The main design criteria for this device were:

- Must be able to be constructed from easily available materials and components.
- Must be rugged and durable especially if it is to be used in hostile environments.
- Must be easy and intuitive to operate to facilitate ease of use.
- Must have sufficient power and runtime to make its deployment worthwhile.

The Figure below shows the final layout for the track drive assembly.



Final track assembly CAD model

In conclusion, the device which was designed and constructed implemented various components; a large number of these components had to be custom manufactured for this device. Once construction was complete, it underwent numerous hours of infield testing in order to determine its effectively as a remote mobile tracked reconnaissance and inspection vehicle.

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Certification of authenticity

I, the undersigned certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Matthew Downing

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Signed: Matthew Downing

October 2010.

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The development of this project, on the construction and implementation of a remote control tracked reconnaissance vehicle would not have been possible without the assistance and contributions of many parties. These various parties include various staff members including academic, administrative and technical of the University of Southern Queensland. Their various ideas, thoughts and contributions as well as general discussions on the implications are gratefully acknowledged.

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Matthew Downing

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Nomenclature

ADC	Analogue to digital converter
CRO	Cathode Ray Oscilloscope
IC	Integrated Circuit
LED	Light Emitting Diode
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
PICAXE	Microcontroller used in this project
USQ	University of Southern Queensland (Toowoomba Campus)

Chapter 1

Project outline

Introduction

Before the commencement of this document it is important that we define some of the few terms which are specific to mobile robots that shall be used throughout. Most importantly, the term robot; in modern times, the term robot has come to have a multitude of different meanings. The first of these meanings is best relayed by a quote from the present (2010) CEO of iRobot Corporation, Colin Angle. Mr. Angle defines a robot as a mobile device with sensors that looks at those sensors and decides on its own, what actions to take. (Sandin 2003). For the next possible meaning we look to the manufacturing industry. In this context the term robot is used to describe any reprogrammable stationary manipulator, which has a limited number of sensors commonly used to perform specific tasks. The Macquarie dictionary defines the term robot as a mechanical, sometimes self controlling apparatus designed to carry out a specific task normally performed by a human. (Macquarie 1991). Therefore a suitable definition can be formed by the combination of each of these three characterisations.

Throughout the remainder of this document, the term robot shall be used to refer to a semiautonomous radio controlled mobile vehicle designed to carry out a task which is normally performed by a human. In this case, 'semiautonomous' is where the robot draws information from some sensors and partially acts on its own for self-preservation, but relies upon human control through a radio link or umbilical. This is a generally accepted definition as there are very few fully autonomous robots, which act entirely upon information gained from sensors. (Sandin 2003)

The outline of this chapter is to provide relevant background information on the subject, including the recent design improvements as well as the specific research objectives of the project. The chapter shall also cover the assessment of consequential effects, project methodology, resource planning and a brief risk assessment.

1.1 Background information

Throughout history, robots and robotic devices have generally been seen as either experimental apparatuses or as sources of great amusement. It is not until recent times, where modern technology and manufacturing techniques, coupled with exotic materials and powerful microprocessors, has the true potential for the robot been recognised. Although the word 'robot' is a relatively new word, coined in 1921 by Czechoslovakian playwright Karel Capek, the origins of robotics date back to the early Greek era.

During the early era, robotics and animatronics were generally regarded as devices of amusement. The first record of an animatronic device dates back to 350 BC, where the Greek mathematician Archytas of Tarentum constructed a mechanical pigeon like bird that was powered by steam. Then, in 200 BC a Greek physicist and inventor of Alexandria called Ctesibus designed and constructed one of the first water clocks. These early water clocks had movable figures on them and were a great breakthrough as all of the previous timepieces relied on the hourglass. The Greeks were great pioneering mechanical inventors and were extremely fascinated with the ideas and concepts of automation.

The next great inventor to add to the history of robotics was Leonardo da Vinci. Throughout his life da Vinci, produced numerous mechanical and automated inventions such as a mechanical device that represented an armoured knight. This armoured knight was designed to replicate the movements of a human. Da Vinci's design was so successful that many mediaeval inventors replicated this mechanical 'robot' to amuse members of royalty. It wasn't until 1738 that the idea of robotics and automation for amusement took off. This concept was started by French inventor Jacques de Vaucanson, whom built various models for entertainment. The most notable of these was his mechanical duck. This mechanical duck was capable of many feats, such as moving, quacking and flapping its wings.

The 1800 and early 1900's saw the shift of robotics and automation towards industry. This shift is generally attributed to Joseph Jacquard's, 1801, automated loom controlled by punch cards. This era saw many great inventions such as Charles Babbage's difference engine in 1882, George Boole, and his mathematical representation of logic with Boolean algebra. In 1921 the term 'robot' was coined by Czechoslovakian playwright Karel Capek in his play titled Rossums Universal Robots. The word robot was used in this play, derived from Czechoslovakian word meaning 'worker'. 1936 saw the introduction of the hypothetical concept of the theoretical computer by Alan Turing. In the early 1940s the three governing laws of Robotics were developed by Isaac Asimov. These three laws are generally used to define human robot interactions. (Dhillon 1991)

1. A robot may not injure a person nor, through interaction, allow a person to come to harm.
2. A robot must always a obey orders from people except in circumstances in which such orders are in conflict with the above law.
3. A robot must protect its own existence except in circumstances in which it is in conflict with the above two laws.

The era from the 1950s to 2000 saw many great advances in the ideas, concepts and technology surrounding robotics, automation and mechatronics. During this time, there were a large number of developments, especially in the area of mobile autonomous and semiautonomous robotics. This is discussed in great detail in chapter 2.

1.2 Definition of the problem

The aim of this project is to investigate, construct and evaluate a radio controlled tracked reconnaissance and inspection vehicle. For this project the following requirements were essential to the successful completion of the mobile robotic device.

1. Conduct a brief literature review on the current “state of the art” in miniature unmanned mobile reconnaissance robots. The idea of this step is to begin to gain a deeper understanding of the requirements for robots in this field of operation.
2. Devise a suitable design based on some of the relevant elements of unmanned mobile robots constrained by the available components.
3. Produce AutoCAD and SolidWorks drawings and models of each individual component.
4. Construct the mobile robot and adjust the design as required.
5. Evaluate the mobile robot that was constructed in accordance with a series of defined benchmarks.

As time permits, the following steps will be undertaken to improve the usefulness and functionality of the robot and to extend the project outcomes.

1. Define further performance criteria for practical ‘in field’ task completion.
2. Conduct a feasibility study on the integration of the video system, with the main microprocessor.
3. Look at implementing navigational systems such as GPS or a solid-state compass.

1.3 Research Objectives

The final objective of this project is to investigate, construct and evaluate a radio controlled inspection vehicle. In this case, the solution will be derived from the selection of a chassis, drive system, motors, suitable microprocessor and wireless camera/radio control system. The project and research objectives shall be satisfied successfully, if the software and hardware configurations cooperate together to remotely control the vehicle within a series of different environments.

Although there are many different possible, locomotion systems, this project will mainly concentrate on the use of automotive timing belts for tracks. This was decided because of the inherent ability of tracks to traverse many different terrains easily. The implementation of this differential drive technique is widely known as the skid steer approach. With this approach, steering is achieved by the intentional slipping, driving or braking of either track. This approach is implemented in many different tracked vehicles such as bulldozers and military armoured vehicles such as tanks and tracked personnel carriers.

Therefore, we conclude that the mobile robotic device shall have a series of features including a series of wireless video cameras and microphones, which will provide both video and audio to a remote portable location. This remote portable location will consist of a receiver for the wireless audio and video system, a radio control system, as well as an LCD to allow for visual display of the video feed. Also on the device will be an array of sensors which will provide the user with a HUD (heads up display) of robot vitals such as the battery charge level.

1.4 Consequential effects

The final outcome of this project is to provide a highly movable and stable tracked remote inspection vehicle for future development. This project will not be developed to commercial completion for marketing purposes. It is therefore provided as a base and proof of concept only.

The device, which is being designed for the completion of this project, will be both mechanically and electrically complex. But since this project is not intended to be developed to a commercial standard, there are no direct ethical or legal implications. It is noted that if the concept were to be extended than undoubtedly, there would be some ethical and legal constraints.

Since the control system utilises electronic components is very important to ensure that they do not pose an electrical hazard. The risk of electrocution posed under normal operation is very low as the system will be designed to run on 12 V. This is necessary, as all of the batteries available of sufficient capacity are 12 V only.

1.5 Project methodology

The undertaking of a project of this high level of magnitude and complexity is required to be conducted in a structured and ordered manner to ensure that all aspects of the research, construction, development and evaluation are completed in a timely manner. The first task, which is required to be undertaken, is to research the types of presently existing mobile robots that are available in the marketplace with a view to identifying relevant features. The background information that is available is generally found in books or online. Some information is also available in robotics journals and magazines.

Once all of this information has been analysed and interpreted the next step is to examine the currently available designs, with a view to implementing the best relevant features. Also some investigation into the required features of these types of robots may need to be conducted. This process will generally involve advanced research on the specific attachments and their integration into to the robotic system. As well as these attachments, a series of initial tests and benchmarks should also be researched to assess the abilities of the robot to perform under different environmental situations.

After all of this research has been completed and the benchmarks determined, the next step would be to use the gathered information to devise a series of possible robotic design solutions. Once all designs have been completed then a feasibility study will be carried out for each option and the most feasible option will be selected.

The next step in the process will be to construct the robot from this 'best design'. It is expected that this shall be a long and time consuming process as it is estimated that the majority of the components will need to be custom manufactured for this project. Once this initial design has been constructed it will undergo a series of rigourous benchmarking tests. If, during the benchmarking tests any problems are discovered then they shall be rectified. This may include redesigning the mobile robot until suitable benchmark results are obtained. The analysis and features of the final design shall then be reported on in conclusion to the project.

1.6 Resource planning

There is a large variety of components that will be required to successfully complete this mobile robotic project, and due to the large variety they will be sourced from a various different places. Due to the limited number of sources in Australia for the purchasing of suitable robotic components, as well as their extreme cost, many of the components will have to be custom-made. This will not be too much of an issue as all of the components, once manufactured, are unlikely to be broken due to the nature of their design. The manufacture of these custom components will be undertaken in a private workshop.

The components which are likely to be used in the design can be split into two main categories, which are; mechanical components and resources; and electrical components and resources. The following tables outline the components and their possible source locations.

Table 1- Mechanical components and resource requirements

Resource	Description	Requirements	Source	Manufacturing requirements
Chassis.	25.4 x 25.4 x 1.5 steel rectangular hollow section.	Lightweight, durable, weldable and rigid.	Available at any steel supply yard. To be custom manufactured.	Full fabrication, including drilling, sawing and welding etc.
Motors and gearbox (two of).	Windscreen wiper motor.	Powerful, efficient, must have attached gearbox, low power consumption.	Available at any car wrecker or auto shop.	Limited primarily to the construction of motor mounts.
Small idler wheels (six of).	Round aluminium wheels.	Durable and of the correct size.	Not available anywhere. To be custom manufactured.	Full fabrication, including casting drilling and machining.
Large idler wheels (four of).	Round aluminium wheels.	Durable and of the correct size.	Not available anywhere. To be custom manufactured.	Full fabrication, including casting drilling and machining.
Automotive timing belts (two of).	To be used as tracks.	Durable and of the correct size as well as having sufficient treads.	Available at any car wrecker or auto shop.	Limited primarily to the construction of drive wheels.
Drive wheels	Round aluminium	Durable and of	Not available	Full fabrication,

(two of).	wheel with teeth that mesh with the timing belt.	the correct size.	anywhere in the correct size or within reasonable price range (more than $60 each). To be custom manufactured.	including casting drilling and machining.
Aluminium skid pan plates.	Flat aluminium sheet to be used as a floor of the robot, as well as the bash pan.	Lightweight, durable and rigid.	Available at any steel supply yard. To be custom manufactured.	Full fabrication, including drilling and sawing.

Table 2 - Electrical components and resources

Resource	Description	Source	Manufacturing requirements
Microcontroller	PICAXE, 18 X on project development board	Available from pickaxe.co.uk or other Australian suppliers	Case and mounts
Radio control unit	Minimum of two channel radio control unit	Available from any hobby shop	Suitable protective case, to avoid damage
Wireless camera system	5.8 GHz wireless camera system	Available from most good electronics stores	Brackets and mounts as well a suitable portable location and power circuitry
H Bridge controller for the motors	MOSFET type H Bridge controller.	MOSFET's available from most good electronics stores	Construction of all the required circuitry, including voltage doubler and microcontroller interface circuitry.
Wiring and hook up wire	Assortment of generic hook up wire	Available anywhere	Nil

Both of these tables are not conclusive, and only outline the basic requirements for the project as well as a basic plan for the sourcing of the components. It is highly unlikely that any of the custom-built components will ever fail, as they are generally solid, machined aluminium or welded steel; therefore no contingency plan is necessary. Whereas all of the other non-custom components are generally easily available for example, the MOSFET's are available through Jaycar electronics, which have over 50 stores and 100 stockists and agents throughout Australia and New Zealand (Jaycar 2010). Therefore should a MOSFET fail a replacement should be easily available.

After this project has been completed, the mobile robotic device will be left in the assembled, usable state. This is so that if, in the future, a small mobile inspection robot is required to undertake a reconnaissance or inspection task, it is already available in the assembled state.

1.7 Risk assessment

Before the commencement of the construction of this project it was necessary to undertake a safety and risk analysis of the processes and procedures that were in use. This risk analysis and assessment was then used to develop a series of controls to avoid injury. The majority of these controls draw on the commonsense of the operator to implement. For example, use of ear muffs or earplugs to control and avoid injury from exposure to excessive noise.

All the construction and fabrication of the custom components for this project were completed in a private workshop where all of the individual machines and processes that were used in the fabrication have their own risk assessments and safety data sheets available. This is in accordance with the *Workplace Health and Safety Act* of 1995, and the *Workplace Health and Safety (Plant) Code of Practice* 1993. The following tables outline brief extracts from a selection of the processes that we used in the fabrication of components for this project.

Table 3 - Drop and band saw, risk assessment sheet extract

Hazard	Likelihood of occurrence	Consequences	Controls to avoid injury	Risk after controls
Loud noise	High- Aluminium and steel are both noisy materials to work with	H – Hearing damage will occur for multiple cuts	Hearing protection must be worn including ear muffs and earplugs	L – Adequately protected
Flying debris	High – Hot spatter and swarf from saw blade may become airborne	H – Blinding if caught in eyes, minor burns possible on skin	Eye protection to be worn, face mask preferable, non-loose – long sleeved clothes	L – Adequately protected
Saw jamb	Medium – If work not secured piece may fly	H-Possible loss of fingers in blade or pinching of skin	Clamp work piece when cutting	L – If adequately clamped

Table 4 - Lathe risk assessment sheet extract

Hazard	Likelihood occurrence	Consequences	Controls to avoid injury	Risk after controls
Loud noise	High- lathe work is an inherently noisy operation	H – Hearing damage will occur for multiple cuts	Hearing protection must be worn including ear muffs and earplugs	L – Adequately protected
Flying debris	High – Hot swarf from lathing operation becoming airborne	H – Blinding if caught in eyes, intermediate burns possible on skin	Eye protection to be worn, face mask preferable, non-loose – long sleeved clothes	L – Adequately protected
Lathe jam, resulting in possible breakage of lathe tool	Medium – If work not secured in chuck piece may fly resulting in damage to machine and tool bit	H-Possible loss of fingers due to rotating work, piece or pinching slicing , abrasion and crushing of skin and muscle tissue	Clamp work piece well, in the chuck when performing work	L – If adequately clamped

Table 5 - Bench, hand and portable grinder, risk assessment sheet extract

Hazard	Likelihood occurrence	Consequences	Controls to avoid injury	Risk after controls
Loud noise	High- grinding is an inherently noisy operation	H – Hearing damage will occur for multiple cuts	Hearing protection must be worn including ear muffs and earplugs	L – Adequately protected
Flying debris	High – Hot spatter and sparks from grinding disk may become airborne	H – Blinding if caught in eyes, minor burns possible on skin	Eye protection to be worn, Face mask preferable, non-loose – long sleeved clothes	L – Adequately protected
Grinding machine jam or flying debris	Medium – If work not secured piece may fly	H-Possible loss of fingers in grinding disk or pinching or abrasion of skin	Clamp work piece when grinding as well as the use of appropriately sized grinder	L – If adequately clamped

Table 6 - Pedestal, bench and hand drill as well as milling machine risk assessment sheet extract

Hazard	Likelihood occurrence	Consequences	Controls to avoid injury	Risk after controls
Loud noise	High- Drilling is an inherently noisy operation	H – Hearing damage will occur for multiple cuts	Hearing protection must be worn including ear muffs and earplugs	L – Adequately protected
Flying debris	High – Hot swarf from drill may become airborne	H – Blinding if caught in eyes, intermediate burns possible on skin	Eye protection to be worn, Face mask preferable, non-loose – long sleeved clothes	L – Adequately protected
Drilling machine jam, resulting in possible breakage of drill bit	Medium – If work not secured piece may fly, resulting in damage to machining and drill bit	H-Possible loss of fingers due to rotating work, piece or pinching slicing or abrasion of skin and muscle tissue	Clamp work piece when drilling as well as the use of appropriate drilling apparatus such as a pedestal bench drill, where suitable	L – If adequately clamped

The preceding tables briefly outline extracts from some of the tools and equipment that are to be used in the construction of the robotic device.

Conclusion

At the commencement of this chapter, the terms robot and mobile robot were defined and outlined as a precedent to be used throughout the remainder of the document. The next section briefly discussed the history of robotics from the early developments by the Greeks to the modern high-tech machines of the present era. We then went on to define the problem that this project is aiming to investigate and provide solutions for. In section 1.3, the overall project objectives were thoroughly discussed and subdivided into manageable sections then, the consequential effects of this project were evaluated.

The project methodology outlined the intended steps that need to be taken for the successful and timely completion of the project. As well as outlining, in some detail, what each of these individual steps involves, including the designing and benchmarking of the robotic device. The resource planning was also discussed in general terms as the exact requirements of the robotic device are not known. Before any work was undertaken the preliminary risk assessments were completed for each step and mechanical device that is to be used in the construction of the robot.

Chapter 2

Literature review

Introduction

The purpose of this chapter is to provide basic background information and a brief review of the available literature. In this chapter we aim to discuss the concepts of a mobile inspection and reconnaissance vehicle. This review of the presently existing systems will provide a suitable starting point from which work and research on the project can be continued.

This chapter contains the following subsections relating to tracked mobile inspection and reconnaissance platforms.

- Brief overview on semiautonomous robots.
- Differential steering using two motors.
- Research on track based robots and their applications.

It is to be noted that the vast majority of the applications of this particular type of robot are military in nature, and therefore *classified information* and unavailable under the *Official Secrets Act* 1951 (United Kingdom, Australia and New Zealand), the *Executive Order* 13292 (America), as well as various other Federal legislations.

2.1 Semiautonomous robots

The concept of having mobile robots that are able to control themselves, in either an autonomous or semiautonomous operational mode is not at all new. Over the years there have been many different attempts at constructing robots capable of this feat. These many different attempts have had various degrees of success. Generally, most robots of this nature are designed primarily for military use. Under military use, these robots are often deployed for bomb diffusion, bomb placement as well as general reconnaissance. Some examples of robots that are designed for these applications are the TALON, shown in figure 1 and the TELEROB, shown in figure 2.

Figure 1 -TALON bomb defusal and placement robot (Robot Central, 2010)

Figure 2 - **TELEROB bomb placement robot (Robot Central, 2010)**

These robots are designed so they are able to be sent safely into dangerous or hazardous environments without the risk of injury or death to a human. Generally, this results in faster and safer bomb defusing as well as placement, and inspections.

Another mobile robot that is closely related to the aim of this project is the American designed SWORDS robot shown in figure 3. These robots are slowly becoming the norm on the American battlefield. It is the opinion of the American Defence Force that these robots are going to prove to be an invaluable resource on the future battlefield (Brooks 2002). They are also of the opinion that if one of these unmanned ground vehicles is able to be disabled by the enemy, it is better than an American soldier or a US Marine getting wounded or killed. The argument for their use is that, although they are expensive, they are able to be replaced, whereas the life of a human and the hours of training are not. The American Defence Force also believes that with the adoption of these robots the casualty rate for each battalion will be dramatically reduced. This is highly beneficial, given the present media climate, where the events and casualties from each counterinsurgency battle are broadcast virtually live.

Therefore, in the future, the military has to attempt to increase soldier lethality and presence, whilst decreasing the soldier casualty rate if the military wishes to save taxpayer money. The benefits of using these high cost robots in the place of soldiers and marines may not be immediately apparent, but it is sizeable. The majority of these savings come from the reduction of medical treatment and rehabilitative costs for wounded soldiers/marines. For example, if a U.S. Marine were to lose his arms/legs or become disabled by enemy fire or by the defusing of a bomb during a battle, the financial cost of his rehabilitation and surgery would be extremely high (tens or hundreds of thousands of dollars) , and that's not including the significant human and emotional costs. (Defence Review, 2010). Therefore, if a robot is able to engage and neutralise as many combatants or terrorists as possible while keeping soldiers out of the line of fire it is well and truly worth the initial investment costs.

Figure 3 SWORDS robot system equipped with M240 7.76mm 100 rnd machine-gun (Defence Review, 2010)

The SWORDs weapons platform is able to be equipped with a large number of different options, including sniper rifles, machine guns, assault rifles, rocket launchers, grenades as well as a combat shotgun. The versatility of this weapons platform is quite large, with an even larger number of other attachments available such as thermal cameras and rangefinders. This provides a basic direction for the aim of this project.

2.2 Differential steering using two motors

There are a large number of modern day, appliances and devices as well as farm machinery and construction equipment which use two motors for direction control. A twin motor drive system is also known as either a skid steer or a differential drive system. Using this system, if both motors are driven in a forwards direction, the device will move in the forwards direction. If one motor is driven and the other one is stopped the device will turn towards the stopped motor. If both motors are driven in opposite directions the device will counter rotate on the spot. A common industrial application of these principles is found in a bulldozer. This method works well, as it allows tracked vehicles to turn corners and provides superior manoeuvrability.

It is noted that there are some design problems with the system, which are introduced due to slight differences/mismatches in either the gearbox or the driving motors. In either case, the device tends to drift slightly to one side and refuses to drive in a straight line. There are many different methods used for correcting this, such as monitoring the number of rotations on each output shaft and comparing them and slowing one of the two motors so their speeds both match. Another method involves the use of a single motor and a series of clutches, gearboxes and differentials. This method is generally not practical for the construction of mobile robotic devices as miniature gearboxes, clutches and differentials are generally not available.

One of the simplest methods is to simply determine a value by trial and error that whereby either motor, slowed or sped up by that coefficient will cause the device to travel in a straight line. This method is usually done in these sort of semiautonomous radio operated mobile robots, where navigational feedback is not important. Should a tracking problem occur is easily corrected by the user either by setting a bias on the RC unit or by continuously correcting.

Therefore, the choice for this project is clear, the mobile robotic device will use the trial and error method to determine a coefficient, to which one of the motors will be pulse width modulated to cause the device to traverse in a straight line. That is, if there are any form of tracking errors or motor mismatches. In future, if time permits. The first method could be implemented and a control algorithm written to ensure that both of the drive wheels, and therefore tracks rotate at the same speed. This will also be useful if, in the future this device were to be made fully autonomous; whereby the robot will use 'dead reckoning' where it calculates its position, according to how far each drive wheel has rotated since a known origin point.

2.3 Tracked based robots

Through the research it was discovered that tracks were by far the best design option for mobile robots of this type. The general advantages of tracks over wheels or legs are that tracks provide increased stability to the device as well as increased traction and a greater amount of torque transmission over any of the aforementioned options. For these reasons many manufacturers such as the makers of the SWORDs robot recognise the need and potential of tracks early in their design phase. (Defence Review, 2010).

Tracks are also highly useful when the robot has to climb and descend stairs and slopes as well as cross ditches, mount obstacles and generally traverse rough and hostile terrain in any direction including turning. There are many different styles of tracked systems from those which are quite simple and consist of nothing more than a frame, a track and a pair of pulleys; to those which are highly complex and are able to fold and reorient themselves to climb stairs and other seemingly insurmountable obstructions.

For this project an initial design was chosen, which is reminiscent of an early tank track design and is shown in figure 4. Although this design works well in theory, when put into practice, many problems were discovered. These problems included the friction between the rear drive wheels and the track not being sufficient to provide positive drive during all situations. When turning the vehicle tended to walk off its tracks and the method of adjusting the track tension was also not very suitable.

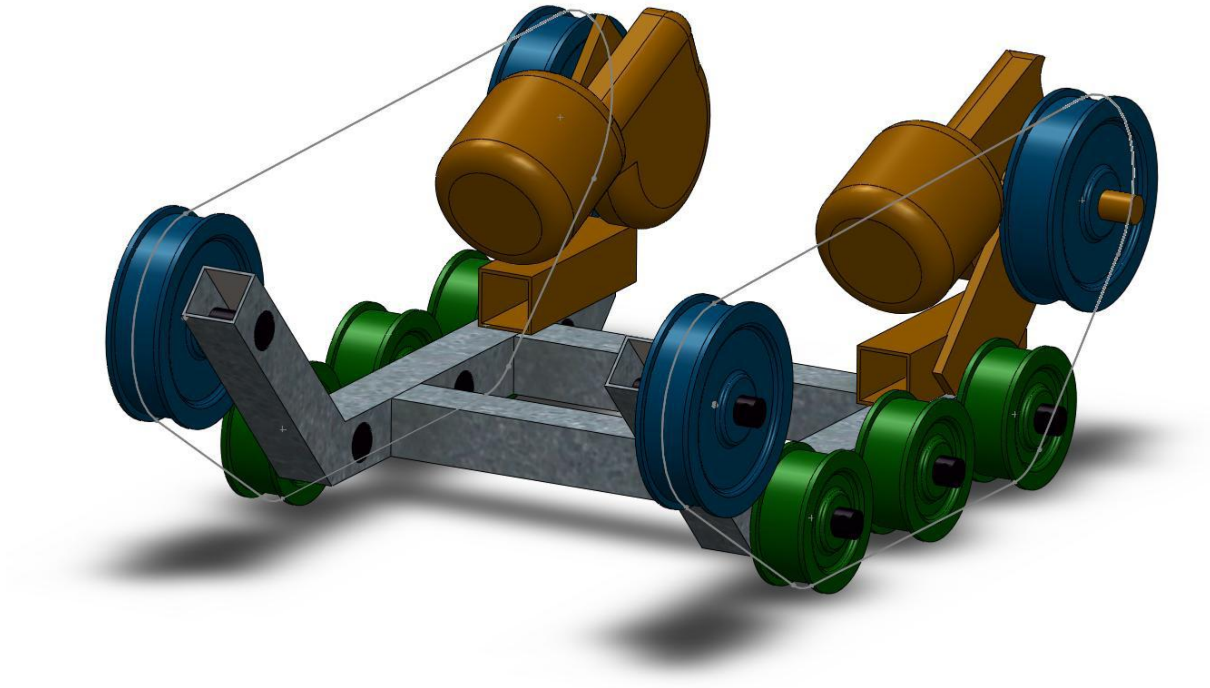

Figure 4 - **Initial track design**

Since this design was not very suitable. It was obvious that a revised design would need to be implemented. The major downside to using automotive timing belts for tracks is that there is a limited amount of information available on their use. The only reference that was deemed suitable was found in a book titled, 'Mechanical Devices', written by Britt Robabaugh. The design from this book is shown in figure 5 and is specifically for single sided automotive timing belts, and will work quite well.

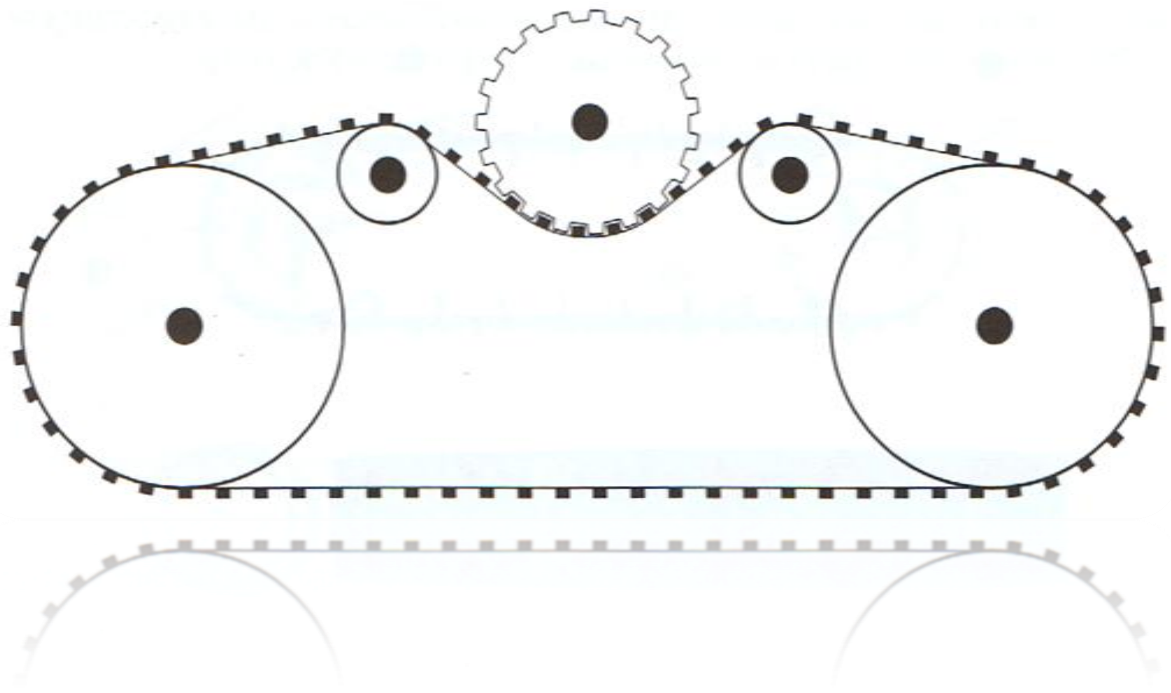

Figure 5 - **Driving and support arrangement for track made from single sided timing belt (Robabaugh 1995)**

This design was slightly modified to include different features, as shown in figure 6. This variation included a track tensioning method. It was desirable for the tensioner to tension and hold the track tight under all circumstances, as well as stop the tracks from walking off the idlers, provide a cushioning effect as well as to help avoid shock loading on the drivetrain and reduce track stretch. In addition, the adjuster had to be dynamic or self adjustable to reduce the need for constant tightening and adjusting.

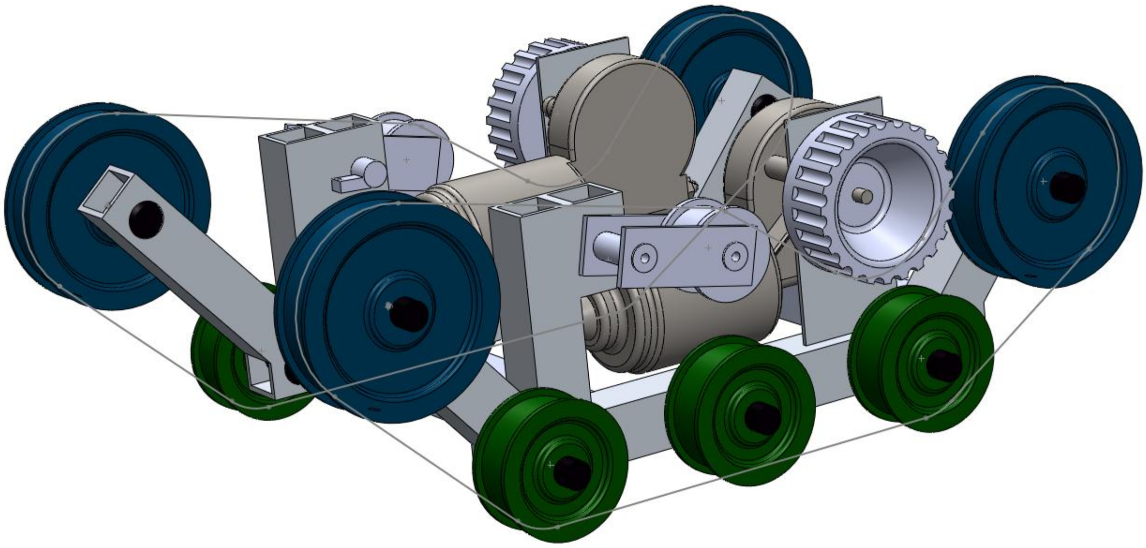

Figure 6 - **Final track assembly including modified driveline and tensioners**

One of the most notable disadvantages of tracks is their tendency to require a considerable amount of power to turn. As one track is stopped, and the other is driven the leading and trailing edges of the track get dragged sideways, perpendicular to the direction of the normal track drive. This effect is outlined in figure 7 below; where, for the purpose of illustration, the worst-case scenario is depicted, a neutral turn. Turns of this nature should be avoided as they tend to require a large amount of power to execute sometimes even more power than is required to travel at full speed. (Robabaugh 1995). Where the space is available it is much better to turn with a small amount of speed through a greater radii as this will consume less power and be a lot more forgiving on driveline components.

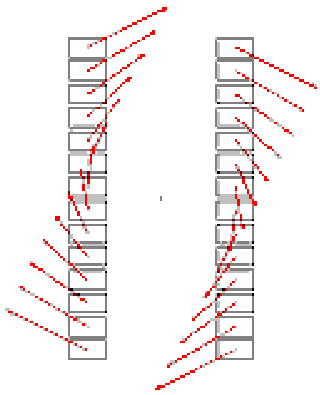

Figure 7 - **Tracked vehicle clockwise neutral turn (Robabaugh 1995)**

In the above diagram the red lines indicate direction in which each of the contacting elements of the track gets dragged during a clockwise turn. It is seen that the segments nearest to the end get dragged a significant distance, and therefore experienced a greatly increased amount of wear. Performing turns of this nature, significantly decrease driveline and track life. With any tracked vehicle is no way to negate these problems, but the effects of this can be minimised by concentrating the weight towards the centre of the machine. This acts to reduce the wear as all of the weight is directly upon the point where the sliding movement and drag is the smallest. Figure 8, below shows, a solid model of the optimum design for this tracked robotic system.

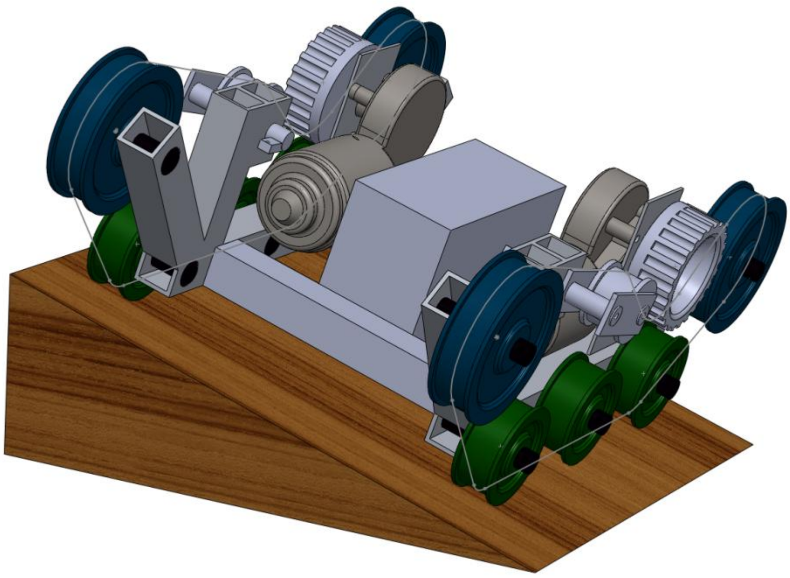

Figure 8 - **Optimum design for the tracked robotic system**

It is also seen that having the weight concentrated towards the centre and in the lower portion of the robot will also act to increase stability on an incline.

Conclusion

In conclusion, this literature review investigated the concepts involved in the construction of a mobile robot and has uncovered and discussed many different design concepts. It has also been seen that a lot of these concepts are not new, and that many different robots have been built using them. But it is useful to note that the majority of the design and research carried out by these inventors and companies is generally classified information, and is not available due to various legislations including; *Official Secrets Act* 1951 (United Kingdom, Australia and New Zealand) and the *Executive Order* 13292 (America).

Chapter 3

Mechanical component selection

Introduction

The purpose of this chapter is to provide detailed technical information upon the selection of each individual mechanical component used in the device. This chapter aims to discuss many different features, such as the chassis type and selection requirements, the materials that were considered to be used for the construction of the chassis, the features of a well-designed chassis, as well as the preliminary final designs for the chassis.

Before the commencement of this chapter, it is important that some of the key terms used are defined. The most important of these terms is chassis. The Macquarie dictionary defines the term chassis as a frame, wheels and machinery of a vehicular device upon which the body and internal components are supported. (Macquarie 1991).

In this case wheels are taken to mean tracks, drive sprockets, idlers and other miscellaneous track components. This chassis selection shall also include details upon the suspension and relevant suspension components.

3.1 Chassis selection, type and specific requirements.

Since this robot is designed primarily to be used in hostile environments and is going to be exposed to a multitude of abuse from the terrain which it shall encounter, the appropriate design of the chassis is of primary importance. Since this is an integral part of the success of the robot, the following materials and features were deemed to be of importance.

It was envisaged early on in the project, that the robot be small, very rigid and be very agile. This, from the start, ruled out the use of any sort of conventional steering mechanism, whereby there are a pair of driving wheels, either straight geared or through a differential and a pair of driven wheels, which take on the role of steering. This was ruled out immediately as it is an overly complex method and would require the fabrication of a great deal of intricate componentry to a high degree of accuracy. The components that would have to be manufactured include a steering rack, a differential, all of the steering linkages as well as various complex mechanisms to keep the wheels in the correct alignment.

A second option for the driving/steering componentry is with the use of three wheels. In this design two of the three wheels are driven, whereas the third is of a typical caster design and simply rolls along trailing the two driven wheels. Under this technique, a method of steering called differential steering is used. This steering method relies on the friction between the stopped wheel and the ground acting as a pivot point around which the device is turned. For example, for the device to perform a right turn, the right wheel is stopped and the left wheel is driven, thus turning the device to the right around the stopped wheel.

This method of locomotion was discarded because this technique, although used quite often in the robotics world, is not the most durable or stable and was also discarded as the end device, would be rather clumsy. This would be especially evident on the rough terrains, slopes, crevices and otherwise hostile environments encountered in the robots operational environment. This clumsiness is caused by the inherent instability associated with the use of three wheels which acts to position the centre of gravity in a slightly forward location. This method, in practice often requires considerable counterbalancing to ensure a reliable operation on any sort of slope or inclined surface.

The third option which was selected was locomotion by the use of tracks. This is deemed to be the most appropriate method of locomotion, as it is by far the most stable. Tracks are also used to great success in many different modern/real/full-size world applications. Examples of this include modern war fighting tanks, crawler type loaders and excavators as well as bulldozers, such as many of the famous examples produced by Caterpillar, Komatsu and other manufacturers. These real-world full-size applications depict their versatility across a large number of different applications, especially in areas where rough undulations or slopes, would make the terrain impassable. Tracks also provide increased stability and manoeuvrability, above all other forms of locomotion. It is for these reasons that tracks were selected as this device is undoubtedly going to see operation in many of the harsh environments encountered in modern workplaces.

There are very few track kits available commercially, which would be able to fulfil many of the roles, which would be asked of this device and certainly none that would be able to fulfil all of the roles. It was therefore decided that the only option was to construct a track system. This track system would require that a custom-made chassis be manufactured to form the basis of this track system. It was decided early on in the build that the tracks would be formed from single sided timing belts. This imposed a few significant problems as discussed previously.

Figure 9 - **Single sided timing belt intended to be used for the track system (Auto Parts 2010)**

3.2 Materials.

This section outlines each of the individual materials that were considered for use in the construction of the chassis. There are many different impositions placed upon the chassis in order to ensure that the best possible chassis material was chosen. It is important that the material chosen be easy to join, rigid, stable (not degradable), especially inflammable as well as durable and hard wearing.

3.2.1 Wood and fibrous natural materials.

Wood is a very common construction material seeing use in many different applications. Wood in all forms is easily available from local hardware departments and timber stores. It is also lightweight, easy to work and cheap especially in bulk. But with these advantages come some very steep disadvantages, which include;

- Timber, being a natural fibre is very raw and unpredictable in structure, thereby compromising durability and rigidity. Also, being a natural fibrous material, it is prone to splintering and warping, making it highly unsuitable for this project.
- Although Wood has some amount of flexibility to it, it is by no means indestructible, therefore should it take a tumble it may break and splinter causing injury.

- Wood displays a very specific tensile strength direction. This is because of the grain structure. Screwing or nailing into the end of the wood, may cause it to split or the fastener to pull out, thereby causing the joint to fail.

It is for the above reasons, as well as the fact that producing joins in wood that resist torsional loadings and remain stable is not very easy. Also the fact that wood is not flame resistant meant that it was ruled out, not only for use in the chassis, but in all aspects of the device.

3.2.2 Acrylics and other plastics.

Acrylics and plastics in general, especially over the past 50 years, have begun to see vast use in many different construction applications. Plastics are not as readily available as woods, but are still often to be found at most hardware stores. Plastics are seeing increased use in the construction industry, as they are especially lightweight and easy to work as well as they are relatively strong. Some of the other general advantages include good multidirectional tensile strength, high impact resistance providing that the integrity of the surface is intact, relatively good to excellent insulating properties, high stability, easily fabricated and are generally non-toxic (unless being heated or melted).

The primary disadvantage with using plastic as a construction material is that it is comparatively soft. This is a very limiting disadvantage, as it affects the rigidity of the system. It is for this particular reason that plastics and acrylics were also ruled out for use in any of the major construction components of the device. Plastics were undoubtedly quite useful in the construction of non-mission-critical components to provide environmental protection such as the microprocessor control housing and other housings and casings.

3.2.3 Steels, alloys and other metals.

Steels and other metals, since their discovery, have played an integral role in the construction industry and have seen use in many different applications over the years. Steels and alloys are often easily available either at hardware stores or metal yards and are available relatively cheaply. These metals are available in many different configurations such as flat plate, rectangular hollow section, square hollow section, triangle, pipe, checker plate, angle, rectangular bar, square bar, etc. This means that no matter what the application is it will be easy to find a specific size, length or diameter of metal section to fulfil the task.

This option offers by far the most strength and rigidity as well as flame resistance, ease of joining, stability, durability and hard wearing nature that this project requires. Even though there are some small disadvantages such as the advanced skills that it requires to manufacture components from these materials, the special tools and equipment that are required for the manufacture as well as the increased weight over other options that this option provides. All things considered, the advantages far outweigh the disadvantages. This is because of all of the skills and equipment that are required to process these materials were possessed by the author, and that the increased weight was a very little importance, as it would assist in giving the device extra traction, especially over rough and undulating terrain.

3.2.4 Final chassis material selection.

After careful and comprehensive consideration of all of the above listed materials. The use of steels, alloys and other metals was the obvious choice. The ease of joining, stability, as well as the durability and hard wearing nature of the materials make them far superior for use in this project to any of the other choices. This was further compounded by the author having easy access to all of the tools and equipment that were required for the processing of these materials, the cheap nature of steel presently as well as the authors' easy access to an abundant source of aluminium only requiring it to be cast into the shapes required. The use of steels and metals also provide the project, with a rugged and durable look to match the indestructible nature of the device. The use of metals, over plastics and timbers also makes a device look more professional in finish than the other options could possibly hope to provide.

3.3 Features required of the chassis.

This section outlines each of the individual considerations that were important in the design of the vehicle chassis. Throughout the design phase of the project, there were a large number of constraints placed upon the chassis. These constraints included the steering methods, and the forces introduced by them, the structural rigidity of the chassis, the mounting of components as well as the battery and power supply mountings. It was always envisaged from the start of the project, that the design be simple enough to be placed together without any significant instructions and in the field, if need be.

It was also necessary that the chassis for the vehicle be highly stable, non flexible, and easily adaptable in order to form the basis for future attachments. These attachments may include robotic manipulators such as arms and hands, lights and lighting apparatuses as well as various military applications and attachments such as firearms and rifles. In general the following design considerations were some of the governing factors which heavily influenced the design and construction of the chassis.

- In order for the design to be successful, the chassis must be able to be constructed from easily available materials and components. This was important in order to ensure that any modifications required to be made, were able to be made easily. For example, if it was found that the frame was not of the correct size, design or shape then by simply cutting and welding it in a slightly different position instead of having to remodel the frame would modify it.
- Obviously, since the machine is to see extensive use in hostile and rugged environments, it is imperative that it is as durable and resilient as possible. A lot of this durability and resilience is attributable to the design of the chassis. For example, if the chassis is too small and weak. It is likely to be easily damaged, thereby needing repairs, conversely if the chassis is too bulky and heavy, it is likely that the device will not see any operation, as it will be simply too clumsy to deploy. Also, a bulky chassis, translates directly into an increase in the cost of motors and drivetrain assembly as well as battery power and runtime operation.
- Thirdly, it was envisaged from the outset of the project, that the device be modular in design. This means that should a component fail, it would be able to be easily replaced in the field instead of having to send the entire robot to a repair shop.

- The final major design constraint was that the device must be safe and functional under all circumstances, and not pose any unnecessary threats or injury to anybody.

The following points outline some of the major areas of design, which were considered important in the chassis construction.

3.3.1 Steering

The choice that was made at the start of the project in regards to the use of tracks as the form of locomotion instantly meant that a lot of the considerations to the design of the steering mechanisms for the device were simplified greatly. Since the only method of steering using tracks is differential drive, there was no need to consider the construction of complex steering components. The only downside with using differential steering for turning is that it tends to require a considerable amount of power to turn, and also introduces a considerable amount of twisting stress into the chassis and tracks. This is probably best understood by use of a diagram.

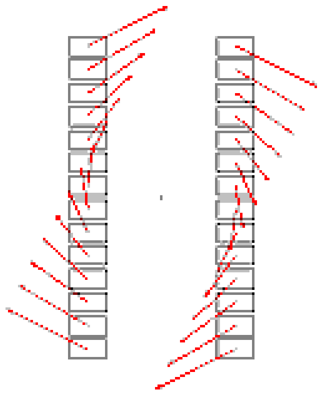

Figure 10 - **Track movement through a neutral turn (Robabaugh 1995)**

The above image shows the direction in which each of the contacting elements of the track move when executing a neutral clockwise turn. It is seen that the further a contact element is from the centre of the device, the more it is dragged in the direction other than the one in which it would normally move. The next diagram shows the extent of the forces of friction to be overcome for the device to perform this particular turn.

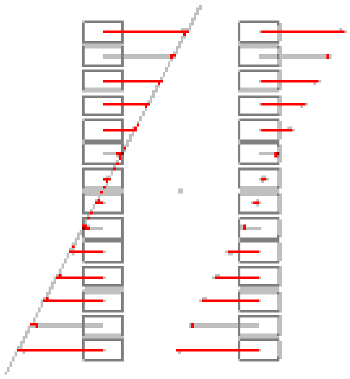

Figure 11 - **Frictional forces to be overcome for clockwise neutral turn (Robabaugh 1995)**

These forces are the horizontal component of friction that each of the contacting elements of the track overcome in order for the device to turn. As before, it is seen that the amount of force is directly proportional to the distance that the contacting element is away from the centre of the device. The amount of force, and therefore the length of these force vectors is dependent upon the weight of the vehicle, the length and width of the contact patch and the radius of the turn.

From this it follows that if the device is long and very narrow, these forces are to be quite large and very punishing upon the track and driveline components. Therefore, the track design, which was selected, was shorter than what the maximum length of track would allow. Also from this it was gleaned that a wider vehicle would also be a lot more forgiving and less abusive on the track and driveline components as well as providing stability. Another important design considerations also noted from the above diagram was that if the majority of the weight was concentrated around the middle portion of the vehicle, where the induced forces were minimal, then the driveline components would see less induced frictional forces.

3.3.2 Rigidity and assembly

Since this robot is most likely going to see large amounts of abuse, especially in hostile and rough undulating terrain its rigidity and durability were of primary importance. In a robot of this size and stature, the majority of the rigidity comes from the design and manufacture of the chassis. Having a properly designed chassis is very important especially in regards to the drivetrain and the forces applied to it throughout normal operating conditions, such as turning.

The main consideration was that the chassis had to remain stiff, under all conditions as this permits its behaviour to be easily predicted. Since it was determined that the chassis was to be made from either steel or another alloy a suitable method of joining had to be achieved in order to maintain the stiffness of the chassis. Many different methods were considered, such as the joining of cross members using bolts or screws, pop rivets, and by the use of permanent fixing techniques such as welding.

Almost immediately, the method of using screws and bolts on their own was discounted as they have a tendency to come loose or vibrate out, especially under adverse conditions of operation. Although there are many different types of screws, nut and bolt combinations, which may have been suitable, these were not easily or feasibly obtainable. Some of these combinations, which may have been able to be used are screws with spring washers set underneath the head in order to stop them from vibrating loose. Another technique is the use of bolts and nuts with spring washers or by the use of 'Nylok' nuts or through the use of other retaining compounds such as Loctite. Through the use of these retaining techniques the fastening methods proved useful, especially in the mounting of sheet metal work, for example, the base plate, and the retaining of other small components such as the microprocessor housing, and the mounting of the cameras.

The use of pop rivets was also rejected, especially for any of the main chassis work. This was for a multitude of reasons, such as the fact that at least two are required in every side of every joint to stop it from pivoting around, and that once they have become loose there is no possible method of tightening them, except for drilling and re-riveting. The use of pop rivets was therefore reserved for special occasions where no other fastening technique would be suitable. This was the case for the battery level indicator tang at the front of the device, whereby the steel angle brackets were to be fastened to the aluminium base plate. In this case rivets were by far the most useful fastening technique as screws, would easily vibrate loose thereby losing the nuts and damaging the thread in the ground so that new nuts could not be used.

This left only one possible technique for the manufacture of the chassis, this technique was of course welding. Welding provides very solid and rigid joints, which are able to resist a large amount of force. Welding is a fabrication process, whereby two or more bits of metal are joined to form a single coherent mass. Welding is generally classified according to the source of energy used. For example, electric arc welding, in this process the energy for the fusion comes from an electric arc created between either the positive and negative (in direct current welding operations), or either side of a welding power supply (in alternating-current operation). This welding power supply is, in essence, a large heavily wound transformer with some regulating and rectifying circuitry (for DC operations). In electric arc welding, a filler material is almost always used, except under some certain cases, where the actual material to be fused forms a filler material (such as a case in TIG welding which is not to be considered further here).

The welding process most valuable to the manufacture of the chassis was the Metal Inert Gas or MIG electric arc welding process. With this welding apparatus, the filler material comes in the form of metal flux cored wire through which the direct current is passed to form the electric arc. This feed wire is passed through the MIG gun and is fed continuously during the welding operation. Metal Inert Gas welding is by far one of the neater forms of welding, because there is no flux used and the joints created are significantly less porous than those created by other techniques. The technique of welding in most cases forms joints, which are as strong as, if not stronger than the parent material. It was therefore concluded that welding was to be the most appropriate technique for the construction and manufacture of the majority of the crucial chassis components.

3.3.3 Component mounting

The final main aspect of the chassis design requiring consideration was in regards to the component and battery mounting. In this case the component mounting covers all of the features of the robot including the mounting of the drive-train elements such as the motors, motor controllers as well as other electrical components including the microprocessor, the camera system and the battery monitoring system.

For the design and construction of the chassis of this robotic system, the rigid and stable mounting of each of the drive motors was considered to be one of the most important aspects of the design. The ultimate success or failure of the longevity and durability of the robot relied ultimately upon the quality of the design and manufacture of the motor mounting plates. Since it was decided early on in the project, to use a pair of 12 Volt windscreen wiper motors for the primary sources of locomotion, a large amount of the troubles encountered by most robot designers were eliminated. These motors were selected as they have an integrated gearbox and are relatively small and quite powerful. Another benefit of using these motors was that they already have precast and threaded mounting screw holes. A solid model of the right-hand drive motor is shown in the following figure.

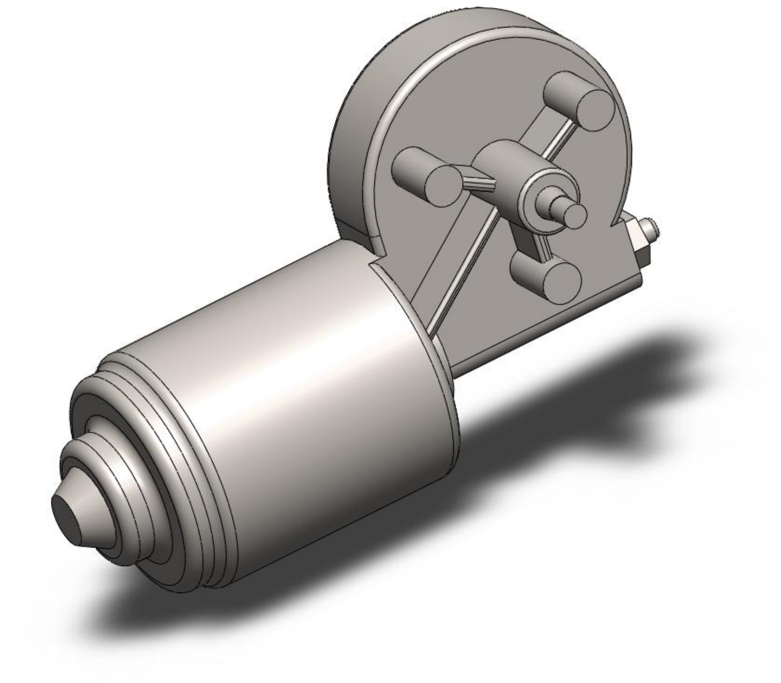

Figure 12 - **Solid model of the right-hand drive motor.**

The motors that were selected have a substantial power output of approximately 60 watts each. This level of power output was deemed necessary to give the robot unrivalled climbing and traversing abilities. With these climbing and traversing abilities came a great need for the strength and rigidity in all of the driveline components, especially in the motor mounts. The following figure outlines the motor mounts, which were designed and subsequently cut from 3 mm thick mild steel plate. This precision cutting was done in a local fabrication shop using a computer-controlled CNC plasma cutting machine. The results of this fabrication were more than pleasing requiring almost no cleanup or re-drilling of any of the holes.

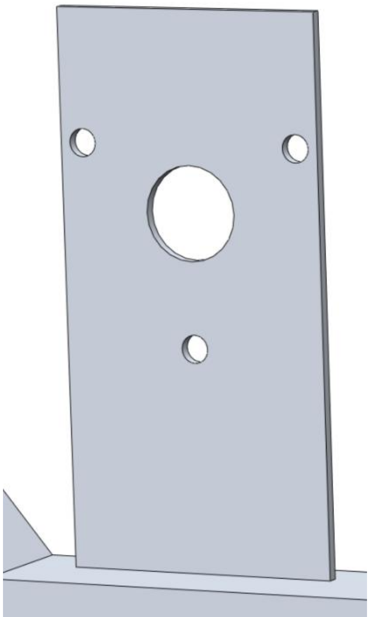

Figure 13 - Solid model of the right-hand side motor mount.

The next chassis components needing consideration were the track pulleys and idlers. Since commercially made drive wheels, idlers and pulleys were out of the question due to the authors' inability to procure any of the appropriate size, it was therefore determined that these components would have to be custom manufactured.

The following picture montage outlines the process, which was undertaken for the fabrication of the drive wheel from the solid model through to the finalised, fully machined components.

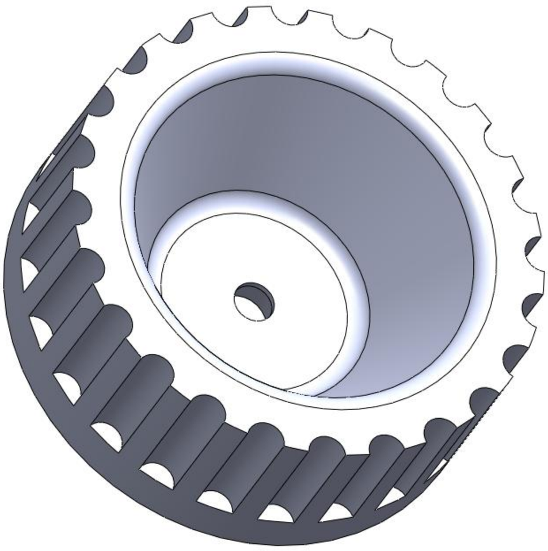

Figure 14 - **Solid model of the drive wheel**

The above figure shows the initial design in solid works for the drive wheel for the finalised design. From the solid model, a wax model was then formed as shown in the following figure;

Figure 15 - **Wax mould formed from solid model**

From this wax model a series of plaster casts were taken using the lost wax process. Molten aluminium was then poured into the cavity, which had been created by the removal of the wax in the process. The resulting aluminium cast is shown in the following figure.

Figure 16 - Rough cast of aluminium drive wheel

This rough aluminium cast, once it had cooled, was taken to the machine shop, where it was tidied up by use of both a lathe and a vertical milling machine to a finished and usable state.

Figure 17 – Final, fully machined drive wheel component

The above figure shows the final fully machined drive wheel component. It is noted that there were some slight casting inclusions in the process. This was deemed unlikely to cause any failure in the component over any of the expected operating conditions. This same process was undertaken for all of the other idlers and pulleys. The following picture shows the solid model and a finished fully machined product.

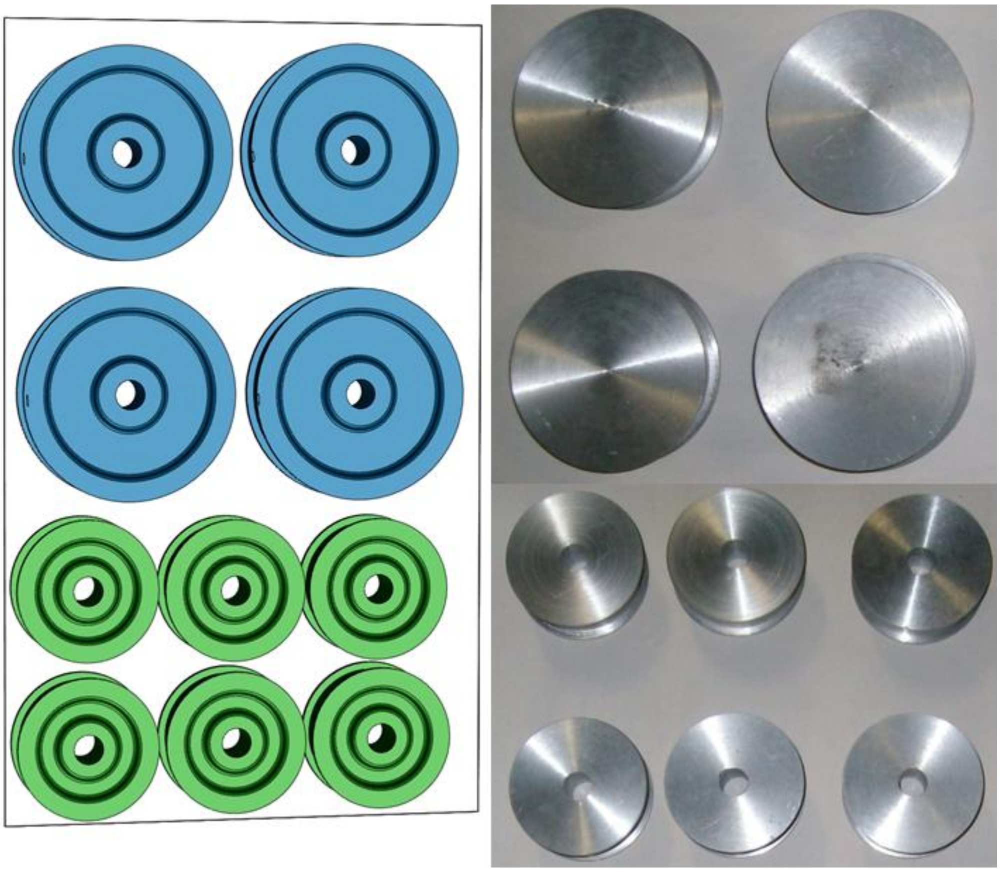

Figure 18 - **Figure showing the solid models and final machined products for the idlers and pulleys. (pulleys (top) and idlers (bottom) solid models on left, fully finished and machined castings on right)**

In conclusion, a large number of custom components had to be manufactured initially for this vehicle. The custom manufacture of these components proved to be a very time-consuming process but the results were well and truly better than expected. The manufacture of these components from the chosen material ensures that the robot is to remain stable and rigid under all of the harsh and abusive operating conditions expected.

3.4 Preliminary design

During the initial design phase, there were several different ideas, which were modelled and analysed before initial prototype and proof of concept robot was constructed. With all of the previously mentioned design considerations in mind, the following design was modelled in SolidWorks. This model was modified and adapted within the simulation environment, until a suitable design for the prototype model was arrived at.

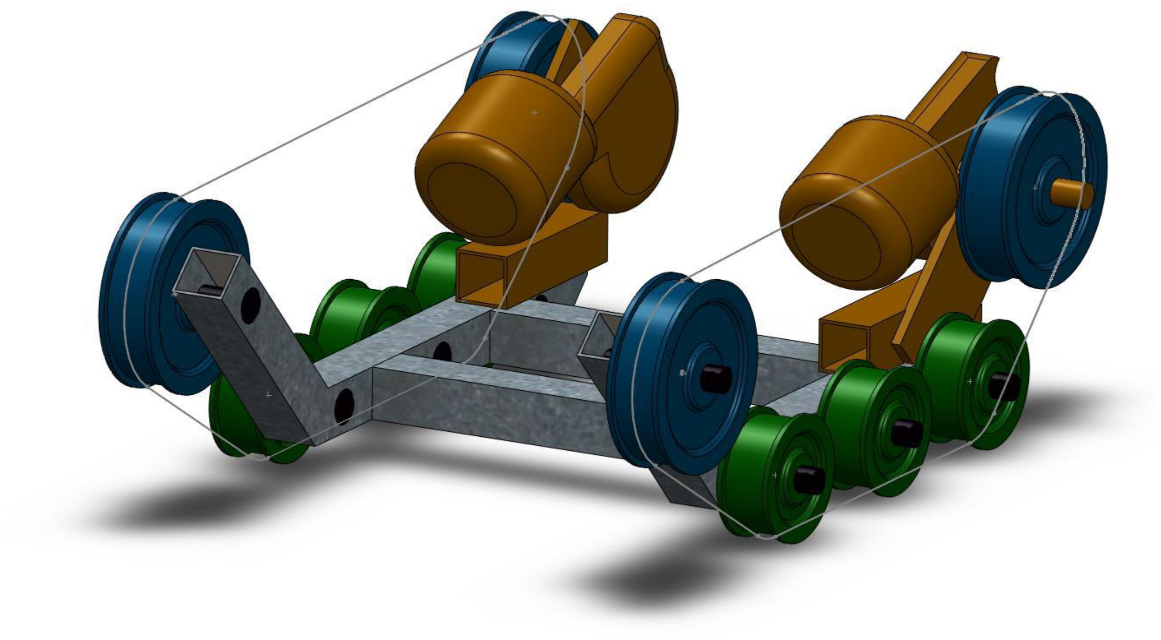

Figure 19 - **Initial driving and support arrangement for the tracked device**

As can be seen, the inspiration for this particular track layout comes from a military fighting tank, whereby there are a series of idler wheels and a driven pulley and a pulley which is fixed to a driven axle on each side of the device. This initial prototype was deemed worthy of testing due to its simple layout and its ease of construction. Detailed design drawings and construction notes can be found in Appendix B.

3.4.1 Failure of this design

In theory this design seemed idealistic for the application especially due to its small size and ease of construction. From the outset of the construction of this prototype, there were a large number of errors and failures, which doomed this initial design. The first of these failures occurred with the construction of the initial frame of the chassis. This failure was in the use of an inappropriate size and type of steel for the construction of the frame. The following figure shows initial design of the frame.

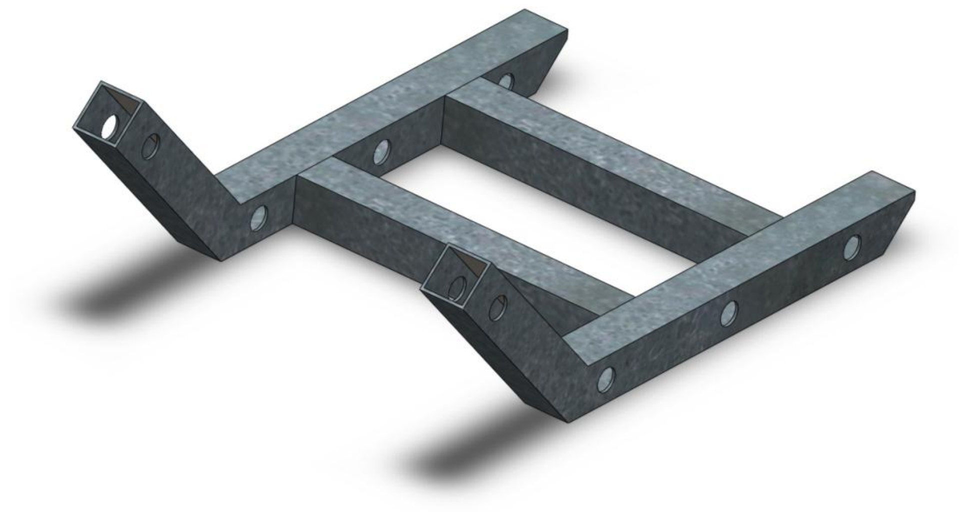

Figure 20 - **Initial design of the frame of the chassis**

When this prototype was constructed, it was constructed using 25 x 25 x 3 mm thick rectangular hollow section steel. While the frame was extremely strong and rigid, it was overly heavy meaning that the runtime of the robot was severely decreased due to the fact that the motors needed to work a lot harder to move the added mass around. This would undoubtedly have to be rectified in the final construction, primarily through the use of a lighter grade of steel.

Another failure of this initial design, discovered through testing was the fact that the friction between the rear drive wheels, and the single sided timing belt/track was not sufficient to provide positive engagement under all operating conditions. Several different modifications were made to the rear driving wheels in order to try to overcome this problem. These modifications included the knurling of the inside contact elements of the drive wheels in order to attempt to gain some more bite on the belts. This knurling only aided in the chewing out of the backing of the belt/track, which was unacceptable. It was obvious that this would have to be remedied in the final design for the robot to become successful and efficient.

The third and final major failure of this initial design was the fact that there was no method of adjusting the track tension. This was due to the fact that it was fixed in one single position and not able to move according to the undulations in the terrain. It was noted that when the device was driving over any sort of lump or undulation, the track was pulled tight onto the drive wheel, thereby leading to positive drive, and conversely, when the device was driving on flat ground, the track was not pulled as tight around the drive wheel, allowing the drive wheel to spin, which leads back to the previous failure. It was therefore concluded that the track tensioning method would have to be improved in the final design, with preference going towards a dynamic or self adjusting system.

3.5 Final design.

The second prototype and ultimate final design was based on a complete overhaul of the initial prototype. In this overhaul, the frame chassis and drive-train were based loosely around the design by Britt Robabaugh in his book, Mechanical Devices for Robot Building. This design is specifically for single sided timing belts and in theory and practice worked quite well for this application.

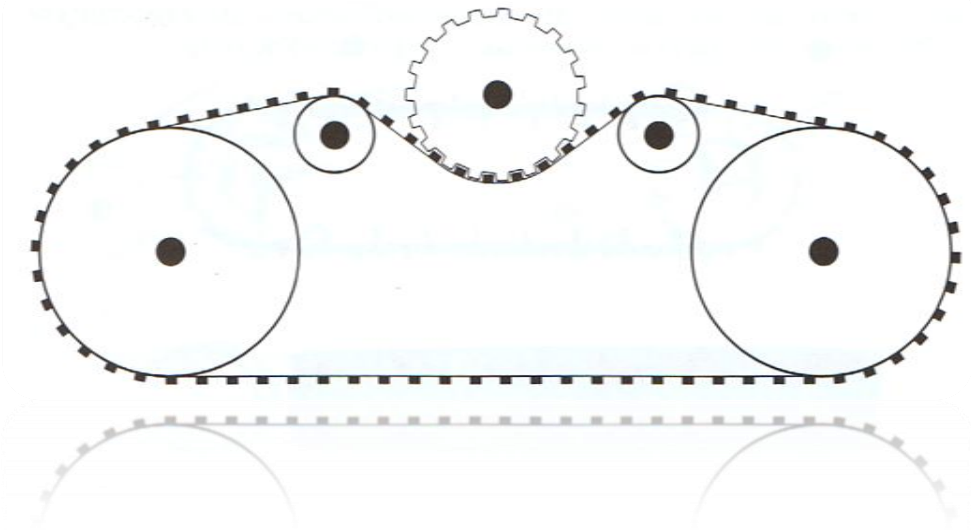

Figure 21 - **Driving support arrangement for single sided timing belt (Robabaugh 1995)**

As seen in the above figure this is a very complex method, but it does provide positive engagement between the drive wheel and the track under all circumstances, which means that the problem encountered in the initial design with friction slip would be completely eliminated. It is also noted that because the teeth in the belt, mesh directly with the teeth of the drive wheel, more force is able to be transferred to the belt without causing tooth or belt damage.

Secondly, it was obvious from the initial design that a better method of track tensioning was required in order to keep the belts on the pulleys and idlers properly and under all circumstances. This track tensioning method should also aim to keep the tracks in line and tight under all conditions as well as act to reduce the chance that the belt, should wander off the idlers, thereby incapacitating the vehicle. In addition, this track tensioning method should aim to be dynamic and self adjustable and in doing so be able to absorb and provide some cushioning to help avoid shock loading on the drive-train and bearings.

It was therefore decided that a cantilever spring arrangement would be the best for providing this dynamic shock absorbing track tensioning system. After much deliberation, the following design was engineered;

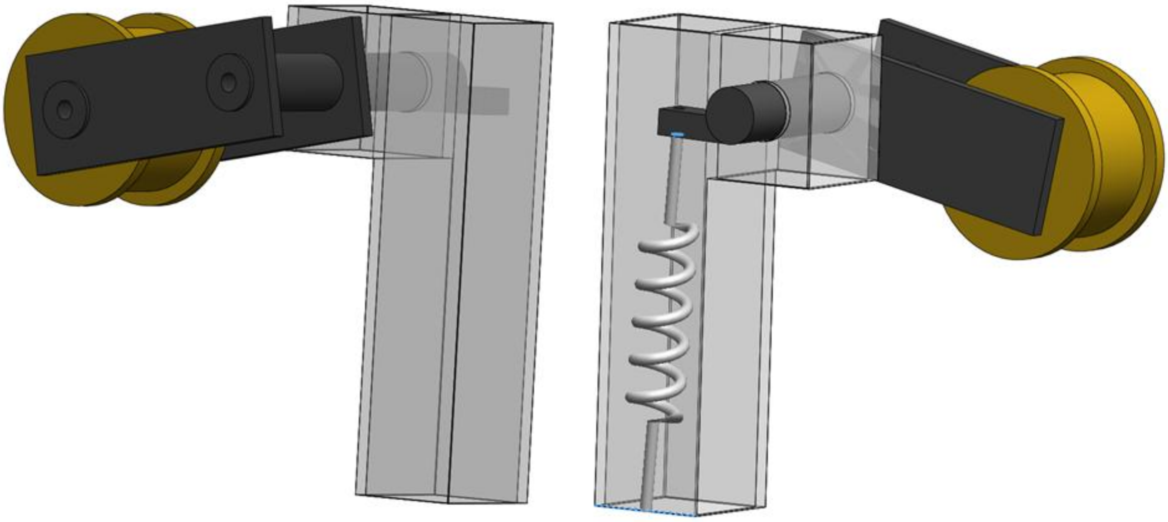

Figure 22 - **Left and right-hand side views of the track tensioning system**

This track tensioning method proved to be invaluable in operation, and once tweaked required no further adjustment or maintenance. These tensioners also provide a large amount of extra spring in the track and acted like shock absorbers, especially when the device was driving over rough terrain. Another unexpected bonus of this system is that when the front of the device contacts an obstacle, they permit the track to extend over the lip of the obstacle and thereby aid the device in traversing it.

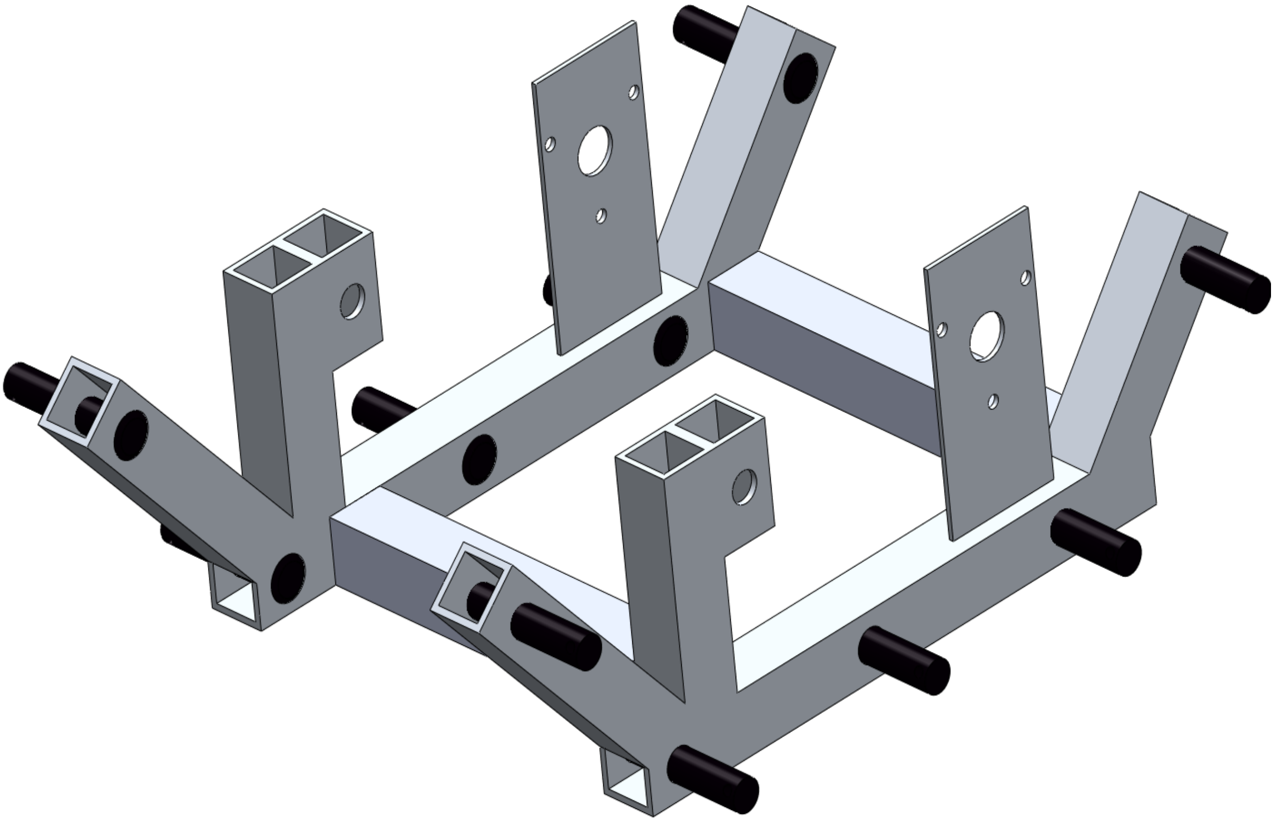

Figure 23 - **Solid model of the final chassis assembly showing the motor mounts and track tensioners in position.**

The final design consideration of importance in the construction of the chassis was with regards to the grade of steel used. For the final construction, 25 x 25 x 1 mm thick rectangular hollow section steel was used. This acted to reduce the weight of the initial bare chassis from 8.254 kg, for the initial prototype, down to 3.415 kilograms for the bare final chassis design. Thereby giving a 59% reduction in weight of the bare chassis and aiding to greatly increase the battery life and efficiency of the robot.

The following figure shows the solid model of the final track design for the robot. Further detailed design drawings and construction notes can be found in Appendix C.

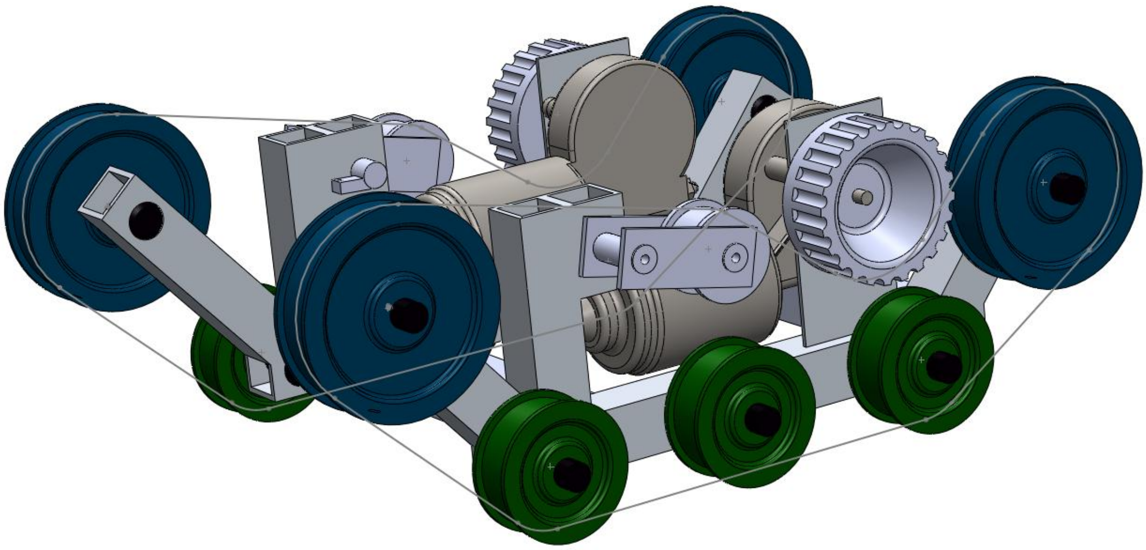

Figure 24 - Solid model of the final track layout showing all of the major mechanical components in position

The next figure shows, all of the components that form the chassis for the robot.

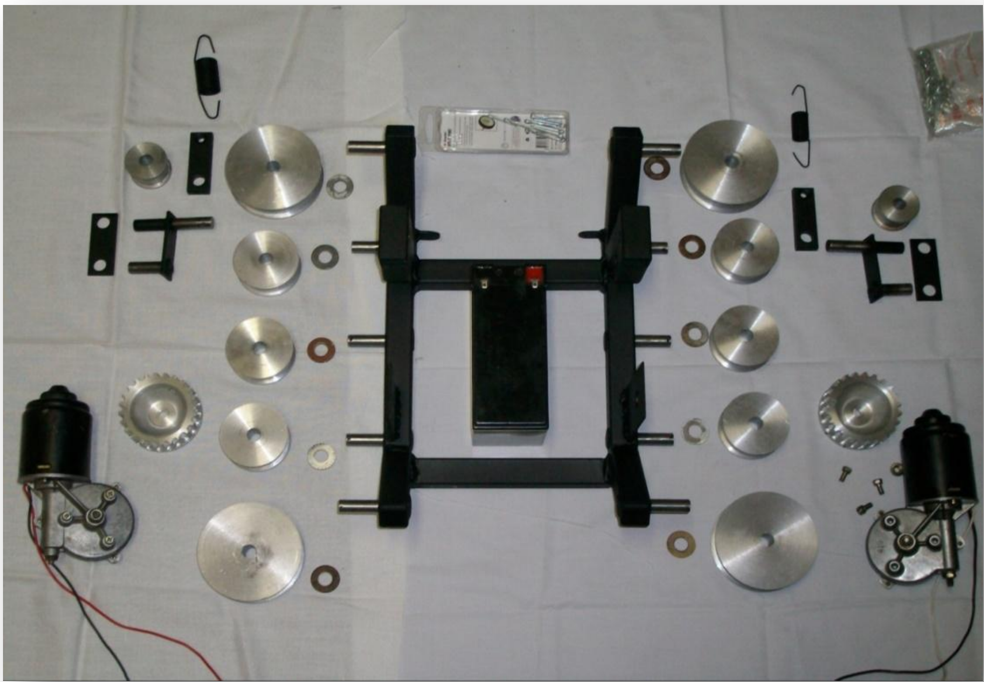

Figure 25 - Exploded picture of assembly showing each of the individual components of the chassis and their relative location on the robot. (It is noted that the only tools required for assembly were a pair of pliers and a Philips #2 screwdriver)

This final figure shows the construction of all of the mechanical components of the chassis. Clearly seen are the track tensioners and motor mounts as well as the position of the battery is to be noted for future reference.

Figure 26 - **Final assembly and construction of the robot chassis clearly showing all components in their correct positions.**

Conclusion

In conclusion, this chapter has covered the details of the technical information upon the selection of the individual mechanical components used in the construction of the device. This chapter discussed features such as the chassis type and selection requirements, the materials considered to be used for the construction of the chassis, the features of a well-designed chassis, as well as the preliminary final designs for the chassis.

Chapter 4

Electrical component selection

Introduction

The purpose of this chapter is to provide detailed technical information upon the selection of each of the individual electrical components used in the device. This chapter aims to discuss many different features such as, the selection of motors, motor drive circuitry, the wireless control system and the video circuitry.

Since the overall size of this robot had been defined in the chassis stage of construction a large number of the individual electrical components were required to fit within this predefined structure. In many cases, these electrical components were scavenged from many sources such as previous projects, repair yards, electrical suppliers and various other distributors or retail outlets.

4.1 Motor selection.

In all modern robotic projects motors form the most essential components of the entire apparatus. In this project, as with all mobile robotic projects motors and their often attached gearboxes are one of the sources of great expense. Expense forms one of the five primary considerations for the selection of motors; the other considerations include;

1) Alternating-current (AC) or direct current (DC)
2) Brush, brushless, permanent magnet or servo
3) The motors rpm (revolutions per minute) and whether or not it requires a gearbox
4) Operating voltage
5) The expense

Some of these considerations are obvious for example, the choice between alternating or direct current. In almost all robotics alternating-current motors are out of the question as there is no readily portable source of AC, whereas, direct current can be provided from any battery without the need for an inverter or chopper circuit. This makes direct current motors an obvious choice in all field vehicles.

Another design consideration is the operating voltage of the motor. For this project, a supply voltage of 12 volts was chosen, although 3, 6, 24 volts are also common operating voltages. In this case, the 12 Volts is to be supplied by an ordinary lead acid battery.

Early on in the design phase, it was decided that a pair of motors would be implemented on each side of the robot to provide differential steering. This drive type was selected to reduce the complications that would be incurred with the use of a single drive motor and a steering assembly. The use of two individual motors means that there are no complex steering calculations or algorithms to be performed and there are also no frictional or rotational losses through differentials and clutches. The following figure outlines the differential driving technique to be employed for this robot.

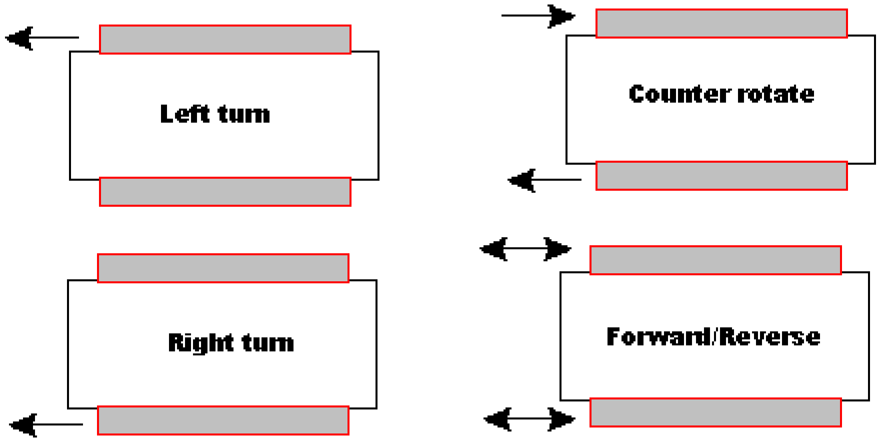

Figure 27 - **Differential drive technique**

As shown in the diagram, if the right side motor is stopped or reversed then the device will turn to the left, and vice versa. If both motors are run in opposite directions, then the device will counter rotate on the spot provided each motor provides equal torque and speed. The direction of counter-rotation is dependent upon which motor is in forward or reverse. If both motors are moving forward than the device will traverse forward. By the same token, if both motors are moving in reverse then the device will move in reverse. The next point of consideration was the choice of motor type to use in order to provide this motion.

4.1.1 Stepping motors.

The first motors that were considered for the locomotion of this device were stepper or stepping motors. These motors, by their construction are very powerful (providing large torque at low speed), and already incorporate a coarse method of position sensing, which would make them a perfect candidate for this robot. These motors are a brushless direct current synchronous electric motor in which one complete rotation is divided up into a large number of steps.

Stepper motors are quite different to ordinary direct current motors in that stepper motors consist of a series of coils which have to be energised in a particular pattern for the motor to rotate in either direction. Due to this fact, the motors are quite large and bulky. Also their power to weight ratio (watts to kilogram ratio) is nowhere near as large as other motors. This means that for a given power output a stepper motor is going to be significantly larger than both of the other options considered. Another problem with stepper motors is that, although they may produce a large amount of torque at low speeds, when the speed increases, the amount of torque produced decreases quite significantly.

This low speed torque meant that quite substantial motor mounting brackets would have to be fabricated to counteract the forces involved. These substantial mounting brackets would also introduce extra unnecessary weight into the project thereby compromising battery life and operational efficiency.

Figure 28 - **Stepper motors (RepRap 2010)**

The final limiting factor was the extreme expense of these particular motors. Motors of the appropriate size for this project run at between 200 and 400 dollars each. This extravagant price was deemed unacceptable for the project.

It is to be noted that smaller stepper motors can be obtained from many different sources such as computer printers. Often these printers have one or two stepper motors inside, which can be easily extracted for use in other projects. These motors may come in handy for other external attachments to the device, such as robotic manipulators and arms and hands. The primary concern with obtaining parts from many different sources is the variance between product size, specification, ratings and the power outputs from each different manufacturer.

Each of these individual disadvantages thereby lead to the exclusion of stepper motors from further consideration for use in this device. Although it is to be noted that they may prove valuable in the attachments and further development stages of this project.

4.1.2 Servo motors with integrated encoders.

Servo motors most commonly see use in robotic and radio controlled steering mechanisms or in applications where actuation is required. For example, these motors, in their smallest forms are often used on radio control buggies for control of functions such as a steering and the throttle. In general, servo motors are quite powerful and produce large amount of torque. The servo motors that were considered for the locomotion aspect of this project are shown in the figure below. These 60 W versions would easily provide the power, torque and speed that this robot requires. In addition these motors would also allow for fine position control, which may be necessary for autonomous use.

Figure 29 - **60 W Servo motors considered for drive (Drives and controls 2010)**

In an optimal world these motors would have been ideal for this project, although the real world is seldom optimal and the following implications of their use in the project needed to be considered.

1. Extreme expense. Motors of this particular power output were extremely expensive. In excess of $350 each, excluding the driver board that is required. Considering that two were required for the differential drive method, the costs associated with their use quickly exceeded the total budgeted cost of the robot.
2. This price of $350 each did not include the driver and controller board, required to interface these motors to any form of microprocessor or radio control unit. This board would then have to be purchased at additional cost which was unacceptable.
3. The technical skills and expertise that are required to implement these motors with their associated control boards in any robotic device using a microprocessor is quite technically advanced. Also, these motors can be easily damaged by incorrect operating procedures or incorrect use of the driver control board.

These three main considerations, thereby excluded the use of servo motors from the locomotion and drive-train system. Although it is to be noted that smaller servo motors, such as the one pictured in figure below were of great importance to the project.

Figure 30 - **Servo motor used in the camera adjustment system (Futuba - Active Robots 2010)**

These particular servo motors are comparatively inexpensive (approximately $15-$20 each), and come with an integrated controller board, meaning that they are able to be easily interfaced to the radio control system and the microprocessor. It is also noted that these small servo motors can be controlled directly by the particular microcontroller that was selected for this project.

4.1.3 Permanent magnet DC motors with gearboxes.

The final motor choice and the one selected was the use of permanent magnet direct current motors with integrated gearboxes. These motors are often a lot smaller than their stepper motor or servo motor counterparts for the same power output. The only downside with these motors is in operation, they have to be coupled with a gearbox to obtain any usable torque output. This is because these motors generally have a very high level of rpm (1000+).

These motors are available in an almost infinite variety of power outputs. For this project it was determined that motors with the power output of 50 W or more would be sufficient to provide locomotion. This was determined from the authors' previous experience with robotic devices as well as in consultation with many other experts in the field of robotics and mobile autonomous vehicles. Motors of this particular size are available from a large number of sources and distributors and therefore obtaining motors was not a problem. The problem lay in the fact that obtaining a suitably geared medium to heavy duty gearbox, proved impossible.

Upon further investigation, a worm drive gearbox appeared to be the next logical choice. These gearboxes are available from many different sources, for example semiautonomous auto drive mowers. This then raised the question of how to couple the motor to the gearbox.

After much consideration and consultation it was decided that a pair of windscreen wiper motors would negate all of these individual questions of motor coupling and gearbox integration. The following figure shows the windscreen wiper motors used.

Figure 31 - **Windscreen wiper motors used as drive motors in the project**

These particular windscreen wiper motors were sourced from old Suzuki's and purchased from an automotive wrecker. These particular motors were ideal as they are left and right-hand sided, which is a fairly rare occurrence for windscreen wiper motors. Also these motors were perfect as they are of matched pair meaning that they both have the same power output characteristics and would not be constantly trying to fight with each other in the project, thereby causing the vehicle to steer off to one side, consistently requiring correction.

The specifications these motors are as follows;

Table 7 - **Drive motor specifications**

Specification	
Type	Permanent magnet DC motor with integrated worm drive gearbox
Weight	1.35 kg
Operating voltage	12 V
No load current	2.13 amps (motor and gearbox)
Full load current	3.97 amps (motor and gearbox)
Revolutions per minute	60 revolutions per minute
Power output	60 Watts, maximum

From the specifications these motors were ideal for this project, as they have a low power consumption (even under maximum load) operate on 12 V, and have a usable output speed. These motors, like all DC motors have a fairly high stall current meaning that during start-up should the motors stall, they will consume a fair amount of current 10+ amps. This meant that the motor control circuitry had to be quite powerful. For this vehicular device the motors would spend most of their time starting, stopping or running slowly.

4.2 Motor drive circuitry.

Motor drive circuitry also known as the motor controller controls each of the motors speed and direction. This regulation is achieved by varying the input voltage signal and polarity to the motor. Throughout the years there have been many different techniques used for the implementation of this regulation. Each of these different techniques is often specific to the application in which the motor is to be used and on the type of motor used. Some of the common controlling methods include direct control with a switch, relay control, transistor or MOSFET control and transistor or MOSFET H bridge control. These latter forms of control easily enable the use of pulse width modulation (also known as PWM).

Pulse width modulation is a highly efficient method for digital circuits to emulate a range of analogue values. This is achieved by rapidly switching between full power and no power creating an average voltage in proportion to the mark space ratio. The following figure shows three typical signals from a pulse width modulated system.

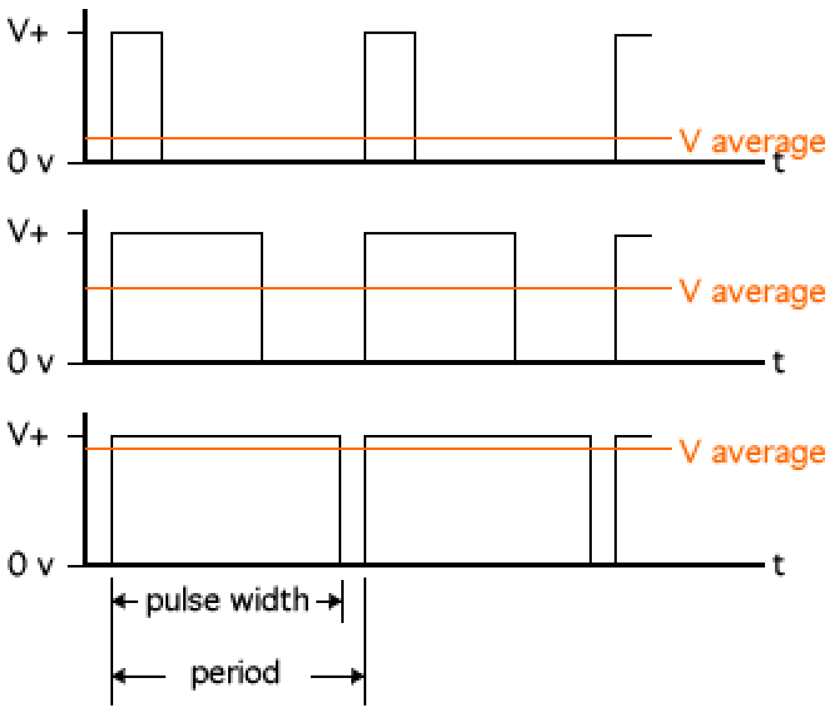

Figure 32 - **Output from a pulse width modulated system, showing the simulated average values**

Each of these three signals in the figure above have the same frequency, but the width of the train of pulses is different. Therefore, by varying the duration of the on-time within each period, an average voltage is simulated and this average voltage is applied to the motor. This average voltage, because it is less than the full voltage V+ means that the motor will rotate slower than it normally would, if V+ were applied. Using this technique any voltage between full off (V0) and full on (V+), can be simulated, thereby altering the speed of the motor in proportion to this duty cycle percentage.

For any pulse width modulated system, it is highly recommended that the frequency, which is selected for the pulse width modulation system be over 20 kHz. This is in order to make any hum or noise generated by the motor, above the maximum human auditory range and therefore imperceptible.

For this particular mobile device, a drive system which implements pulse width modulation will provide the best method of regulation. This is as applying direct voltage level inputs of full forward, full off or full reverse will tend to abuse the drive system and cause severe loading on the drive-train components. Also, the use of pulse width modulation to control speed reduces the overall power consumption of each motor, especially when used in a reduced speed mode.

The general characteristics considered to be important for the motor controller are;

- Accept Pulse Width Modulated signals.
- Have sufficient current capabilities.
- Not require a very large heatsink to save space and weight in the robot.
- Have an adequate switching and response time.
- Be efficient, not only in use of electrical energy, but in use of components
- Be extremely durable and long-lived.
- Be easy to work with and program for.
- Have integrated fail-safe's

To satisfy these characteristics two controlling techniques were investigated. These controlling techniques include the use of MOSFET H - bridges and a hybridised MOSFET - relay design.

4.2.1 Initial H-bridge design.

The control of any direct current motor brings many control issues in regards to the controlling of its speed and direction. The use of an H-bridge is common practice in most robotic apparatuses for the controlling of motors. Essentially an H-bridge works by the use of electronic switches, which permit electrical current to flow in a particular direction through the motor. The following figure outlines the basic principles of operation of a standard transistor H-bridge.

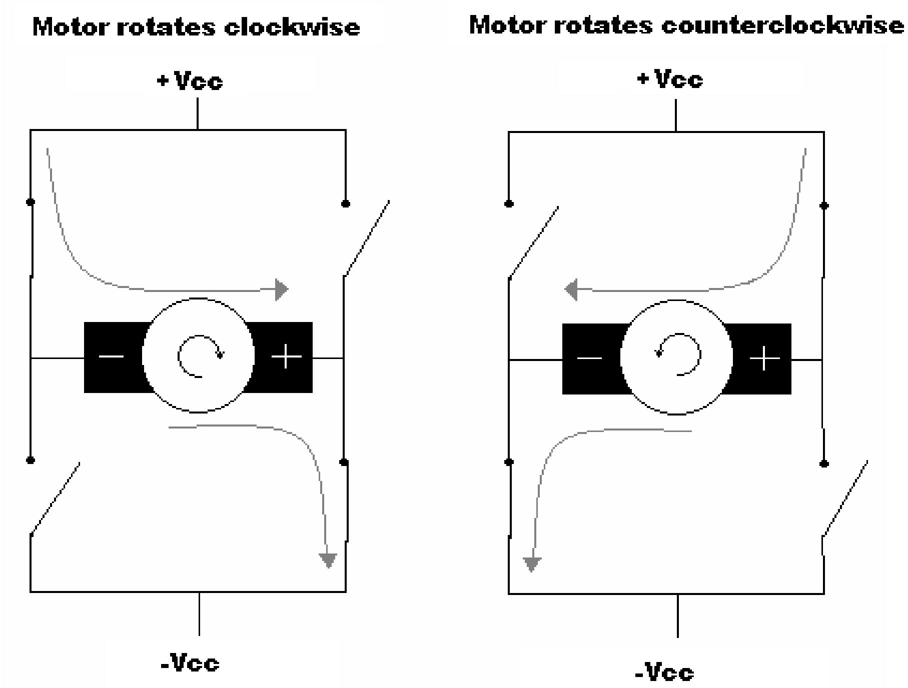

Figure 33 - Elementary circuitry equivalent of a transistor H-bridge.

The current flow in the circuit is indicated by the grey arrows. It is noted that diagonally opposing switches, should only be triggered together. If both of the switches on one side are triggered, a costly short-circuit condition arises. This condition generally results in the irreparable damaging of both transistors and often the circuit board. This condition is also known as shoot through.

Switches are triggered by applying a small voltage such as in the form of a logic high from the microcontroller. This high closes the switches and permits, the current to flow in the direction indicated by the grey arrows. In this case, the switches are arbitrary representative items and can be replaced by anything capable of switching such as MOSFET's (often), transistors (most commonly) or relays (rarely). In this case, there were two initial tests circuits constructed, one utilising transistors (TIP41C) and one using MOSFET's.

Test circuit one, using TIP41C transistors;

The following figure outlines the major components forming the test circuit for the H-bridge. There were of course, some other discrete components used, such as transistors to trigger inputs A and B from the microprocessor, as well as some EMF suppression diodes.

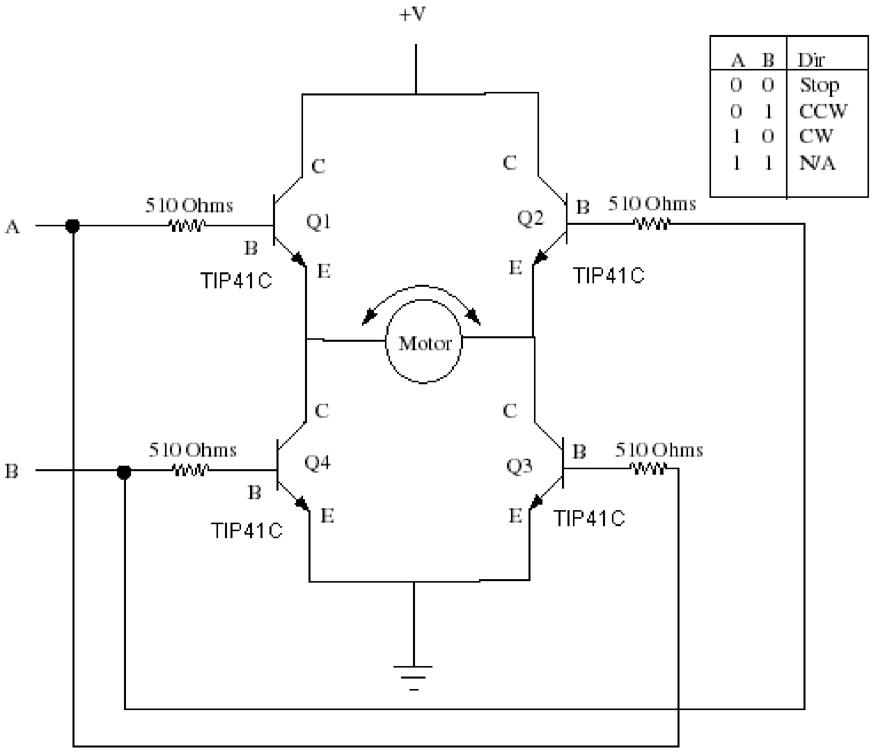

Figure 34 - **TIP41C H-Bridge schematic**

This is first H-bridge test circuit that was constructed used TIP41C transistors; these transistors have the following characteristics;

Table 8 - **General characteristics of the TIP41C transistor**

Characteristic	specification
Type	NPN Epitaxial Planar transistor
Maximum power dissipation (total)	65 W
Maximum voltage (collector-base)	100 V
Maximum voltage (collector-emitter)	100 V
Collector current	6 amps
Maximum temperatures	-55 ~ +150 ° C

Further details on these transistors are available in Appendix D.

It is seen that upon comparing the characteristics of these transistors to the table extracted from the motor specifications chart below that the transistors should indeed be capable of handling the current involved.

Table 9 - Extract of motor specifications chart

Motor Specifications	
Operating voltage	12 V
No load current	2.13 amps (motor and gearbox)
Full load current	3.97 amps (motor and gearbox)

These transistors were mounted to a considerable heatsink using thermal compound, mica insulating pads and rubber grommets; it was always envisaged that some sort of heatsink would be required. This is in addition to the aluminium body panels, which could also be used as further heatsink material.

In practice even with all of this heatsinking the transistors still got very hot under extended operation. It was determined that this was due to the considerable current draw of the motors during starting and under complete stall conditions. The heat that was generated meant that extra energy was being used inefficiently, and therefore leading to shorter battery life. As the vehicle is intended to be used for extended periods of time under these conditions it was therefore necessary that this drive controller be modified to negate these effects.

Test circuit two, using 5N06HD MOSFET's;

The next obvious choice for the H-bridge was with the use of MOSFET's. MOSFET's or Metal Oxide Semiconductor Field Effect Transistors are essentially transistors, the same as before, but are a lot more efficient and therefore generate a lot less heat and in addition, have a faster switching speed. The MOSFET's selected were 5N06HD's and were left over from a previous project. Their general characteristics are shown below in the following table.

Table 10 - General characteristics of the 5N06HD MOSFET

Characteristic	specification
Type	N Channel Enhancement Mode Silicon Gate
Maximum power dissipation (total)	150 W
Maximum voltage (collector-base)	60 V
Maximum voltage (collector-emitter)	60 V
Continuous current drain	75 amps
Maximum temperatures	-55 ~ +175 ° C

Further details on these MOSFET's are available in Appendix E.

It is seen that upon comparing the characteristics of these MOSFET to the characteristics of the transistors used previously, it is noted that these MOSFET have considerably higher ratings, and therefore should easily be able to handle this application. The typical circuit layout for using these N Channel, enhancement-mode MOSFET's is shown in the figure below. This, as before, shows only layout of the main components of the H-bridge.

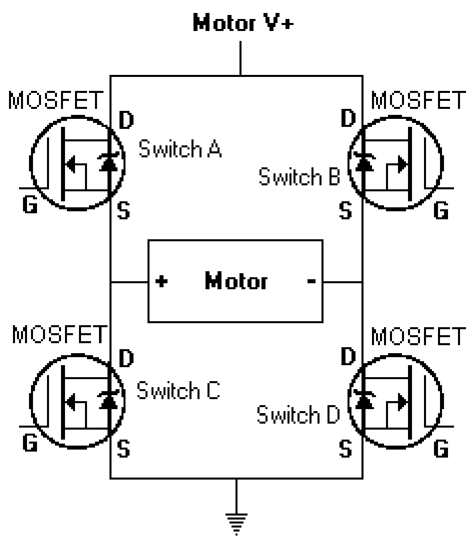

Figure 35 - Typical schematic for H-bridge made from N Channel MOSFET's (Control and embedded systems 2010)

With this particular design using only N Channel MOSFET is there is one major problem. This problem is that when these N Channel MOSFET's are used for switches A and B, the drain is connected directly to the V+ Supply for the motor and the source is connected to the motor. The problem occurs that when the gate is switched on (made 2 volts greater than the source). The MOSFET will turn on. But as the MOSFET turns on the voltage at the source increases, until there is no longer a 2 volt difference between the source and the gate at which point the MOSFET will turn back off.

This means that another voltage source will be required, that is always greater than 2 V above the motor V+ voltage. This may be done using a variety of methods such as an extra battery or in the form of a voltage doubler. The use of a second battery as a voltage source was discarded due to the weight, size and the room constraints on the robot. Therefore, the only option was to use a voltage doubler to gain the required increased voltage.

The voltage doubling circuit that was implemented was based on the 555 timer integrated circuit configured as an oscillator. The circuit is shown in the figure below.

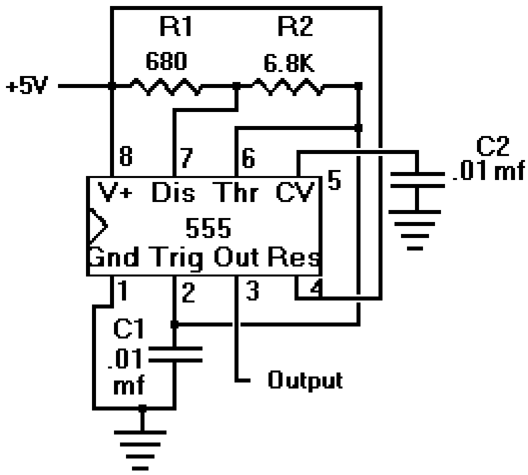

Figure 36 - 555 Timer/oscillator voltage doubling circuit (Control and embedded systems 2010)

The output of this voltage doubling circuit is then rectified, using a bridge rectifier, which consists of four diodes in a single plastic package to provide approximately 24 V from a 12 V source. The specific operation of this circuit is not discussed any further in this document and it is to be noted that this voltage doubler worked surprisingly well in this application.

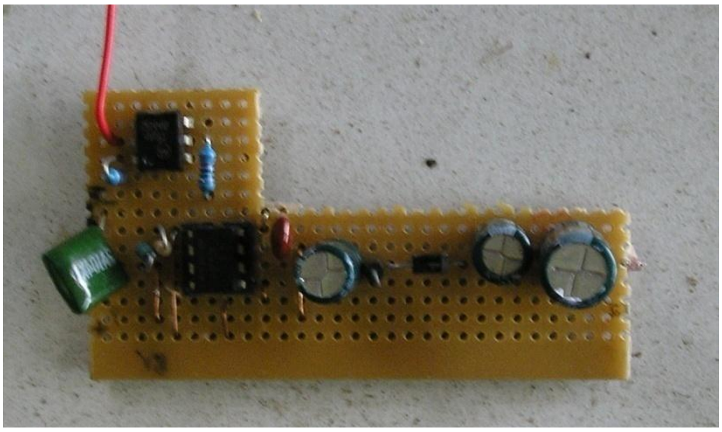

Figure 37 - **555 timer/oscillator voltage doubling circuit for MOSFET drive**

This technique was substantially more efficient and effective than the previously constructed transistor H-bridge. An area in which the improvement was most noted is with the heat generated by, the MOSFET's as opposed to the previously used transistors. With this circuit, the heatsink (the same heatsink as used in the previous initial design) barely warmed up during extended operation.

Although with this highly successful circuit came a number of inescapable disadvantages, which led to its eventual scrapping. These disadvantages include;

- The control methods for this H-bridge technique were more complex than would be desired in this simple robotic device.
- This H-bridge for some reason or other interfered with the radio control receiver unit, thereby causing a dramatic drop in the effective range of the radio controller and was deemed to be unacceptable.
- These N channel MOSFET's were extremely difficult to find replacements for. This was especially apparent when a slight mechanical mishap damaged a couple of the MOSFET's. The replacements for these were extremely expensive and had to be shipped from overseas as there were none available locally. This predicated the demise of this particular test circuit

It was also noted that the switching of the motors was a lot more violent as it occurred quicker than with the transistors. This caused considerable heat generation within the motors that, if it were allowed to continue, would cause irreparable damage. The author acknowledges that this problem could have been remedied by further programming in the microprocessor or with the addition of other external components. But this would have led to reduced motor and overall radio control response time. Also, the further time, resources and expense taken in this additional programming, research and development was deemed better spent elsewhere, especially on the development of a better, more simplistic, less expensive motor controller circuit.

4.2.2 Relay - MOSFET hybrid design.

Due to the failings of the previously discussed motor controllers it was evident that a custom-designed one would have to be constructed for this project. Keeping in mind, the general characteristics considered important, it was necessary that this design be functional as well as highly reliable. As listed previously, the amended characteristics for this motor controller are;

- That it operate in a way similar to the H-bridge, with the provision for motor forwards and reverse.
- Accept Pulse Width Modulated signals to regulate the speed of each individual motor.
- Have sufficient current capabilities in order to limit the amount of heat sinking that is required, and the amount of heat generated.
- Have an adequate switching and response time, as seen from test circuit two, an extremely fast response time is not desirable, as it tended to abuse the motors.
- Be efficient, not only in use of electrical energy, but in use of components. Especially in the use of easily obtainable components, and not exotic single integrated circuit H-Bridge motor controllers such as an L298 motor drive IC as these are quite difficult to find.
- Be extremely durable and long-lived. This is probably the most important part for the entire design. Both of the previous designs are highly susceptible to mechanical damage in the form of vibration, snapping legs off the MOSFET's/transistors as was the case for test circuit two.
- Be easy to work with and program for.

- Have integrated fail-safes especially important to prevent short-circuiting and shoot through across the H-bridge.

A number of different designs were considered before one was settled upon. This final design relied on the use of both a relay and an N channel MOSFET. The inspiration for this relay-MOSFET design came from a very unlikely source. This unlikely source was the large, Dresser/Komatsu 630 E electric drive mining truck. These trucks use contactors to select forward or reverse and then control the armature drive. This design operates on similar principles, whereby either forward or reverse is selected by the relay and speed regulation is provided a MOSFET or bank of MOSFET's which effectively cut up and pulse width modulate, the supply side to the motor armature.

The following circuit diagram shows, a highly simplified layout for this system, neglecting most of the discrete components used, such as transistors to trigger inputs ‘ forwarded/reversed select’ and to trigger the ‘motor speed control’ MOSFET. Also omitted are all of the resistors as well as some EMF suppression diodes across the relay necessary to prevent spikes from resetting the microcontroller.

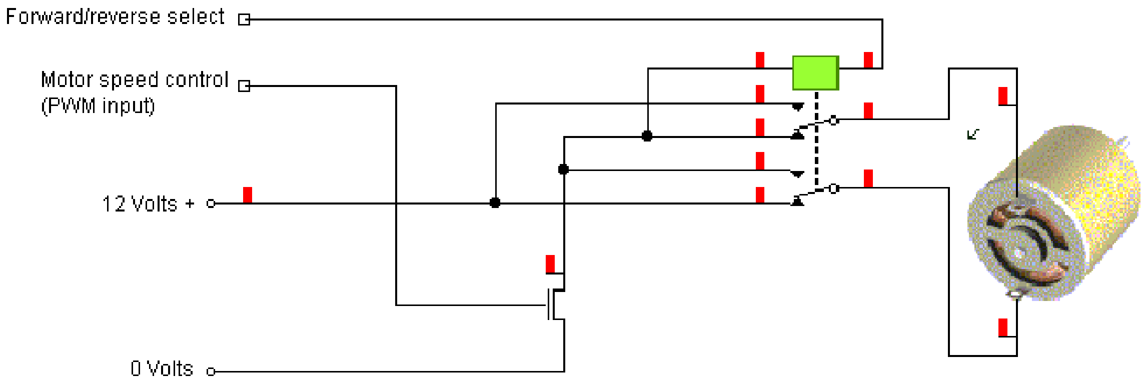

Figure 38 - Layout for the final motor controller circuit

In this circuit the relays used are 12 V DC relays manufactured in Japan by Izumi industries. These relays are triggered from a 12 V DC source and are capable of switching 30 V DC at 10 amps continuous or 10 amps at 110 V AC thereby making these relays an ideal choice for this application.

For further data on these relays see appendix F. It is to be noted that their AC rating is equally important as their DC rating as the signals they will be switching will not be true, direct current, due to the pulse width modulation MOSFET. The signals they will switch will look like a semi-rectified square wave alternating-current source as shown in the following figure;

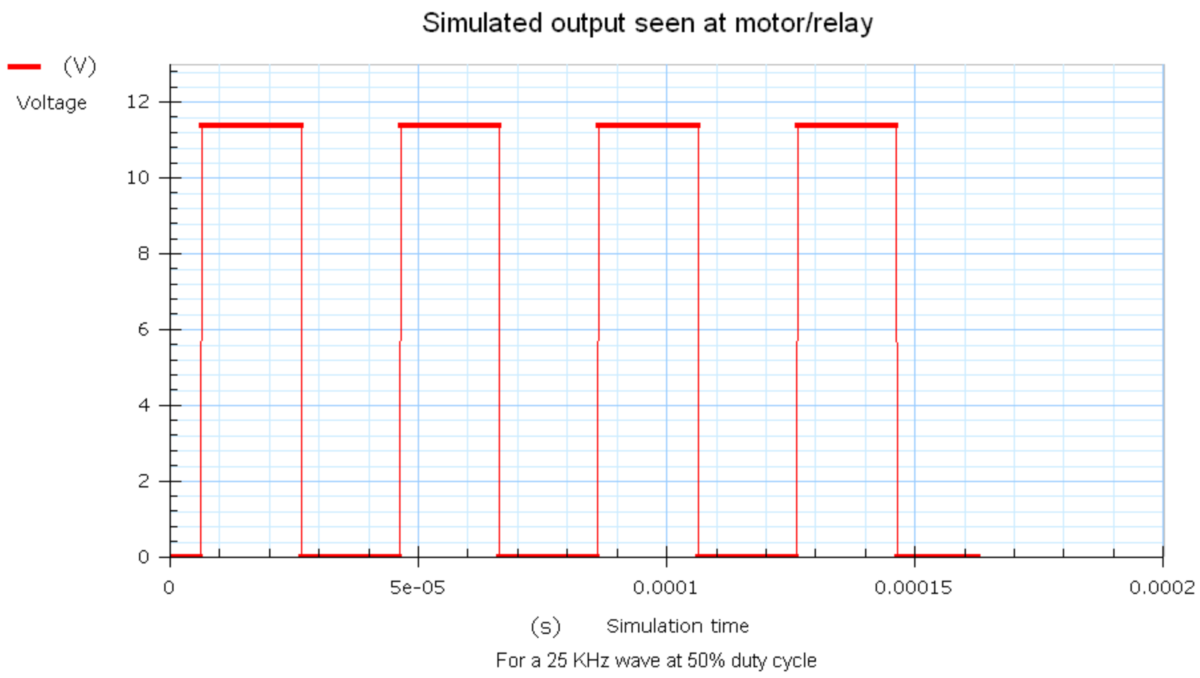

Figure 39 - **The simulated voltage seen at the motor/relay from the MOSFET for a 25 kHz PWM carrier at 50% duty cycle**

The operation and circuitry for this motor controller is very simplistic and the programming for it is equally easy. This motor controller acts in the same way as an automatic drive car, whereby the user (microcontroller program) selects either forward or reverse ('forward/reversed select' on the motor controller), and the speed is controlled by the accelerator ('motor speed control (PWM input)' on the motor controller). The design of this hybrid controller is particularly reliable as there is essentially a built in backup unit.

For example, if in a time sensitive military operation the N channel MOSFET were to fail the user would simply be able to bridge across the MOSFET and cut the motors speed control wire. This operation is shown in the following figure.

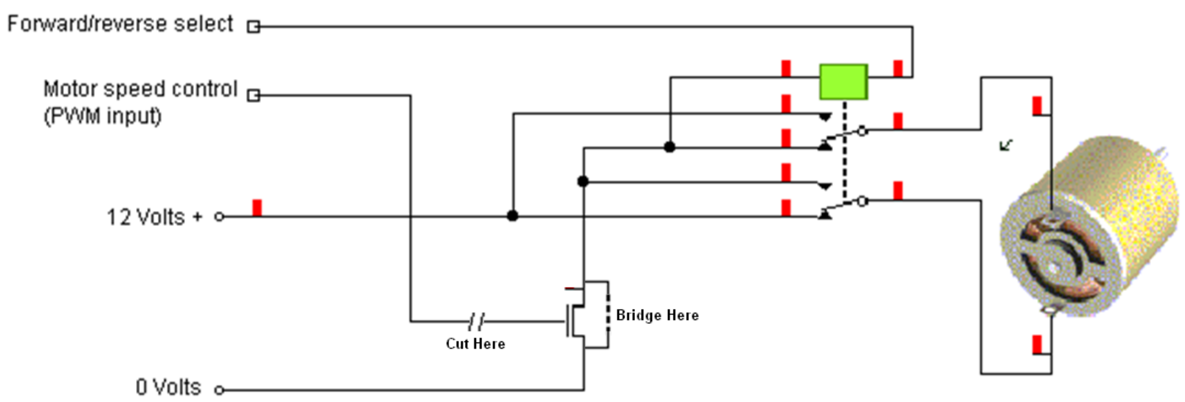

Figure 40 - **Fix to negate a blown/burnt out MOSFET**

This is not an ideal situation, although it would see the robot back in operation, which may be necessary under many cases. This is especially true for a time sensitive military operation or an operation in which there are no spare parts available. This therefore makes this circuit extremely durable and user configurable.

The final concern to be addressed is to do with the longevity of this motor controller circuit. From the data sheets available, we are able to calculate the theoretical life expectancy of this particular circuit. It is assumed that, the MOSFET's as used are capable of handling currents approximately 10 times the amount that is present in the circuit therefore; they will never fail under any ordinary operational condition. This leaves the relay as the only other component in the circuit capable of failing. Since a relay is a mechanical device it is inevitably going to fail at some point. From the datasheet, we see that this relay operating in these conditions is expected to last 50,000,000 cycles. It is noted that there is no current during relay changeover as the MOSFET is turned off and current is only applied once the contacts have made contact. It is switching when current is present, which burns out and shortens the expected life of the relay.

$$\frac{50\ 000\ 000}{number\ of\ switches\ during\ use}$$

To calculate the number of switches during use, we assume that typical battery life is 45 minutes (conservative estimate), and the number of switches from forwards to reverse is approximately 3 per minute.

$$\frac{50\,000\,000}{45\ \times 3} = 370\,370.370$$

Therefore it is expected that the relays should last in excess of 370,000 deployment cycles, which equates to over 277,000 hours of runtime. So therefore this motor control circuit should well and truly out last the rest of the remote reconnaissance vehicle.

4.3 Communications and control systems.

Communication systems allow the vehicle operator to interact with the robot when it is in the field. This may be achieved in a number of possible ways, either through a direct connection or a wireless or radio control link. This communication control system allows the robot's actions such as motion as well as data capture to be controlled. In addition these systems also aim to monitor various activities such as the battery charge, and the monitoring of the program and the microprocessor.

Permitting complete wireless radio control allows the robotic vehicle to be able to operate in many different locations including locations that are hazardous or detrimental to human health. This was a vital component of the radio control system and lead to the development of the following criteria;

- The wireless control system had to have a large range; i.e. a range longer than the video system, and therefore that if a video signal was lost, than the robot would able to be returned safely to video feed distance.
- At least a two channel radio receiver was required, one for left and right and another for forward and backward.
- It had to be easily interfaced to the standard microcontroller used in this project.

Very few communication systems offered all of these features. The two most notable ones include wireless control over a closed WiFi network and radio control with a typical RC model aeroplane controller.

4.3.1 WiFi control.

The first consideration was, with the implementation of a closed WiFi network. A WiFi network is a wireless local area network, which uses high-frequency radio signals to transmit and receive data with an effective range of up to 100 m on the 802.11 protocol.

This wireless network would be incorporated within the system and would allow the robot to maintain a continuous communication link with its operator/s as well as with other robots, which may be operating in the field. Another benefit with using this system would be that captured video imagery and audio would be able to be streamed directly to either the operator or a base station for recording.

This option of control was eliminated due to a number of factors which act to limit its effectiveness. These various factors include;

- With this method of control, a separate computer would have to be integrated into the actual robot itself. With this comes a large number of disadvantages such as the added cost of purchasing a small netbook computer, such as the ASUS EEE pc to be attached permanently to the robot. This in turn brings further complications, especially with its use. This includes the added power consumption (2.1 amps when used in this particular configuration), and all of the added issues with vibration and shocks (which would be encountered during normal operation over rough and undulating terrain) to computer components such as hard drives.
- The WiFi network operates on the 2.4 GHz bandwidth. This may interfere with other external components such as wireless cameras/wireless receivers. It may also be subject to interference from the motor controller.

- Another of the major disadvantages in the implementation of this control system is the fact that all the programming would have to be done in a higher level programming language such as C+ or C++ thereby adding to the complexity of the project overall.

These disadvantages were quite steep and far outweighed all of the possible advantages for the use of this system for control. It is for these reasons that this method of control was removed from consideration.

4.3.2 Radio control.

The second control system option that was considered was standard radio control. Radio control or RC uses radio signals of a medium frequency to remotely control any device. These methods of control are often used on small model vehicles such as model cars, model boats, model helicopters, model planes, etc. to control the vehicle from a hand-held radio transmitter. The range of these radio transmitters is often considerably larger than other methods used for control such as WiFi. Also the handsets for these radio transmitters are considerably easier to use and implement then many other techniques. This makes these methods of control, more suitable for many applications in which remote control is necessary.

The advantages of using this particular technique over the use of WiFi include;

- The receivers and transmitters operate on a lower waveband and use analogue signals, meaning that they are less susceptible to dropouts and often have longer usable ranges then other digital control techniques. For example the particular receiver that was selected operates on the 36 MHz waveband and provides digital proportional control over an analogue carrier.
- Because of the previously discussed transmission method these units have extended ranges often many kilometres or more. For example a receiver that was chosen, has a line of sight range of 5 km and an obstructed range of approximately 3 km.
- Because less processing needs to be undertaken, the response times of these systems are generally quicker than their WiFi counterparts.
- Because the outputs from the radio control receiver are meant to drive servomotors they are easily able to be adapted to be read from the particular microprocessor selected. For

example the microprocessor that was chosen has a function dedicated to this specific task. This makes the programming for these controllers considerably easy in comparison to the high language programming that would be required for the implementation of a WiFi system.

The controller selected, was a spare four channel radio control model aeroplane receiver left over from a previous project. For the motor controller, two of the four channels were used (one for left/right and the other for forwards/reverse). This meant that there were two channels left over, which can be used for other attachments or inputs to the microprocessor. The following figure shows a picture of the radio control unit.

Figure 41 - HITEC radio control unit used for the control of this robotic device

As mentioned previously this radio control system has a range in excess of 5 km. This makes it idealistic for the control of this particular robot. This range also means that if the video feed is lost during operation the robot should easily be within radio control distance, and be able to be reversed directly back until the video feed signal is returned.

4.4 Wireless video.

At the beginning of this project, it was envisaged that the robotic vehicle be a proper reconnaissance device. This meant that a series of wireless video cameras would have to be implemented for the device to be considered a proper reconnaissance vehicle. For the implementation of this wireless surveillance system, a number of considerations were required to be met. These considerations meant that the video system which is to be selected, should be;

- Not on the 2.4 GHz bandwidth as it will/be interfered with by wireless LAN and other AV senders. Also since this bandwidth is common with most security surveillance systems it was avoided. This was in order to prevent unauthorised accessing of the wireless camera by a third party. For a person to access cameras on this particular frequency, all they require is a 2.4 GHz AV receiver/scanner attached to an LCD screen.
- Small and self contained. This was a primary consideration for the head unit/LCD display, a small self-contained LCD screen and battery combination meant that there was less concern with the wiring and external power supply/battery/AC adapter. This was primarily for a matter of convenience
- Battery powered. In the case of the camera, this is necessary, as tethering to an AC outlet would mean that the device was not a true remote semiautonomous vehicle and would severely limit its infield applications. In the case of the LCD handset, this was less of a concern, but still would be a good feature to have.
- Good picture quality
- Good range (~ 100 m)
- Real time (no lag between picture and real-time)
- Common video output. This was especially important for the interfacing between the receiver unit and an external television/video recorder for the likelihood that infield reconnaissance footage would need to be recorded
- Audio preferable. This was especially important for the device to function as a proper reconnaissance vehicle.

The video system that was selected is manufactured by Signet. This system operates on the 5.8 GHz waveband and is capable of receiving up to 4 different video feeds from four different video cameras. The LCD TFT colour monitor selected is manufactured by Response and is a 9 inch 1024 x 768 pixel display. The complete video system is shown in the following figure.

Figure 42 - **Complete video system, ready for implementation**

This system operates on the 5.8 GHz waveband, which means that it will be subject to less interference/pirating than any system operating on the 2.4 GHz waveband. This is due to the fact that wireless surveillance systems operating on the 5.8 GHz waveband are relatively new to the market place and receivers are a lot less common and more expensive. This particular system has a range of approximately hundred metres and provides audio feedback capabilities as well as real time response. All of these factors coupled with its Component AV signal output meant that this system was an ideal selection.

Conclusion

In conclusion, this chapter has covered the details of the technical information upon the selection of the individual mass electrical components used in the construction of the device. This chapter discussed features, such as the selection of motors, motor drive circuitry, the wireless control system and the video circuitry.

In summary, a pair of worm gearbox, 12 V 60 watt electric windscreen wiper motors were selected for the drive motors; a custom hybrid motor controller using relays and MOSFET's was constructed; a 5.8 GHz wireless video system, manufactured by Signet was selected and a 5 km range, radio control unit manufactured by Hitec were the main components selected in this section.

Chapter 5

Power supply

Introduction

The purpose of this chapter is to provide detailed technical information upon the selection of each of the individual power supply components used in the device. This chapter aims to discuss many different features, such as the selection of battery type and size, anticipated runtime of the vehicle as well as the battery monitoring circuitry.

Since the overall size of this robot had been defined in the chassis stage of construction a large number of the individual power supply components were required to fit within this predefined structure, as well as the structures imposed by the electrical components.

5.1 Battery type selection.

The power source forms an integral part of all robotic devices and is essential for providing the electrical energy to the device. Without a sufficient source of power, even the best designed, most elaborate robot would not function correctly or be able to perform all of the tasks required of it to a sufficient level. The source of power can come from many different individual sources such as alternating current through electrical mains/adapters as well as direct current, from batteries and solar panels.

For this robotic device all the power that is required will come from standard chemical batteries. These batteries in general, are rated according to their power output, which is a combination of their voltage output as well as their amps per hour output. For example, a 10.8 V DC 4400 mAH Lithium ion battery pack is capable of supplying 10.8 V DC at 0.44 amps for ten hours or 10.8 volts at 0.22 amps for 20 hours. This equates to a total power output of approximately 48 W hours. The 4400 mAH is nominally a 10 or 20 hour rating and higher current draws will give considerably less battery life than those theoretically calculated with attendant high battery temperatures.

Since batteries often form the weakest link of any remote semiautonomous vehicle. It is best practice to minimise all of the contributing factors to power consumption during the design phase. This minimisation generally leads to a smaller power source and distribution system required to be implemented. This is often a necessity as the batteries and components for the power system are generally the heaviest single components in the robotic design.

The use of 12 V motors predicated the need for a 12 V battery supply. This was quite lucky as there are a number of readily available 12 V power supply batteries and systems available. Also standard car components such as battery level meters and battery charges are able to be implemented with ease. The only downside to using 12 V meant that a voltage regulator system had to be constructed to power the 5 volt microprocessor and radio control unit. As well as a 9 volt system to provide power for the wireless camera. Standard voltage regulator IC's are available for both of these voltages, which meant that the design of these power supply circuits was relatively straightforward.

The regulators that were used are the 7805 and the 7809 for the 5 V and 9 V supplies respectively. Datasheets for these particular ICs are included in appendices G and H.

On the market today, there are a number of different batteries available. For this device, a battery with a native 12 volt output was required with sufficient current capabilities to power the device for at least half an hour. In an ideal situation this battery should also have a very low internal resistance. This is in order to allow it to deliver maximum power and current to the drive motors, without excessive losses. For this device three different battery options were considered. These battery options include;

- **Nickel cadmium (NiCad)**

The basic layout of these types of batteries was first set out in 1899 by Waldmar Jugnaer, but it wasn't until 1947 that the design was perfected. These batteries use Nickel Hydroxide as the positive electrode and a Cadmium Metal and Cadmium Hydroxide for the negative electrode. In these batteries Potassium Hydroxide is generally used as the electrolyte.

These types of batteries are not particularly fussy as to their orientation this therefore makes them ideal candidates for mounting anywhere within the vehicular device. This feature is why they are typically used as a power source in many applications such as portable equipment, cordless power tools as well as portable vacuum cleaners and torches. This makes the procurement of these batteries relatively easy as many places, such as hardware stores have replacement batteries for these devices, enabling them to be easily integrated into the robot.

One of the main problems with the Nickel Cadmium batteries is that they do exhibit a memory effect. This means that they are not suitable for applications, which involve shallow cycling or constant float charging. Since the end use of this robot is likely to see it sitting constantly on a float charger means that these batteries will not be suitable. Also, these batteries have a comparatively higher self discharge rate than either of the other options. Typically 10% in the first 24 hours after charging then approximately 10% per month, also the self discharging is exacerbated with temperature rise doubling for each 10°C rise.

- **Nickel Metal Hydride (NiMH)**

Nickel metal hydride batteries, use similar principles to NiCad batteries. The same Nickel Hydroxide is used as the positive electrode and Potassium Hydroxide as the primary electrolyte, the primary difference is in the negative electrode. This negative electrode is generally formed from a Hydrogen storing alloy, such as Lanthanium Nickel or Zirconium Nickel.

These Nickel Metal Hydride batteries have the comparatively highest energy density as opposed to both Sealed Lead Acid and Nickel Cadmium batteries. These batteries also demonstrate some memory effect, although not to the extent of NiCad's. These batteries are also more expensive, will not handle deep discharge cycles and often have considerably shorter working life than both NiCad's and sealed lead acid batteries. Also the correct charging of the batteries requires a very complicated and expensive charger to ensure that they are not overcharged or charged so quick as to catch fire.

Another major disadvantage is that they exhibit a higher self discharge rate than NiCad and a significantly higher discharge rate than Sealed Lead Acid batteries. Even with all of these major disadvantages these batteries commonly see use in many robotic projects, although they will not be considered further for this project.

- **Sealed Lead Acid battery (SLA)**

Sealed Lead Acid batteries were the second type of battery available preceeded only by the familiar flooded Lead Acid battery typically used and referred to as a car battery. Sealed Lead Acid batteries were developed more than 150 years ago by Gaston Plante a French experimental physician.

These types of batteries have a positive Lead Oxide electrode, a negative porous metallic lead electrode and used a gel type of Sulphuric Acid as the primary electrolyte. Since the electrolyte is in gel form, no water or other liquid is lost during the discharge and recharge cycles meaning that the battery is able to be sealed. These batteries require no maintenance and are able to be used in any position, which makes their implementation ideal for this robot.

Sealed lead acid batteries have the lowest power densities of all of the batteries considered. This means that for a battery of a given power output, it is likely to be slightly larger and heavier than any of the other batteries available. In this case, this was not a large disadvantage, as, with proper battery placement, this could indeed become a great advantage. This is discussed further in the battery placement section.

There were three main advantages which led to the implementation of this battery type for this project. These advantages include;

- These batteries are considerably cheaper than any of the other battery types considered. This means that for a given price, a larger, higher capacity battery could be purchased with the only disadvantage being the added weight.
- Of all of the battery types considered Sealed Lead Acid batteries have the lowest rate of self discharge. Approximately 5% per month. These batteries also do not suffer from any form of memory effect, such as that displayed by NiCad's and NiMH's making them ideal for both deep and shallow cycling.
- These batteries perform best under both deep and shallow cycling. This means that regardless of how the robot is used, no battery damage will occur. Also these types of batteries are able to be float charged, which means that they are able to stay connected to a charger of the appropriate voltage indefinitely. This means that the robot would be able to be permanently connected to its charger when not in use, thereby keeping the battery fully charged at all times.

All of these advantages well and truly outweighed any of the perceived disadvantages and lead to the choice of Sealed Lead Acid batteries for the power supply system for this robotic vehicle. The following figure shows a picture of the battery which was selected for this project.

Figure 43 - **Century 12 V, 7 Ah battery that was selected for this project.**

The battery which was selected is manufactured by Century and is a PS series 12 V 7.0 Ah Sealed Lead Acid Battery. This battery comes with a five-year warranty and is of the valve regulated type. In operation, it is expected that this battery will last between 400 and 1 000 charge cycles depending of course upon how deeply it is cycled.

5.2 Battery placement.

In chapter 3, Selection of mechanical components, the importance of having a properly balanced robotic tracked vehicle was thoroughly discussed. With reference to the following figure, It was determined that the most efficient track configuration was slightly shorter than the maximum length allowable. To facilitate easier turns, and therefore maximise efficiency, it was concluded that the majority of the weight should be concentrated about the centre point of the vehicle.

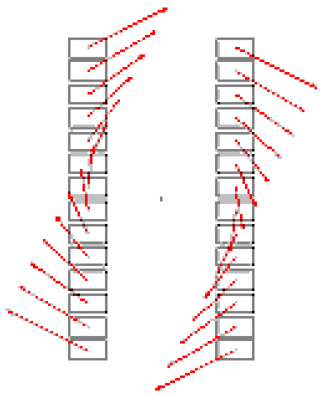

Figure 44 - **Track movement through a neutral turn (Robabaugh 1995)**

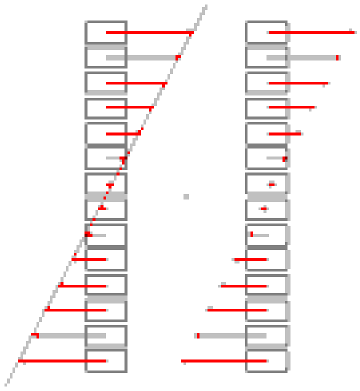

Figure 45 - **Frictional forces to be overcome for above turn (Robabaugh 1995)**

Since the batteries are the heaviest single component in the device, their placement has the greatest effect on the weight distribution and balance of the robot. For example if the battery was placed too far forwards or backwards, then the device would have trouble turning as the frictional forces to be overcome, would be a lot higher than necessary. This would also lead to increased wear on the tracks and increased damage to the surface upon which the vehicle is driving. Therefore, it is idealistic for the battery to be placed as close as possible to the vehicle's centre and centre of gravity.

This is an ideal situation, and one which was replicated and implemented within reason for this robot. The placement of this battery was a primary design consideration which had been kept in mind throughout the duration of the project. The following figure shows the battery in its final position, just slightly back of the centre of the robot.

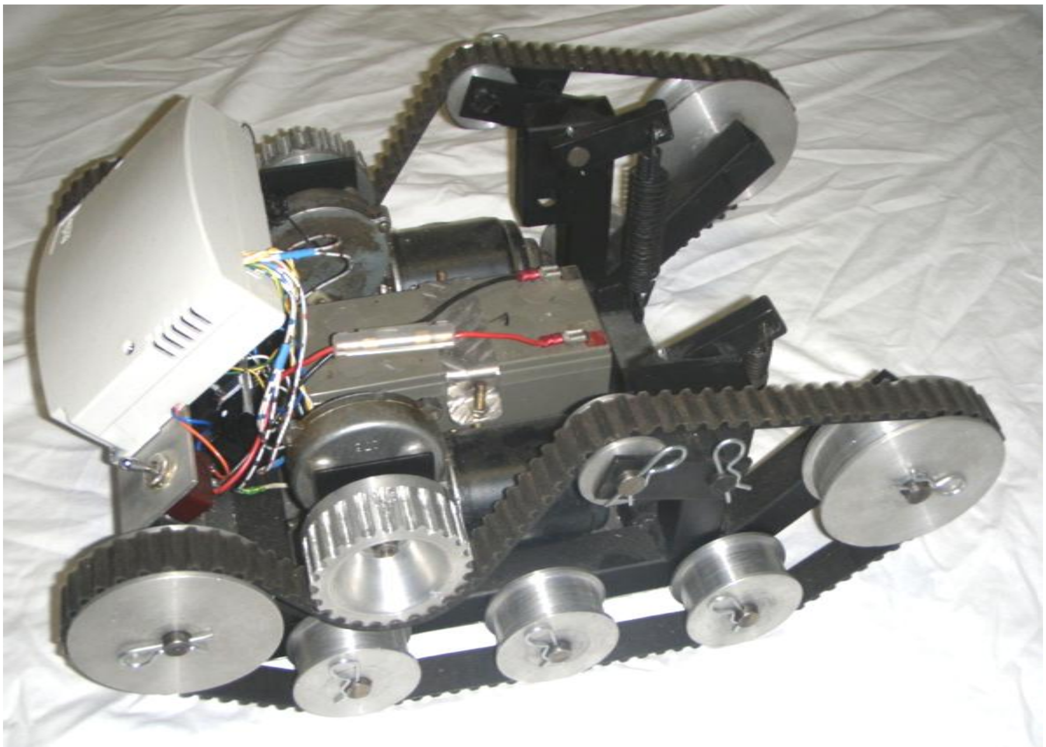

Figure 46 - **Showing the placement of the battery in relation to the motors and chassis**

The battery was placed slightly back of the centre of the robot to counter the weight of the front pulleys as well as to slightly lighten the front of the robot to enable it to climb movable obstacles, easily. In practice this tended to be quite an advantage as the robot is easily able to climb up obstacles which are considerably higher than the front pulleys (such as stairs, bricks and boxes).

5.3 Battery monitoring.

For this device with this type of battery, monitoring of the battery charge level is very important to ensure that, at no point the battery voltage drops below a level which will cause irreparable damage to the battery. There were a couple of different techniques considered for this monitoring such as monitoring the battery level with the microprocessor, and having an override for when the battery level drops below a certain point. Using this technique would be rather annoying from an operator standpoint as there would be no pre-warning method for the user to be able to drive the robot out of a hazardous location.

The other method that was considered and ultimately implemented was the use of a battery level monitor. In this case the battery level monitor kit that was selected is produced by Jaycar Electronics and is based on the LM3914 LED display driver integrated circuit. This kit uses 10 regular LEDs to indicate the voltage of the battery. The following figure shows the completed circuit as implemented.

Figure 47 - **Battery level monitor, Jaycar kit KA1683 constructed and ready to be implemented**

This particular battery monitor continuously measures the voltage at the battery and displays the level by illuminating a single LED. In operation, the closer the illuminated green LED is to the red LED, the higher the battery charge, and conversely, should any of the yellow LEDs become illuminated when the device is stationary, this indicates that the battery should be charged. Another important feature is that if the red LED becomes illuminated at any point that means that an overvoltage condition is present, and should be rectified immediately, otherwise battery damage is likely to occur.

The positioning of this battery monitor was very important, as it had to be placed in a spot which is easily able to be seen. It was therefore decided that the best spot, would be at the front of the vehicle mounted rigidly in a position so as not to block the view of the wireless camera but to be able to be seen by the wireless camera. The following figure shows, both a picture of the device showing the mounting and a screen capture from the LCD hand-held display.

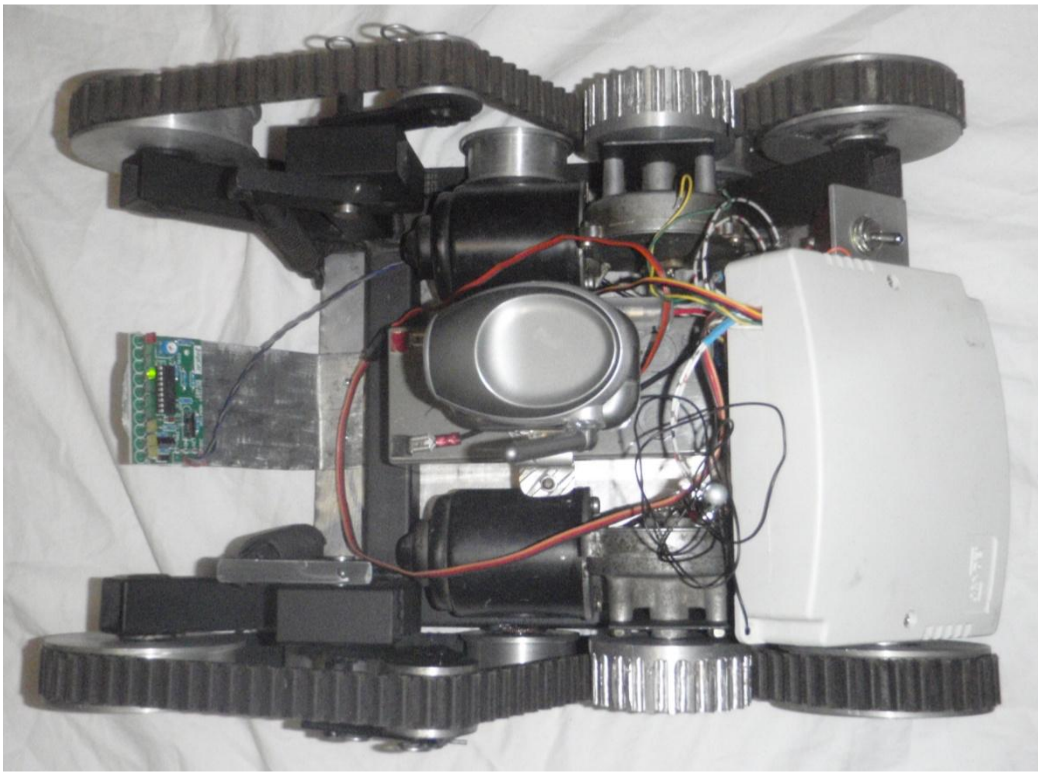

Figure 48 - **Picture showing the mounting location of the battery monitor**

Figure 49 - **Screen capture of the handheld display showing the heads up display**

This mounting configuration was considered ideal as it forms a typical heads up display common in many applications. Mounting in this location would be familiar to many people, especially people who have played any form of computer game before, where this position is typical of health, life or strength bars. In many of these people is almost instinctive that, should any of the yellow LEDs illuminate when stationary, something is wrong and the remaining charge of the battery is low.

Conclusion

In conclusion, this chapter has covered the details of the technical information upon the selection of the individual power supply components used in the construction of the device. This chapter discussed features, such as the selection of the batteries, the battery placement, and the monitoring of the battery levels.

In summary, a 12 V, 7 Ah PS Series sealed lead acid battery manufactured by Century was selected for the primary power source; it was decided that the best placement of the battery was slightly back of the centre of gravity to enable the robot to traverse steep terrain with ease; and an LM3914 LED display driver integrated circuit based kit produced by Jaycar Electronics, KA1683, would be used to monitor the battery levels during operation.

Chapter 6

Electronic control selection

Introduction

The purpose of this chapter is to provide detailed technical information and specifications upon the selection of each of the individual electronic control components used in the device. This chapter aims to discuss many different features, such as the selection of guidelines for the design, the microcontroller selection as well as a description of the microcontroller, operational code descriptions and the actual implemented program.

Since the overall size, shape, power supply and motor controller components of the robot have been defined previously, the electronic microcontroller and its components were required to fit within these structures. In addition the microcontroller also has to interface to these electrical components.

6.1 General guidelines of the microcontroller system.

The microcontroller system that will be explored in this chapter will be based around the use of the previously selected standard hobby radio control system. The only outputs from the selected receiver are in the form of standard servo commands for driving typical hobby servo motors. Two channels of the receiver are used to control locomotion of this vehicle. One of these two channels controls the left and right direction, and the other channel controls forwards and reverse.

Another consideration for the microprocessor is that it be able to accept inputs from various different sensors, such as ultrasonic transducers, light sensors, distance sensors, compasses, global positioning systems, etc. This is an important consideration especially if the robot is to be used in a semiautonomous or fully autonomous mode at a later stage in its development. Further consideration was given to the implementation of a series of tilt sensors/tilt switches, which would act to prevent the robot from tilting at such an angle as to cause it to roll over. This system would be highly important especially if the robot was going to be used in a hazardous, toxic or irradiated area, where its incapacitation due to roll over would be quite dangerous.

Since this device was only going to be used in an experimental capacity, no external sensors were added. This also greatly reduced the amount of programming and the subsequent microcontroller processing power required. In this case, the two channels of the radio control system were connected to a PICAXE 18 X microcontroller project board. The interfacing and operation of this system are further described below. Simply put, the microcontroller reads the signals from the radio control receiver and interprets them into the correct signals required by the motor controller.

6.2 Microcontroller selection and description.

PICAXE microcontrollers follow the standard ISO integrated circuit patterns. This means that these chips are able to be placed in standard size receiver sockets. The following figure shows, a pictorial representation of both the 18 and 24 pin units.

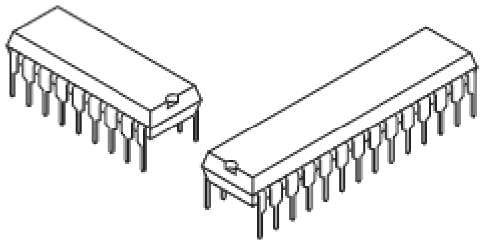

Figure 50 - **18 and 28 pin PICAXE integrated circuit microcontrollers. (Revolution education - PICAXE 2009)**

These configurations are two of the four pin out configuration of these microprocessors, with the other two having 8 and 40 pins. There is also a 20 pin version available, but it is a microcomputer and well and truly above the scope of this project. These four categories of pin out configurations are then further subdivided into different families. For example, the 18 pin variety has four members in its subcategory, which are the; 18 (discontinued), 18 A (recently discontinued), 18 X (preferred component) and 18 M (recently introduced).

Each of these four different members exhibits different properties, such as number of configurable ports, amount of internal flash memory, number of analogue to digital converters , etc with the 18 M being the most advanced and powerful component in the family. A complete list of the PICAXE components as well as their schematics and pin labels is outlined in appendix I.

This particular microcontroller was selected over the variety of other microcontrollers such as the ATMEL AVR or the Motorolla MC68HC11/12 as these microcontrollers are very difficult to implement and program for. Also, many of these other microcontrollers require external components such as a resonator in order to operate. The PICAXE system, which was chosen, does not require any external components as it has all of the components built into the chip. In addition, the programming for the PICAXE system is easily done by a standard computer serial port or with a USB to serial adapter.

6.3 Operation of PICAXE microcontroller system.

PICAXE microcontrollers act as a complete miniature single chip computer. All of the chips in the range have sufficient integrated memory to hold a fair sized program, as well as all of the variables used by the processor. The memory that is used in these chips is the same as the memory used in USB jump drives as well as solid-state drives and is known as flash memory. Flash memory is a non-volatile form of storage which retains its written data, regardless of the power state. This form of memory is able to be electrically erased and reprogrammed typically in excess of 100,000 times.

The normal operating speed of these processors is 4 MHz, although they are capable of being overclocked to either 8 MHz or even 16 MHz, and there is a function prewritten into code specifically for this task. It is to be noted that in this project, this overclocking function will not be used as the overclocking function, affects all aspects of the microprocessors operation. This means that microprocessor would not be able to interface using a standard command to the radio control unit.

The PICAXE system uses a simple BASIC language with a number of predefined functions. This makes this microprocessor a lot easier to learn, implement and debug than a lot of other microprocessors which use high-level languages such as C and Assembler. Also, unlike most other microprocessor systems, all BASIC programming operates at the chip level. This means that there is no Assembler required, and there is no need for the purchasing of a complex preassembled surface mount module with the microprocessor contained within, such as is the case for the MC68HC11 system. The PICAXE system is a single chip, which is purchased and plugged directly into a project prototyping board or breadboard or strip board etc.

This system is very powerful as it requires no programmer, eraser or other complicated electronic interface system. The microcontroller is programmed directly via a 3 wire connection to the serial port of the computer. In addition to the PICAXE, two other components are required; these additional components are a 10 K and 22K resistor. The following figure shows the basic outline of the programming circuit.

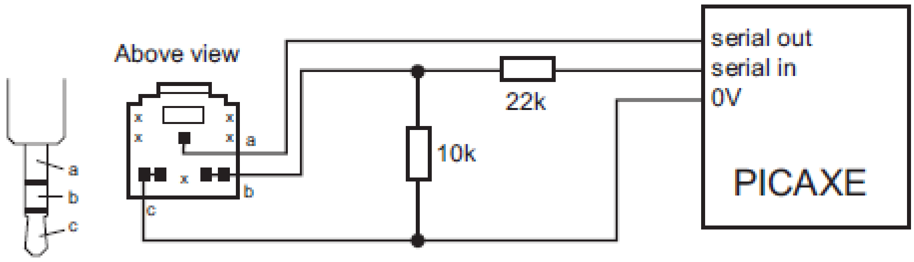

Figure 51 - **Basic outline of the programming circuit (Revolution education - PICAXE 2009)**

The above programming circuit is able to be left connected to the PICAXE at all times. This means that the PICAXE never has to leave the project board, and is therefore less susceptible to leg damage. This leg damage is common with other systems where the chip has to be removed from the project board to a separate programming board for programming.

6.4 Construction of the microcontroller system.

The PICAXE chip used in the initial model is of the 18 X variety. The PICAXE 18 X has 18 pins, memory space for 600 lines of code 14 dual-purpose input or output pins (nine outputs, five inputs), three analogue to digital converter channels and supports the i2C interface(not used). This chip was selected as it will easily fulfil all the functions required of it as well as provide the user with options for further developments, such as the addition of sensors to the analogue to digital converter inputs and attachments to the other outputs.

The circuit board used is a custom manufactured standard project board, produced by Revolution Education. This board was selected, as it was easily available and has an integrated Darlington driver IC. This was an important feature, as it allowed the PICAXE project board to be directly connected to the motor controller. The following figure shows a picture of the project board without the PICAXE inserted.

Figure 52 - **Image of the actual project board, produced by Revolution education**

This project board is powered by the previously mentioned 5 V, 7805 regulator with the negative and positive being connected to their respective terminals on the board (lower middle left in figure. The power terminals (lower middle right in figure) on the project board are connected to the 12 V DC supply in order to control the relays.

The serial programming/interfacing cable is connected via the stereo socket towards the top right-hand side of the project board. The serial programmer interfacing cable enables software on the computer to download programs into the memory of the PICAXE. Through debugging and general program testing the serial interfacing cable is able to be left connected, thereby enabling quick program changes.

Once all of the power connections had been made, a simple program was written to ensure that the PICAXE was working. This program simply flashed a series of LEDs that were connected to the outputs intended to be used for this device. These particular outputs are listed in the following table. This table shows the title of each connection, what it is connected to, the data direction, and the PICAXE pin that it is connected to.

Table 11 – **PICAXE hardware connection table**

Connection title	Connected to	Input/output requirement	PICAXE pin connected
Master power for motors	Motor controller, master relay	Output	Output pin 0
Left-hand drive motor forward/reverse select	Motor controller, left side relay	Output	Output pin 7
Right-hand drive motor forward/reverse select	Motor controller, right side relay	Output	Output pin 6
Left-hand drive motor pulse width modulation circuit	Motor controller left side MOSFET	Output	Output pin 1
Right-hand drive motor pulse width modulation circuit	Motor controller right side MOSFET	Output	Output pin 2
Forwards/reverse channel from RC receiver	Connected to servo output one on RC receiver	Input	Input pin 1
Left/right channel from RC receiver	Connected to servo output two on RC receiver	Input	Input pin 2

The following figure shows the PICAXE 18 X chip. It is seen that from the table above outputs 0, 1, 2, 6, 7 are used, which correspond to physical PICAXE pins 6, 7, 8, 12, 13 respectively. Additionally, the inputs 1 and 2 are connected to physical pins 18 and 1 respectively. It is noted that in this configuration, both of these input pins are used in ‘digital only’ mode, meaning that the only inputs that they register are digital ones.

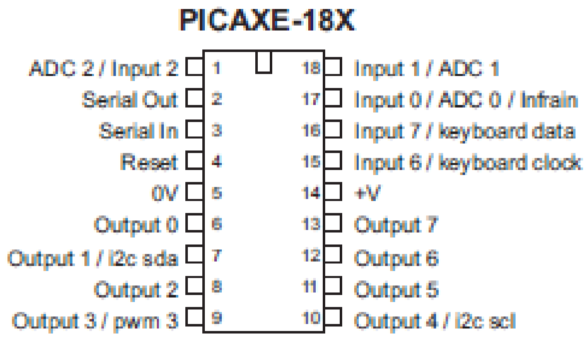

Figure 53 - Pin out diagram of the PICAXE 18 X used (Revolution education - PICAXE 2009)

When it is all connected properly the microcontroller reads in the two values from the radio control receiver, compares the two values against a table of known values, which in turn determines a direction in which the device is to move. Once this is determined a control algorithm outputs the correct signals to the motor controller, which moves the device in the direction intended. Thereby achieving complete radio control of the vehicular robotic device.

6.5 Programming of the microcontroller system.

After the initial connection and primary functional tests, the actual programming of the chip could begin. All of the programming for the PICAXE was undertaken using the manufacturer supplied program, Revolution Education Pickaxe Programming Editor, Version 5.2 .7. As mentioned previously, the PICAXE system uses its own in-house version of BASIC operating commands. There are approximately 170 different BASIC commands, which are valid for this microprocessor system. For the programming of this device, eight different commands were used. These are described further in the following section.

6.5.1 Description of the microcontroller program.

The first PICAXE programming approach was to develop a program which would fulfil all of the tasks which were required. These tasks were to read the outputs from the radio control receiver and interpret them into valid speed and direction signals which would be recognised by the motor controllers. Once this interpretation was complete, the microprocessor is then to output the generated signals to their respective motor controller which, in turn causes the device to move in the desired direction. The program is able to be found, in full, in Appendix J.

The main function of the program resides within the *main* loop. Essentially, this loop reads the radio control signal using the *PULSE IN* command, and then determines in which direction the robot is required to travel then activates the required outputs. This loop is then repeated indefinitely, while the robot has power.

The main function of this loop is the pulse in command. The pulse in command, *PULSIN,* is a command specifically for measuring the length of an input pulse. For example, if no pulse occurs within the specified timeout period, a value of zero will be returned to the wordvariable. This command is able to function, in two specific states; if the common state is always on, then a low to high transition will begin the timing period, whereas if the state is always off then a high to low transition will start the timing period.

This command is typically used for reading the outputs from a servo mechanism controller. The exact position of the controlling joystick is able to be calculated according to the value from the pulse in command. In this system the pulse in command was read on input pins one and two using the low to high transition for the commencement of timing and the value was saved into wordvariables B1 and B2.

The following table outlines the correspondence between each of the wordvariables read from each channel of the radio control receiver, the direction of the joystick on the radio control receiver and the motor controller output from the PICAXE.

Table 12 – Correspondence between wordvariables, joystick position and motor controller output

Wordvariables versus microcontroller output			
B1	**B2**	**Joystick position**	**Motor controller output**
>150	150	Forwards centre	Both motors forward
>150	>150	Right centre (forwards)	Left motor forward right motor stopped
>150	<150	Left-centre (forwards)	Right motor forward left motor stopped
150	150	Centre	Device stopped
<150	>150	Right centre (reverse)	Left motor reverse right motor stopped
<150	<150	Left-centre (reverse)	Right motor reverse left motor stopped
<150	150	Reverse centre	Both motors reverse

This then set up a framework for the program with all of the decisions being made by *if... then... else...* statements. For example;

```
pulsin 1,1,b1 ; reads the radio control receiver forwards/reverse channel
pulsin 2,1,b2 ; reads the radio control receiver left/right channel

; Determine whether device is to drive forwards, reverse or stop
; b4 = 1 for forwards; 0 for stopped; 2 for reverse

if b1>165 then
b4=1
elseif b1<135 then
b4=2
else
b4=0
endif

; Determine whether joystick is centre, left or right.
; b5 = 1 for Right; 0 for stopped; 2 for left

if b2>165 then
b5=1
```

```
elseif b2<135 then
b5=2
else
b5=0
endif

; For stopped right rotation condition

if b4 =0 and b5 = 1 then
low 1
high 2
low 6
low 7
...... Continued elsewhere ........
```

This extract of the code reads the radio controller output, determines exactly in which of the nine possible positions joystick is in and then activates the appropriate outputs to cause the robot to travel in that direction. In this example, if the joystick was in the centre-right condition, then b1 = 150 and b2 = >150 which means that b4 = 0 and b5 = 1 thereby causing the device to stop the right motor and rotate the left side motor forwards thereby turning the device to the right.

It is noted that in this code, the exact values of 150 were not used; instead a range of ±15 was used. This was done in order to reduce the sensitivity of the system. In practice this appeared to work quite well, leading to no false triggering of the system due to interference.

The author is aware that the program that was used is not the most efficient or smallest but it does fulfil the requirements and what it lacks in efficiency it more than makes up for in simplicity. Also, this inefficiency adds a vital time delay to the program, this time delay acts to slow the response of the system to even out any inconsistencies in the radio control signal. It also stops the forward/reverse relays from incessantly switching when the forward/reverse signal reaches the reverse threshold.

6.6 Evaluation of the microcontroller system.

This model system utilising the PICAXE microcontroller proved to be very effective and therefore required no further development once the system had been implemented. This system has performed flawlessly throughout all of the rigorous tests and harsh conditions it has been subject to. However, it was not possible to test the system's response to the infinite array of operating conditions that it is likely to see during real world operations. Further encapsulation and isolation of the electrical components will ensure long-lasting operation, especially under all sorts of hazardous and toxic operating conditions.

For this device to go into large-scale production, it is envisaged that the microprocessor, as well as the radio control receiver would be implemented into a single, sealed, easily replaceable monolithic block. This is to prevent the hazards posed by foreign matter, and to reduce the effects of vibration, heat, dust and sunlight.

Conclusion.

In conclusion, this chapter has covered the details of the technical information upon the selection of the individual electronic control components used in the construction of the device. This chapter discussed many different features, such as the selection of guidelines for the design, the microcontroller selection as well as a description of the microcontroller, operational code and the actual implemented program.

In summary, a PICAXE 18 X was selected for the microcontroller. This was then placed into a Revolution Education project board, which was, in turn connected to all of the various inputs and outputs. Then a simple program was written to decipher the signals from the radio control unit and turn them into valid speed and direction signals for the motor controllers.

Chapter 7

Testing and verification

Introduction

The purpose of this chapter is to provide information upon the rigourous testing, which the robot has undergone to prove its value as a remote reconnaissance vehicle. This chapter aims to discuss many of the different tests that the device underwent. These tests included, angular forward and angular sidewards incline tests, the devices ability to traverse crevices as well as battery life tests and general expected field performance.

All of the tests conducted were all valid as they described how the device could be expected to perform in the field. It is to be noted that these tests are only indicative of the robots performance and are in no way conclusive as it would be impossible to predict and simulate all of the conditions in which this robot is to be operated.

7.1 Foreword

The final objectives of this project were to investigate, construct and evaluate a radio controlled inspection vehicle. Since all of the objectives as outlined previously, are performance based no specific data was obtained. Had this project implemented a compass or a GPS system or other autonomous operation, then specific data on headings and bearings would be of importance to the evaluation of this project. The only measure and assessment of the robot's actual performance is simple 'yes' or 'no' observations. However, the performance of this device is able to be broken down into the three main components, which constitute the device. These main components are the mechanical system, the electrical and power system and finally, the microcontroller. This chapter, firstly, provides information on the performance of each individual aspect, and then considers the device as a whole.

7.2 Mechanical system.

The mechanical system as a whole performed more than adequately throughout the duration of this project. It is therefore expected that the mechanical system will well and truly out last the remainder of the robot. Before the commercialisation of this system a couple of design changes will need to be implemented, although these are outlined further below.

7.2.1 Chassis.

In terms of the construction and durability, the chassis had absolutely no trouble at all dealing with the hundreds of hours of abuse, which it received during testing and proving. All in all there are no foreseeable issues arising with the preliminary design and construction techniques used. The chassis easily met all of the design criteria and easily facilitated the rigid mounting of all of the components.

The major problem from the chassis point of view and an overall limiting factor was in its design. In a fully fledged commercial version of this system it would be highly desirable that the ground clearance be increased from its present value of 18 mm to at least a substantial 50 mm or more. This will greatly aid the performance characteristics as the bottoming out of the chassis hindered a lot of the tests.

Another design feature, which will have to be changed, is the bar which currently resides at the back of the chassis. This bar would have to be moved forward, as presently it hits the ground when climbing an incline or traversing a crevice. More than once this bar and got caught on an obstacle and thereby immobilising the vehicle as it held the rear of the tracks off the ground. Although in many cases, a good operator will be able to overcome this by traversing at an angle or with speed.

7.2.2 Track layout.

The track layout proved to be equally effective as a method of locomotion to this device. The differential drive method of steering performed flawlessly, and easily completed all of the tasks asked of it. The use of automotive timing belts as tracks in this revolutionary design and layout proved to be highly successful as there were no serious issues encountered with the design, build or implementation of this technique.

For future iterations of this device, it would however be advisable that the idlers and pulleys are manufactured from a lighter material or the existing design be modified in order to reduce the weight. The only major downside to reducing the weight is that some of the traction would be lost. But since, the device is easily able to push its own weight, plus many kilograms more on carpet; this is not envisaged as a major issue.

The only other implementation consideration would be with the use of wider tracks. These wider tracks would aid in improving the robots performance characteristics, especially in the incline slope tests as well as the weight push test. The range of track widths available however, is limited by the availability of appropriate automotive timing belts. Under some cases it may be necessary to have the tracks custom-built.

7.3 Electrical system and power supply.

This subsystem as a whole operated an integrated really well with the rest of the chassis, and it is expected that this system will last, in its current configuration, a considerable time. But, as previously, before the commercialisation of this project, a couple of design and implementation changes will need to be made in order to improve the functionality of this robot.

7.3.1 Electrical system.

The Electrical system performed more than adequately under all of the test conditions. The motors which were selected were a good match for the size and weight of this device. The only downside with these motors was their slow speed of revolution. This is not easily fixed as it is dictated by the integrated worm drive gearbox. This means that the only way to change this would be to completely redesign the drive system, implementing slightly faster motors with better, higher ratio gearboxes.

In general, all the cabling that was used in the device was of a high standard required no attention throughout the duration of this project. Also of a high standard were all of the switches that were used; having an expected life of more than 10 million operations. All of the switches that formed main components were suitable for use in the industrial sector and are able to withstand sustained vibration and dust inclusion, additionally, they are UV protected.

The addition of the Jaycar battery monitoring kit was a welcome one. This is as this simple addition, under many circumstances, proved to be quite useful, especially in determining the charge state of the battery when the device is being operated remotely. Additionally, it's layout as a heads up display in full view of the LCD was highly useful.

7.3.2 Power supply system.

The power supply system and the battery that was chosen for this device performed adequately, under all of the test conditions. The battery life of the device was considerably longer than expected, in excess of 1.5 hours as opposed to the 45 minutes that was predicted. This battery may have had a slightly higher power output than the amount that was listed. Also, the implementation of pulse width modulation, as well as the low energy consumption motor controller may have had something to do with this extended battery life. The next generation of this vehicle may implement a better battery system, such as the use of NiCad's or Lithium ion batteries as they will act to reduce the weight of the device, thereby increasing the battery life even further.

7.4 Microcontroller system.

This is the single most system on the robot capable of more adaption and further development. Although the system as a whole performed all of the tasks which were asked of it, it is a fairly clumsy system and could easily be improved with the implementation of better programming and the addition of more functionality. This extra functionality could be in the form of second functions on the remote, the addition of a counter rotation subroutine to make a device turn on the spot as well as the implementation of full pulse width modulation.

As a complete system, the motor controller performed flawlessly and is easily up scalable to future projects especially in the control of large DC motors. The only slight downside to the system is a mechanical clicking of the relays as they change over, although in field operation this proved not to be an issue. Both the radio control and video systems worked exactly as predicted, providing complete control/video feeds under all of the circumstances in which they were designed to be used.

7.5 Test performance.

All of the following tests were carried out on the device using quantitative measures. This means that all the tests were based on yes/no, pass/fail situations. For example, the angular test performance was based on whether or not, the device stayed on the slope and was able to drive around controllably. This form of testing is based and aimed towards determining the devices actual infield performance. All the tests were performed on a medium to low friction surface, intended to replicate worst-case scenarios. A lot of the results which were gathered seemed very surprising, often surpassing the expected performance characteristics.

The results of each test are shown in tabular form and comprised of three categories, the expected results, the actual performance that was obtained and the maximum actual performance. It is important that we define the significance of each of these results.

Expected results

- The expected results were not calculated and are based on the authors' previous experience with track based vehicles. These expected results were defined early on in the design phase of the project and are generally fairly meaningless and only provided starting points for the tests.

The actual performance results

- These results are the actual results received from the testing of the device, when the device is in complete control and capable of all functions including steering. In general, these results provide a safe margin of error and are only guidelines for any results expected in the field. This is because all of the testing was done on a low to medium friction surface, whereas the device is likely to see use on a multitude of higher friction surfaces including concrete, dirt, gravels, mud, grass, etc.

Maximum actual performance

- These results, like above are derived from actual testing, where the device is driven until it either breaks traction and slides or cannot successfully meet the objectives of the test.

7.6 Angular forward test.

This is a very important test, as it outlines the slope climbing abilities of this robot. This test was set up and conducted as per the following figure. Except in place of the solid woodblock an adjustable block was used so that the angle could be changed accordingly.

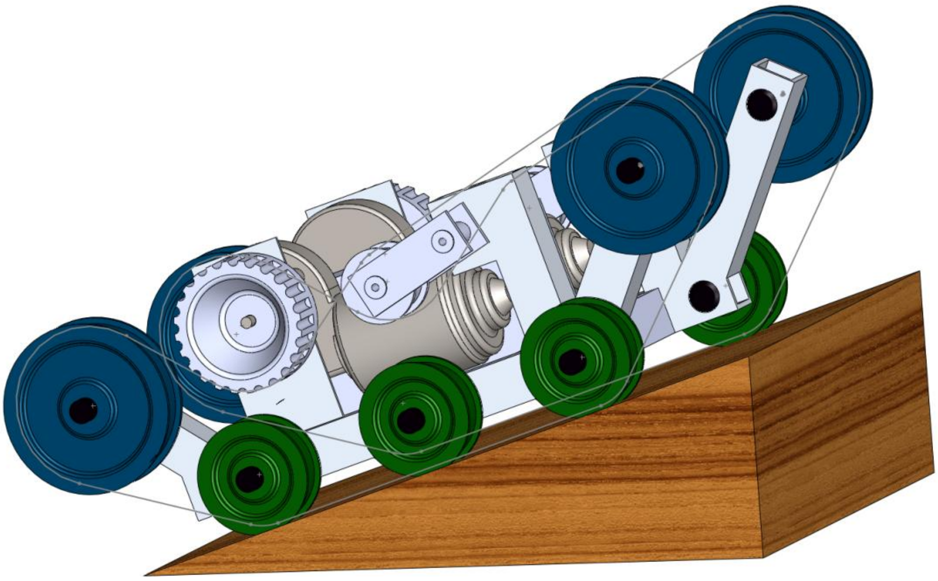

Figure 54 - **Angular forward incline test**

Table 13 - **Angular forward incline test results**

Angular forward incline test results			
Expected performance	**Actual performance**	**Maximum actual performance**	**Comments**
15 -20 degrees	25° with full control	Breaks traction and start sliding at 35°	The performance in this test was considerably better than expected

In this test, the device started at the base of the woodblock and in order to fill the requirements, the device had to be able to drive all the way up the woodblock turn around and drive back without failing or sliding. The actual performance which was obtained is significantly higher than the expected performance outlined this is due to the fact that the expected performance was outlined during the design phase of the project. But during the construction phase the device gained a significant increase in weight not considered during the design and planning phase. This extra weight aided in providing traction especially on both of the incline tests and the push test.

7.7 Angular sidewards test.

This is an equally important test as it outlines the slope traversing abilities and limitations of the reconnaissance vehicle. Slopes as such as these will undoubtedly be encountered in all aspects of its operation. For example in the inspection of stormwater pipes, where it would not be desirable to drive directly down the lowest portion of the pipe, as it is likely to be damp/mouldy/slimy, etc. This test was carried out as per the following figure using the same set up as previously.

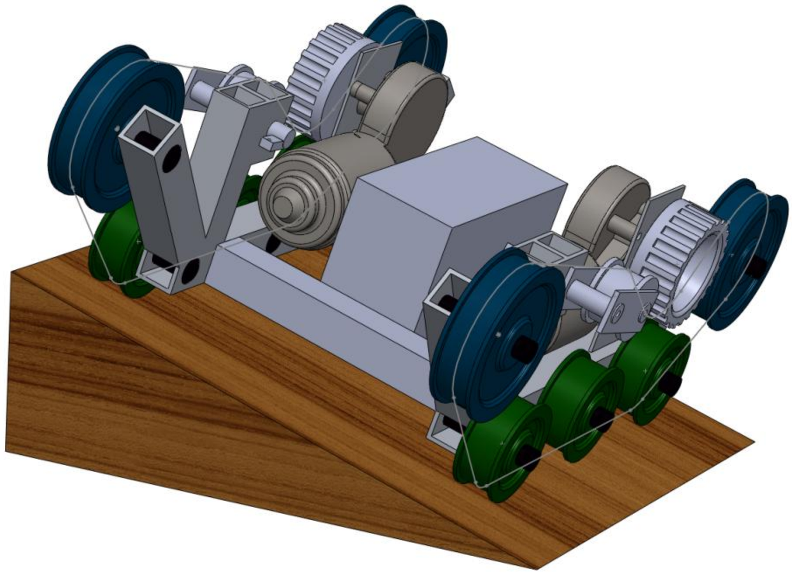

Figure 55 - **Angular sidewards incline test**

Table 14 - Angular sidewards incline test results

Angular sidewards incline test results			
Expected performance	**Actual performance**	**Maximum actual performance**	**Comments**
25 -30 degrees	32° with full control	Breaks traction and start sliding at 36°	The performance in this test was moderately better than expected

In this test, the device started upon the woodblock, and in order to successfully fulfil the requirements, the device had to drive straight along the slope, turnaround and return without sliding, rolling or falling. The actual performance which was obtained is moderately better than the expected performance. This performance increase is attributable to the extra weight, as it aided the digging in of the tracks of the device on the low-medium friction surface.

7.8 Crevice traversing test.

This test is aimed specifically at the devices ability to cross crevices. This test is important as it outlines the devices expected performance when operating under these conditions. An example of this is if the device were to be used by a plumber for the inspection of plumbing works then the device may need to cross small pipe/irrigation ditches. This particular test was carried out in accordance with the following figure using the same adjustable wooden blocks as before.

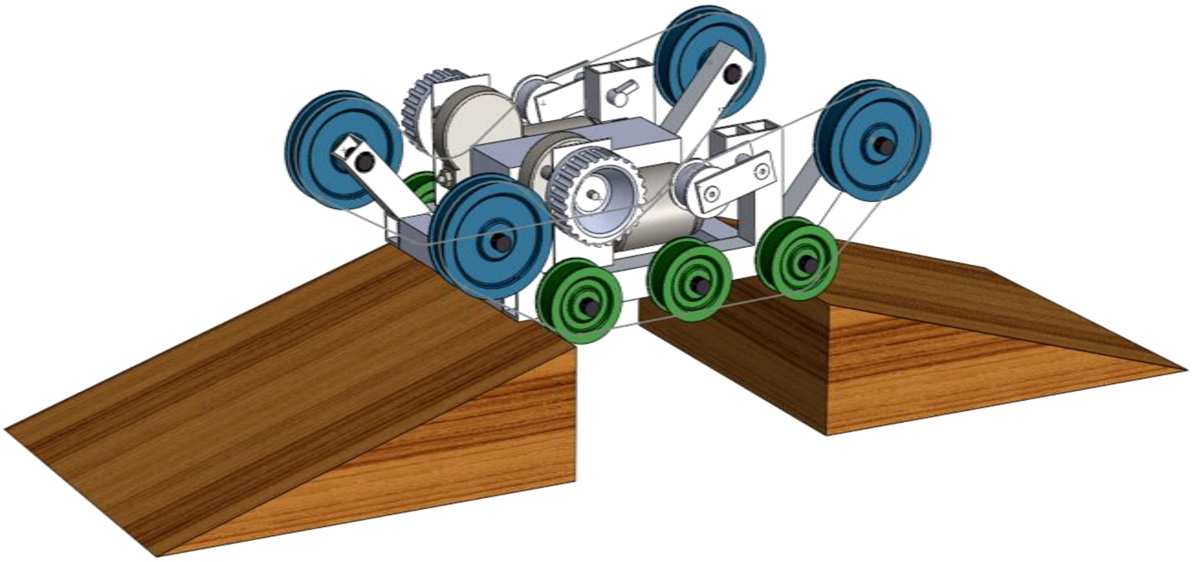

Figure 56 - Crevice traversing test

Table 15 - Crevice traversing test results

Crevice traversing test results			
Expected performance	**Actual performance**	**Maximum actual performance**	**Comments**
150-200 mm	180 mm reliably	185 mm only sometimes depending on angle of approach	The performance in this test was within the range that was expected

In this test, the device started upon one of the wooden blocks and was required to drive up the block across the crevice, without falling in the gap between, then down the other block. As in all of the previous tests, both of the blocks height was adjustable to ensure that the robot was not able to touch the ground at any time during the crossing. The actual performance from this test matched closely with the expected performance. This is because the designed measurements remained relatively similar throughout all phases of the project.

7.9 Obstacle climbing test.

In order for the robot to be a successful remote reconnaissance vehicle, it should be able to traverse a wide variety of different terrains. The objective of this test is to quantify the robot's ability to traverse straightedge obstacles such as would be encountered when climbing stairs, ledges, etc. This test was conducted using the same adjustable wooden blocks used for all other tests and was conducted as outlined in the following figure.

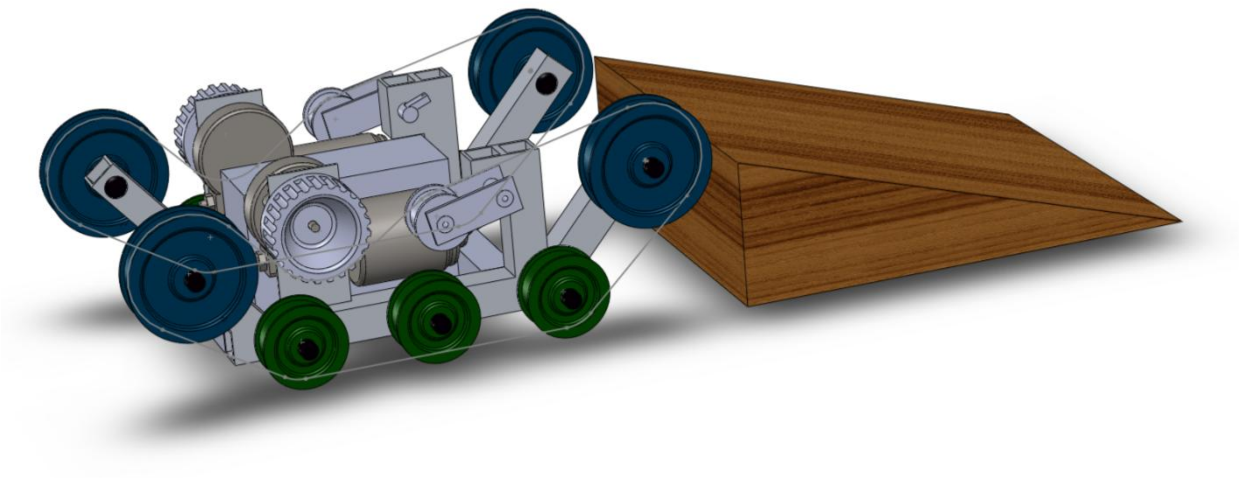

Figure 57 - **Obstacle climbing test**

Table 16 - **Obstacle climbing test results**

Obstacle climbing test results			
Expected performance	**Actual performance**	**Maximum actual performance**	**Comments**
100-120 mm	51 mm reliably	55 mm only sometimes depending on angle of approach	The performance in this test was well below that which was expected

For this test the robot begins on the ground and it is required to climb up the vertical edge. Then drive down the down ramp. The results obtained from this test were quite below that expected. This is due to the poor design and implementation choice with the rear bar on the chassis. If this bar were removed than the device, should easily be able to meet the expected performance criteria.

7.10 Push test.

The objective of this test was primarily to determine the amount of power and traction of the device. This test yielded some surprising results and the robot's performance, easily outdid what was expected. This test was conducted according to the following figure, whereby the timber cube was a box, which was subsequently filled with weight until the device could no longer push it. This test was conducted on a hard carpet, which would simulate the devices performance on smooth concrete or hard-packed dirt.

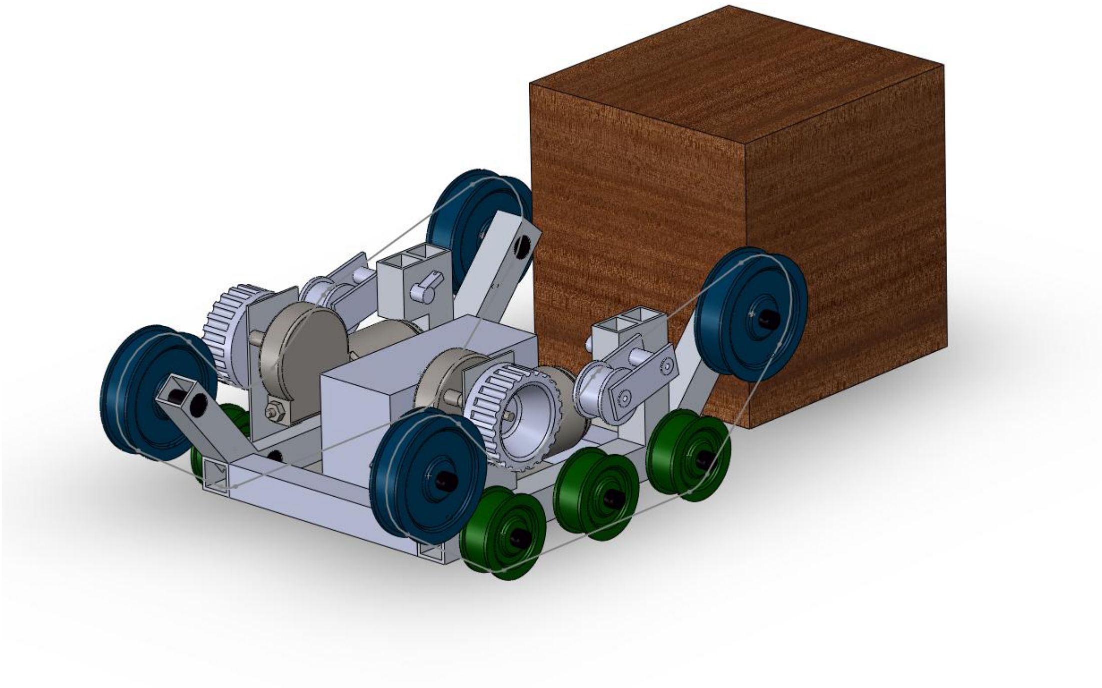

Figure 58 - **Push test**

Table 17 - **Obstacle climbing test results**

Obstacle climbing test results			
Expected performance	**Actual performance**	**Maximum actual performance**	**Comments**
5-10 kilograms	34 kilograms reliably without track slip	40+ kilograms with some track slip	The performance in this test, far exceeded anything that was expected

The actual performance results from this test indicated that something unusual may be going on as a device should theoretically not be able to push more than its own weight upon a flat surface with a low coefficient of friction. Upon conversing with numerous experts it was soon discovered that the device was actually trying to lift the rear of the box and in doing so, was transferring weight onto the driven wheels of the device. This had the effect of adding additional weight to the device, meaning that it was able to push a lot more than was previously expected.

It is also noted that this device, with these drive motors has a large amount of torque under almost all testing conditions. This torque far exceeded the amount of traction that was available and if the device were to run into an obstacle which it could not move, it would simply spin the tracks.

Conclusion

In conclusion, this chapter has covered the details of the technical information upon the testing of the device in order to determine its suitability for use as a mobile reconnaissance vehicle. This chapter discussed elements such as the devices ability to traverse crevices, its handling of incline slopes as well as obstacles. Also discussed were some of the features requiring modification in the final commercial design to enable the robot to meet its full potential as a complete tracked reconnaissance vehicle candidate.

In summary, the device performed more than adequately in four of the five tests, to which it was subjected. In addition to these five tests the robot has undergone tens of hours of in field testing over various terrains such as grass, dirt, hard-packed gravel, gravel, bitumen, sand, etc. Additionally the robot has seen many more hours use in indoor environments such as on carpet, concrete, tiles, etc.

Chapter 8

Conclusions and recommendations

Introduction

The purpose of this chapter is to summarise all of the conclusions made throughout the duration of this project. This chapter aims to bring together and conclude upon all of the previous chapters. Discussed herein will be the achievement of the project objectives, as well as the recommended further developments and improvements.

Whilst the exact final cost for the device is incalculable due to many factors, primarily to the large number of custom components and testing which has gone into the development of this device. Suffice to say that if these devices were to go into mass manufacture, the costs associated with production would be considerably less than that of a comparable military unit. The only downside is that it may not have as many functions, although with the microprocessor used, adding extra functions to the device and attachments such as grapplers, hands and firearms is not totally out of the question.

8.1 Summary.

After investigating the needs and functions of presently available remote reconnaissance vehicles, a number of different designs were considered. Since the beginning of the project it was always envisaged that, whatever device was implemented it would use tracks as its main form of locomotion. The system, which was initially proposed, had a number of design flaws and problems which, if left under the rectified, would cause catastrophic failure of the device. The main failures of this first design were;

- Inappropriate selection of materials.

When this device was initially prototyped, it was constructed using too heavy a grade rectangular hollow section steel. While this made the frame extremely strong and rigid, it was overly and unnecessarily heavy meaning that the runtime of the robot was severely compromised. This design also lead to increased wear on vital drivetrain components as well as adding unnecessary stress upon the motors and their gearboxes.

- Unsuitable drive techniques

A further failure of this initial design was the fact that the friction between the rear drive wheels, and the track was not sufficient to provide positive engagement under all circumstances. Even after various modifications it was evident that this would have to be rectified in the final design.

- No method of track tensioning

The final major design flaw with this initial prototype was the fact that there was no positive method of adjusting the track tension. This meant that the track would be tight under some conditions and loose under others. This would undoubtedly have to be remedied in the final design, as the tracks repeated contraction and expansion was stretching the belts, which eventually would lead to their failure.

With all of the failures of the above prototype, it was evident that a new design was required. This new design was found in an unlikely place, being a book written by Britt Robabaugh upon mechanical devices. This book outlined some fascinating and valid drive techniques for using these single sided timing belts. With reference to this book came the second design and prototype. This second design was considerably more successful, as it addressed all of the previous issues.

From a mechanical standpoint this new design was truly revolutionary, and easily surpassed all of the expected performance criteria leading to it being selected as the final configuration and layout for the robot. Once this mechanical layout had been finalised, attention was then turned to the selection of the Electrical components.

Firstly, appropriately sized motors were selected, these motors were 12 V windscreen wiper motors sourced from an old Suzuki purchased from an automotive wrecker. These particular motors were ideal, as they are left and right-hand sided, which is a fairly rare occurrence for windscreen wiper motors. Also these motors were perfect as they are of matched pair meaning that they both have the same power output characteristics and would not be constantly trying to fight with each other in the project, thereby causing the vehicle to steer off to one side, consistently requiring correction.

Once the motors had been selected, and therefore the power requirements known, a custom motor controller circuit was designed and built in order to facilitate their control. This control circuit uses a relay to select forward or reverse and a pulse width modulated MOSFET to control the speed in either direction. Inspiration for this control circuit came from a Komatsu 630 E, electric drive dump truck. In practice this was a relatively easy method of motor control, requiring only two inputs for each side motor, (forward/reverse and acceleration).

A PICAXE 18 X on a standard developmental project board formed the microcontroller component of this project. This microprocessor was required to read the inputs from the radio control receiver, decipher these inputs, and then output the appropriate motor control signals. This processing was done by the use of a very simple program relying on *if... then... else...* statements. All of the major components of the electrical system were then mounted in an ABS plastic security box attached to the device. This was in order to provide some sort of environmental protection from hazards which would be encountered during the devices operation. The particular layout of this box is shown in the following figure.

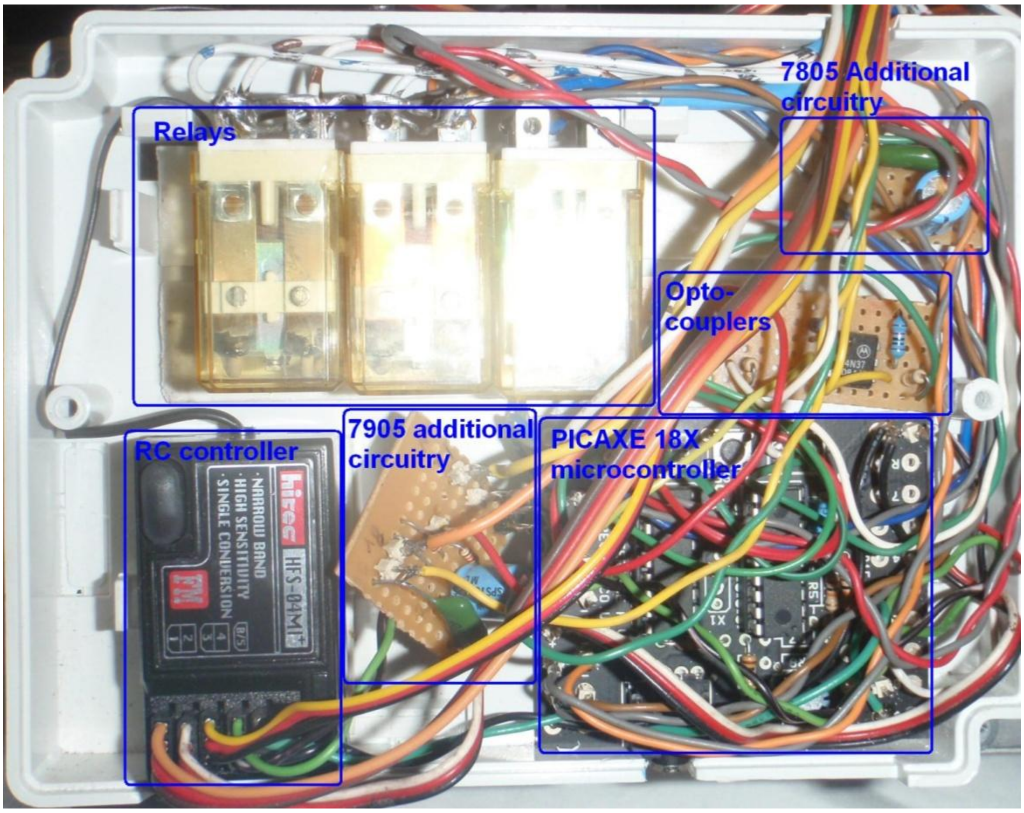

Figure 59 - **Image showing the internal layout of the ABS control box.**

Once all of the decisions had been made, all of the components were manufactured and the device was assembled. The following image shows each of the individual components of the chassis immediately before final assembly. This final assembly took less than 10 minutes and required only a Philips number two screwdriver and a pair of pliers. This fulfilled the initial design requirements of the device being easy and quick to assemble with it being able to be assembled '*quickly and in the field if need be*'.

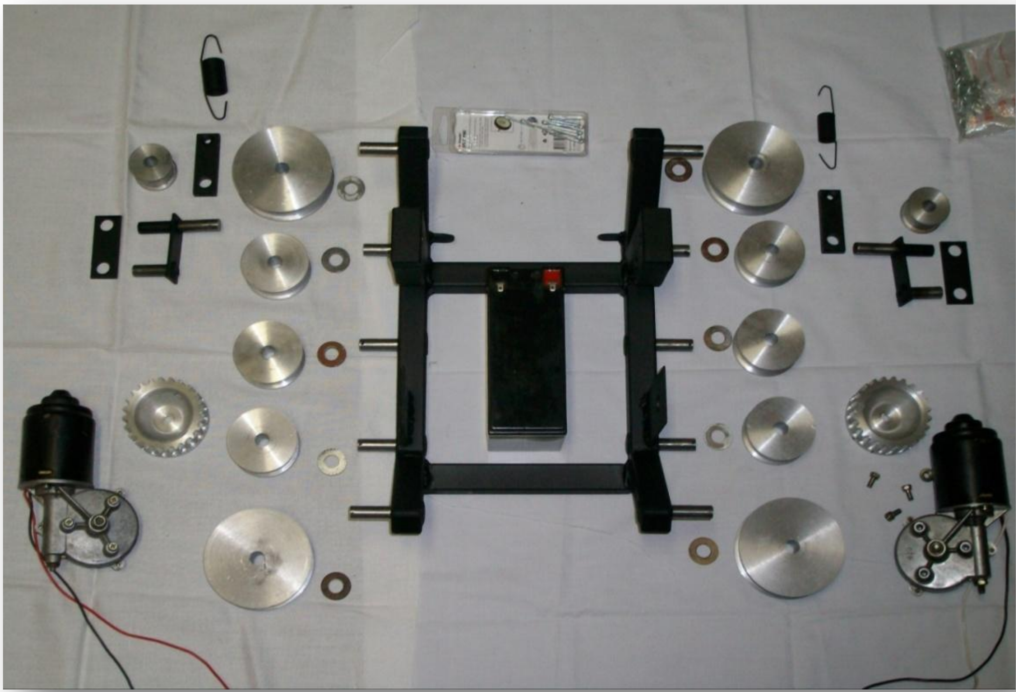

Figure 60 - **Components laid out for final assembly.**

After the final assembly of the device it then underwent rigourous testing to determine its infield expected performance. The specific results of the tests which it undertook numerous times are outlined in chapter 7. In summary, the device generally exceeded all of the expected performance benchmarks set during the initial design phase. This indicates that this robot would indeed make a good remote reconnaissance and inspection vehicle for use in a multitude of situations.

In addition, the robot undertook many tens of hours of outside 'infield' tests. The reconnaissance vehicle's performance in these tests was highly outstanding, making it an ideal candidate for further development. Also during this testing a number of slight design changes became apparent, which are discussed further in the following section.

8.2 Further work.

In the future, there is a considerable amount of work, which could be done to further advance the design, construction and usefulness of this mobile reconnaissance device. These further design considerations can be broken down into three main sections. These main sections include mechanical enhancements, electrical enhancements and software and microprocessor based enhancements. Each of these three categories is discussed in more detail in the following sections.

8.2.1 Mechanical enhancements.

As this device has barely left its prototyping stages there are a large number of mechanical changes which could be implemented to better the device. These enhancements include;

- Wider tracks. The use of wider tracks would be beneficial as it will allow more of the motors traction to be transmitted to the ground. Their implementation will also allow the device to travel over a lot steeper and more undulating terrain without sliding or sinking in. In addition these tracks will increase the stability of the device and aid in greatly reducing the vibration experienced by all components.
- Better ground clearance and better chassis design. The adjusting of the design to allow for better ground clearance will aid the robot's ability to traverse larger obstacles than it can currently. The low ground clearance compounded with the poor chassis design, that the device has presently, hindered its performance especially in the infield tests.
- Lighter weight. This future improvement is aimed primarily at increasing the performance and life of the battery. The only downside to lightening the device would be the associated reduction in traction and the reduction in stability.
- Steel tracks. The use of steel tracks could also be investigated in order to increase the traction and a usable life over the presently existing system. Although the use of steel tracks may, in some circumstances, be somewhat detrimental especially if the device is used in an indoor environment.

The implementation of some of these mechanical enhancements would dramatically increase the usefulness of the device especially for its outdoors performance.

8.2.2 Electrical enhancements.

These enhancements are aimed primarily at the problems that were envisaged or encountered during, the devices in field testing. These enhancements include;

- Better speed. This is an obvious enhancement, because currently the device does not travel very fast. To increase the speed of the device, a complete redesign of the drive system, would need to occur, implementing slightly faster motors with higher ratio gearboxes.
- Batteries. In future iterations of this device, better batteries could be implemented in order to improve the usable life-to-charge time ratio of the device. These better battery options may include the use of Nickel Metal Hydride or Lithium ion batteries.

If these electrical enhancements were implemented the usefulness and infield ability of the device would be increased. The only aspect of the electrical system, which would not be changed, is the motor controller as its performance was better than some commercially available systems also its integration was considerably easier than the aforementioned systems.

8.2.3 Software and microprocessor enhancements.

This is an area in which a large number of enhancements can be made to increase the performance of the device. These enhancements include;

- The implementation of a better program. In the future, it is envisaged that proper pulse width modulation be implemented in order to control the motors with a higher degree of accuracy. Also, this future program may implement second functions using the other channels on the remote control unit. These second functions may perform tasks such as counter rotation; move attachments; adjust the system response speed, etc.

- GPS or a compass. The addition of GPS or a compass would be quite helpful, as it would allow the microprocessor to log the devices journey as well as to provide semiautonomous guided reconnaissance.
- Integration of video into microprocessor. The integration of the video system, with the microprocessor, would allow the device to operate in a semiautonomous mode, and to automatically take pictures or videos of points of interest, as defined by the microprocessor program.

If all of these mechanical, electrical and software/microprocessor based enhancements were included in the next iteration of the device, the resultant device would be a fully featured highly mobile reconnaissance device. This device would parallel, many of the presently available systems in terms of both functionality and agility.

8.3 Conclusions and recommendations.

From the completion of the aim of this project, which was to design, construct and test a remote controlled tracked reconnaissance vehicle; the conclusions are as follows:

1. From the brief literature review conducted in Chapter 2, it is seen that there have been numerous attempts at the construction of remote mobile reconnaissance vehicles. Each of these different attempts has had varying degrees of success, depending of course upon the use. The fact that there are so many different reconnaissance robots available means that there is no specific or ideal reconnaissance vehicle for all situations.
2. Since it would be impossible to make a device capable of performing under all circumstances a number of key criteria were defined. From these key criteria a suitable design was devised. This design was limited by the availability of components.
3. Once a suitable design had been selected, AutoCAD and SolidWorks drawings were produced for each component then the device was constructed from these drawings.
4. Adjustments were made to this initial design along the way in order to overcome any of the problems that were encountered.

5. The device constructed was then evaluated against the previously defined benchmarks and key criteria. The device was found to perform more than satisfactorily on, the majority of the key criteria.

Final picture of the completed device.

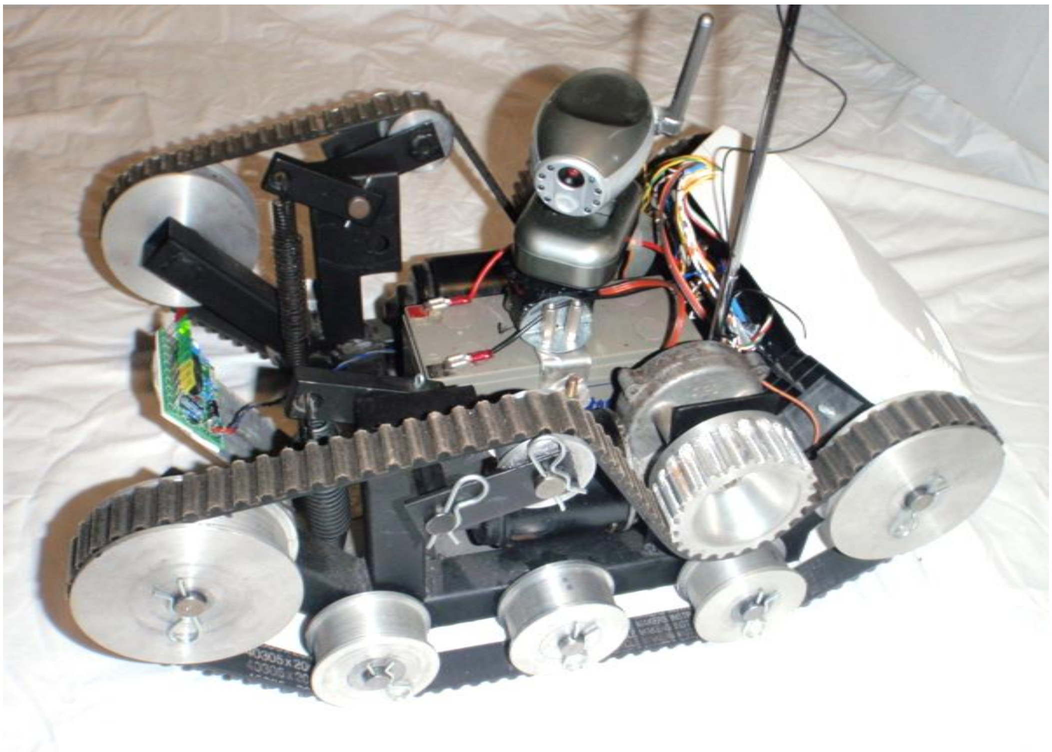

Figure 61 - **Image of the final, fully completed device.**

Key conclusions from this project;

- Single sided automotive timing belts will not work in a friction drive arrangement.
- The motor controller devised for this project, uses less components than most standard motor controllers, while still providing full functions and high current capabilities.
- The speed of the windscreen wiper motors was sufficient as a source of locomotion for this device.
- A strong and rigid chassis is highly desirable for ensuring that components stay where they are fixed during infield reconnaissance.
- The range of the video system needs to be increased as 100 m proved insufficient.

- The PICAXE microcontroller used was the correct selection, as it proved to be highly functional and easy to program for. Although better programming methods, and the addition of sensors would allow the capabilities of this microprocessor to be fully exploited.
- The device, which was constructed, was indeed a true remote controlled tracked reconnaissance vehicle and would perform admirably under many infield conditions.

8.4 End note from author.

In conclusion, this project has allowed the demonstration of the authors' numerous skills and abilities from simple design techniques to complex solid modelling; from basic assembly to hard-core component manufacture requiring casting, lathework, milling, welding. As well as many other complex assembly and manufacture methods.

Totally new skills had to be learnt as well, especially with the use of the wireless video cameras and the implementation and interfacing of the radio control receiver with the microprocessor. In summary, this was a very rewarding and enjoyable experience, providing endless learning opportunities along the way.

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Appendices

Upon the construction of a remote controlled tracked reconnaissance vehicle

Appendix A

Project specification

Faculty of Engineering and Surveying
ENG4111 Research Project Part 1
PROJECT PROPOSAL FORM

Note:
1. ***Students who wish to undertake a project of your own, or employer, invention, complete sections A and C only***
2. ***Students undertaking a project from the Faculty "Offer" of Topics, complete section A and B only.***

PART A

Full Name (Please PRINT & UNDERLINE FAMILY NAME): Matthew Downing

Student Number: 0050071825

Program:(circle one) BEng BBus / BEng BIT / BEng BSc / BEng / BSpSc / other_____ (specify)

Anticipated completion date of your project ? 11 (month), 2010 (year)

Proposed study mode for your project work (ENG4111 and ENG4112): (D/X) onc

Major: (circle one) Agricultural / Environmental / Civil / Electrical / Computer Systems / Software / Instrumentation & Control / Mechatronic / Mechanical / Survey / GIS/ Power Engineering

PART B (FACULTY OFFER PROJECT PROPOSAL ONLY)

PROJECT PREFERENCES: First / Second / Third / Fourth / Fifth

Topic No. / / / /

COMMENTS to the Examiner (if any)

PART C (OWN PROJECT PROPOSAL ONLY)

NOTE: refer to Section 3.3 of the ENG4111/2 Project Reference Book:

Provisional Title (be brief): Remote Micro processor controlled tracked experimental platform (Vehicle)

Project Origin (e.g. own idea / employer suggestion / etc.): own idea, based on the lack of a Suitable industry Grade Alternative.

Description / details – *attach pages as appropriate.* (Total pages attached = Ten)

Supervising Staff *(if known through prior negotiations, or a preference, or leave blank)*

Staff Member: Dr Sam Cubero **Staff signature:** ______ **Date:** 2/11/09
(Signifying acceptance of this topic as suitable AND the willingness to supervise).

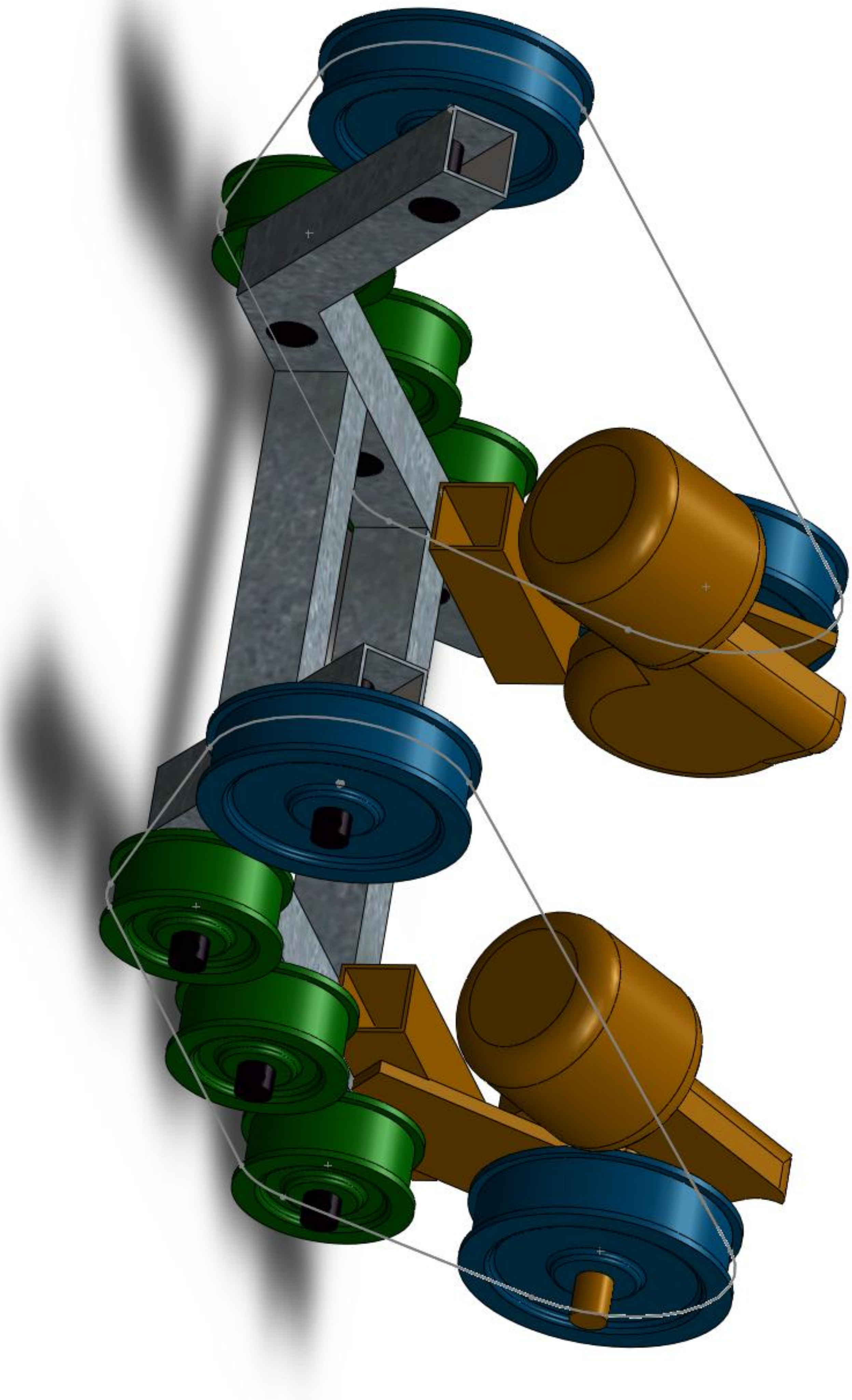
Return this form to:

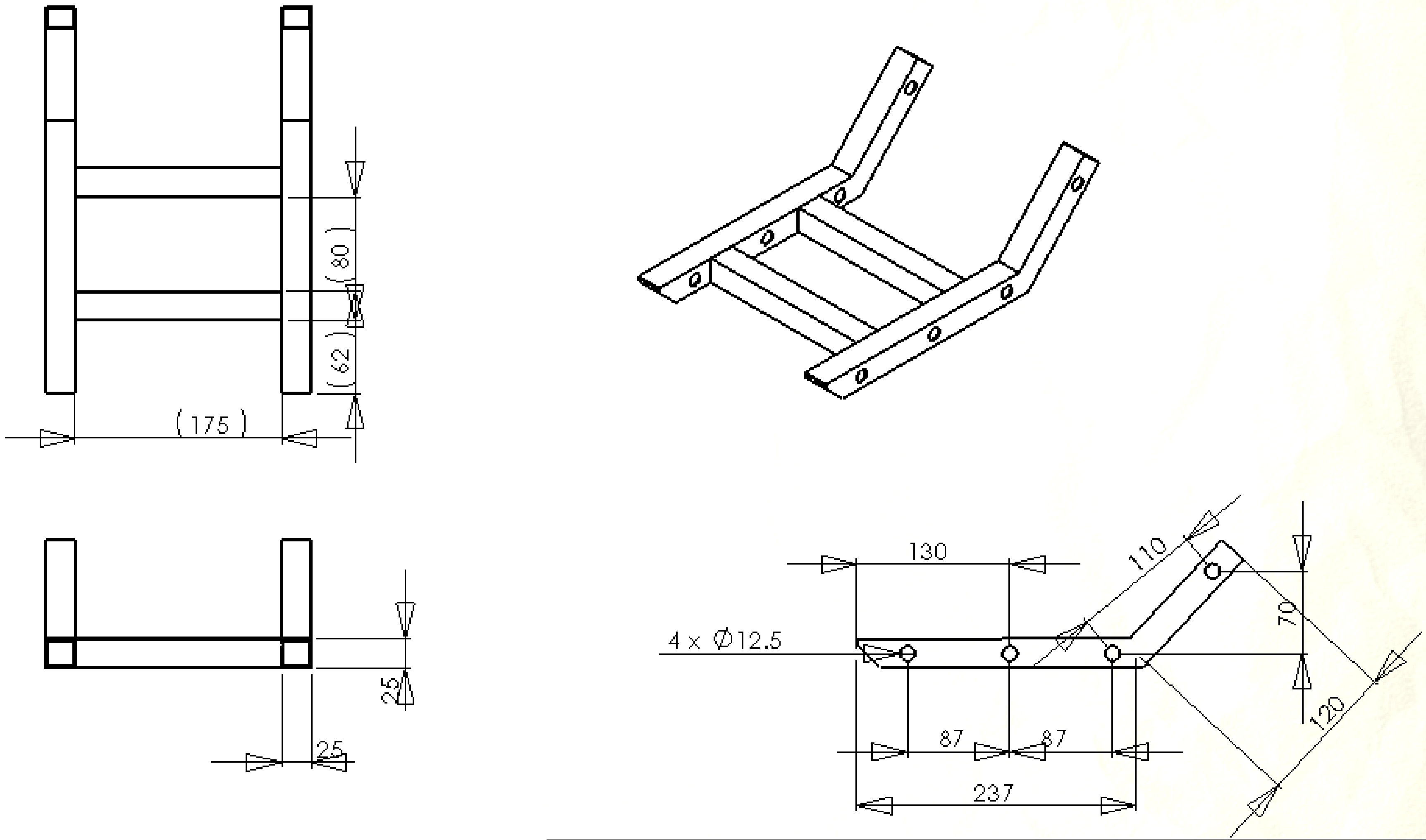
EITHER Level 4 Assignment Box Slot "ENG4111/2" (on-campus students);

OR The ENG4111/2 Project Administrator, Faculty of Engineering and Surveying (external students).

Appendix B

Initial design drawings





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NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL —
FINISH --
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

Matthew Downing

Chassis

SIZE A DWG. NO. REV.
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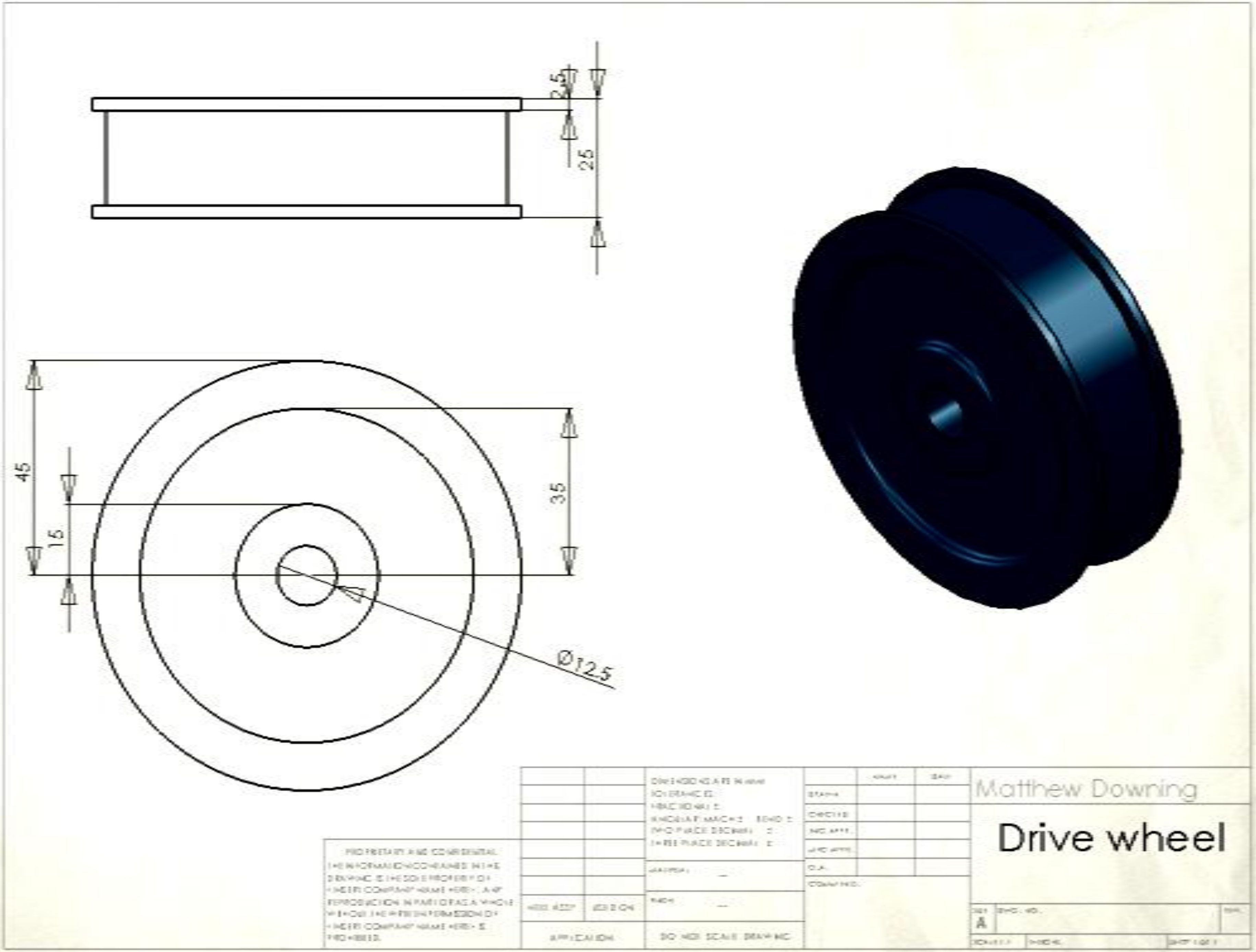
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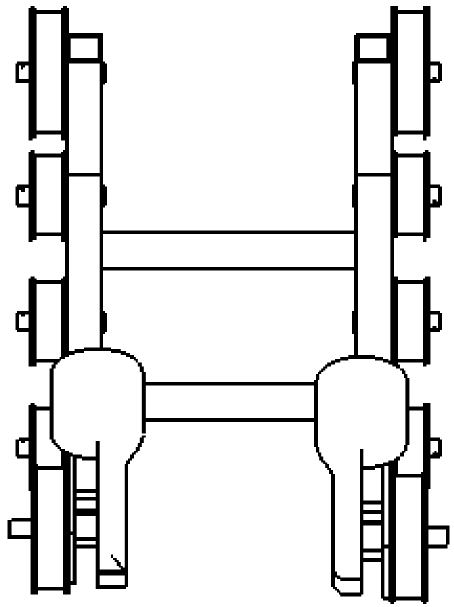
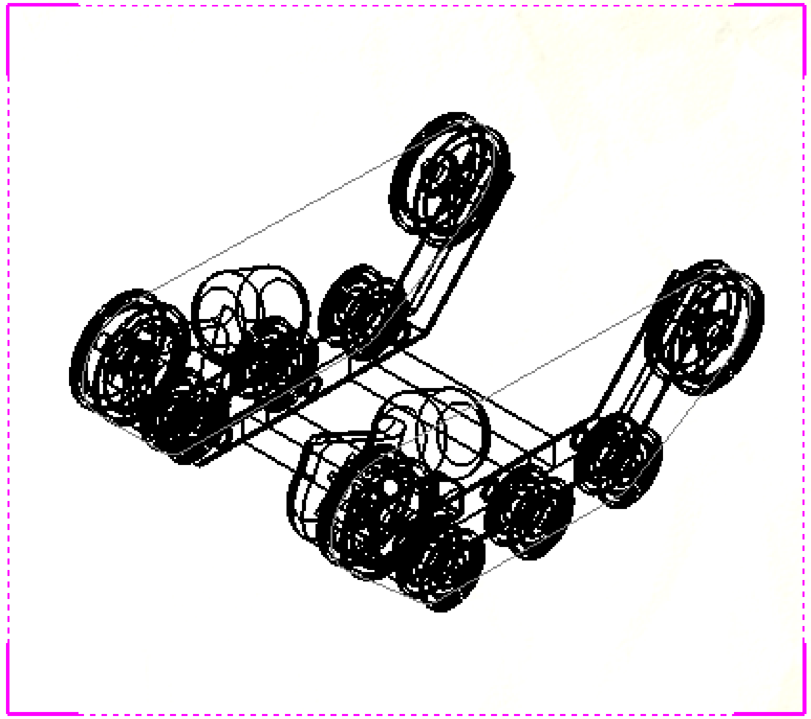
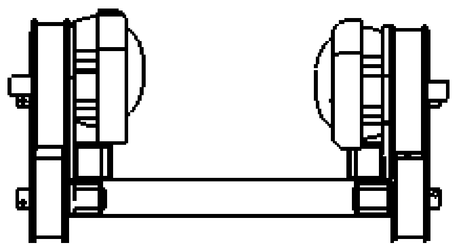
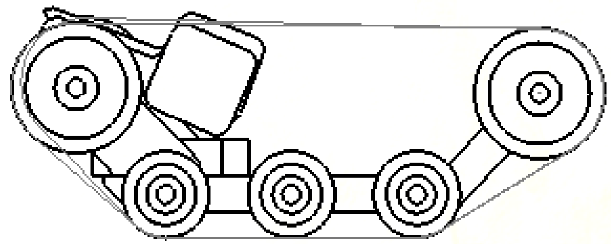
APPLICATION
DO NOT SCALE DRAWING
Matthew Downing
Drive wheel
A









PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL —

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MFG APPR.		
Q.A.		
COMMENTS:		

Matthew Downing

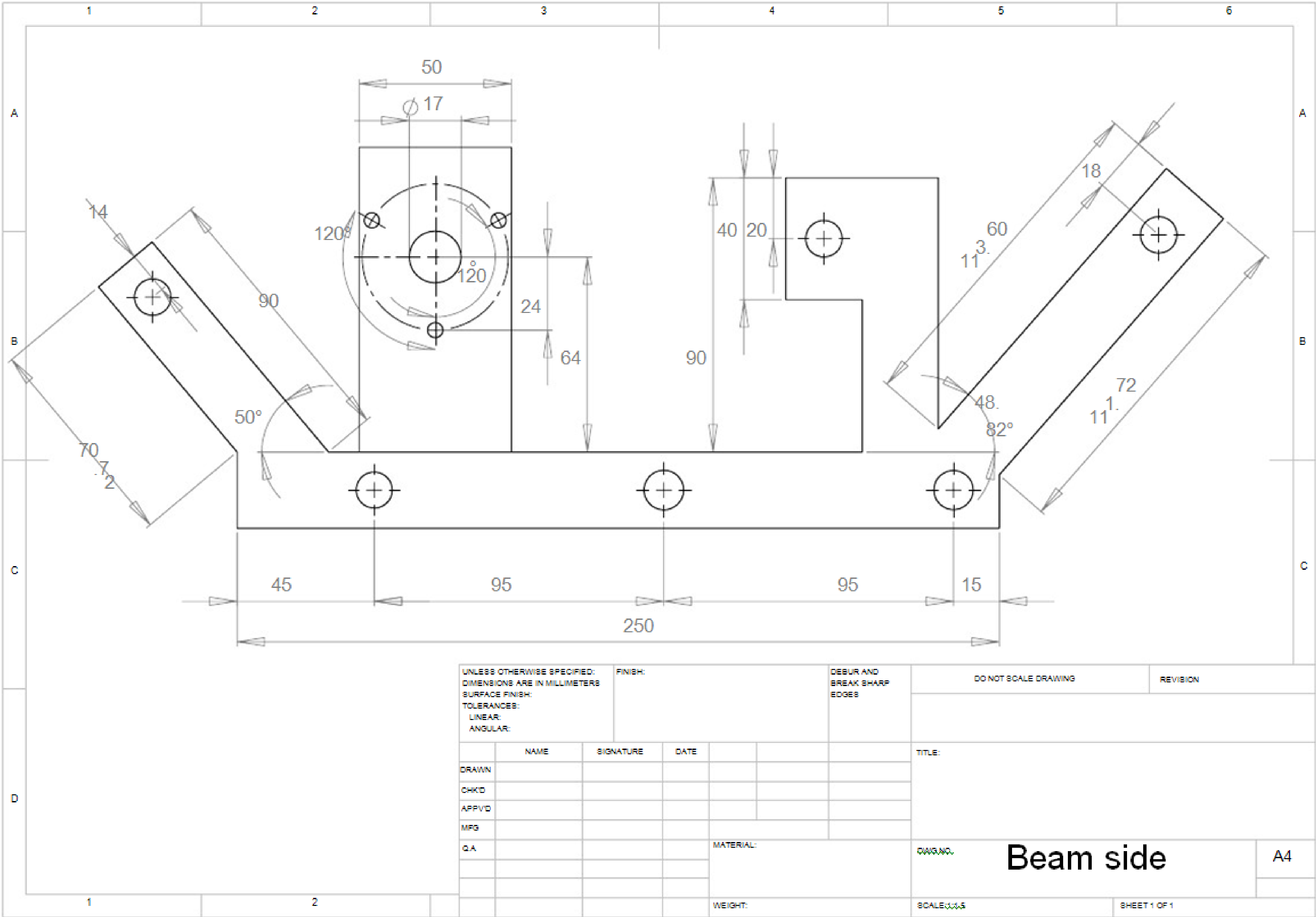
Assembly

SIZE A DWG. NO. REV.

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

Appendix C

Final design drawings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TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
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DATE
DRAWN
CHK'D
APPV'D
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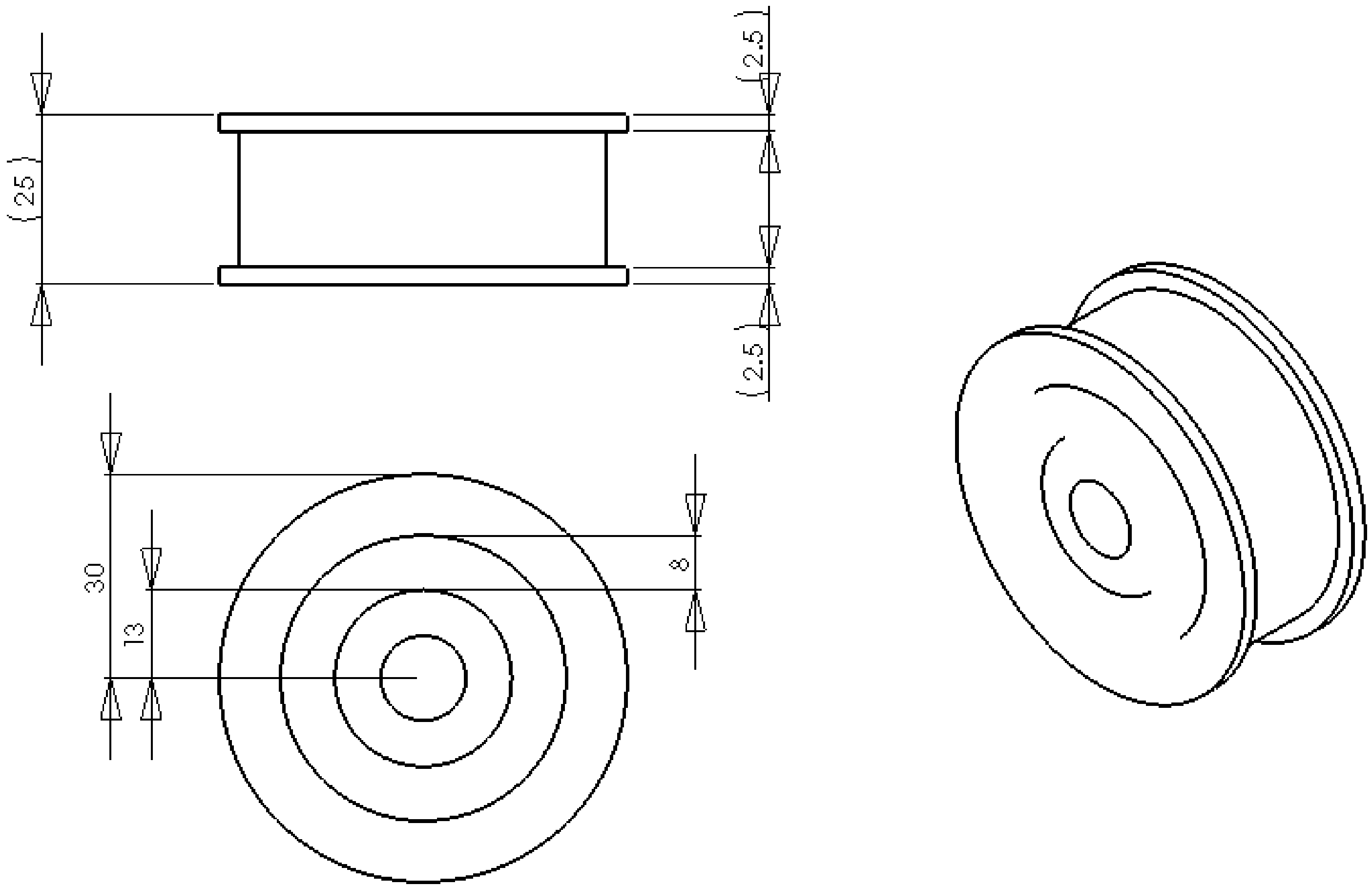
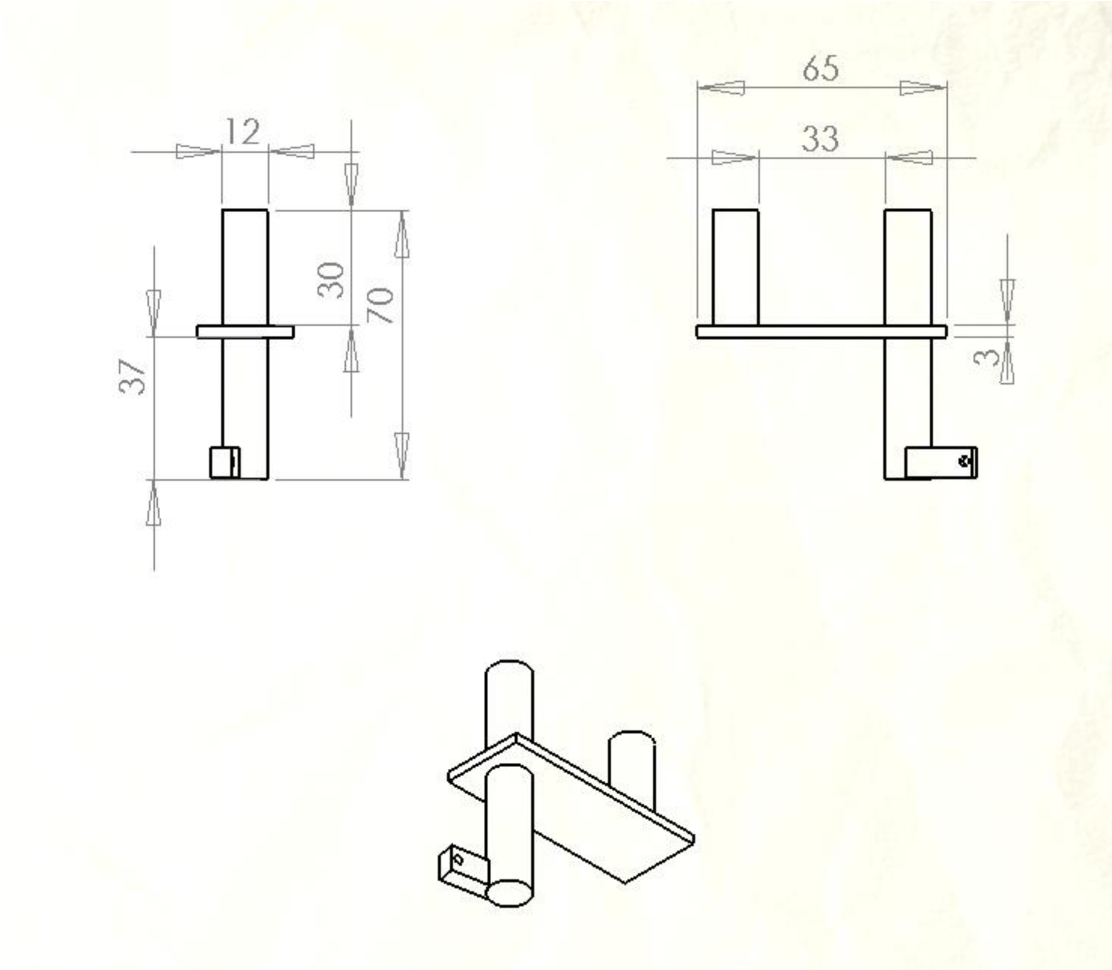
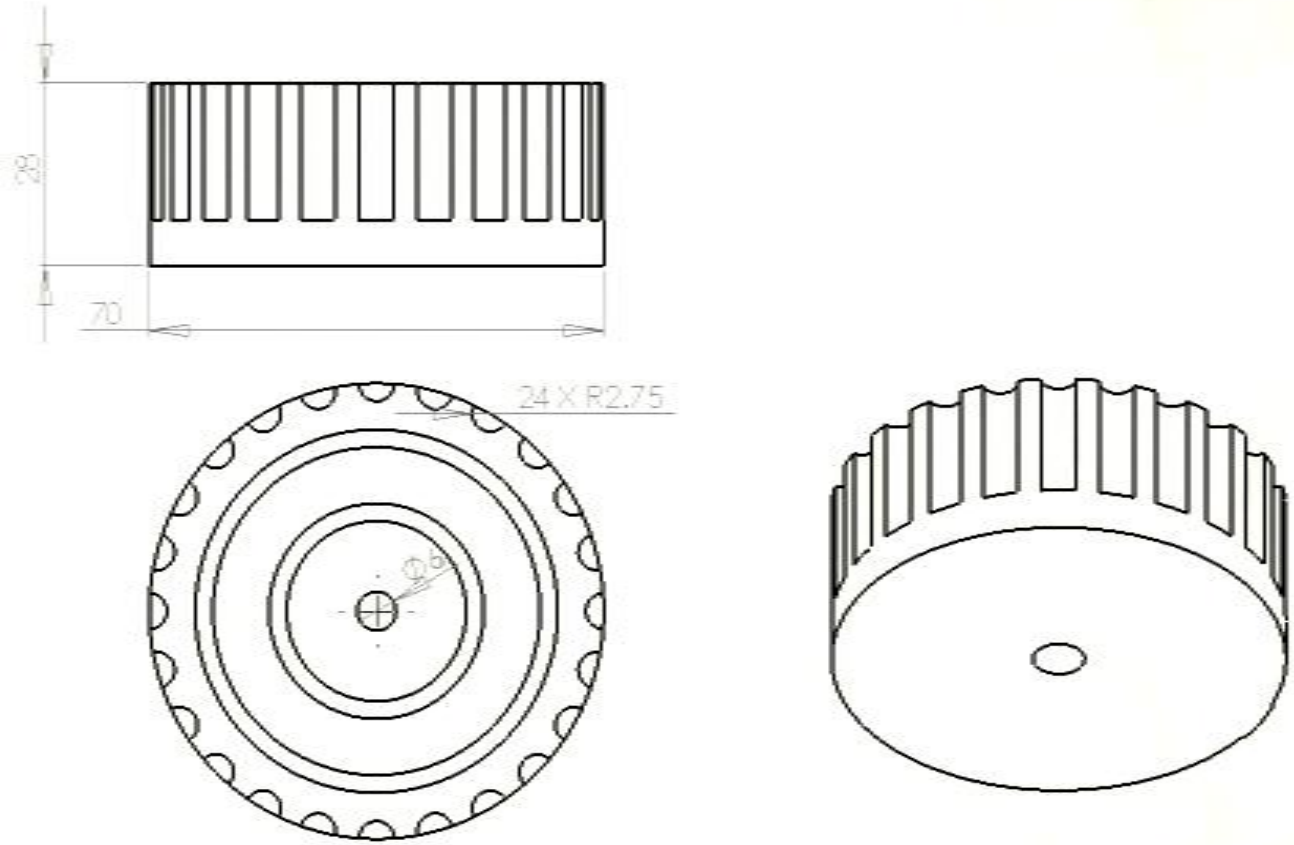
Beam side
A4
SCALE:1:1.5
SHEET 1 OF 1



Roller wheel

Tensioner





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	MFG APPR.		
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MATERIAL	COMMENTS:		
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APPLICATION	

TITLE:

SIZE A DWG. NO. sprocket REV

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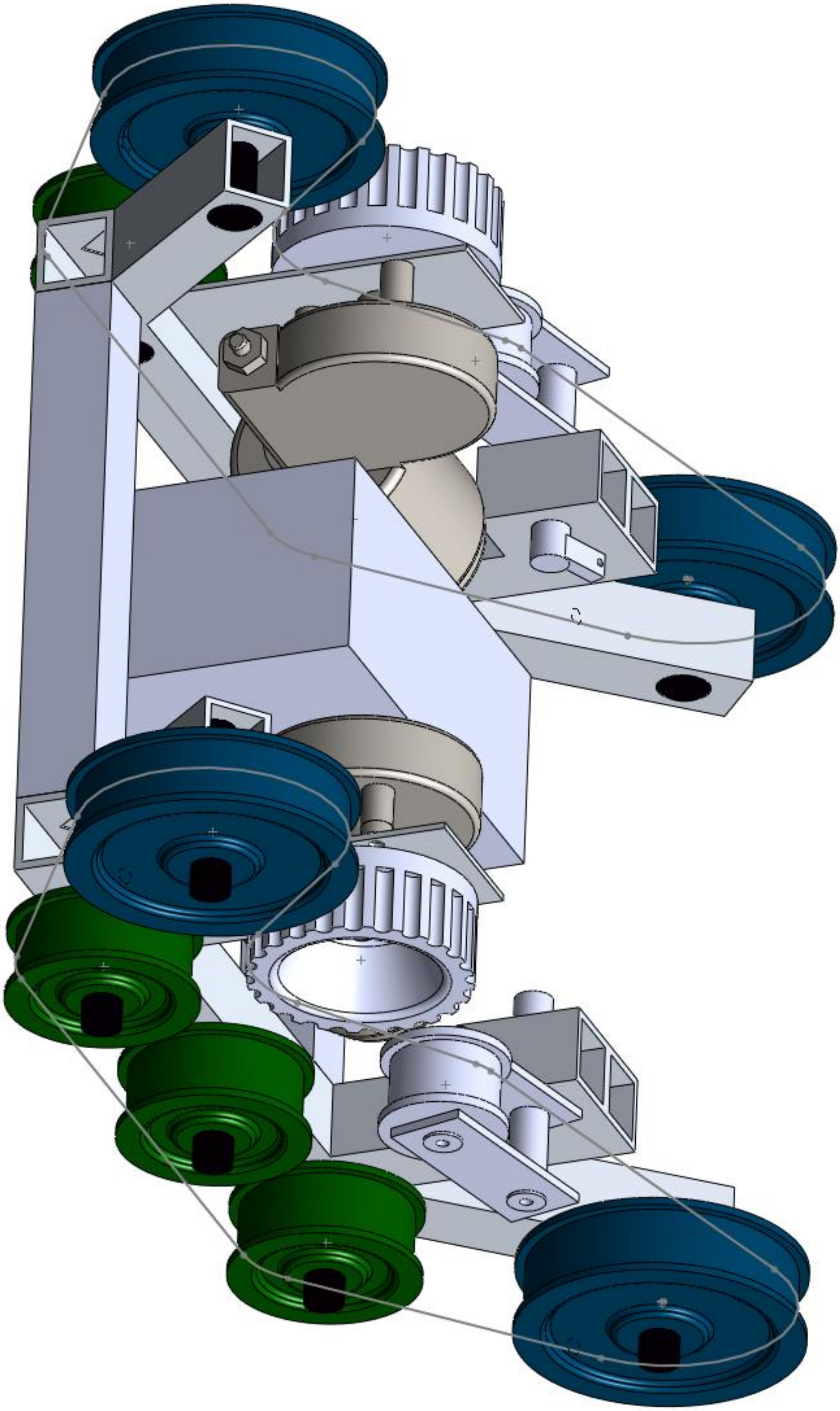


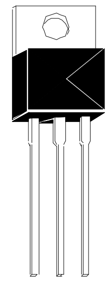
Appendix D

TIP41C datasheet

Spec. No. : HE6707
Issued Date : 1993.01.13
Revised Date : 2002.03.04
Page No. : 1/3

HTIP41C

NPN EPITAXIAL PLANAR TRANSISTOR



TO-220

Description

The HTIP41C is designed for use in general purpose amplifier and switching applications.

Absolute Maximum Ratings (Ta=25°C)

- Maximum Temperatures
  Storage Temperature .... -55 ~ +150 °C
  Junction Temperature .... +150 °C Maximum
- Maximum Power Dissipation
  Total Power Dissipation (Tc=25°C) .... 65 W
  Total Power Dissipation (Ta=25°C) .... 2 W
- Maximum Voltages and Currents
  BVCBO Collector to Base Voltage.. 100 V
  BVCEO Collector to Emitter Voltage.. 100 V
  IC Collector Current.. 6 A

Characteristics (Ta=25°C)

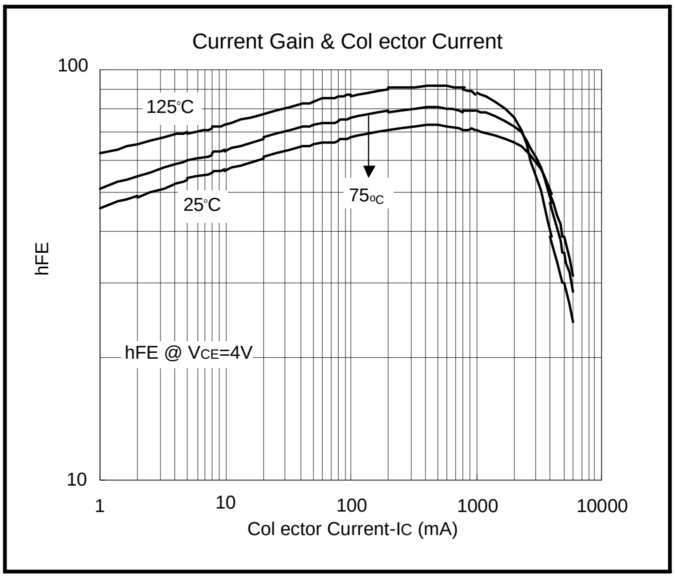
Symbol	Min.	Typ.	Max.	Unit	Test Conditions
BVCBO	100	-	-	V	IC=1mA, IE=0
BVCEO	100	-	-	V	IC=30mA, IB=0
ICES	-	-	400	uA	VCE=100V, IB=0
ICEO	-	-	700	uA	VCE=60V, IB=0
IEBO	-	-	1	mA	VEB=5V, IC=0
*VCE(sat)	-	-	1.5	V	IC=6A, IB=600mA
*VBE(on)	-	-	2	V	IC=6A, VCE=4V
*hFE1	30	-	-		IC=0.3A, VCE=4V
*hFE2	15	-	75		IC=3A, VCE=4V
fT	3	-	-	MHZ	VCE=10V, IC=500mA, f=1MHz

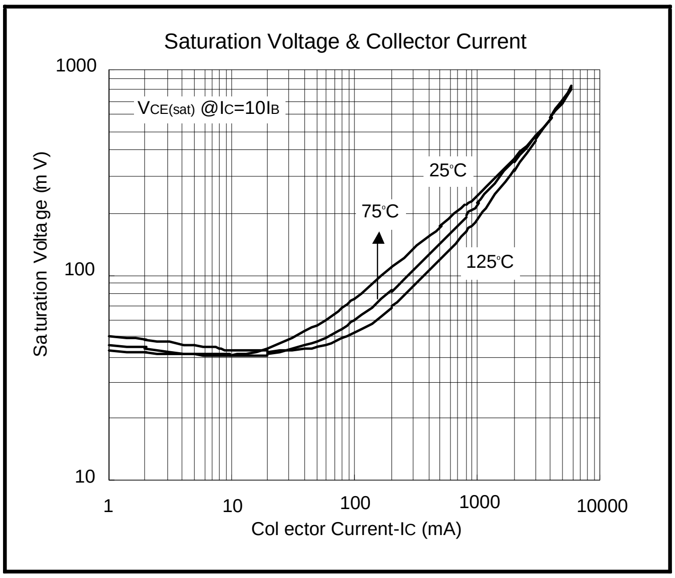
*Pulse Test: Pulse Width δ380us, Duty Cycleδ2%

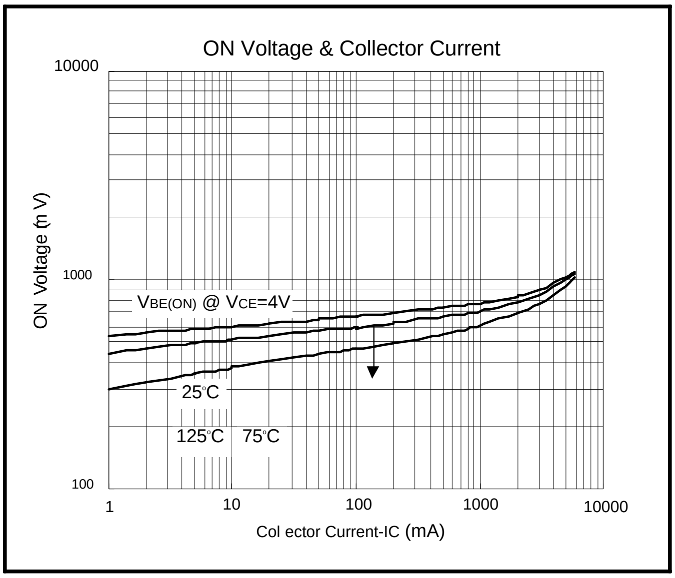
Classification Of hFE2

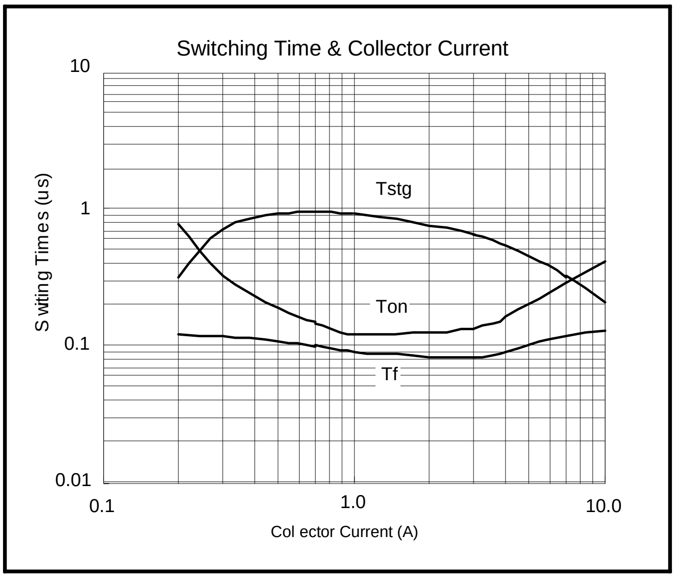
Rank	A	B
hFE2	15-50	40-75

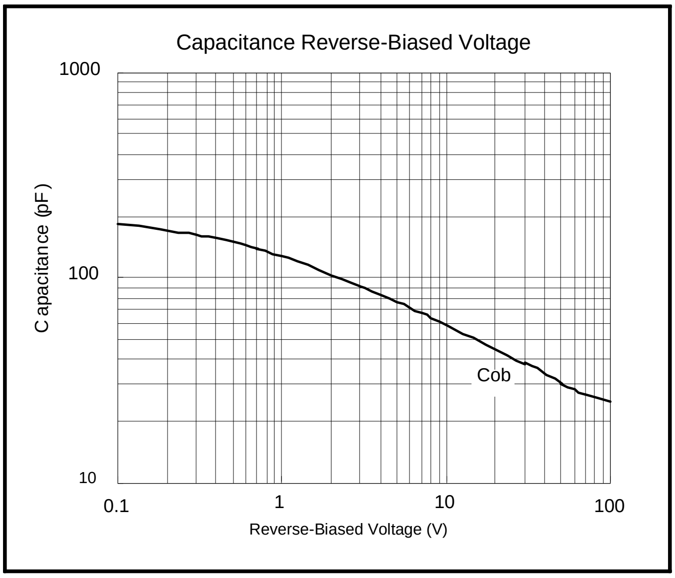
Characteristics Curve

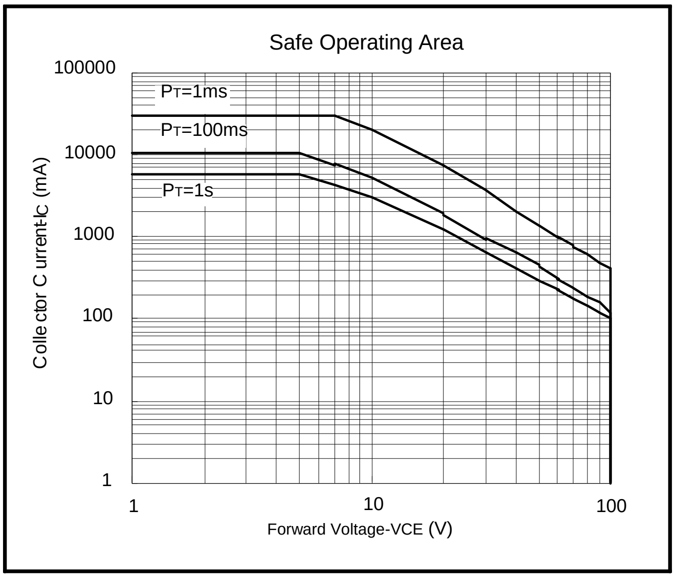




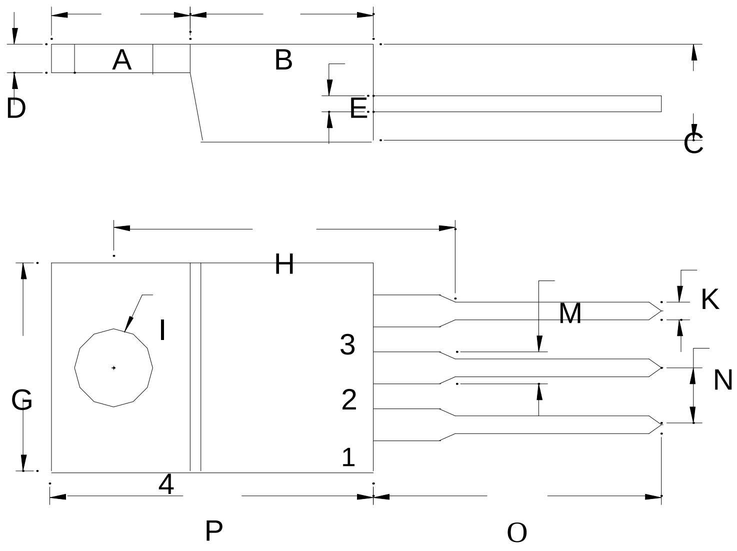






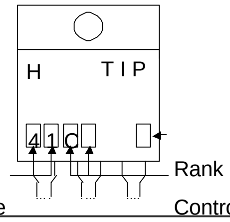


TO-220AB Dimension



3-Lead TO-220AB Plastic Package
HSMC Package Code: E

Marking:



Style: Pin 1.Base 2.Collector 3.Emitter

*: Typical

DIM	Inches Min.	Inches Max.	Millimeters Min.	Millimeters Max.	DIM	Inches Min.	Inches Max.	Millimeters Min.	Millimeters Max.
A	0.2197	0.2949	5.58	7.49	I	-	*0.1508	-	*3.83
B	0.3299	0.3504	8.38	8.90	K	0.0295	0.0374	0.75	0.95
C	0.1732	0.185	4.40	4.70	M	0.0449	0.0551	1.14	1.40
D	0.0453	0.0547	1.15	1.39	N	-	*0.1000	-	*2.54
E	0.0138	0.0236	0.35	0.60	O	0.5000	0.5618	12.70	14.27
G	0.3803	0.4047	9.66	10.28	P	0.5701	0.6248	14.48	15.87
H	-	*0.6398	-	*16.25					

Notes: 1.Dimension and tolerance based on our Spec. dated Sep. 07,1997.
2.Controlling dimension: millimeters.
3.Maximum lead thickness includes lead finish thickness, and minimum lead thickness is the minimum thickness of base material.
4.If there is any question with packing specification or packing method, please contact your local HSMC sales office.

Material:

- Lead: 42 Alloy; solder plating
- Mold Compound: Epoxy resin family, flammability solid burning class: UL94V-0

Important Notice:

- HSMC reserves the right to make changes to its products without notice.
- ***HSMC semiconductor products are not warranted to be suitable for use in Life-Support Applications, or systems.***
- HSMC assumes no liability for any consequence of customer product design, infringement of patents, or application assistance.

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- **Head Office** (Hi-Sincerity Microelectronics Corp.): 10F.,No. 61, Sec. 2, Chung-Shan N. Rd. Taipei Taiwan R.O.C.
  Tel: 886-2-25212056 Fax: 886-2-25632712, 25368454
- **Factory 1:** No. 38, Kuang Fu S. Rd., Fu-Kou Hsin-Chu Industrial Park Hsin-Chu Taiwan. R.O.C
  Tel: 886-3-5983621~5 Fax: 886-3-5982931

Appendix E

5N06HD datasheet

Order this document
by MTP75N06HD/D

Designer's Data Sheet
HDTMOS E-FET
High Density Power FET
N–Channel Enhancement–Mode Silicon Gate

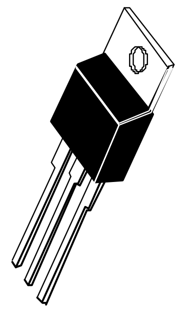
MTP75N06HD

Motorola Preferred Device

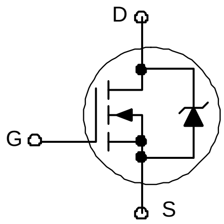
This advanced high–cell density HDTMOS E–FET is designed to withstand high energy in the avalanche and commutation modes. This new energy efficient design also offers a drain–to–source diode with a fast recovery time. Designed for low–voltage, high–speed switching applications in power supplies, converters and PWM motor controls, and inductive loads. The avalanche energy capability is specified to eliminate the guesswork in designs where inductive loads are switched, and to offer additional safety margin against unexpected voltage transients.

- Ultra Low RDS(on), High–Cell Density, HDTMOS
- Diode is Characterized for Use in Bridge Circuits
- IDSS and VDS(on) Specified at Elevated Temperature
- Avalanche Energy Specified

TMOS POWER FET
75 AMPERES
RDS(on) = 10.0 mOHM
60 VOLTS



CASE 221A–06, Style 5
TO–220AB



MAXIMUM RATINGS (TC = 25°C unless otherwise noted)

Rating	Symbol	Value	Unit
Drain–Source Voltage	VDSS	60	Vdc
Drain–Gate Voltage (RGS = 1.0 M&)	VDGR	60	Vdc
Gate–Source Voltage — Continuous — Single Pulse	VGS	± 20 ± 30	Vdc Vpk
Drain Current — Continuous — Continuous @ 100°C — Single Pulse (tp δ 10 ∝s)	ID ID IDM	75 50 225	Adc Apk
Total Power Dissipation Derate above 25°C	PD	150 1.0	Watts W/°C
Operating and Storage Temperature Range	TJ, Tstg	– 55 to 175	°C
Single Pulse Drain–to–Source Avalanche Energy — Starting TJ = 25°C (VDD = 25 Vdc, VGS = 10 Vdc, IL = 75 Apk, L = 0.177 mH, RG = 25 &)	EAS	500	mJ
Thermal Resistance — Junction to Case — Junction to Ambient	R\JC R\JA	1.0 62.5	°C/W
Maximum Lead Temperature for Soldering Purposes, 1/83 from case for 10 seconds	TL	260	°C

Designer's Data for "Worst Case" Conditions — The Designer's Data Sheet permits the design of most circuits entirely from the information presented. SOA Limit curves — representing boundaries on device characteristics — are given to facilitate "worst case" design.

Preferred devices are Motorola recommended choices for future use and best overall value.

REV 1

ELECTRICAL CHARACTERISTICS (TJ = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS					
Drain–Source Breakdown Voltage (Cpk ε 2.0) (3) (VGS = 0 Vdc, ID = 250 ∝Adc) Temperature Coefficient (Positive)	V(BR)DSS	 60 —	 68 60.4	 — —	Vdc mV/°C
Zero Gate Voltage Drain Current (VDS = 60 Vdc, VGS = 0 Vdc) (VDS = 60 Vdc, VGS = 0 Vdc, TJ = 125°C)	IDSS	 — —	 — —	 10 100	∝Adc
Gate–Body Leakage Current (VGS = ± 20 Vdc, VDS = 0 V)	IGSS	—	5.0	100	nAdc
ON CHARACTERISTICS (1)					
Gate Threshold Voltage (Cpk ε 5.0) (3) (VDS = VGS, ID = 250 ∝Adc) Temperature Coefficient (Negative)	VGS(th)	 2.0 —	 3.0 8.38	 4.0 —	Vdc mV/°C
Static Drain–Source On–Resistance (Cpk ε 2.0) (3) (VGS = 10 Vdc, ID = 37.5 Adc)	RDS(on)	—	8.3	10	m&
Drain–Source On–Voltage (VGS = 10 Vdc) (ID = 75 Adc) (ID = 37.5 Adc, TJ = 125°C)	VDS(on)	 — —	 0.7 0.53	 0.9 0.8	Vdc
Forward Transconductance (VDS = 15 Vdc, ID = 37.5 Adc)	gFS	15	32	—	mhos
DYNAMIC CHARACTERISTICS					
Input Capacitance (VDS = 25 Vdc, VGS = 0 Vdc, f = 1.0 MHz)	Ciss	—	2800	3920	pF
Output Capacitance	Coss	—	928	1300	
Reverse Transfer Capacitance	Crss	—	180	252	
SWITCHING CHARACTERISTICS (2)					
Turn–On Delay Time (VDS = 30 Vdc, ID = 75 Adc, VGS = 10 Vdc, RG = 9.1 &)	td(on)	—	18	26	ns
Rise Time	tr	—	218	306	
Turn–Off Delay Time	td(off)	—	67	94	
Fall Time	tf	—	125	175	
Gate Charge (VDS = 48 Vdc, ID = 75 Adc, VGS = 10 Vdc)	QT	—	71	100	nC
	Q1	—	16.3	—	
	Q2	—	31	—	
	Q3	—	29.4	—	
SOURCE–DRAIN DIODE CHARACTERISTICS					
Forward On–Voltage (IS = 75 Adc, VGS = 0 Vdc) (IS = 75 Adc, VGS = 0 Vdc, TJ = 125°C)	VSD	 — —	 0.97 0.88	 1.1 —	Vdc
Reverse Recovery Time (IS = 75 Adc, VGS = 0 Vdc, dIS/dt = 100 A/∝s)	trr	—	56	—	ns
	ta	—	44	—	
	tb	—	12	—	
Reverse Recovery Stored Charge	QRR	—	0.103	—	∝C
INTERNAL PACKAGE INDUCTANCE					
Internal Drain Inductance (Measured from contact screw on tab to center of die) (Measured from the drain lead 0.253 from package to center of die)	LD	—	3.5	—	nH
Internal Source Inductance (Measured from the source lead 0.253 from package to source bond pad)	LS	—	7.5	—	nH

(1) Pulse Test: Pulse Width δ 300 ∝s, Duty Cycle δ 2%.
(2) Switching characteristics are independent of operating junction temperature.
(3) Reflects typical values.

$$Cpk = \left| \frac{\text{Max limit – Typ}}{\text{3 x SIGMA}} \right|$$

TYPICAL ELECTRICAL CHARACTERISTICS

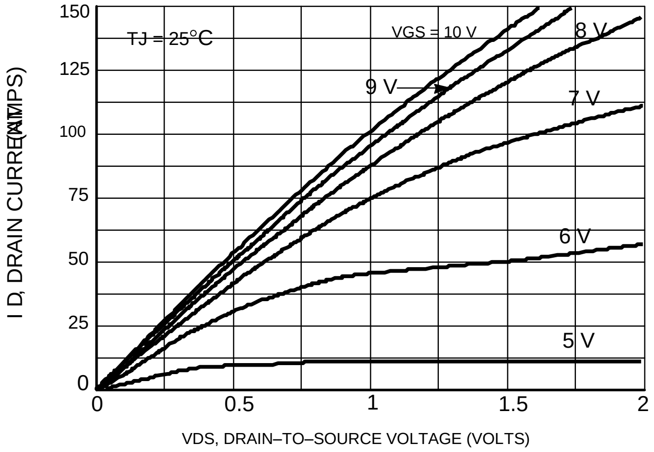


Figure 1. On–Region Characteristics

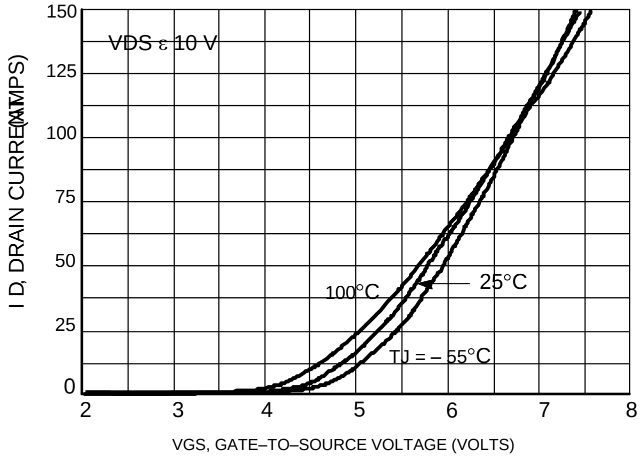


Figure 2. Transfer Characteristics

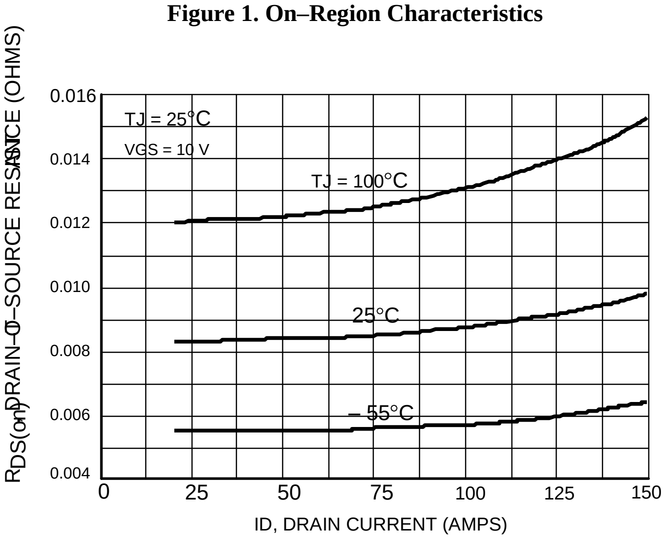


Figure 3. On–Resistance versus Drain Current and Temperature

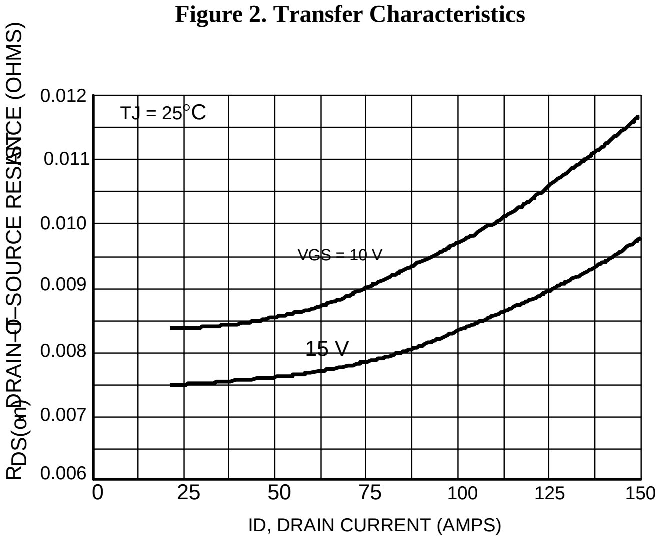


Figure 4. On–Resistance versus Drain Current and Gate Voltage

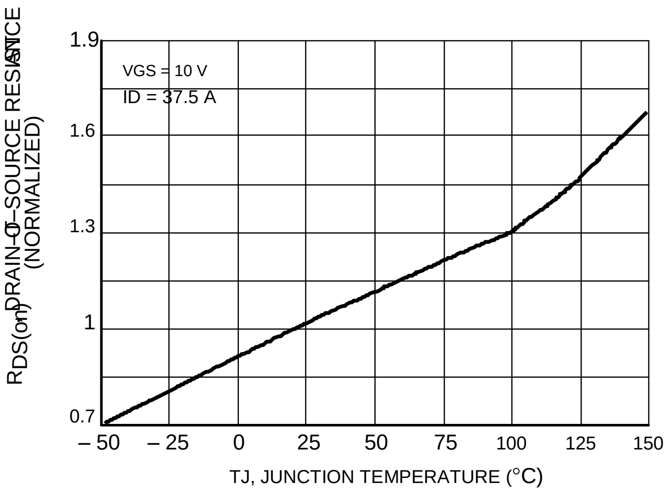


Figure 5. On–Resistance Variation with Temperature

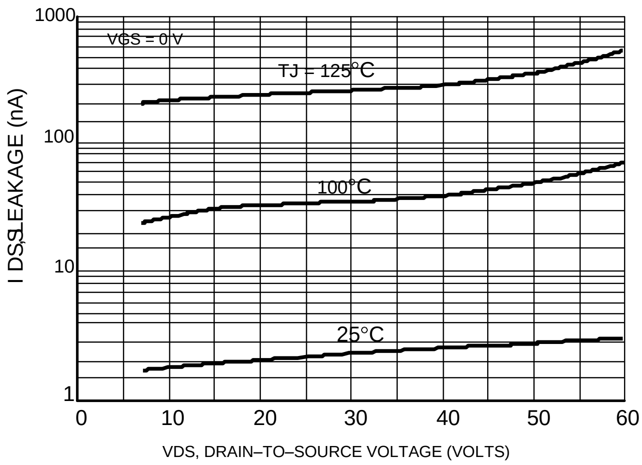


Figure 6. Drain–To–Source Leakage Current versus Voltage

POWER MOSFET SWITCHING

Switching behavior is most easily modeled and predicted by recognizing that the power MOSFET is charge controlled. The lengths of various switching intervals (Δt) are determined by how fast the FET input capacitance can be charged by current from the generator.

The published capacitance data is difficult to use for calculating rise and fall because drain–gate capacitance varies greatly with applied voltage. Accordingly, gate charge data is used. In most cases, a satisfactory estimate of average input current (IG(AV)) can be made from a rudimentary analysis of the drive circuit so that

t = Q/IG(AV)

During the rise and fall time interval when switching a resistive load, VGS remains virtually constant at a level known as the plateau voltage, VSGP. Therefore, rise and fall times may be approximated by the following:

tr = Q2 x RG/(VGG – VGSP)

tf = Q2 x RG/VGSP

where

VGG = the gate drive voltage, which varies from zero to VGG

RG = the gate drive resistance

and Q2 and VGSP are read from the gate charge curve.

During the turn–on and turn–off delay times, gate current is not constant. The simplest calculation uses appropriate values from the capacitance curves in a standard equation for voltage change in an RC network. The equations are:

td(on) = RG Ciss In [VGG/(VGG – VGSP)]

td(off) = RG Ciss In (VGG/VGSP)

The capacitance (Ciss) is read from the capacitance curve at a voltage corresponding to the off–state condition when calculating td(on) and is read at a voltage corresponding to the on–state when calculating td(off).

At high switching speeds, parasitic circuit elements complicate the analysis. The inductance of the MOSFET source lead, inside the package and in the circuit wiring which is common to both the drain and gate current paths, produces a voltage at the source which reduces the gate drive current. The voltage is determined by Ldi/dt, but since di/dt is a function of drain current, the mathematical solution is complex. The MOSFET output capacitance also complicates the mathematics. And finally, MOSFETs have finite internal gate resistance which effectively adds to the resistance of the driving source, but the internal resistance is difficult to measure and, consequently, is not specified.

The resistive switching time variation versus gate resistance (Figure 9) shows how typical switching performance is affected by the parasitic circuit elements. If the parasitics were not present, the slope of the curves would maintain a value of unity regardless of the switching speed. The circuit used to obtain the data is constructed to minimize common inductance in the drain and gate circuit loops and is believed readily achievable with board mounted components. Most power electronic loads are inductive; the data in the figure is taken with a resistive load, which approximates an optimally snubbed inductive load. Power MOSFETs may be safely operated into an inductive load; however, snubbing reduces switching losses.

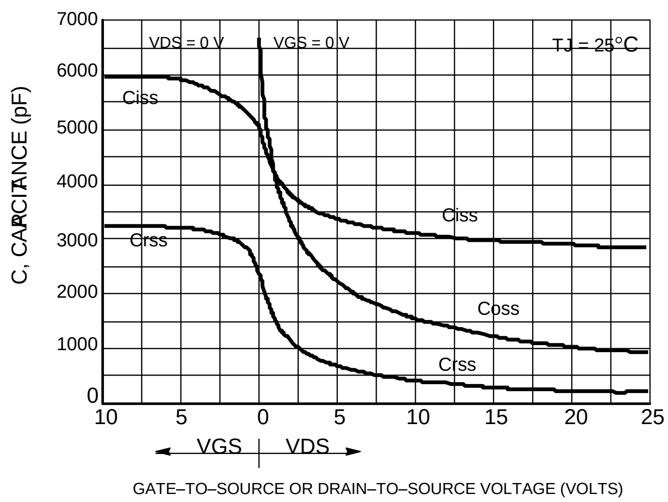


Figure 7. Capacitance Variation

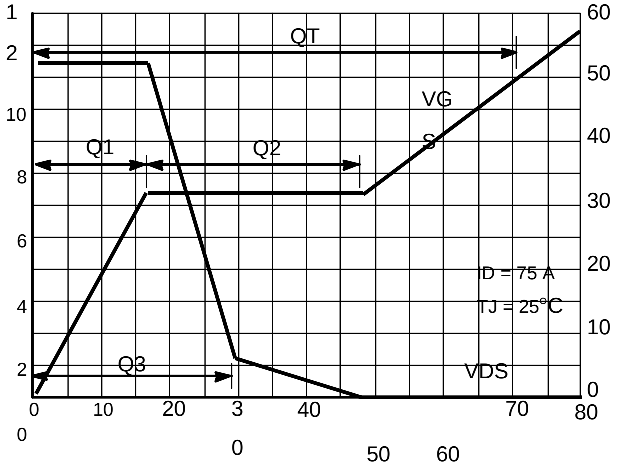


Figure 8. Gate–To–Source and Drain–To–Source Voltage versus Total Charge

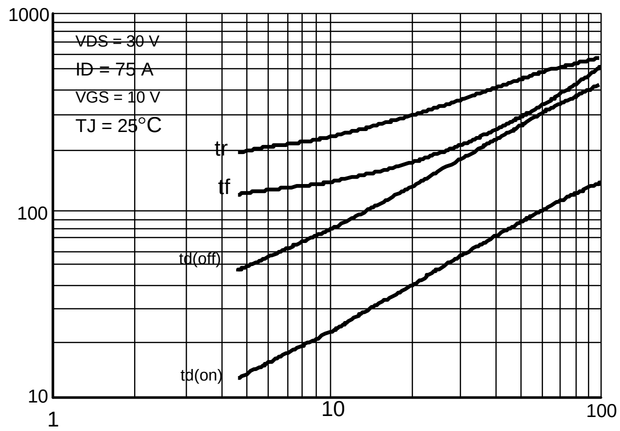


Figure 9. Resistive Switching Time Variation versus Gate Resistance

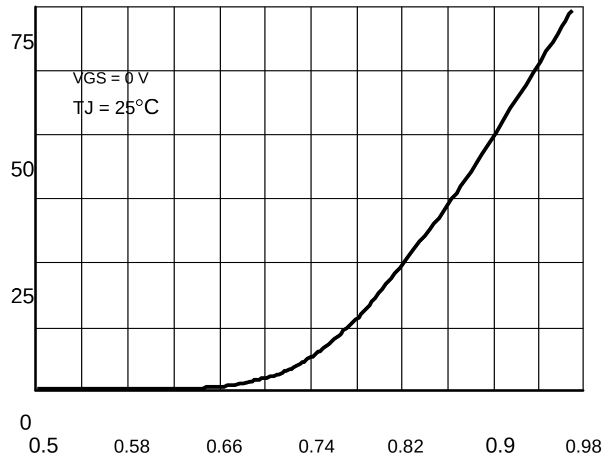
DRAIN–TO–SOURCE DIODE CHARACTERISTICS

The switching characteristics of a MOSFET body diode are very important in systems using it as a freewheeling or commutating diode. Of particular interest are the reverse recovery characteristics which play a major role in determining switching losses, radiated noise, EMI and RFI.

System switching losses are largely due to the nature of the body diode itself. The body diode is a minority carrier device, therefore it has a finite reverse recovery time, trr, due to the storage of minority carrier charge, QRR, as shown in the typical reverse recovery wave form of Figure 12. It is this stored charge that, when cleared from the diode, passes through a potential and defines an energy loss. Obviously, repeatedly forcing the diode through reverse recovery further increases switching losses. Therefore, one would like a diode with short trr and low QRR specifications to minimize these losses.

The abruptness of diode reverse recovery effects the amount of radiated noise, voltage spikes, and current ringing. The mechanisms at work are finite irremovable circuit parasitic inductances and capacitances acted upon by high di/dts. The diode's negative di/dt during ta is directly controlled by the device clearing the stored charge. However, the positive di/dt during tb is an uncontrollable diode characteristic and is usually the culprit that induces current ringing. Therefore, when comparing diodes, the ratio of tb/ta serves as a good indicator of recovery abruptness and thus gives a comparative estimate of probable noise generated. A ratio of 1 is considered ideal and values less than 0.5 are considered snappy.

Compared to Motorola standard cell density low voltage MOSFETs, high cell density MOSFET diodes are faster (shorter trr), have less stored charge and a softer reverse recovery characteristic. The softness advantage of the high cell density diode means they can be forced through reverse recovery at a higher di/dt than a standard cell MOSFET diode without increasing the current ringing or the noise generated. In addition, power dissipation incurred from switching the diode will be less due to the shorter recovery time and lower switching losses.



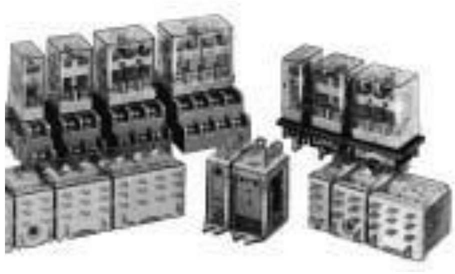
Appendix F

Relay datasheet

RH Series — General Purpose Midget Relays

Key features of the RH series include:

- **Compact midget size saves space**
- **High switching capacity (10A)**
- **Choice of blade or PCB style terminals**
- **Relay options include indicator light, check button, and top mounting bracket**
- **DIN rail, surface, panel, and PCB type sockets available for a wide range of mounting applications**



UL Recognized
Files No. RH1 = E66043
RH2 = E66043
RH3 = E66043
RH4 = E55996

CSA Certified
File No.LR35144

TÜV PRODUCT SERVICE
File No. B020813332452

CE

Specifications

Contact Material	Silver cadmium oxide
Contact Resistance	50m& maximum (initial value)
Minimum Applicable Load	24V DC/30mA, 5V DC/100mA (reference value)
Operating Time	SPDT (RH1), DPDT (RH2): 20ms maximum 3PDT (RH3), 4PDT (RH4): 25ms maximum
Release Time	SPDT (RH1), DPDT (RH2): 20ms maximum 3PDT (RH3), 4PDT (RH4): 25ms maximum
Maximum Continuous Applied Voltage (AC/DC) at 20°C	110% of the rated voltage
Minimum Operating Voltage (AC/DC) at 20°C	80% of the rated voltage
Drop-Out Voltage (AC)	30% or more of the rated voltage
Drop-Out Voltage (DC)	10% or more of the rated voltage
Power Consumption	**SPDT** (RH1): DC: 0.8W AC: 1.1VA (50Hz), 1VA (60Hz) **DPDT** (RH2): DC: 0.9W AC: 1.4VA (50Hz), 1.2VA (60Hz) **3PDT** (RH3): DC: 1.5W AC: 2VA (50Hz), 1.7VA (60Hz) **4PDT** (RH4): DC: 1.5W AC: 2.5VA (50Hz), 2VA (60Hz)
Insulation Resistance	100M& min (measured with a 500V DC megger)
Dielectric Strength	**SPDT** (RH1) Between live and dead parts: 2,000V AC, 1 minute; Between contact circuit and operating coil: 2,000V AC, 1 minute; Between contacts of the same pole: 1,000V AC, 1 minute **DPDT** (RH2), **3PDT** (RH3), **4PDT** (RH4) Between live and dead parts: 2,000V AC, 1 minute; Between contact circuit and operating coil: 2,000V AC, 1 minute; Between contact circuits: 2,000V AC, 1 minute; Between contacts of the same pole: 1,000V AC, 1 minute
Frequency Response	1,800 operations/hour
Temperature Rise	Coil: 85°C maximum Contact: 65°C maximum
Vibration Resistance	0 to 6G (55Hz maximum)
Shock Resistance	SPDT/DPDT: 200N (approximately 20G) 3PDT/4PDT: 100N (approximately 10G)
Life Expectancy	Electrical: over 500,000 operations at 120V AC, 10A; (over 200,000 operations at 120V AC, 10A for SPDT [RH1], 3PDT [RH3], 4PDT [RH4]) Mechanical: 50,000,000 operations
Operating Temperature	–30 to +70°C
Weight	

Order standard voltages for fastest delivery. Allow extra delivery time for non-standard voltages.

Basic Part No.	Coil Voltage:
RH2B-U	AC110-120V

Part Numbers

Part Numbers: RH Series with Options

Termination	Contact Configuration	Basic Part No.	Indicator Light	Check Button	Indicator Light and Check Button	Top Brac
B (blade)	SPDT	RH1B-U	RH1B-UL	RH1B-UC	RH1B-ULC	RH1B-UT
	DPDT	RH2B-U	RH2B-UL	RH2B-UC	RH2B-ULC	RH2B-UT
	3PDT	RH3B-U	RH3B-UL	RH3B-UC	RH3B-ULC	RH3B-UT
	4PDT	RH4B-U	RH4B-UL	RH4B-UC	RH4B-ULC	RH4B-UT
V2 (PCB 0.078" [2mm] wide)	SPDT	RH1V2-U	RH1V2-UL	RH1V2-UC	RH1V2-ULC	—
	DPDT	RH2V2-U	RH2V2-UL	RH2V2-UC	RH2V2-ULC	—
	3PDT	RH3V2-U	RH3V2-UL	RH3V2-UC	RH3V2-ULC	—
	4PDT	RH4V2-U	RH4V2-UL	RH4V2-UC	RH4V2-ULC	—

Ratings

E Relays

Coil Ratings

Rated Voltage		Rated Current ±15% at 20°C								Coil Resistance ±15% at 20°C			
		60Hz				50Hz							
		SPDT	DPDT	3PDT	4PDT	SPDT	DPDT	3PDT	4PDT	SPDT	DPDT	3PDT	4PDT
AC	6V	150mA	200mA	280mA	330mA	170mA	238mA	330mA	387mA	18.8&	9.4&	6.0&	5.4&
	12V	75mA	100mA	140mA	165mA	86mA	118mA	165mA	196mA	76.8&	39.3&	25.3&	21.2&
	24V	37mA	50mA	70mA	83mA	42mA	59.7mA	81mA	98mA	300&	153&	103&	84.5&
	120V*	7.5mA	11mA	14.2mA	16.5mA	8.6mA	12.9mA	16.4mA	19.5mA	7,680&	4,170&	2770&	2220&
	240V†	3.2mA	5.5mA	7.1mA	8.3mA	3.7mA	6.5mA	8.2mA	9.8mA	3,1200&	15,210&	12,100&	9120&
		SPDT		DPDT		3PDT		4PDT		SPDT	DPDT	3PDT	4PDT
DC	6V	128mA		150mA		240mA		250mA		47&	40&	25&	24&
	12V	64mA		75mA		120mA		125mA		188&	160&	100&	96&
	24V	32mA		36.9mA		60mA		62mA		750&	650&	400&	388&
	48V	18mA		18.5mA		30mA		31mA		2,660&	2,600&	1,600&	1550&
	110V‡	8mA		9.1mA		12.8mA		15mA		13,800&	12,100&	8,600&	7,340&

** For RH2 relays = 110/120V AC.*
† For RH2 relays = 220/240V AC.
‡ For RH2 relays = 100/110V DC.

Rated Voltage		Coil Inrush				Coil Inductance							
						Energizing				De-Energizing			
		SPDT	DPDT	3PDT	4PDT	SPDT	DPDT	3PDT	4PDT	SPDT	DPDT	3PDT	4PDT
AC	6V	250mA	340mA	520mA	620mA	0.09H	0.08H	0.05H	0.05H	0.06H	0.04H	0.03H	0.02H
	12V	120mA	170mA	260mA	310mA	0.037H	0.30H	0.22H	0.18H	0.22H	0.16H	0.12H	0.10H
	24V	56mA	85mA	130mA	165mA	1.5H	1.2H	0.9H	0.73H	0.9H	0.63H	0.5H	0.36H
	120V*	12mA	16mA	26mA	33mA	37H	33H	21H	18H	22H	15H	12H	9H
	240V†	7mA	8mA	12mA	16mA	130H	130H	84H	73H	77H	62H	47H	36H
		SPDT		DPDT		3PDT		4PDT		SPDT	DPDT	3PDT	4PDT
DC	6V, 12V, 24V, 48V, 110V	N/A		N/A		N/A		N/A		N/A	N/A	N/A	N/A

** For RH2 relays = 110/120V AC.*
† For RH2 relays = 220/240V AC.

Ratings con't

Contact Ratings

# of Poles	Max Contact Power		General Ratings		
	Resistive	Inductive	Voltage	Resistive	Inductive*
RH1	AC1540VA DC300W	AC990VA DC210W	AC110	10A	7A
			AC220	7A	4.5A
			DC30	10A	7A
RH2 RH3 RH4	AC1650VA DC300W	AC1100VA DC225W	AC110	10A	7.5A
			AC220	7.5A	5A
			DC30	10A	7.5A

**cosø = 0.3*
L/R - 7ms

UL Ratings

Voltage	Resistive			General Use			Horse Power Rating	
	RH1, RH2	RH3	RH4	RH1, RH2	RH3	RH4	RH1, RH2	RH3
AC240V	10A	7.5A	7.5A	7A	6.5A	5A	1/3HP	
AC120V	10A	10A	10A	7A	7.5A	7.5A	1/6HP	
DC30V	10A	10A	—	7A	—	—	—	—
DC28V	10A	10A	10A	7A	—	—	—	—

TUV Ratings

Voltage	RH1	RH2	RH3	RH4
AC240V	10A	10A	7.5A	7.5A
DC30V	10A	10A	10A	10A

CSA Ratings

Voltage	Resistive				General Use				HP Rating
	RH1	RH2	RH3	RH4	RH1	RH2	RH3	RH4	RH1, 2, 3
AC240V	10A	10A	—	7.5A	7A	7A	7A	5A	1/3HP
AC120V	10A	10A	10A	10A	7.5A	7.5A	—	7.5A	1/6HP
DC30V	10A	10A	10A	10A	7A	7.5A	—	—	—

Applicable Sockets

Part Numbers: Sockets

Relay	Standard DIN	Finger-Safe DIN Rail Mount	Surface Mount	Panel Mount	PCB Mount
RH1B	SH1B-05	SH1B-05C	—	SH1B-51	SH1B-62
RH2B	SH2B-05	SH2B-05C	SH2B-02	SH2B-51	SH2B-62
RH3B	SH3B-05	SH3B-05C	—	SH3B-51	SH3B-62
RH4B	SH4B-05	SH4B-05C		SH4B-51	SH4B-62

Spring & Clips (optional)	
SY2S-02F1③ SFA-101① SFA-202②	SH1B-05, 05C
SY4S-51F1③ SFA-301① SFA-302②	SH1B-51, 62
SY4S-02F1③ SFA-101① SFA-202②	SH2B-05, 05C
SY4S-51F1③ SFA-301① SFA-302②	SH2B-51, 62
SH3B-05F1③ SFA-101①, -202②	SH3B-05, 05C
SY4S-51F1③ SFA-301① SFA-302②	SH3B-51, 62
SH4B-02F1③ SFA-101①, -202②	SH4B-05, 05C
SY4S-51F1③ SFA-301① SFA-302②	SH4B-51, 62

See Section F for details on sockets. All DIN rail mount sockets shown above can be mounted using DIN rail BNDN1000.

① *Top latch*
② *Side latch*
③ *Pullover spring*

Internal Circuits

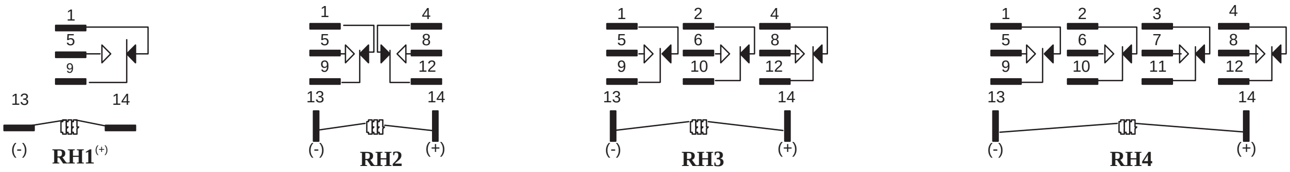
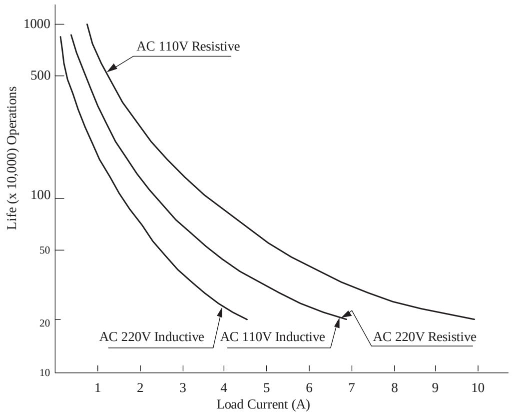
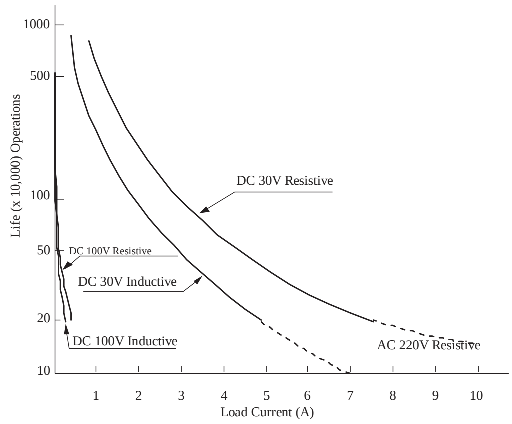


Image as viewed from bottom of relay. Refer to socket for exact wiring layout (Section F).

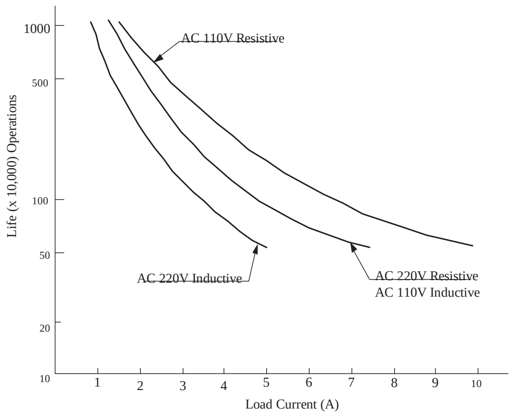
Electrical Life Curves

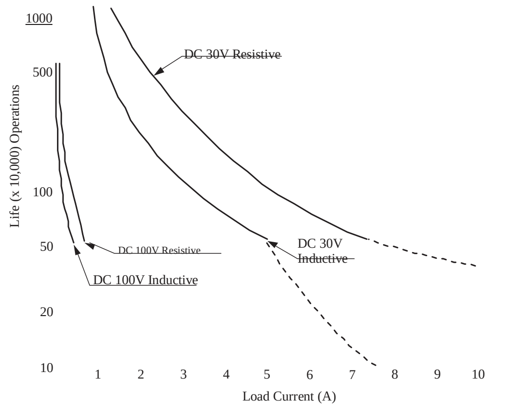
RH1



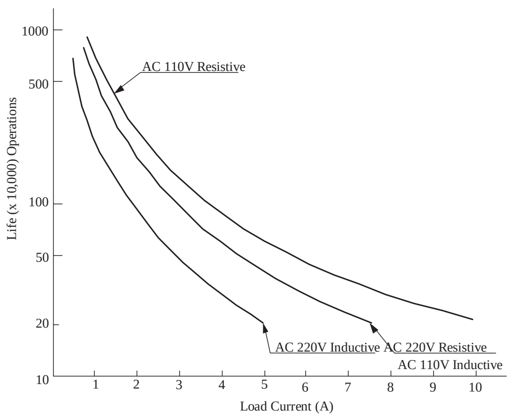


RH2

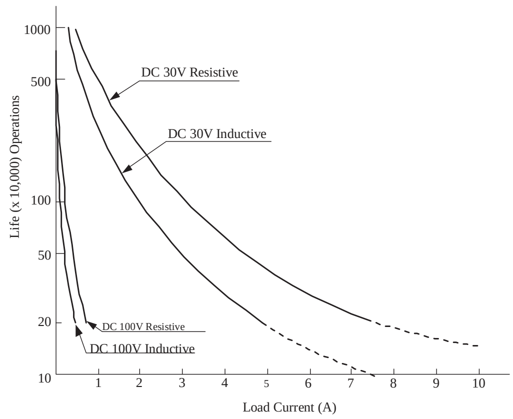




RH3

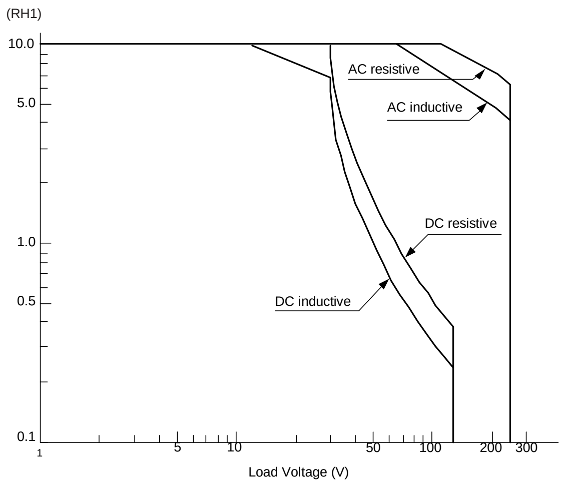


RH4

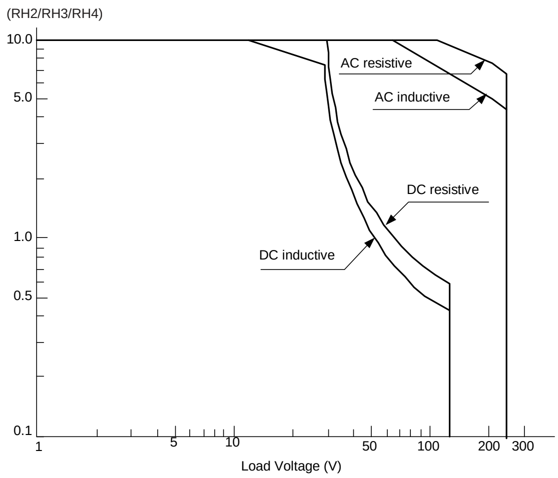


Maximum Switching Capacity

RH1



RH2/RH3/RH4

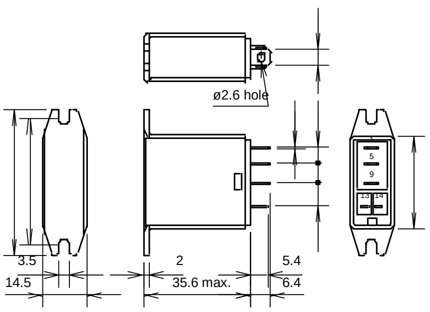


Dimensions

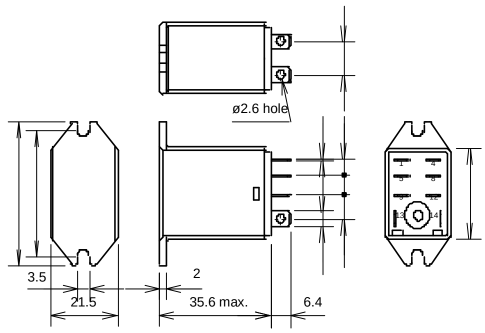
Top Bracket Mounting

Blade Terminal

RH1B-UT

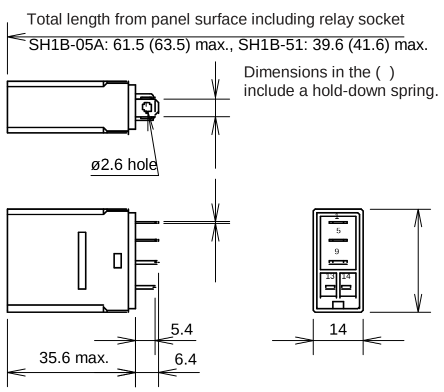


RH2B-UT

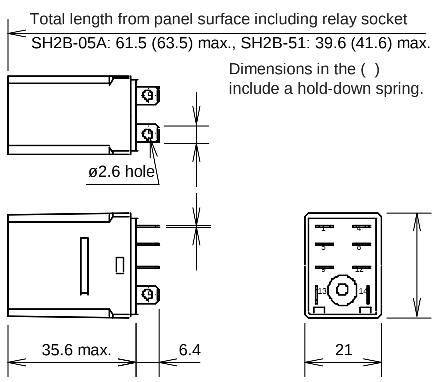


Plug-in Blade Terminal

RH1B



RH2B



All dimensions in mm.

Appendix G

7805 datasheet

FAIRCHILD
SEMICONDUCTOR®

KA78XX/KA78XXA

3-Terminal 1A Positive Voltage Regulator

Features

- Output Current up to 1A
- Output Voltages of 5, 6, 8, 9, 10, 12, 15, 18, 24V
- Thermal Overload Protection
- Short Circuit Protection
- Output Transistor Safe Operating Area Protection

Description

The KA78XX/KA78XXA series of three-terminal positive regulator are available in the TO-220/D-PAK package and with several fixed output voltages, making them useful in a wide range of applications. Each type employs internal current limiting, thermal shut down and safe operating area protection, making it essentially indestructible. If adequate heat sinking is provided, they can deliver over 1A output current. Although designed primarily as fixed voltage regulators, these devices can be used with external components to obtain adjustable voltages and currents.

TO-220

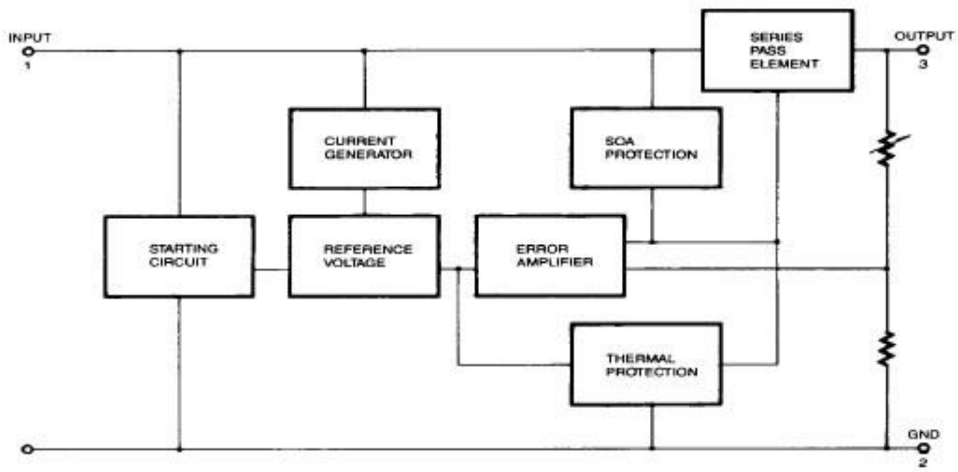
1

D-PAK

1

1. Input 2. GND 3. Output

Internal Block Digram



Rev. 1.0.0

Absolute Maximum Ratings

Parameter	Symbol	Value	Unit
Input Voltage (for VO = 5V to 18V) (for VO = 24V)	VI VI	35 40	V V
Thermal Resistance Junction-Cases (TO-220)	R\ϑX	5	°C/W
Thermal Resistance Junction-Air (TO-220)	R\ϑA	65	°C/W
Operating Temperature Range (KA78XX/A/R)	TOPR	0 ~ +125	°C
Storage Temperature Range	TSTG	-65 ~ +150	°C

Electrical Characteristics (KA7805/KA7805R)

(Refer to test circuit ,0°C < TJ < 125°C, IO = 500mA, VI =10V, CI= 0.33µF, CO=0.1µF, unless otherwise specified)

Parameter	Symbol	Conditions		KA7805 Min.	Typ.	Max.	Unit
Output Voltage	VO	TJ =+25 oC		4.8	5.0	5.2	V
		5.0mA ≤ Io ≤ 1.0A, PO ≤ 15W VI = 7V to 20V		4.75	5.0	5.25	
Line Regulation (Note1)	Regline	TJ=+25 oC	VO = 7V to 25V	-	4.0	100	mV
			VI = 8V to 12V	-	1.6	50	
Load Regulation (Note1)	Regload	TJ=+25 oC	IO = 5.0mA to1.5A	-	9	100	mV
			IO =250mA to 750mA	-	4	50	
Quiescent Current	IQ	TJ =+25 oC		-	5.0	8.0	mA
Quiescent Current Change	□IQ	IO = 5mA to 1.0A		-	0.03	0.5	mA
		VI= 7V to 25V		-	0.3	1.3	
Output Voltage Drift	□çO/ΔT	IO= 5mA		-	-0.8	-	mV/ oC
Output Noise Voltage	VN	f = 10Hz to 100KHz, TA=+25 oC		-	42	-	∝ç/çO
Ripple Rejection	RR	f = 120Hz VO = 8V to 18V		62	73	-	dB
Dropout Voltage	VDrop	IO = 1A, TJ =+25 oC		-	2	-	V
Output Resistance	rO	f = 1KHz		-	15	-	mΩ
Short Circuit Current	ISC	VI = 35V, TA =+25 oC		-	230	-	mA
Peak Current	IPK	TJ =+25 oC		-	2.2	-	A

Note:

1. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.

Electrical Characteristics (KA7805A)

(Refer to the test circuits. 0oC < TJ < +125 oC, Io =1A, V I = 10V, C I=0.33µF, C O=0.1µF, unless otherwise specified)

Parameter	Symbol	Conditions	Min.	Typ.	Max.	Unit
Output Voltage	VO	TJ =+25 oC	4.9	5	5.1	V
		IO = 5mA to 1A, PO δ 15W VI = 7.5V to 20V	4.8	5	5.2	
Line Regulation (Note1)	Regline	VI = 7.5V to 25V IO = 500mA	-	5	50	mV
		VI = 8V to 12V	-	3	50	
		TJ =+25 oC, VI= 7.3V to 20V	-	5	50	
		TJ =+25 oC, VI= 8V to 12V	-	1.5	25	
Load Regulation (Note1)	Regload	TJ =+25 oC IO = 5mA to 1.5A	-	9	100	mV
		IO = 5mA to 1A	-	9	100	
		IO = 250mA to 750mA	-	4	50	
Quiescent Current	IQ	TJ =+25 oC	-	5.0	6.0	mA
Quiescent Current Change	□IQ	IO = 5mA to 1A	-	-	0.5	mA
		VI = 8 V to 25V, IO = 500mA	-	-	0.8	
		VI = 7.5V to 20V, TJ =+25 oC	-	-	0.8	
Output Voltage Drift	□ç/□T	Io = 5mA	-	-0.8	-	mV/ oC
Output Noise Voltage	VN	f = 10Hz to 100KHz TA =+25 oC	-	10	-	∝ç/ço
Ripple Rejection	RR	f = 120Hz, IO = 500mA VI = 8V to 18V	-	68	-	dB
Dropout Voltage	VDrop	IO = 1A, TJ =+25 oC	-	2	-	V
Output Resistance	rO	f = 1KHz	-	17	-	mΩ
Short Circuit Current	ISC	VI= 35V, TA =+25 oC	-	250	-	mA
Peak Current	IPK	TJ= +25 oC	-	2.2	-	A

Note:

1. Load and line regulation are specified at constant junction temperature. Change in VO due to heating effects must be taken into account separately. Pulse testing with low duty is used.

Typical Perfomance Characteristics

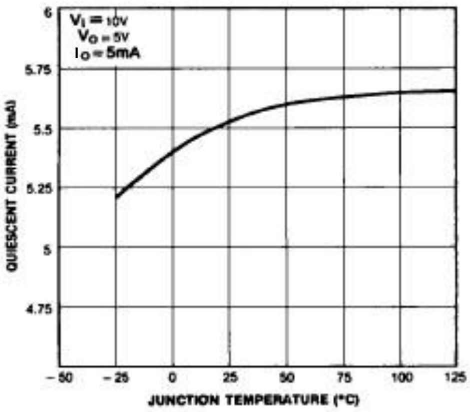


Figure 1. Quiescent Current

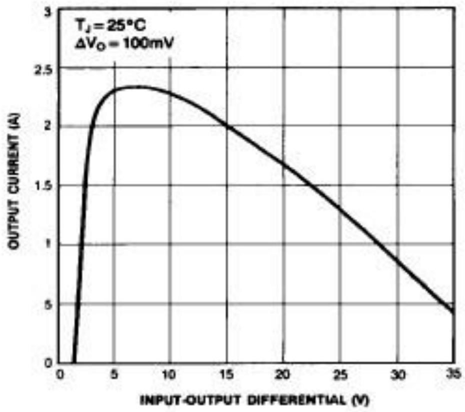


Figure 2. Peak Output Current

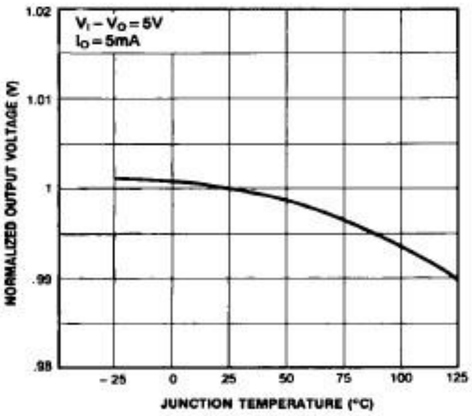


Figure 3. Output Voltage

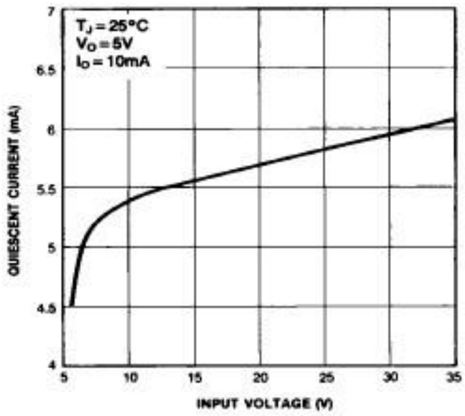
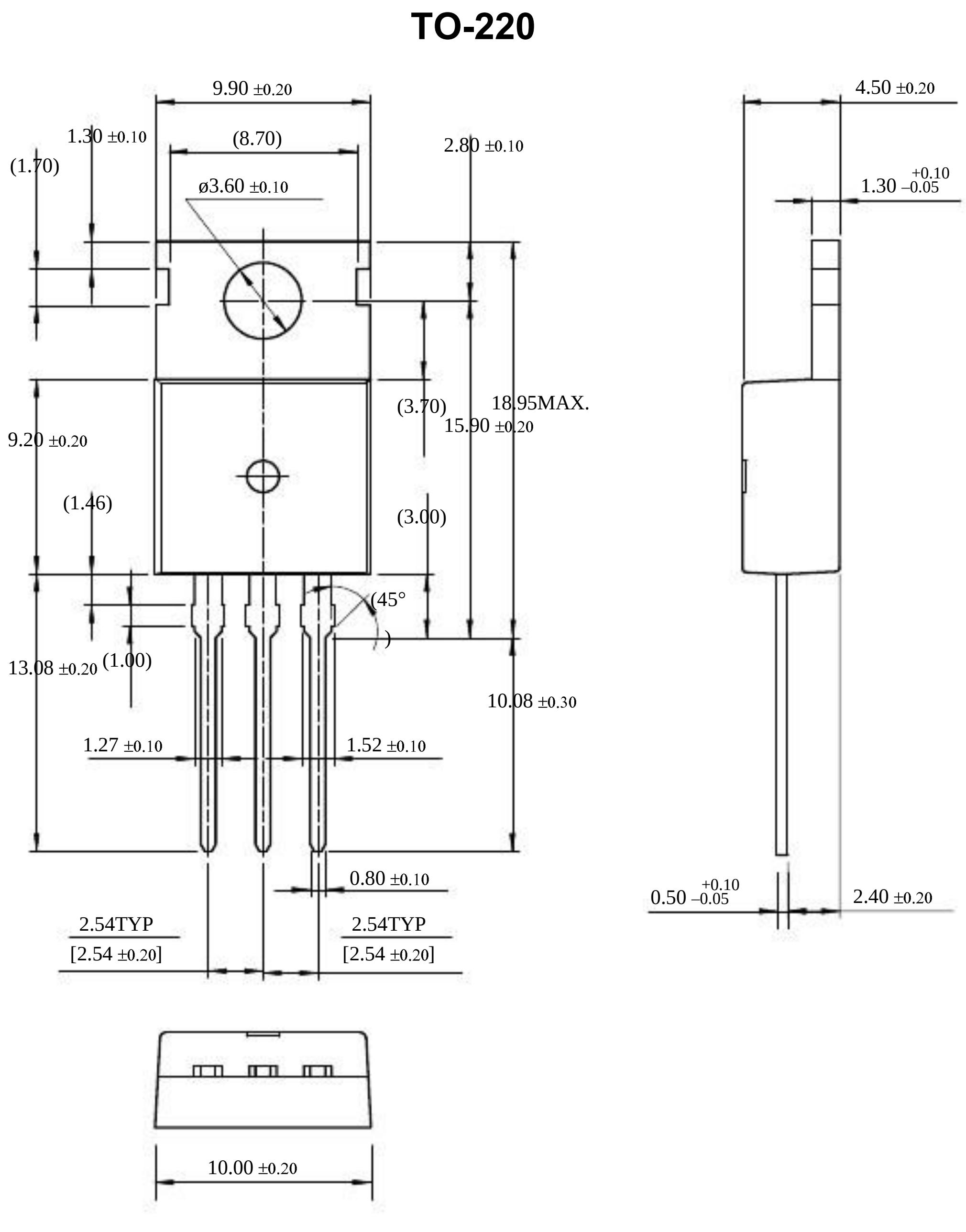


Figure 4. Quiescent Current

Mechanical Dimensions

Package



Appendix H

7809 datasheet

KA78XX/KA78XXA

3-Terminal 1A Positive Voltage Regulator

Features

- Output Current up to 1A
- Output Voltages of 5, 6, 8, 9, 10, 12, 15, 18, 24V
- Thermal Overload Protection
- Short Circuit Protection
- Output Transistor Safe Operating Area Protection

Description

The KA78XX/KA78XXA series of three-terminal positive regulator are available in the TO-220/D-PAK package and with several fixed output voltages, making them useful in a wide range of applications. Each type employs internal current limiting, thermal shut down and safe operating area protection, making it essentially indestructible. If adequate heat sinking is provided, they can deliver over 1A output current. Although designed primarily as fixed voltage regulators, these devices can be used with external components to obtain adjustable voltages and currents.

TO-220

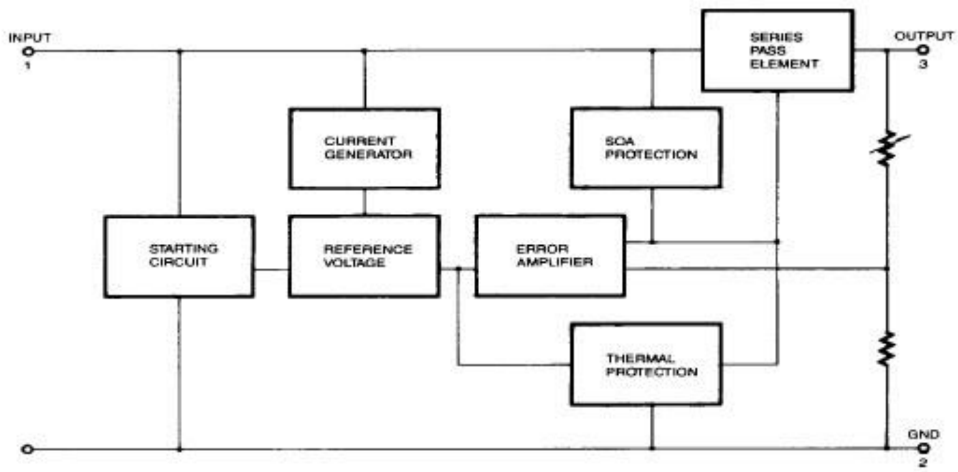
1

D-PAK

1

1. Input 2. GND 3. Output

Internal Block Digram



Rev. 1.0.0

Electrical Characteristics (KA7809/KA7809R)

(Refer to test circuit ,0°C < TJ < 125°C, IO = 500mA, VI =15V, CI= 0.33µF, CO=0.1µF, unless otherwise specified)

Parameter	Symbol	Conditions		KA7809 Min.	KA7809 Typ.	KA7809 Max.	Unit
Output Voltage	VO	TJ =+25 °C		8.65	9	9.35	V
		5.0mA≤ IO δ1.0A, PO δ15Ω VI= 11.5V to 24V		8.6	9	9.4	
Line Regulation (Note1)	Regline	TJ=+25 °C	VI = 11.5V to 25V	-	6	180	mV
			VI = 12V to 17V	-	2	90	
Load Regulation (Note1)	Regload	TJ=+25 °C	IO = 5mA to 1.5A	-	12	180	mV
			IO = 250mA to 750mA	-	4	90	
Quiescent Current	IQ	TJ=+25 °C		-	5.0	8.0	mA
Quiescent Current Change	□IQ	IO = 5mA to 1.0A		-	-	0.5	mA
		VI = 11.5V to 26V		-	-	1.3	
Output Voltage Drift	□çO/ΔT	IO = 5mA		-	-1	-	mV/ °C
Output Noise Voltage	VN	f = 10Hz to 100KHz, TA =+25 °C		-	58	-	∝ç/ço
Ripple Rejection	RR	f = 120Hz VI = 13V to 23V		56	71	-	dB
Dropout Voltage	VDrop	IO = 1A, TJ=+25 °C		-	2	-	V
Output Resistance	rO	f = 1KHz		-	17	-	mΩ
Short Circuit Current	ISC	VI= 35V, TA =+25 °C		-	250	-	mA
Peak Current	IPK	TJ= +25 °C		-	2.2	-	A

Note:

1. Load and line regulation are specified at constant junction temperature. Changes in VO due to heating effects must be taken into account separately. Pulse testing with low duty is used.

Electrical Characteristics (KA7809A)

(Refer to the test circuits. 0_oC < TJ < +125 $_oC$, Io =1A, V I = 15V, C I=0.33µF, C O=0.1µF, unless otherwise specified)

Parameter	Symbol	Conditions		Min.	Typ.	Max.	Unit
Output Voltage	VO	TJ =+25◦C		8.82	9.0	9.18	V
		IO = 5mA to 1A, POδ15Ω VI = 11.2V to 24V		8.65	9.0	9.35	
Line Regulation (Note1)	Regline	VI= 11.7V to 25V IO = 500mA		-	6	90	mV
		VI= 12.5V to 19V		-	4	45	
		TJ =+25◦C	VI= 11.5V to 24V	-	6	90	
			VI= 12.5V to 19V	-	2	45	
Load Regulation (Note1)	Regload	TJ =+25◦C IO = 5mA to 1.0A		-	12	100	mV
		IO = 5mA to 1.0A		-	12	100	
		IO = 250mA to 750mA		-	5	50	
Quiescent Current	IQ	TJ =+25 ◦C		-	5.0	6.0	mA
Quiescent Current Change	□IQ	VI = 11.7V to 25V, TJ=+25 ◦C		-	-	0.8	mA
		VI = 12V to 25V, IO = 500mA		-	-	0.8	
		IO = 5mA to 1.0A		-	-	0.5	
Output Voltage Drift	□ç/□T	IO = 5mA		-	-1.0	-	mV/ ◦C
Output Noise Voltage	VN	f = 10Hz to 100KHz TA =+25 ◦C		-	10	-	∝ç/ço
Ripple Rejection	RR	f = 120Hz, IO = 500mA VI = 12V to 22V		-	62	-	dB
Dropout Voltage	VDrop	IO = 1A, TJ =+25 ◦C		-	2.0	-	V
Output Resistance	rO	f = 1KHz		-	17	-	mΩ
Short Circuit Current	ISC	VI= 35V, TA =+25 ◦C		-	250	-	mA
Peak Current	IPK	TJ=+25◦C		-	2.2	-	A

Note:

1. Load and line regulation are specified at constant junction temperature. Change in VO due to heating effects must be taken into account separately. Pulse testing with low duty is used.

Typical Applications

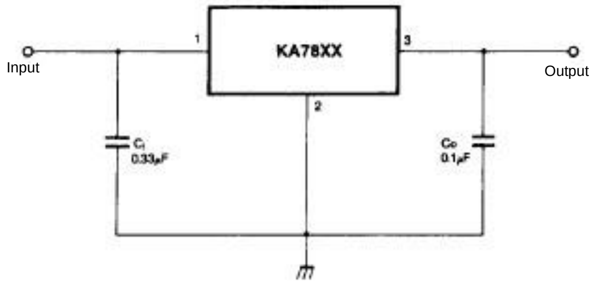


Figure 5. DC Parameters

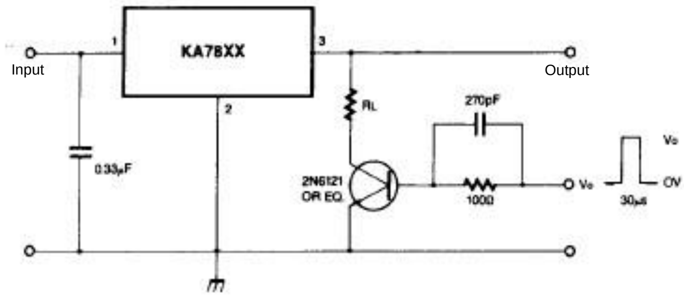


Figure 6. Load Regulation

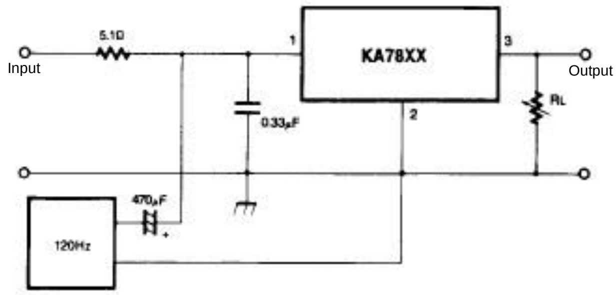


Figure 7. Ripple Rejection

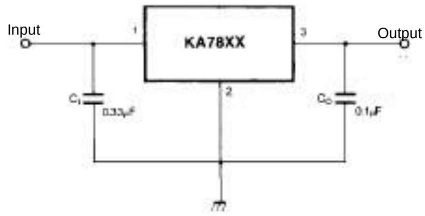
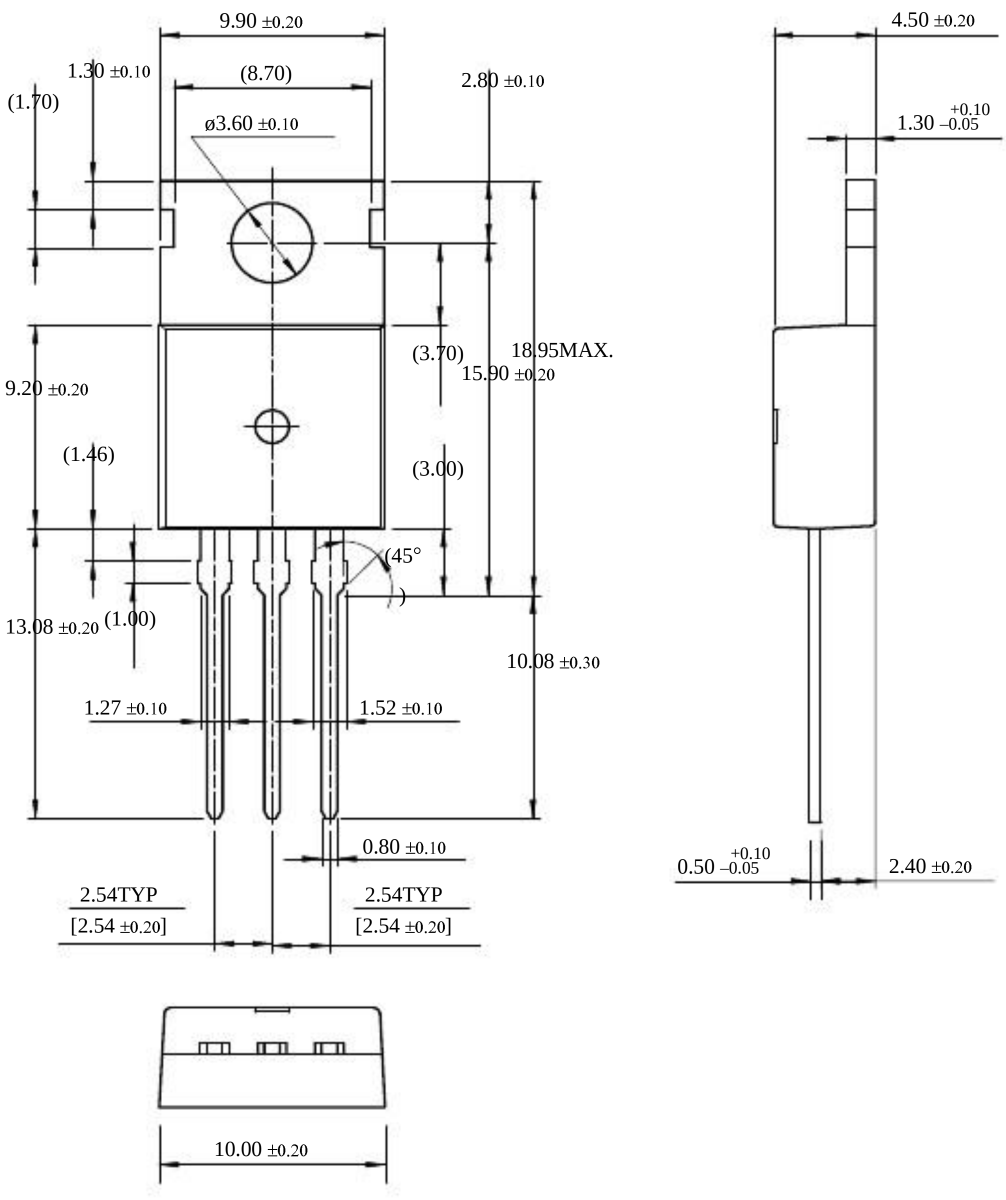


Figure 8. Fixed Output Regulator

Mechanical Dimensions

Package

TO-220



Appendix I

PICAXE Pin-outs and labels

At a glance - pinout diagrams:

PICAXE-08M

+V	1	8	0V
Serial In	2	7	Out 0 / Serial Out / Infraout
ADC 4 / Out 4 / In 4	3	6	In 1 / Out 1 / ADC 1
Infrain / In 3	4	5	In 2 / Out 2 / ADC 2 / pwm 2 / tune

PICAXE-14M

+V	1	14	0V
Serial In	2	13	Output 0 / Serial Out / Infraout
ADC 4 / Input 4	3	12	Output 1
Infrain / Input 3	4	11	Output 2
Input 2	5	10	Output 3
Input 1	6	9	Output 4
ADC 0 / Input 0	7	8	Output 5

PICAXE-18M

ADC 2 / Input 2	1	18	Input 1 / ADC 1
Serial Out	2	17	Input 0 / ADC 0 / Infrain
Serial In	3	16	Input 7 / keyboard data
Reset	4	15	Input 6 / keyboard clock
0V	5	14	+V
Output 0 / infraout	6	13	Output 7
Output 1	7	12	Output 6
Output 2	8	11	Output 5
Output 3 / pwm 3	9	10	Output 4

PICAXE-20M

+V	1	20	0V
Serial In	2	19	Serial Out
ADC 7 / Input 7	3	18	Output 0 / Infraout
Input 6	4	17	Output 1
Input 5	5	16	Output 2
Input 4	6	15	Output 3
ADC 3 / Input 3	7	14	Output 4
ADC 2 / Input 2	8	13	Output 5
ADC 1 / Input 1	9	12	Output 6
Infrain / Input 0	10	11	Output 7

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PICAXE-18X

ADC 2 / Input 2	1	18	Input 1 / ADC 1
Serial Out	2	17	Input 0 / ADC 0 / Infrain
Serial In	3	16	Input 7 / keyboard data
Reset	4	15	Input 6 / keyboard clock
0V	5	14	+V
Output 0	6	13	Output 7
i2c sda / Output 1	7	12	Output 6
Output 2	8	11	Output 5
pwm 3 / Output 3	9	10	Output 4 / i2c scl

PICAXE-28X1

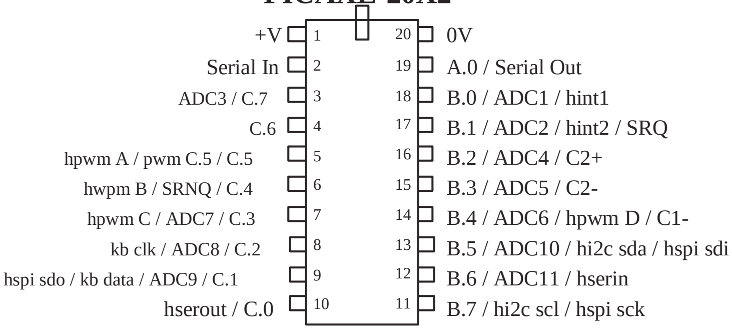
Reset	1	28	Output 7
ULPWU / ADC 0 / In a0	2	27	Output 6
ADC 1 / In a1	3	26	Output 5
ADC 2 / In a2	4	25	Output 4 / hpwm D
ADC 3 / In a3	5	24	Output 3
Serial In	6	23	Output 2 / hpwm B
Serial Out	7	22	Output 1 / hpwm C
0V	8	21	Output 0
Resonator	9	20	+V
Resonator	10	19	0V
timer clk / Out c0 / In 0	11	18	In 7 / Out c7 / hserin / kb data
pwm 1 / Out c1 / In 1	12	17	In 6 / Out c6 / hserout / kb clk
hpwm A / pwm 2 / Out c2 / In 2	13	16	In 5 / Out c5 / spi sdo
spi sck / i2c scl / Out c3 / In 3	14	15	In 4 / Out c4 / i2c sda / spi sdi

PICAXE-40X1

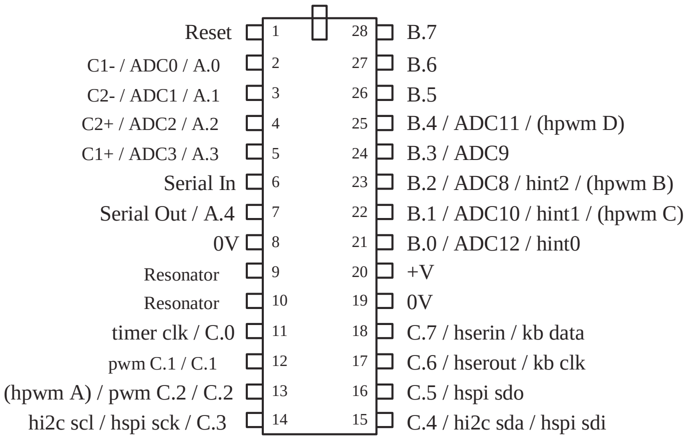
Reset	1	40	Output 7
ULPWU / ADC 0 / In a0	2	39	Output 6
ADC 1 / In a1	3	38	Output 5
ADC 2 / In a2	4	37	Output 4
ADC 3 / In a3	5	36	Output 3
Serial In	6	35	Output 2
Serial Out	7	34	Output 1
ADC 5	8	33	Output 0
ADC 6	9	32	+V
ADC 7	10	31	0V
+V	11	30	Input 7 / kb data
0V	12	29	Input 6 / kb clk
Resonator	13	28	Input 5
Resonator	14	27	Input 4
timer clk / Out c0 / In c0	15	26	In c7 / Out c7 / hserin
pwm 1 / Out c1 / In c1	16	25	In c6 / Out c6 / hserout
pwm 2 / Out c2 / In c2	17	24	In c5 / Out c5 / spi sdo
i2c scl / spi sck / Out c3 / In c3	18	23	In c4 / Out c4 / i2c sda / spi sdi
Input 0	19	22	Input 3
Input 1	20	21	Input 2

At a glance - pinout diagrams (X2 parts):

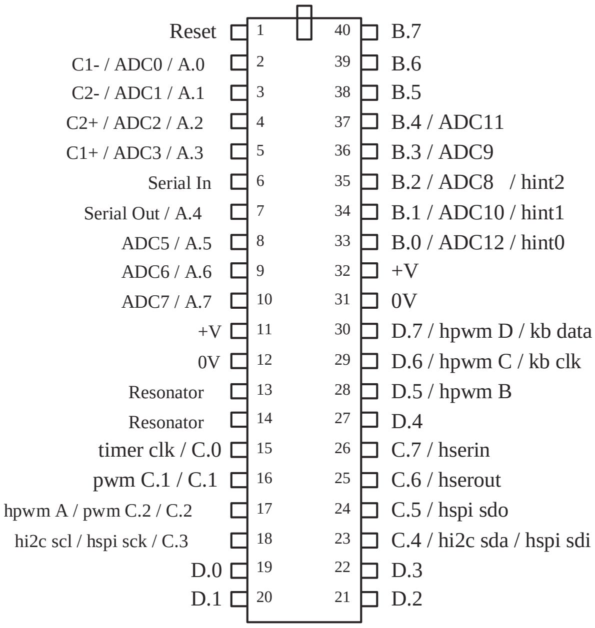
PICAXE-20X2



PICAXE-28X2



PICAXE-40X2



Appendix J

PICAXE Program

Note; for complete code description with commenting see the relevant section in chapter six (6.5.1).

```
high 0

main:
pulsin 1,1,b1
pulsin 2,1,b2

; determine whether device is to drive forwards, reverse or stop
; b4 = 1 for forwards; 0 for stopped; 2 for reverse



if b1>165 then
b4=1
else if b1<135 then
b4=2
else
b4=0
endif

; determine whether left or right is selected

if b2>165 then
b5=1
else if b2<135 then
b5=2
else
b5=0
endif

; stoped right
if b4 =0 and b5 = 1 then
low 1
high 2
low 6
low 7

; stoped left
elseif b4 =0 and b5 = 2 then
high 1
low 2
low 6
low 7

;stopped stopped
elseif b4 =0 and b5 = 0 then
low 1
low 2
low 6
low 7
```

```
;forward forward

elseif b4=1 and b5 = 0 then
high 1
high 2
low 6
low 7


;forward right


elseif b4 =1 and b5 = 1 then
low 1
high 2
low 6
low 7


;forward left


elseif b4 =1 and b5 = 2 then
high 1
low 2
low 6
low 7


;reverse reverse

elseif b4=2 and b5 = 0 then
high 1
high 2
high 6
high 7


;reverse right


elseif b4 =2 and b5 = 1 then
low 1
high 2
high 6
high 7
```

```
;reverse left


elseif b4 =2 and b5 = 2 then
high 1
low 2
high 6
high 7
endif


goto main
```