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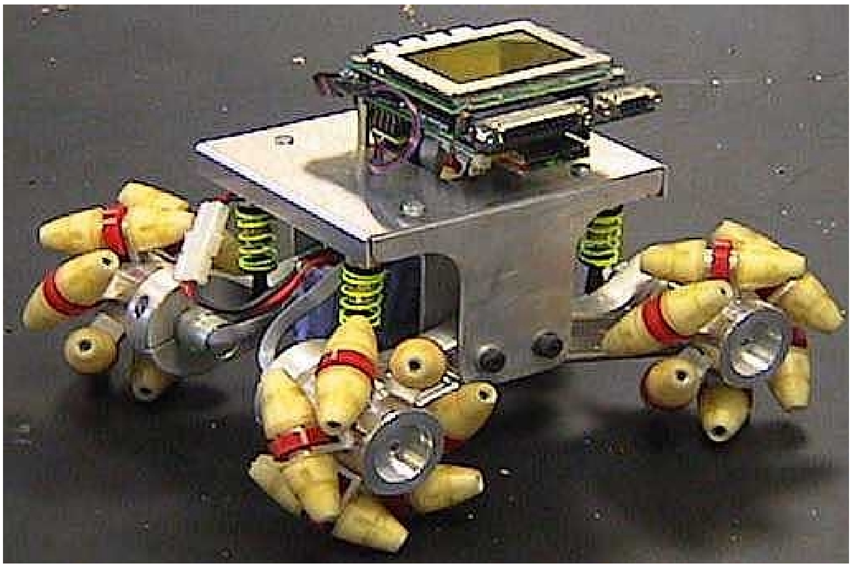
THE UNIVERSITY OF WESTERN AUSTRALIA

DEPARTMENT OF MECHANICAL AND MATERIALS ENGINEERING

Final Year Thesis 2001

Design and Construction of a Robot Vehicle Chassis



Andrew McCandless

Supervisor: Dr Nathan Scott

LETTER OF TRANSMITTAL

Andrew McCandless
171 Derby Road
SHENTON PARK WA 6008

5 November 2001

Professor B. H. Brady
Executive Dean
Faculty of Engineering and Mathematical Sciences
University of Western Australia
CRAWLEY WA 6009

Dear Sir,

Final Year Thesis

It is with great pleasure that I submit this thesis entitled *"Design and Construction of a Robot Vehicle Chassis"* to the University of Western Australia as a requirement for a Degree in Mechanical Engineering.

Yours sincerely,

Andrew McCandless

SYNOPSIS

Omni directional vehicles have been studied and developed quite extensively in a number of robotics laboratories around the world. Such vehicles are characterised by the ability to move sideways and spin on the spot. Their extra maneuverability enables them to navigate through narrow hallways, turn sharp corners and sidestep obstacles.

The Centre for Intelligent Information Processing Systems (CIIPS) developed an omni-directional robot vehicle to develop software for navigating a maze, playing robot soccer etc. Given the above abilities, this type of vehicle is well suited to these tasks. After building the first chassis, the performance of the vehicle was observed to be less than satisfactory, affecting the scope of the research and development that was possible. The design and construction of a second chassis was commissioned so that further research could be conducted. Once complete, tests were carried out showing an improvement in performance over a wide range of surfaces.

This thesis describes the methodology used in the design and construction of the second chassis, as well as a performance evaluation of the finished product.

EXECUTIVE SUMMARY

This thesis discusses the processes developed and considerations involved with the design and construction of an omni-directional, robot vehicle chassis. The work was conducted in collaboration with the Centre for Intelligent Information Processing Systems and the University of Western Australia Mechanical Engineering workshop. For the purpose of software development, this chassis enables the robot vehicle to travel in all directions and turn on the spot via the use of mechanum wheels. The specifications and performance characteristics are as follows.

Length	260mm
Height (without controller)	120mm
Height (with controller)	160mm
Width	220mm
Mass	2.85kg
Longitudinal velocity	0.27m/s
Transverse velocity	0.19m/s
Rotational velocity	1.46rad/s

ACKNOWLEDGEMENTS

The successful completion of this project would not have been possible without assistance from the following people, who I would like to sincerely thank,

To Dr Nathan Scott, for his unlimited enthusiasm, unique open-mindedness and dedicated supervision.

To Ian Hamilton, Chris Ballan, Dennis Brown, Mike Cowell and Brian Sambell of the Mechanical Engineering workshop, for their time and effort during the manufacture of the chassis.

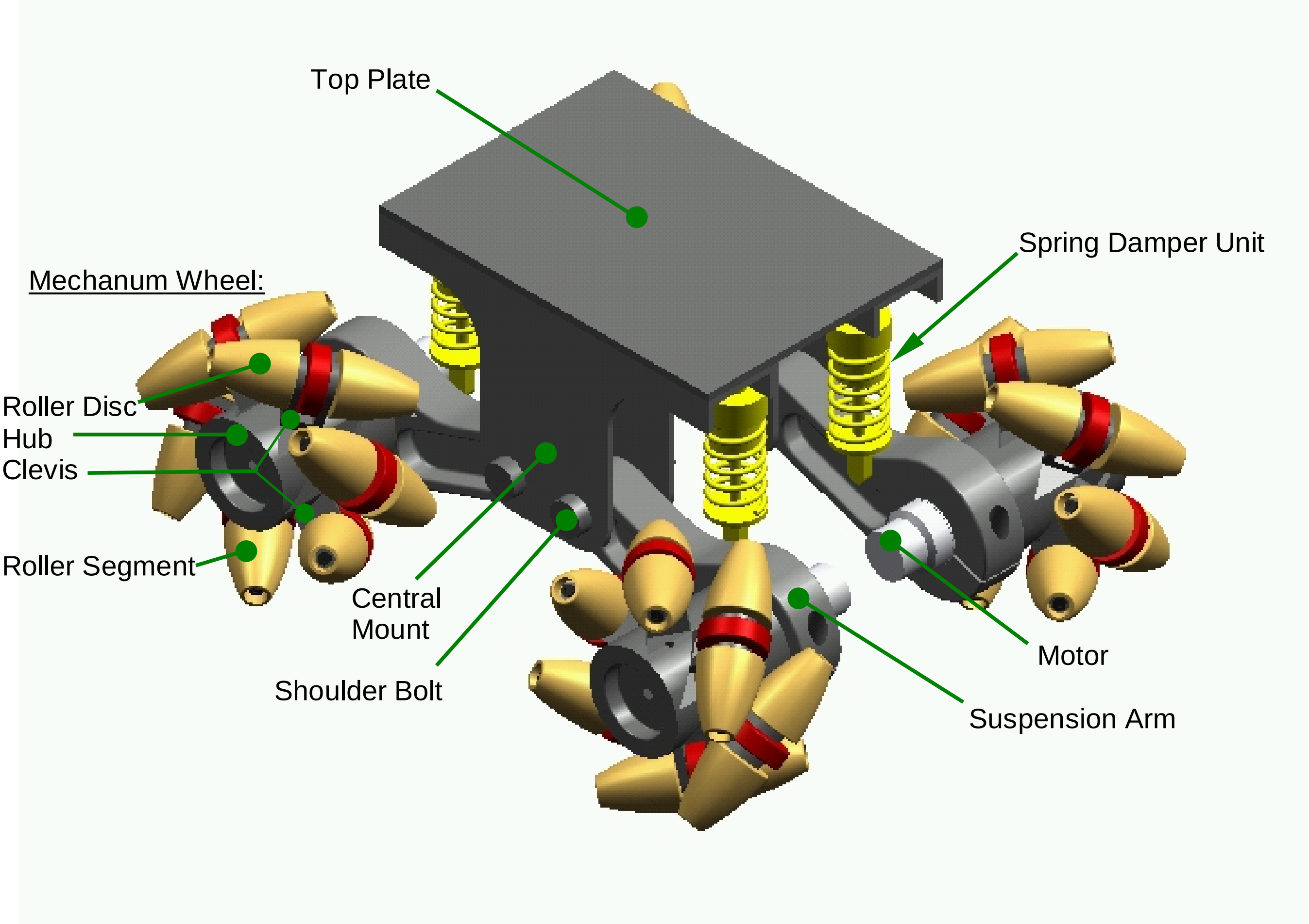
To Anna McLean, for her companionship, comradeship and tolerance over the months and months of countless late nights.

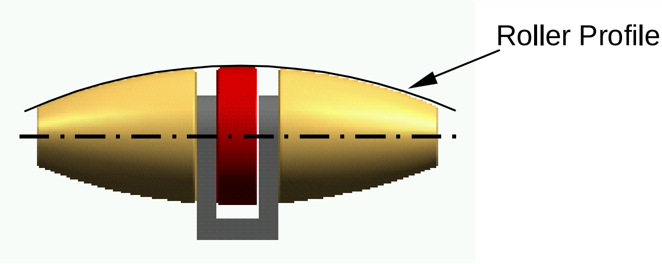
To Tegan Douglas, for her support and editing assistance during the final stages of the thesis.

To my Parents, David and Valerie McCandless, for giving me the support and independence required to take on such a task.

Finally, to the Department of Mechanical Engineering, for accepting my transferal, accrediting my past work and providing an outlet for my interests.

TERMINOLOGY





1 INTRODUCTION

Omni directional vehicles have been studied and developed extensively over the last decade in a number of robotics laboratories around the world. Such vehicles are characterised by the ability to move sideways and spin on the spot. This extra maneuverability enables them to navigate through narrow hallways, turn sharp corners and sidestep obstacles. Such capabilities have the potential to solve a number of challenges in industry and society. For instance, a motorised wheelchair utilising this technology would give the operator greater maneuverability and thus access to places most able-bodied people take for granted. Also, current process for inspection of hazardous areas involves expensive, time consuming safety procedures. These can be avoided by using unmanned robot vehicles equipped with the ability to drive down narrow corridors to get to the required location.

The Centre for Intelligent Information Processing Systems (CIIPS) took the more humble approach of developing a robot vehicle to navigate a maze, play robot soccer etc. Nevertheless, an omni directional vehicle is well suited to these tasks. The project began with Professor Thomas Braunl, of CIIPS, who commissioned the manufacture of a highly maneuverable, autonomous, omni-directional robot vehicle. However, after the chassis was finished, the conclusion was soon reached that the robot vehicle was limited in the range of surfaces that it could operate on. Professor Braunl requested Dr Nathan Scott, of the Department of Mechanical and Materials Engineering, to develop a new wheel design within the context of a third year Mechanical Engineering Project (630.350), or final year thesis. The project was taken on by the Author as a third year Mechanical Engineering Project in Semester 2, 1999, after which the new wheel design was developed. The conclusion was reached that a full analysis and eventual re-design of the chassis would be necessary if the CIIPS research in this field was to continue. Some additional work was done developing a prototype for the wheel during 2000 and this is described in the Background chapter. It is important to note that this work is not submitted as part of this thesis, but should be recognised as work done previously on the overall project.

Having completed the new chassis, this thesis aims to describe in detail the motivations, considerations and constraints behind the design, as well as the lessons learnt and the procedures developed during its construction and performance evaluation.

2 BACKGROUND

2.1 Some Examples of Omni Directional Vehicles

Current research into omni-directional vehicle movement takes a number of forms. The design concepts of this project form part of the research involved with the use of wheels that roll with two degrees of freedom. This research involves revolutionary ideas and concepts that are likely to take years to fully develop, so research institutions are reluctant to share ideas until the research is fully recognised as their own work. Thus only the completed projects are available to the public. This section discusses some of the different design ideas currently being investigated around the world.

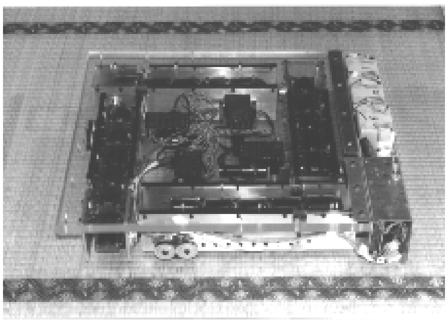
2.1.1 Nasa's OmniBot

The OmniBot project started with the objective to develop a highly maneuverable mobile base that can enter hazardous environments and perform remote inspections. The vehicle is being used to test remote control mediums and umbilical technologies for autonomous control The OmniBot uses four brushless servomotors, each directly driving a mechanum wheel that has rollers mounted around the outside of a central hub.

Figure 2.1.1 *Photograph courtesy of NASA*

The capabilities of the wheels are currently being evaluated over a range of surfaces and speeds, and the sturdiness of the body is also being developed.

2.1.2 The Vuton



The Vuton is a crawling platform that uses a developed form of caterpillar track to perform omni directional movement. Each link of the caterpillar track has a barrel shaped roller that enables the tracks to roll sideways. The difference between this track and a conventional track is that each link circumnavigates the loop in a fashion similar to an escalator in the sense that they maintain a constant horizontal orientation (see Figure 2.1.2). Four caterpillar tracks are used, one on each side, and each individually driven by its own motor. The use of these tracks gives the Vuton a payload capacity of around 1000kg, far exceeding any vehicles with the same weight. For this reason it is proposed for use as a transport vehicle in factories, hospitals and warehouses. There is no evidence of the Vuton possessing any compliance to traverse surface irregularities, but it boasts the ability to run smoothly on carpet, linoleum, and even on fragile tatami mats without leaving any damage.

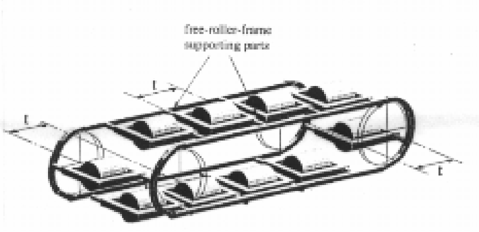


Figure 2.1.2 The Vuton uses a revolutionary form of caterpillar track, enabling a very large payload capacity.

Photographs courtesy of Shigeo Hirose, Shinichi Amano

2.1.3 The Killough Platform

The designs discussed previously, used free rollers supported on the outside of a driving surface to achieve the desired two degree of freedom motion. The Killough platform, however, uses spherical rollers that are driven on an axis through their centre,

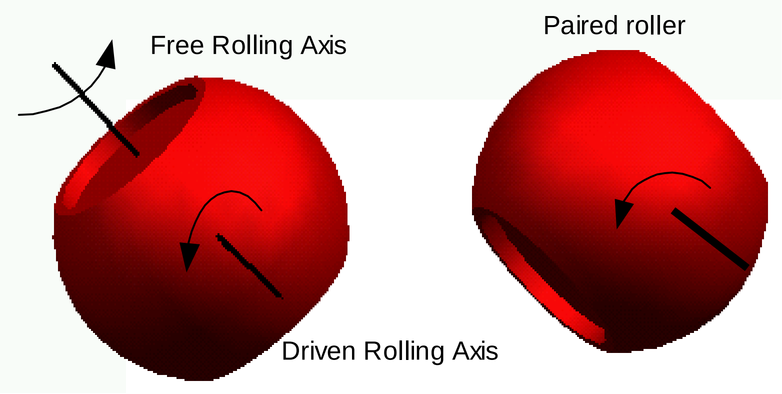


Figure 2.1.3a

perpendicular to their free rolling axis (see Figure 2.1.3a). Named after Steve Killough, the initial designer, the platform and algorithms were developed with the help of Francois Pin. The rollers have vertical sides that enable them to be mounted. Each roller is coupled with an identical roller displaced 90 degrees out of phase with it so that one is in contact with the ground when the other is not. Figure 2.1.3b shows that there are three roller pairs spaced 120 degrees to one another enabling the platform to travel in any direction as well as turn on the spot. The advantage of this set up is that the free rolling wheel diameter is the same as the driven wheel diameter, so the free rolling wheels do not favour one type of rolling to the other.

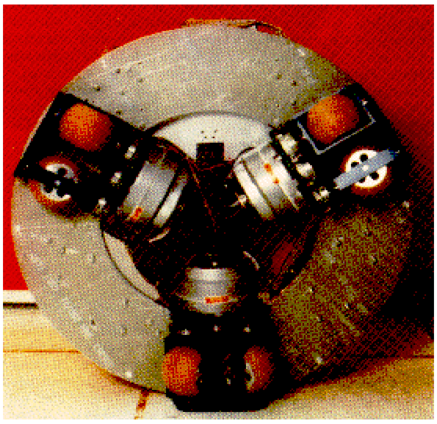


Figure 2.1.3b TransRovr (left) using the Killough Platform (right**)**
Photographs courtesy of Oak Ridge National Laboratories

This concept has recently been developed into a motorized wheelchair named TransRovr, also shown in Figure 2.1.3b. TransRovr boasts all the movement characteristics of an omni-directional vehicle, and keeps the wheels, power train and infrastructure hidden within the platform.

2.1.4 Palm Robot Kit

The Palm Robot uses the three axis idea used with the Killough platform, but it uses mechanum wheels instead of paired rollers. These can be seen in Figure 2.1.4. The kit is designed to enable robot enthusiasts to start building and programming mobile robots cheaply. The mechanum wheels enable the robot to move omni-directionally in the plane defined by the contact of the three wheels. The Palm robot controller runs on batteries and has an interactive user interface that displays graphics, making it ideal for the first-time programmer.

Figure 2.1.4 The Palm Robot Kit, using Three mechanum wheels.

Photograph Courtesy of Carnegie Mellon University.

2.2 Design Space Exploration

The design of the vehicle included the use of *mechanum wheels*. These wheels have rollers radially mounted around the outside. The rotational axes of these rollers must be offset by some angle from the central axis of the wheel. The degree of this offset is governed by a number of factors including the number of wheels and their location about the chassis. For a standard four-wheel configured vehicle, the wheels have rollers with rotational axes around 45 degrees to the wheel rotational axis. The radially located rollers give the wheels an extra degree of freedom in their movement, so any wheel used individually is practically useless because it has the option to roll forward or sideward. When the wheels are used in conjunction with other wheels, they enable the robot to move omni-directionally (see Figure 2.2.1).

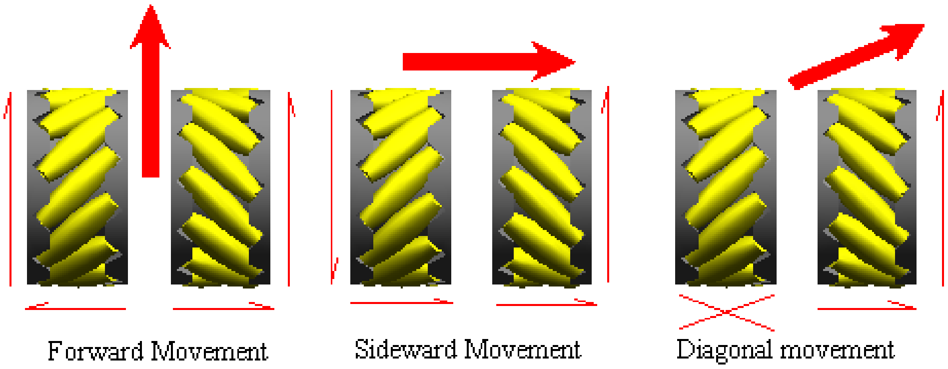


Figure 2.2.1

Any given combination of robot transverse velocity and/or rotational velocity requires a certain combination of wheel velocities. Some movements require all four wheels to be engaged, others need only one or two. This is because even when a wheel is not turning, it stil has a diagonally mounted free roller in contact with the ground, which is also able to govern the vehicle's movement. The necessary condition for the operation of the vehicle is that all four wheels be in contact with the ground. Every driven wheel has another driven counterpart, so if a wheel loses contact with the ground, then the vehicle moves in a way which no longer matches the commands of the processor. Another necessary condition for the wheels is that the rollers are the only part that can touch the ground. If any part of the central hub of the wheel touches, then the wheel loses its second degree of freedom and no longer possesses its omni-directional characteristics.

The shape of each roller is such that its surface never protrudes outside the surface of an imaginary cylinder that represents the outer surface of an ordinary wheel. The proof of this is explained in Appendix 1. Since the axis of rotation is offset by some angle to the axis of the wheel, there is a finite length that each roller can be, depending on the distance of the rollers from the wheels centre (see Figure 2.2.2). If this angle of offset is **Φ** as illustrated, then the profile of the side of the roller is the arc of an ellipse, whose secondary axis is the radius of the wheel, and whose primary axis is 1/sin**Φ** times the radius of the wheel

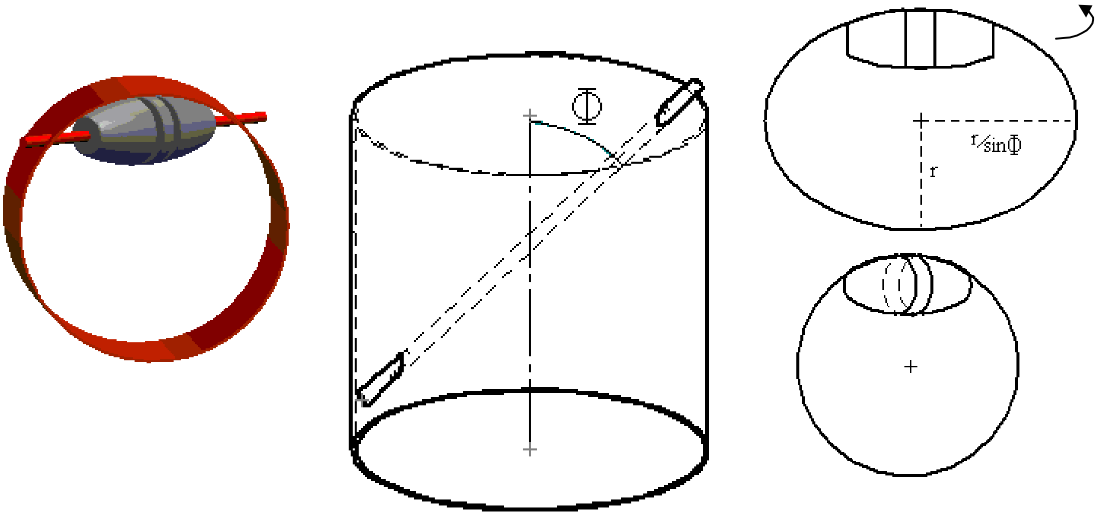
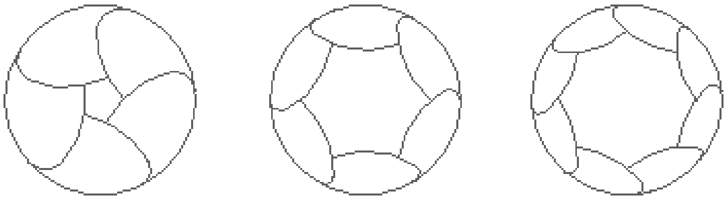


Figure 2.2.2 Factors affecting roller profile

The number of rollers per wheel is dependent upon the size of each roller, which is a function of how close we design the roller axis of rotation to the center of the wheel. The closer the axis of rotation, the longer each roller can be, and so less are needed to span the circumferential area of the wheel. At the same time, the amount of room left in the centre of the wheel also depends on the size, and as a result, the number of rollers (see Figure 2.2.3).



5 Rollers 6 Rollers 8 Rollers

Figure 2.2.3

The size of the rollers also has an effect upon performance of the wheel on a variety of surfaces. Consider a basic step change in surface being ascended by a wheel of this type. The height of step change that the wheel can successfully overcome is a function of the roller minimum diameter. The larger the rollers are the greater the range of surface deviations that can be overcome. Also as the size of the rollers increases, the slower they spin, resulting in lower friction losses in the driving of the wheel. In summary, when designing a new drive system for a robot of this kind, there exists a certain number of rollers that makes the ideal compromise between having a small number of large rollers per wheel, and having a large number of small rollers per wheel.

Whilst exploring the different combinations of roller geometry it is important to also consider how the rollers are to be mounted. The bearing axes can be supported at the edges, in the middle or anywhere in between. By supporting the rollers at the edges, the bearing forces on the mounts are minimised because the force always acts between them, keeping the mounts located in a low bending stress area. Bearing forces in a split central-mounted roller are greater because the end bearings are subjected to the entire weight of one wheel in the maximum bending stress scenario as illustrated in Figure 2.2.4.

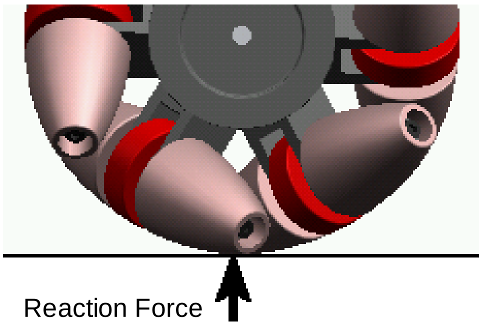
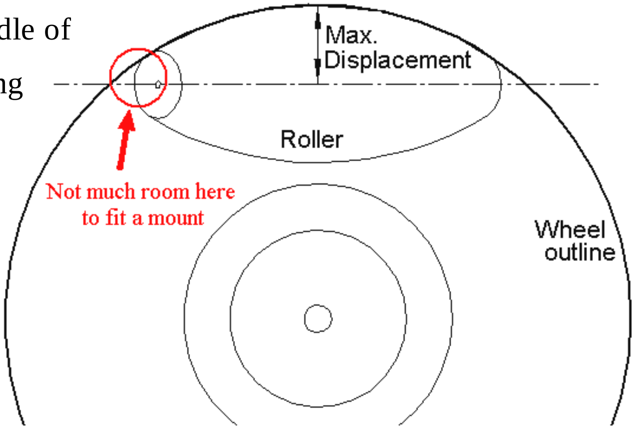


Figure 2.2.4 The maximum bending stress scenario for a central supported roller.

Tighter tolerances and better bearings are needed so that the rollers still roll freely when the maximum bending moment is applied. The key advantage of the central mounting idea is that the mount can be considerably larger and still be far from the outer surface of the wheel. Due to the geometry of the rollers being offset from the wheel axis, the furthest point on the roller axis from the wheel outer diameter, is the point at the middle of the roller (see Figure 2.2.5). Mounting the roller here ensures that the rollers are the only part of the wheel to touch the ground. As a result, a compromise has to be made to achieve good free rolling characteristics as well as reliable roller contact with the ground.

Figure 2.2.5



As mentioned earlier, another necessary condition for a vehicle of this kind is that the wheels are in constant contact with the ground. With a three-wheeled vehicle this is inevitable because three points define a plane, but with four or more wheels, it is important to have a mechanism to ensure the wheels are always in contact. One way to do this is to design a chassis with independent suspension, another is to incorporate a certain level of compliance in each roller, either by making them soft and spongy or by making them spring loaded. Sticking to conventional methods reduces the need for heavy development, but newer, more novel ideas can prove to be more worthwhile. However, one thing is necessary in all cases; as the wheels rotate, there has to be a smooth transition from one roller to the next. Wheels that have suspension must remain in the vertical plane, otherwise the end of one roller on one side of the wheel will not orbit within a profile common with the end of the next roller on the other side of the wheel. Compliant rollers must all squash and spring back to the same degree as each other so the wheel does not jerk up and down along its path.

2.3 Existing robot design

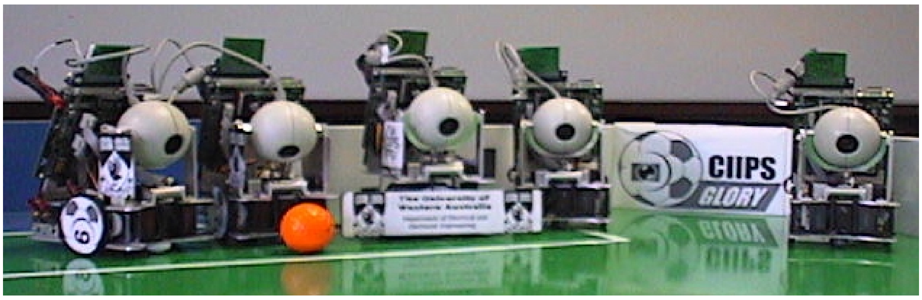


Figure 2.3.1 Small robot vehicles, designed for playing robot soccer

Gordon Menck from Subiaco college of TAFE and Richard Mauger, from CIIPS, designed the first Omni-directional robot vehicle at the University of Western Australia. It was constructed with motors made by Faulhaber, a German micro-drive manufacturer. These motors have a built in gearbox transmission with a 9:1 speed reduction and an axially aligned output shaft. These motors were used in the “Eye bot” mobile robot vehicles, pictured in Figure 2.3.1, that play autonomous robot soccer. It was from using these robots that the incentive to develop an omni-directional robot vehicle originated. The size and weight of the proposed vehicle meant that further gear reduction was necessary, so additional gearboxes were purchased with a 15:1 reduction ratio. When used in conjunction with the motors, the overall reduction was 135:1. The addition of these gearboxes also meant that the motor positions could be staggered to save room, making the vehicle very compact (see Figure 2.3.2).

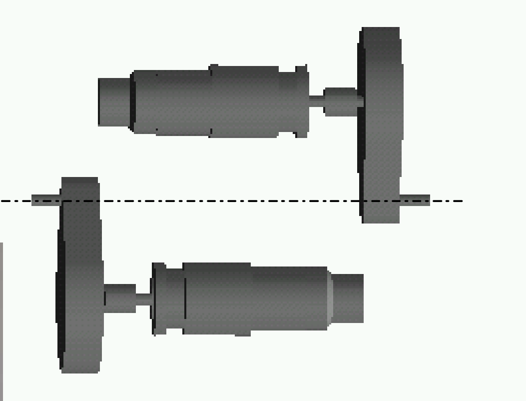
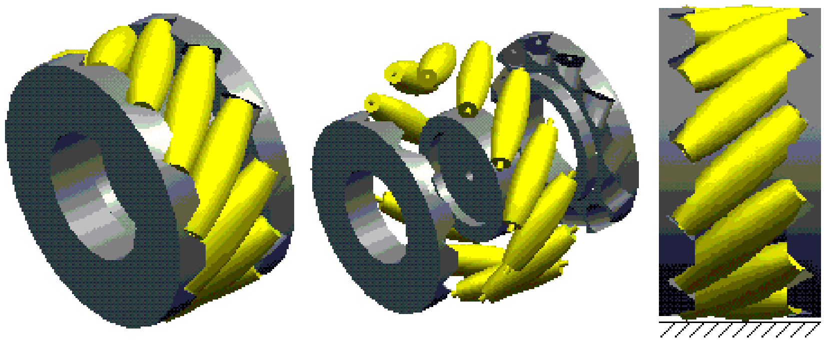


Figure 2.3.2 Existing robot design using staggered motor arrangement

As can be seen from the photos, the chassis is simply an aluminium plate with attachments to mount the battery, motors, wheel shafts and processor. Structural rigidity relies completely on the thickness of the aluminium plate, and the chassis possesses no independent suspension or any form of compliance to enable the wheels to stay in contact with the ground at all times. As a result this vehicle can not work reliably with surface deviations, or work on varying terrains.

Figure 2.3.3



The wheels consist of twelve plastic rollers and a central disk sandwiched between two aluminium mounting rings that have precisely shaped channels cut into them to suit the ends of the rollers (see Figure 2.3.3). The two rings are bolted together using four socket head bolts. The mounting rings leave very little clearance for the rollers to protrude from. This inherent problem is due to the fact that the rollers are mounted at their ends. It can not be fixed by increasing the roller diameter, because the rollers would rub against each other. Nor can it be improved by mounting the rollers further out from the wheel centre because they are already at their limit. Therefore it is imperative to only operate these wheels on hard surfaces because if they sink any more than half a millimetre the mounting rings start to touch the ground and the wheels lose their two-degree-of-freedom characteristics. In addition, the rollers have trouble gripping on a wide range of surfaces because they are made from a plastic known as Pactene. This polymer is favoured in Mechanical engineering circles because of its machinability, which is probably why it was used in this construction, but it has very low friction characteristics. Attempts to operate the robot on some tables or benchtops resulted in the rollers slipping.

From the illustration it is apparent just how much material is used in these wheels. They have an outside diameter of 100mm, weigh around 400g each and are driven by a 4mm shaft. Building the wheels and adapting the processor took up most of the developmental focus and very little was considered about the operation of the wheels, their kinematic requirements or the maximum rated torque of the gearboxes. As a result the additional gearboxes burnt out after about four hours of cumulative use. The wheels were too heavy, their moment of inertia was too high and consequently the required torque to drive the wheels exceeded the gearbox specifications. To solve this problem, an order was placed to get some more motors with a high built in reduction ratio similar to the combined reduction of the previous drive system. This was chosen to be 121.5:1. In the short term however, the processor still required research and the operation of the vehicle was still very novel within the research lab, so more gearboxes were purchased to complete the work on the programming.

When the new motors arrived the chassis was adapted to suit them, but it no longer had the staggered motor configuration, so the vehicle became a lot wider. Unfortunately the drive system is very fragile. The grub screws that are used to lock the wheels on to the motor shafts are consistently wearing dimples into them because the torque required to drive the wheels is too great for extensive use. The robot needs to be continuously checked to see if all wheels are still connected to their shafts properly, and the robot needs to be handled with the utmost of care.

As a first prototype the vehicle was successful in its operation. It displayed the ability to carry out the full range of movement proposed during the projects conception.

However, it is very limited in its applications and is restricted to only working on a specially prepared test bench that is smooth and flat, with a hard, rubberised surface.

2.4 Development of a Prototype Wheel

Originally a request was made by Professor Thomas Braunl, from the Centre for Intelligent Information Processing Systems (CIIPS), to Dr Nathan Scott, that a new form of mechanum wheel be designed, due to the problems getting the existing wheels to work properly on a wide range of surfaces. These problems were a result of both the design, and the choice of materials. As mentioned previously, the design limited the wheels to only working on hard, flat surfaces because the rollers were mounted at the edges. On soft surfaces, the wheels were sinking in so that the mounting rings were touching the ground, disabling their two dimensional kinematic properties. The new wheel had to have the rollers offset at an angle of 45 degrees to the wheel axis to work with existing programming and it was to be driven by the new high reduction Faulhaber motors ordered from Germany.

Early design attempts were built around the idea that the less the number of rollers, the larger each roller would be, improving the surface handling properties. However, there exists a minimum number where the rollers are so big that they interfere with adjacent rollers. Alleviating this problem by omitting interfering material was investigated but it required a roller profile that was very intricate, requiring an unjustifiable degree of manufacturing and development. After much deliberation, it was decided that the most feasible minimum number of rollers per wheel was six. However, a decision still had to be reached about how the rollers were to be mounted.

As discussed earlier, the ideal place to mount the rollers is in the center so that the rollers can run on the ground freely without being fouled by any mounting arrangement. However, there is good reason why it is not advisable to mount the rollers in the very centre. When the tips of the rollers are in contact with the ground, a single central roller mount would be subjected to a considerable bending and twisting twice every wheel revolution, presenting a fatigue possibility. This means that a single central mount would have to be strengthened with excess material in order to retain its correct position and orientation throughout the life of the vehicle. To do this would result in a large gap in the centre of each half of the roller, jeopardizing the smooth running of the wheels.

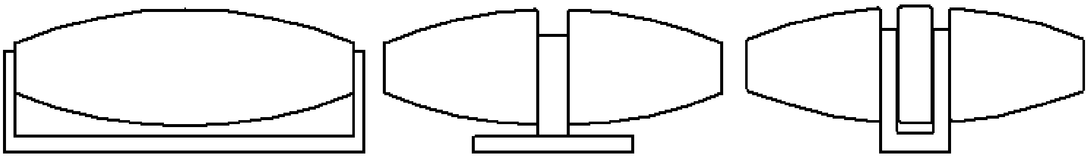
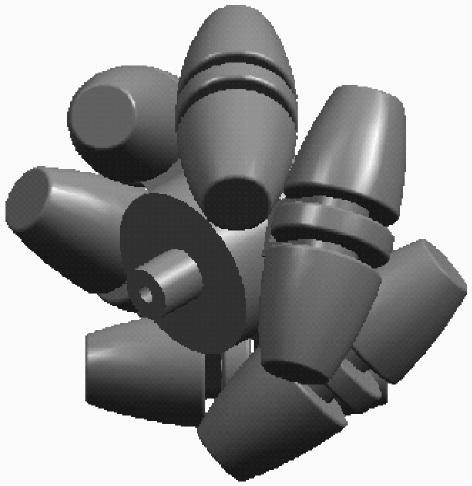


Figure 2.4.1

In Figure 2.4.1 we can see that if the rollers are mounted centrally at two locations, the mounts can be much more discrete because they do not have to be as sturdy. The central region of the roller is still being utilised, so the wheel profile is not affected by the mounting arrangement. Using a small clevis that is detachable from the centre of the wheel, the rollers retain around ninety percent of their theoretical contact profile, whilst solving the clearance and excess mass problems encountered in the wheel design of the previous vehicle. The hub in the centre of the wheel requires six equispaced channels milled into its outside, that are offset the correct angle from the wheel axis of rotation. With the use of a threaded fastener to secure the clevis into place, both the clevis and the hub can be easily machined from stock. The clevis arrangement was chosen on the grounds that it offered effective roller performance for reasonable manufacturing and development ease.

Figure 2.4.2

Early design idea using the clevis mounting idea and three piece roller.



The roller to be used with this arrangement comes in three parts: two identical end pieces and a central disk. These would spin on a common shaft that locates into holes in the clevis and protrudes out either side. The wheel therefore consists of a central hub with the aforementioned milled channels, six clevises to fit into these channels, six roller shafts six roller disks and twelve roller end pieces. All of these components can be manufactured in a workshop and assembled easily using screws and washers. To reduce the shaft friction on the rollers, small teflon coated bushes were purchased to be inserted in the rollers to act as miniature journal bearings.

Th hub had to be big enough to fit the six roller arrangements around the outside. The implications of this were that there would be a lot of redundant volume in the centre of the wheel. This volume would just be adding to the overall weight so if this area could be eliminated or utilised, then it had to be of some benefit to the design. An investigation proposed by Dr Nathan Scott was consequently under way to try to fit the motor inside the wheel hub to save room. The wheels are inherently wide so it is very hard to keep the width of the whole vehicle down without investigating one or more ingenious space saving ideas. To drive the wheel from inside the hub requires some method of supporting the radial loads on the wheel because the motors are only rated for a tiny radial load of 0.04N. For that reason, a very thin needle roller bearing was selected to fit into the centre of the wheel (see Figure 2.5.3).

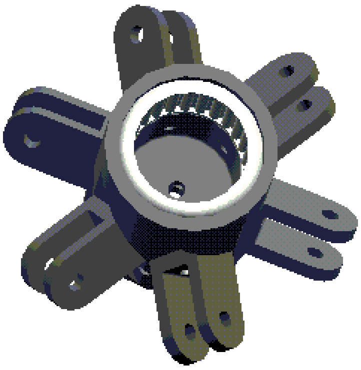


Figure 2.5.3 The rear view of the new hub design, showing the location of the needle roller bearing

The outer diameter of the motor is 24mm and the closest bearing size is 25mm, with an outer diameter of 32mm. The rollers need a diameter of around 25mm to get six of them to span the circumference of a 100mm diameter wheel. So the remaining 9mm either side of the needle roller bearing had to fit a clevis to mount the roller, a shallow milled channel, to locate the clevis, and some material to hold it all together.

After hours spent using a computer-modeling program, trying to fit the geometries together, a final wheel design was completed that had an outer diameter of 96mm and rollers with a maximum diameter of 26mm. The hub was 38mm in diameter with six 2.5mm channels milled into the outside, each locating a clevis 13mm wide to mount the rollers. In order to fit the motor inside the needle roller bearing, a metal sleeve was pressed on to the outer casing of the motor and then the outer diameter of the sleeve was turned down to 25mm. Having established that the design was possible, drawings were submitted to the workshop and the prototype was completed in October 2000.

Within the scope of this proposed wheel design, there was no capacity for including compliance into the rollers themselves. This was because of the later developments to the design proposal. Based on requests from Professor Braunl, there was a need for larger, fewer rollers within a wheel of the same outer diameter or less as the existing wheels. When tied in with the space-saving advantages of mounting the motors in the centre, the combination left no room for developing the idea of compliant rollers. Therefore these wheels need to operate on a chassis with independent suspension so that they are always in contact with the ground.

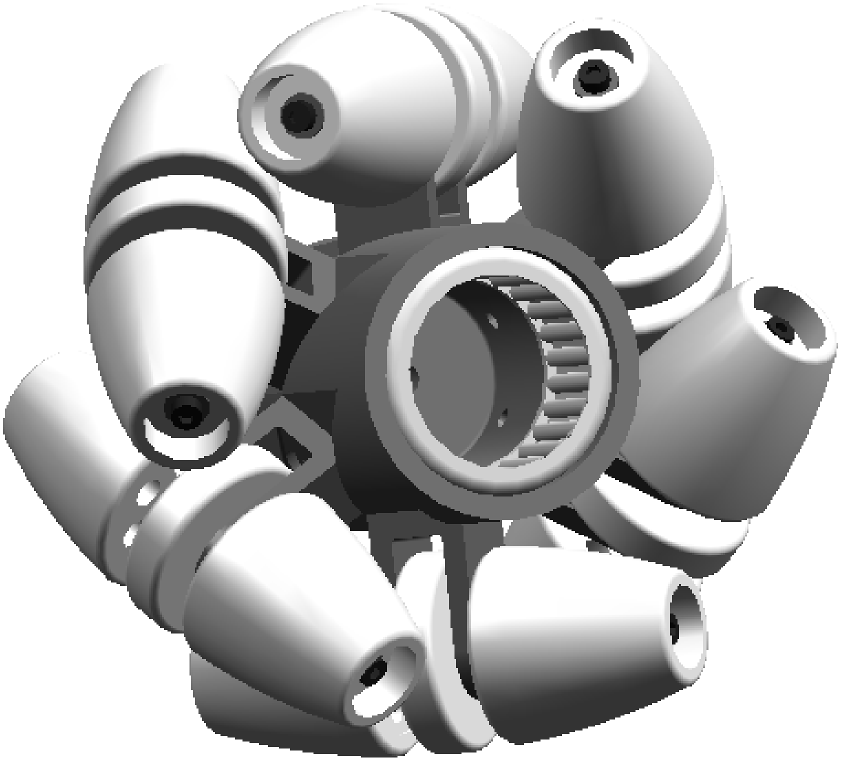


Figure 2.5.4 The completed prototype

3 WHEEL DESIGN & CONSTRUCTION

3.1 Rollers

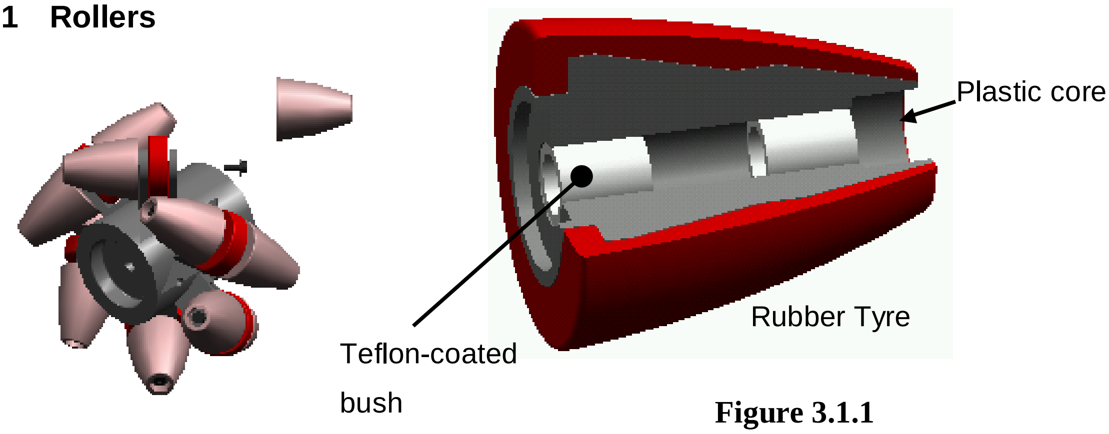


Figure 3.1.1

The preferred mounting arrangement of the rollers was explained in the previous chapter. This arrangement splits up the rollers into three parts, two identical roller segments and a central disc. The roller segments have a plastic core and a moulded rubber coating and the discs are solid polyurethane rubber. Both the segments and the disc have teflon-coated metal bushes pressed into them so that they can run on a shaft. The design is based on a prototype wheel designed and developed in the year leading up to the start of this thesis.

3.1.1 Roller Segment

Having completed the prototype wheel, the next step was to develop smaller, lighter rollers to reduce the mass of the wheel. A good material to choose was plastic, because it is readily available and light. The body of the roller does not require a lot of strength, so the plastic is good to use for taking up the bulk of the volume. The prototype wheel used aluminium rollers and as a result, weight-reducing holes were needed to try to get the overall wheel mass down to an appreciable level. Development emphasis at the time was placed on a quick manufacture and construction to test the initial design theories of the improved wheel. These early ideas were successful, so the wheel design could be improved further before final construction. If plastic was to be used for the rollers, then they would need a high friction coating to achieve the necessary grip characteristics, and the plastic had to be strong enough to fit the small Teflon bushes used to run on the shaft as illustrated in Figure 3.1.1

There were a number of ways of improving the rollers' grip and the feasibility of some were explored as described in Figure 3.1.2.

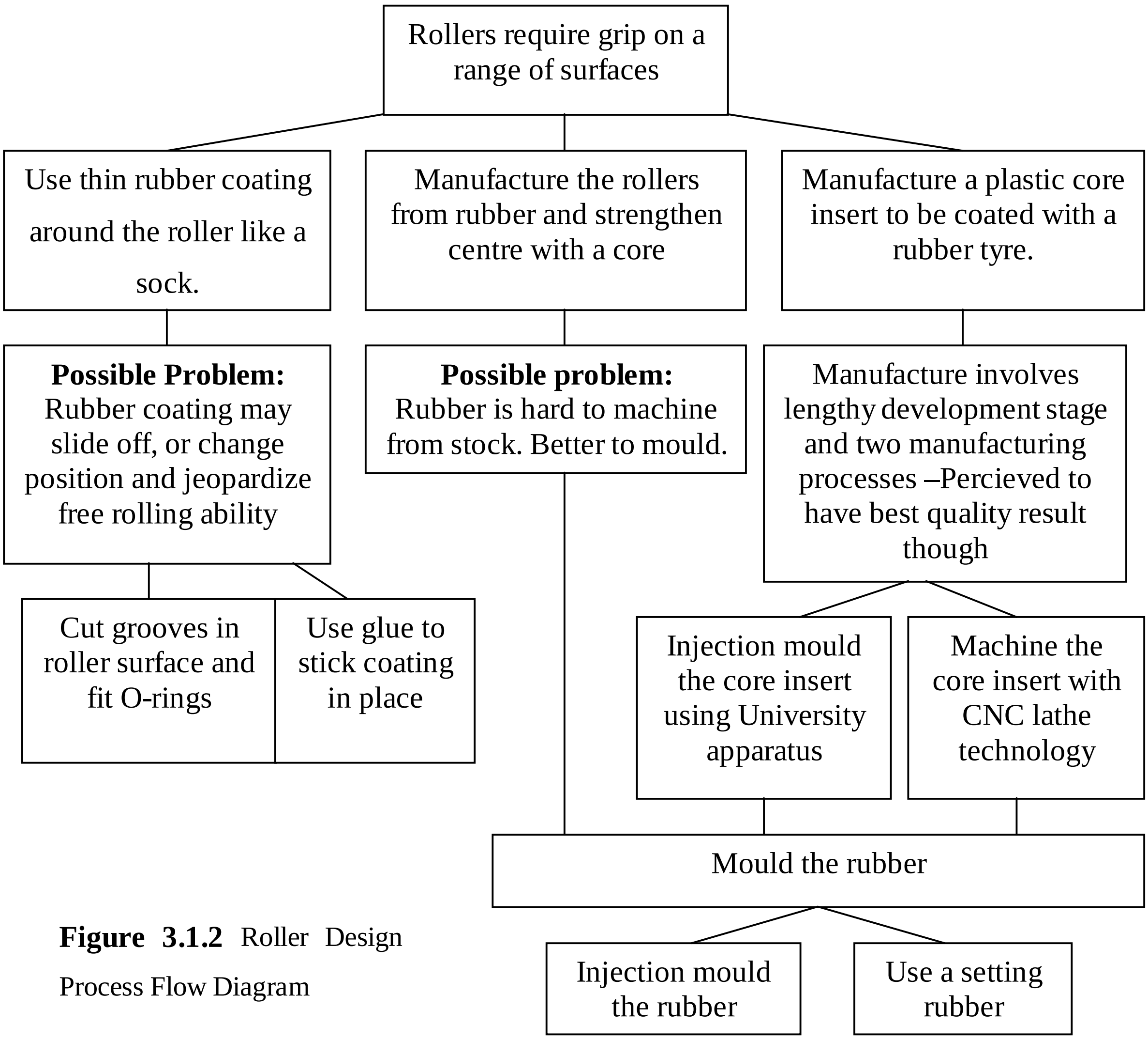


Figure 3.1.2 Roller Design Process Flow Diagram

In the end the chosen proposal was to manufacture a core insert and then mould rubber around it to form a tyre. Covering the roller with O-rings or a thin rubber tube was considered undesirable because:

a) A collection of O-rings may not have provided a smooth enough roller surface.
b) The surface of a rubber film may have been difficult to keep concentric if it is glued, and if it tears, it looks unsightly and is likely to need replacing.
c) Supply of uncommon O-ring diameters was perceived to be difficult.

Manufacturing the roller completely from rubber was also considered undesirable because the roller would need to be made from a hard rubber to resist squashing. Hard rubbers tend to lack grip on some surfaces, so the roller would have to make a compromise between hardness and softness.

A composite construction of the roller was considered to be the best result because it provides the desired surface characteristics and maintains the inner structure, but ensures that the roller stays as one composite piece. The importance of a successful end result greatly influenced this design decision because the vehicle had to look impressive to the clients as well as perform well.

As stated in Figure 3.1.2, the successful proposal involved one of two options:

1. injection mould the core insert, or
2. machine a core insert from stock.

Both of these options made it possible to consider either injection-moulded rubber or Room-Temperature-Vulcanising (RTV) rubber tyres. Ordinarily injection-moulding would not be an option because the low output of parts and high cost of developing moulds would not present a justifiable manufacturing scenario. However the Mechanical and Materials Engineering Department has an experimental injection-moulding machine that is part of tutorials in various manufacturing subjects.

Core design #1

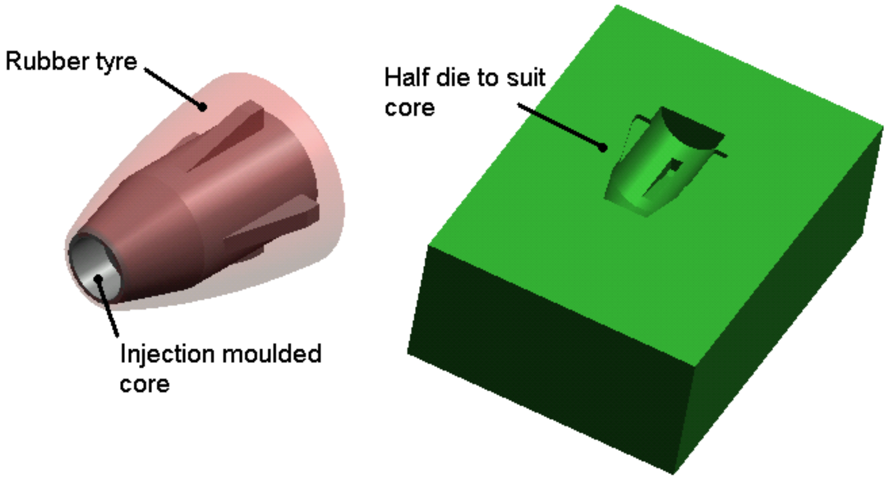


Figure 3.1.3

This design was conceived with the intention of injection-moulding both the core and the rubber coating. The fins are on the core to provide the rubber coating with some geometry to locate onto so that it does not roll off like a sock. The fins still enable an easy manufacture of the mould using a computer-numerically-controlled machining device. Although a more intricate form of geometry would do a better job, this shape is easily cut out of a block to make a mould. After the core is moulded, then the rubber around the outside can be moulded using the core as an insert (see Figure 3.1.4).

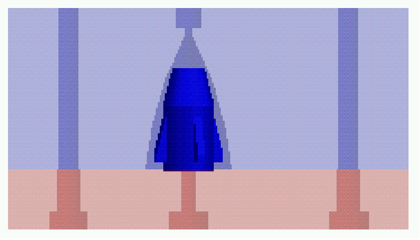


Figure 3.1.4

Core Design #2

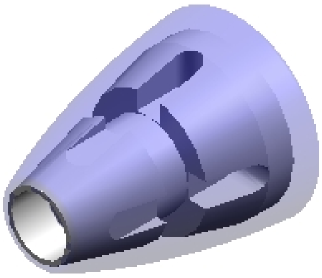


Figure 3.1.5

The design for this core was intended to provide a keyway for the rubber tyre to locate on. The core is not easily moulded because it would be hard to make a mould for the injection-moulding process. The core is designed to be machined easily using a CNC lathe. The outer profile is machined using two turning processes and then the chuck is locked while a 3mm end mill carves the four channels on the outside. These channels serve two functions:

a) They provide a keyway for the rubber to locate on, and

b) They allow the liquid rubber to flow more easily into the mould

When comparing the two proposals it is important to think about the costs involved of both time and money. With around fifty of these rollers required for the vehicle, the manufacturing processes involve repetition.

If the core is injection-moulded, then final production time is greatly reduced because it is possible to produce one every two minutes, but set up requires a lot of development. Tests have to be made to determine the optimum pressure, temperature and dwell time, an allowable degree of shrinkage must be calculated to incorporate into the roller geometry, then the mould has to be modeled with a computer package before being machined and polished. An injection-moulding process for a low output run is difficult to justify, especially with this object because it has to be moulded around a dummy shaft and then ejected. Normally in industry, injection-moulding produces numbers of units in the millions so that the cost of set up per unit is minimal.

If the core is machined, some set up time is required; first to set up a reliable chuck arrangement and second to enter the commands into the CNC machine. However this can be done in an afternoon, so the set up cost per unit is minimal even with a unit output as low as five or ten. Production time, on the other hand, costs a lot more when machining because the process takes longer. The overall cost per unit of a machining operation is reasonably constant.

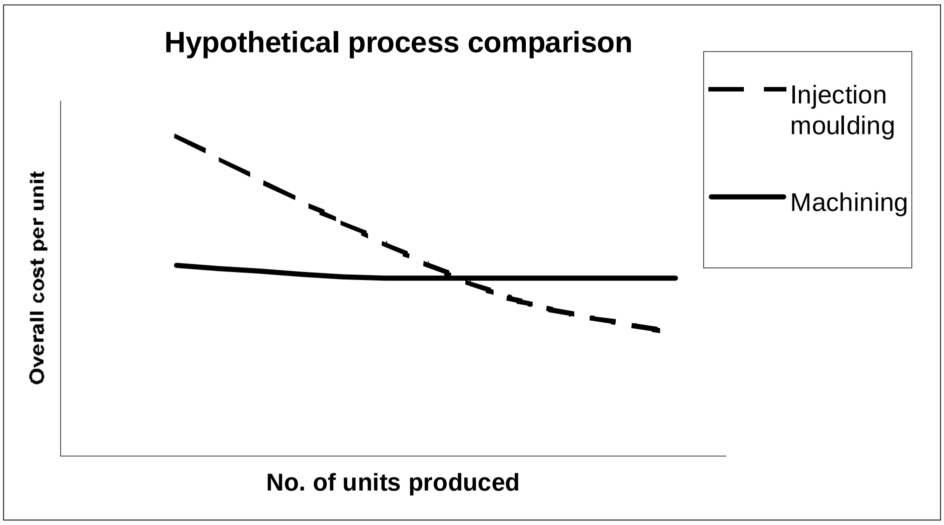


Figure 3.1.6

Although this graph is schematic, it illustrates where and when either manufacturing process is more appropriate. Minimising cost of manufacture was not so important for this project because there was no need to turn a profit. However, since it is the driving force behind most if not all industry, it is a good habit to get into, so the decision was made for the core to be machined.

Having chosen the more appropriate design, the choice had to be made between injection-moulding and using RTV rubber. RTV rubbers come in a range of hardness and either set when poured from the tube, e.g. Shoe Goo™, or have a resin and catalyst that undergoes a chemical reaction (similar to epoxy resins).

The injection-moulding process presented certain significant difficulties:

- ◊ Staff at the university had not investigated injection-moulding rubber, and it was believed that only a small number of rubber types could be used.
- ◊ Availability of these rubbers was not known.
- ◊ A set of high-pressure mould dies would have to be manufactured to match the available injection-moulding machine, an exercise that generates a high cost per part.

The use of RTV rubbers on the other hand presented a number of advantages:

- ◊ The mould does not have to fit into any apparatus and thus can be a lot smaller.
- ◊ The mould is not required to withstand high temperatures or pressures, so it can be made from a range of materials.
- ◊ The rubber is available from a local supplier (Kirkside Products of Osborne Park)

The disadvantages of RTV rubbers are that the process is a lot messier and more time consuming. The compound uses a resin and a hardener mixed in with a ratio of 100:35 by mass. The manufacturer stipulated that an accurate ratio was important, so because the batch size was only 4-8g, a micro balance was required to measure the quantity of the constituents. The scope of the moulding operation could not justify the expense of both time and money to manufacture an injection mould and find a suitable rubber compound. RTV rubber was chosen as the more suitable candidate.

The mould for the rollers needed two things. A central pin to accurately locate the core insert, and an escape hole for excess material to squeeze out. A prototype mould was made initially to formulate a successful manufacturing process (see Figure 3.1.5) and after several moulding attempts, a reliable quality control level was established.

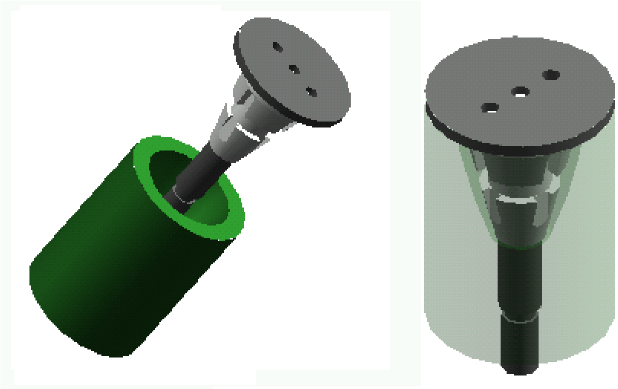


Figure 3.1.5

This activity also shed light on how the mould design could be improved and how to avoid implementing a messy process.

The first three attempts were ruined in the name of ascertaining how soon the finished product could be removed from the mould. The conclusion was reached that four hours was around the minimum time required for the rubber to set enough to be removed from the mould. The compound was said to set in around 15 minutes and reach full hardness after 24 hours. Setting time refers to the time it takes for the compound to lose its liquid properties. Unfortunately it does not gain any appreciable resistance to shear stress until after about two hours. Removal of the finished product from the mould is recommended after six hours, but can be done after four if one is careful.

The next two attempts were riddled with air bubbles because the mixing process was very vigorous. The viscosity of the compound in its liquid form is similar to that of honey so it was tedious to pour and did not creep into small cracks all that quickly. As a result the compound had to be mixed completely within five minutes, leaving ten minutes working time to pour into the mould around the core. This problem was solved by using zip lock bags, which was an ingenious idea suggested by Dr Nathan Scott. The correct mixtures were placed into the bag, the air was pushed out the top and the bag sealed. Then the mixture could be mixed as violently as required without mixing in any bubbles. When mixing was complete, the bottom corner of the bag was cut and the compound was squirted out into the mould in a fashion similar to squeezing whipped cream from a piping bag. Not only did this process greatly reduce the amount of air trapped in the rubber, but it also helped the liquid get into the mould quickly because it was forced down the gap in a thin stream. The pouring time was reduced from ten minutes to a manageable four minutes.

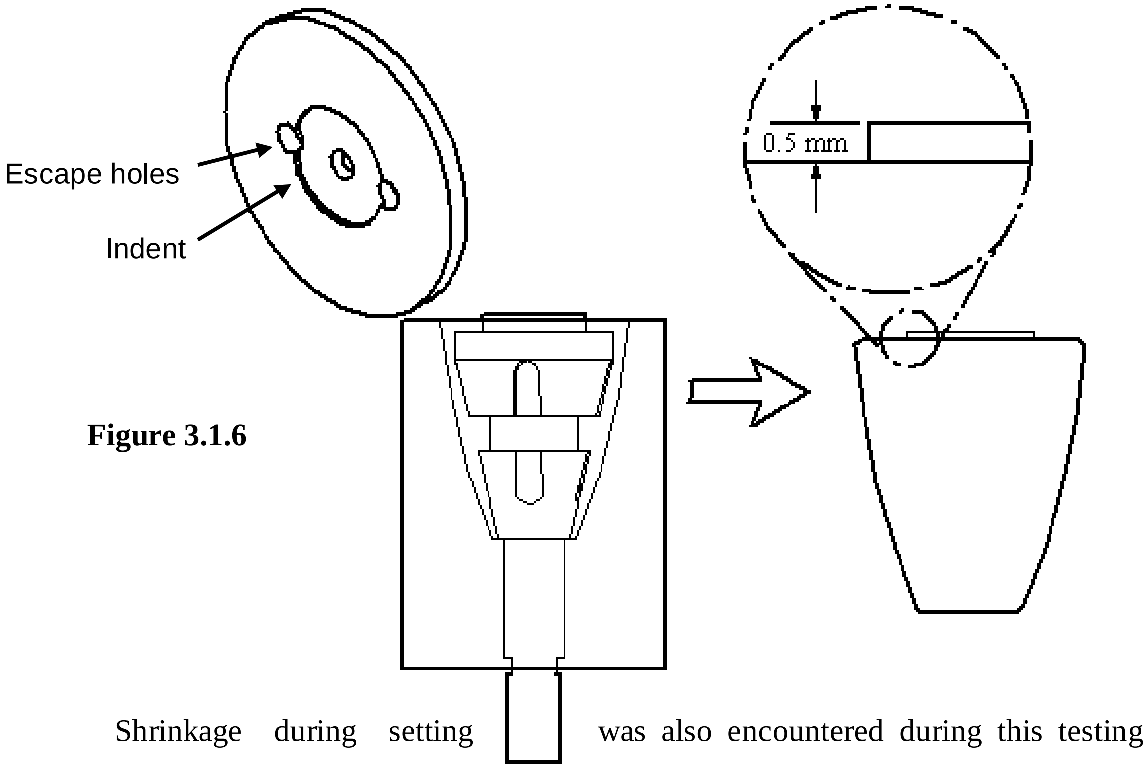


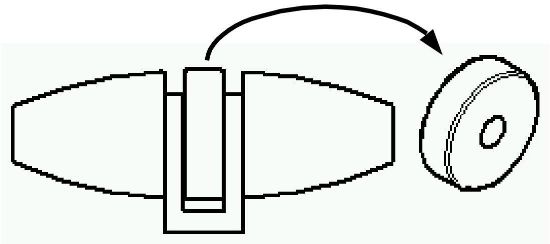
Figure 3.1.6

Shrinkage during setting was also encountered during this testing phase and it was observed that the rubber would retract, sucking air back down into the mould as it cured. The clean-up process of the excess was altered to leave two puddles over the escape holes and the problem was no more. Also, the finished product was consistently difficult to remove from the mould, and a tedious process was necessary for successful removal. The mould was cooled down in a freezer, then dipped into hot water to expand the mould while leaving the product cool, thus releasing the rubber from the mould walls. This process took around ten minutes per roller, so it had to be improved. Release agent was used eventually, which gave the surface finish dimples, but improved the grip. The final glitch that was rectified was the back face of the roller segment that ran against the side of the clevis. The rubber coating came around the back and was flush with the face of the core and so was gripping on the side of the clevis, impeding the free rolling of the segment. The lid of the mould was given an indent (see Figure 3.1.6), which fixed the problem easily.

Now that the process was improved to enable simultaneous, reliable, manufacture of multiple roller segments, the subsequent design was submitted and five more moulds were manufactured. The moulding process was completed two weeks later.

For the benefit of all who are interested, a detailed set of instructions for the rubber moulding process, including photographs, appears in Appendix B.

3.1.2 Roller discs



The discs on the prototype wheel were also made out of aluminium and so required a development process of their own. A similar process to the manufacture of the roller segments was considered to produce composite discs made from plastic with a rubber coating, but this seemed very excessive in terms of the time required and the projected effectiveness of the finished product. If the discs were made from solid rubber then they could be cut from a rod and be ready to install in a day or two, so the search for an appropriate rubber rod commenced. Failing this the discs would have to be punched out of rubber mat, which is a lot more readily available, but the process does not produce outer diameters that are as accurate or concentric. The suitable product came in the form of a 22mm diameter hard rubber rod, which was semi machinable and had a surface friction coefficient less than, but similar to the rubber coating on the rollers. After the rod was drilled in the centre and sliced into discs, the teflon bushes were fitted to the discs and the rollers were complete. Given the time and economic constraints, this manufacturing process was the quickest and the easiest at the time. The discs vary a lot in size, some are buckled while others are not. A more reliable consistency could be gained by moulding them, but for reasons similar to the manufacture of the roller segments, this was not viable under the circumstances.

3.2 Hub Construction

The hub design was finalised during the development of the prototype wheel. The design changes to the rollers did not affect the dimensions of the central hub, so all that was required was to submit the drawings to the mechanical engineering workshop. These components were being manufactured at the time of the University of Western Australia Open Day, so they were used as the demonstrational piece for the Wasino Automatic lathe machine in the CAD/CAM centre of the Department of Mechanical and Materials Engineering. A minor problem was encountered in the machining process that stands as an interesting case study for those who submit designs to be produced on a CNC machine.

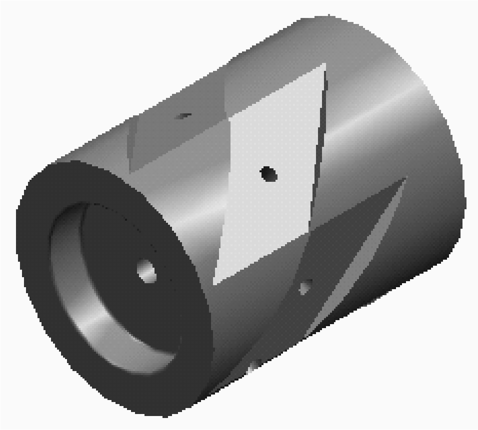


Figure 3.3.1

Figure 3.3.1 shows the hub design with six milled channels equispaced around the outside, and each channel has a hole located in the centre. When the first hub was finished, a small lump was found on one wall of each channel, adjacent to the hole. This lump, although very minor, was big enough to affect the fit of the clevis that was supposed to locate in it. At first the problem was believed to be a calibration problem, since the machine had not been re calibrated in a while, but closer inspection of the hub revealed that each lump was exactly the same shape and size and location as its counterparts. Since the lump was in line with the hole, it was speculated that the hole might be in some way related to the reason why this lump appeared in the same location on every channel. An analysis of the machine code was carried out to look at what was happening during the process. The order of operations was such that the holes were being drilled first and then the channels were milled. Because the channel was wider than the milling cutter, the channel was being cut in two passes. However, most of the material was being removed in the first pass, including the material containing the hole, and it was during this pass that the lump was being formed.

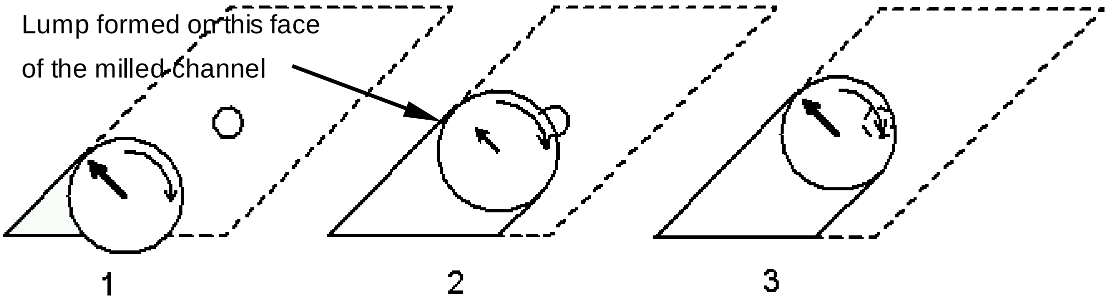


Figure 3.3.2 The deflecting force in (2) is not as great as (1) or (3)

What was happening was that the tool was being deflected a small amount by the cutting forces of the full-face milling operation. (see Figure 3.3.2) but when the tool got to the hole, there was temporarily less material to remove and thus less deflecting force. At this point the tool would relax a little closer to its neutral position, forming a lump on the side of the channel, before being deflected fully again once the tool had milled past the hole. The solution was to either swap the operations over so that the milling was done before the holes, or to make the milling cutter plough through the center of the channel first and then do a finishing pass of each side. Since all the code for the machining operation was already written, it was easier to change the milling operation to accommodate the hole, rather than rewrite all the code for the drilling operations. If the problem was known before the code was written, it would easily have been avoided by putting the drilling operation after the milling operation. Unfortunately no evidence of this occurrence existed on the prototype or the test pieces used for writing the milling code. The prototype was machined manually and it is likely that the order of operations was different, and in the test runs the holes were not included. Any unsuspecting person would deem them unnecessary.

By choosing this solution to the problem, not only was the lump prevented, but also it gave the channel a better surface finish because the second and third passes involved a lot less material removal. With the machining process now completely rectified, the wheel hubs were completed in an afternoon and were ready for the assembling of the wheel.

4 CHASSIS DESIGN & CONSTRUCTION

4.1 Suspension arm

During the later stages of the new wheel design, the conclusion was reached that all these improvements would achieve very little if the chassis possessed no suspension. If the robot vehicle was to travel on a variety of surfaces, then the wheels would have to adjust to any surface irregularities to make sure that they all remain in contact with the ground at all times. An additional design constraint was added that the wheels had to remain in the vertical plane so that each roller of each wheel maintains a smooth transition of ground contact to the adjacent roller as the wheel rotates. This left two more common suspension alternatives, Double wishbone suspension or trailing/leading arm suspension.

4.1.1 Double wishbone suspension

Double wishbone suspension has the potential to be lighter, and more compact. It is possible to use very small and light suspension arms because there are many fastening points to spread the load of the chassis. The University of Western Australia Motorsport team has conducted considerable research and development into double wishbone suspension as part of their car design process. Admittedly the scale is much larger but the groundwork has been laid for future ideas. Unfortunately this type of suspension is very complicated to manufacture because of its many parts and fasteners, and would only be justified if a large number of robots were intended to be built.

4.1.2 Trailing/Leading arm suspension

Trailing arm suspension effectively has only two parts per wheel, the arm and the spring. Not only that but the transmission of rotation to the wheels can be mounted to the arm itself to reduce the complexities of driving the wheels, e.g. motorcycle rear suspension. To resist buckling under the weight of the chassis, the arms have to be quite thick and heavy, but the saving in manufacturing time and costs far outweighs the disadvantages in small production numbers. Trailing arm suspension seemed to offer more promise for fast and successful development so it was chosen.
Figure 4.1.1 shows an early design concept that used a small rubber toothed belt to transmit the power to the wheels. This suspension arm enabled the motor to be mounted on the same side as the wheels so they did not have to fit in the gap between the wheels.

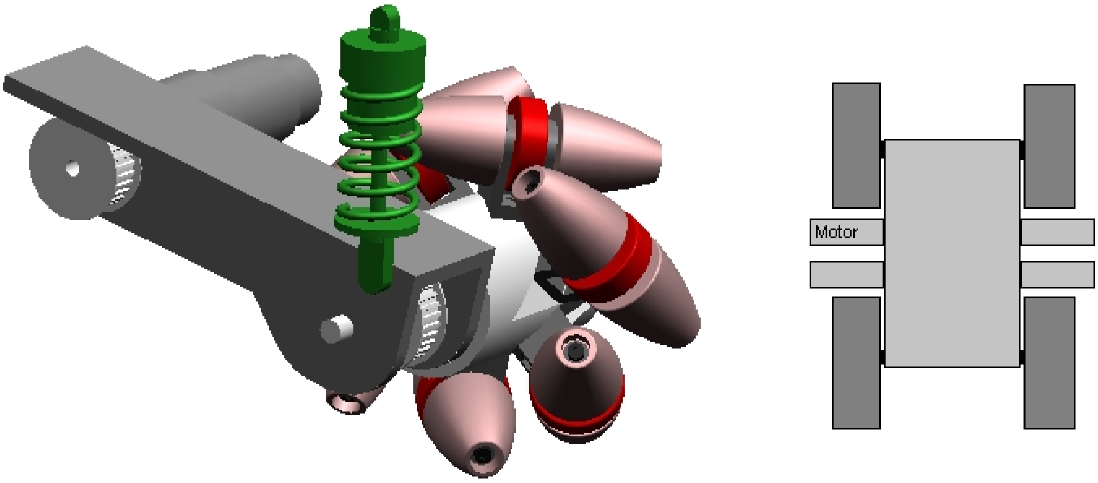


Figure 4.1.1 Early design concept using miniature toothed belt to transmit drive to wheels

During the later developments of the wheel design, the motors became located in the hub of the wheel and the base of the motor casing stuck out the back. This normally redundant part of the motor was ideal for the motor to be mounted to a suspension arm. Using a close-fitting cylindrical gripping surface, the suspension arm could clamp down onto the motor casing using an adjustable screw (see Figure 4.1.2). From this point each progessive design step remained based around this wheel mounting idea and the suspension arm became smaller and lighter as it came closer to being a finished product. A brief summary of its conception is as follows.

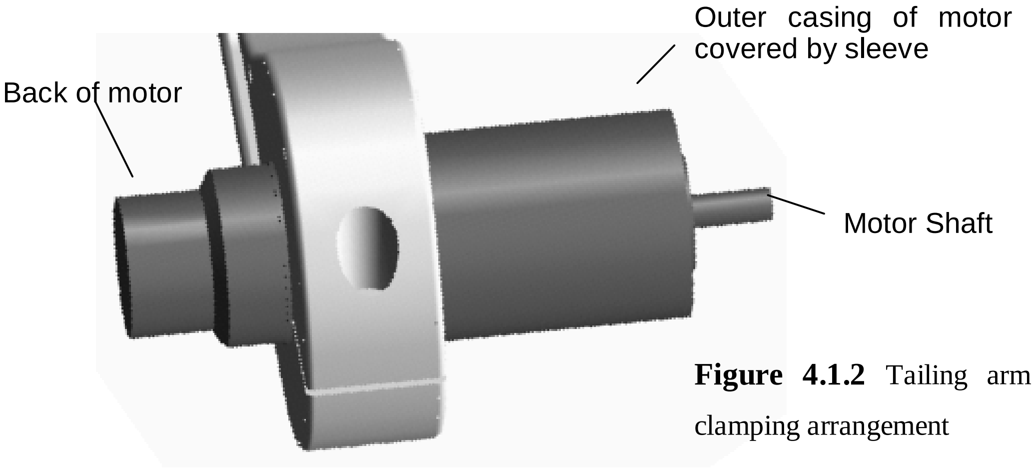
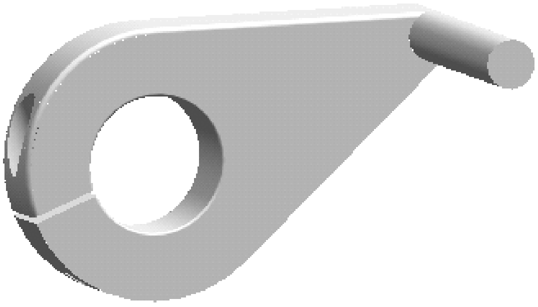


Figure 4.1.2 Tailing arm clamping arrangement

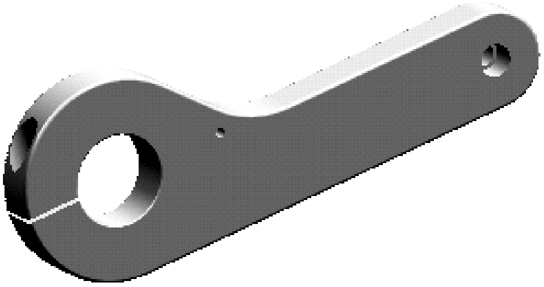
First proposal

This was basically an attempt to conceptualise the geometry of the clamp and the methods of mounting the arm onto the rest of the chassis. However it required complicated manufacture because of its inherent three-dimensional geometry. The pivoting shaft protruding out the side could easily be swapped with a separate attachable bolt.

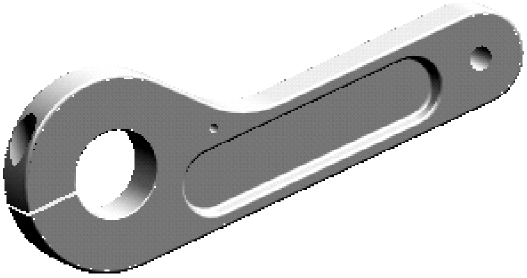


Improved design

The subsequent design had some of the unnecessary material removed in order to save weight and has a hole for attaching a shaft to it. Its geometry enabled this arm to be cut from a flat slab. It was intended to be fastened to a mounting flange with a set screw and nut, which was also an improvement, but it was quite long and still retained a lot of "dead metal" i.e. metal adding to the weight without adding noticeable strength.

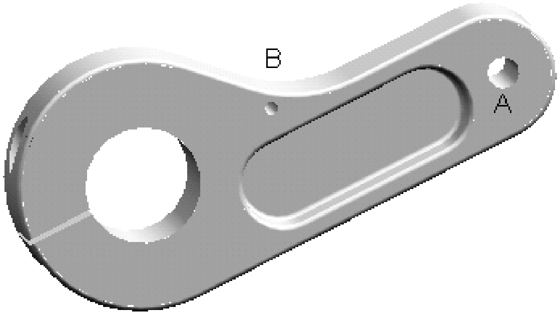


Further improvements



With large cut outs on either side, the central region of this arm had similar mechanical properties to an I-beam. This improvement involved a 20% reduction in mass with little or no compromise on strength. A chassis using these arms would still be too long however.

Finished product



Smaller and lighter than the previous idea, the finished arm mounted onto a smaller bolt and involved less waste metal in its manufacture. It meant that the chassis could be smaller than the earlier one.

The final design had a simple 6mm hole (A) that locates on a shaft with a slight clearance fit for low friction pivoting. Also, a small M3 threaded hole (B), located just above the weight reducing cut outs, was for the ball joint of a suspension spring damper unit. This unit is described in the next section.

In summary, the task of the arm is to mount the motor in place, keep the wheel in a vertical plane and enable the wheel to follow varied surface deviations. These three tasks are satisfied with the manufacture of one component, so the overall size and complexity of the suspension system is kept to a minimum.

4.2 Spring Damper System

A number of suspension proposals were considered to use with the suspension arm. The most simplistic idea was a flap of spring steel screwed into the pivoting end of the arm and then fixed to the chassis. This would provide adequate surface tracking ability for the application because the robot really does not go fast enough to require a separate damping mechanism. However, it was foreseen that a number of different flaps would have to be tested because at the time the mass of the complete vehicle could not be estimated, and to calculate the required stiffness would use too much research time. One choice of leaf spring leaves very little room for adjustment, so an arduous process of trial and error would be necessary to ensure the idea worked. A torsion bar was considered as well, but this had similar disadvantages to the leaf spring idea.

Because of the robot vehicle’s likeness to a radio-controlled (RC) car, both in size and weight, considerations were made to use a mass-spring damper system, available from a RC car manufacturer, for the suspension arms. This proposal had a number of advantages. Firstly, the units were already manufactured and did not need to be modified to suit the robot. Secondly, they could be very simply snap-fitted into place. All that was required was to attach a small ball joint to each arm and another corresponding one to each corner of the underside of the top plate that formed the body of the chassis. Thirdly, they had a wide range of springs with different stiffness and a range of piston shapes for a range of damping ratios. There was also a range of oil viscosity to further adjust the damping ratio.

Because of the considerable time and effort required to design a new robot, there was considerable pressure placed on the new design to work well. In recognition of the design limitations of the initial robot, its replacement should be engineered so that any limitations that exist with the new robot vehicle are not a result of the chassis design. Based on the resources available and the given timeframe, it was decided that the use of small spring damper kits was the optimal solution because it was guaranteed to work, it could be adjusted and finely tuned, and its implementation would not render other ideas unusable at a later stage.

4.3 Suspension arm central mount

During the time of the suspension arms development, the method for its attachment and the shape of the part that the arm attached to changed along with these developments. There were, however, some fundamental design factors that were common to all designs. The control circuit board assembly was to be connected to a flat plate in the centre of the vehicle and there needed to be some extra room for future attachments to be connected. Although a little draconian, the flat plate idea features frequently in the design of robots from the CIIPS lab because if ideas change it is easy to mount new attachments. As adaptability was an important feature in this project, using a flat plate seemed the logical alterantive. The suspension arms were to protrude forward and aft from the central region so that the front half of the chassis is symmetrical to the rear half. This design feature was intended to make forward motion of the vehicle indiscernible from reverse motion. To make flanges for the attachment of the arms, either the flat plate is bent around the edges or another component is designed as an interface between the flat plate and the suspension arms. Components machined from solid must not have a shape that requires excessive machining, and components made from a standard cross section are limited, in shape, to cross sections that are available from nearby sources.

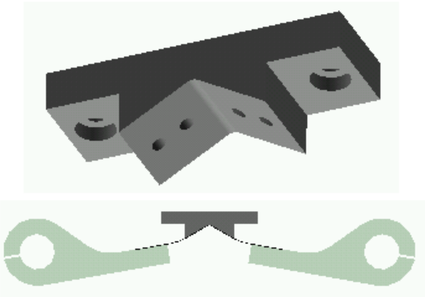
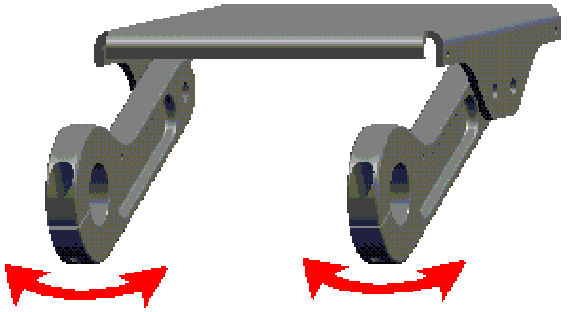


Figure 4.3.1

The earliest idea was designed in conjunction with a small strip of spring material connecting the arm to the rest of the chassis. It is screwed up to the underneath of the plate in two places (see Figure 4.3.1). Although short lived, this idea exhibits a crude, but novel simplicity. The idea was aborted due to the necessary trial time needed to decide the fastening method, the required stiffness of the strip and how to achieve sideways rigidity. From Figure 4.3.2 it can be seen that this type of rigidity is an important feature of the chassis because in some modes of movement, wheels on opposite sides push in to each other to create a net movement in a forward or backward direction

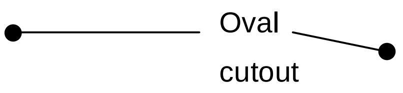
The ideas to follow were to use a bolt to connect the arm to a flange or between two flanges. Using the sheet metal from the top plate to mount the bolt, there is a problem with tolerance, because the bends have to be perfectly parallel to make sure the arms are aligned properly. Also, the top plate need only be around 0.5mm thick to support the processor, but to support the bearing loads from the bolt, it has to be around 1.5mm thick, which is a little more difficult to bend accurately. The loads on a single flange may cause it to elastically deform, resulting in the arms lacking sideways rigidity (see Figure 4.3.2.). The arms are required to rotate freely in the vertical plane, but must be held in place so they move very little in the other planes. Thus a very close fitting bolt must be used as the bearing surface at the pivot point of the suspension arm.

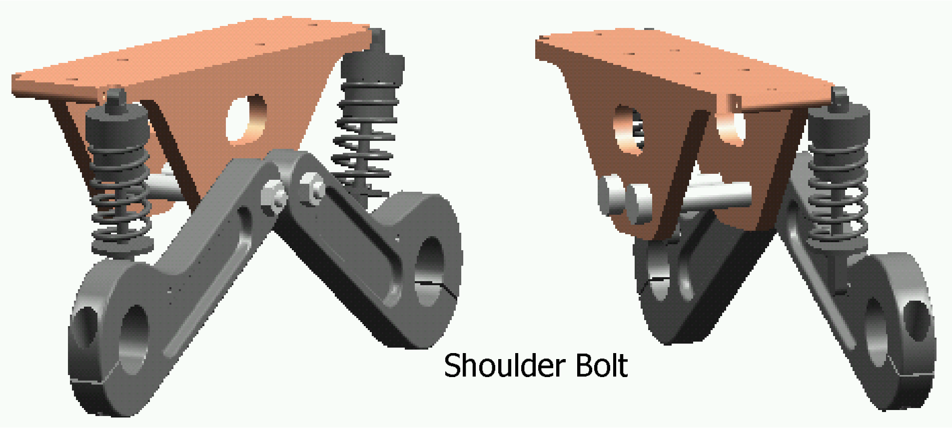
Figure 4.3.2



The ideal bolt for mounting in this situation is known as a shoulder bolt. This bolt has a long polished shank for precise fitting with a smaller-sized thread on the end. The bolts can be ordered with varying lengths and diameters of shank. Using this bolt held in two places, either the bolt can be connected to the arm and used to spin freely in the central mount, or the bolt can be fastened to the mount and the arm pivots around the shank of the stationary bolt. The idea of using such a bolt was suggested by Chris Ballan, a workshop technician who manufactured the prototype wheel earlier, and this shaped the design for the next mount idea. Using a U-shaped channel, the bolt is fastened to the arm with a nut, which fits neatly in to holes cut into the flanges, and the centre section of the channel is extended to provide a place for the spring to locate on to (See Figure 4.3.3).

Figure 4.3.3 Preferable mounting arrangement using shoulder bolts and spring damper units.





This design also provided a place for the battery by adding an oval shaped cutout, making good use of the volume. At this point it became easy to work out the length of the proposed chassis if it were made with the part in question. Therefore further modeling was carried out to see if the arms could be shortened and the mount could be made more compact in order to achieve an added bonus of creating a new chassis that is smaller than the existing one. It was at this stage that the aforementioned changes in length to the suspension arm took place. The design of this component was heavily reliant on the sections of aluminium available, so the scrap stocks of the mechanical engineering workshop were scoured for an appropriate section to alleviate the problem of needing to order an inconveniently small length of aluminium section from a distributor.

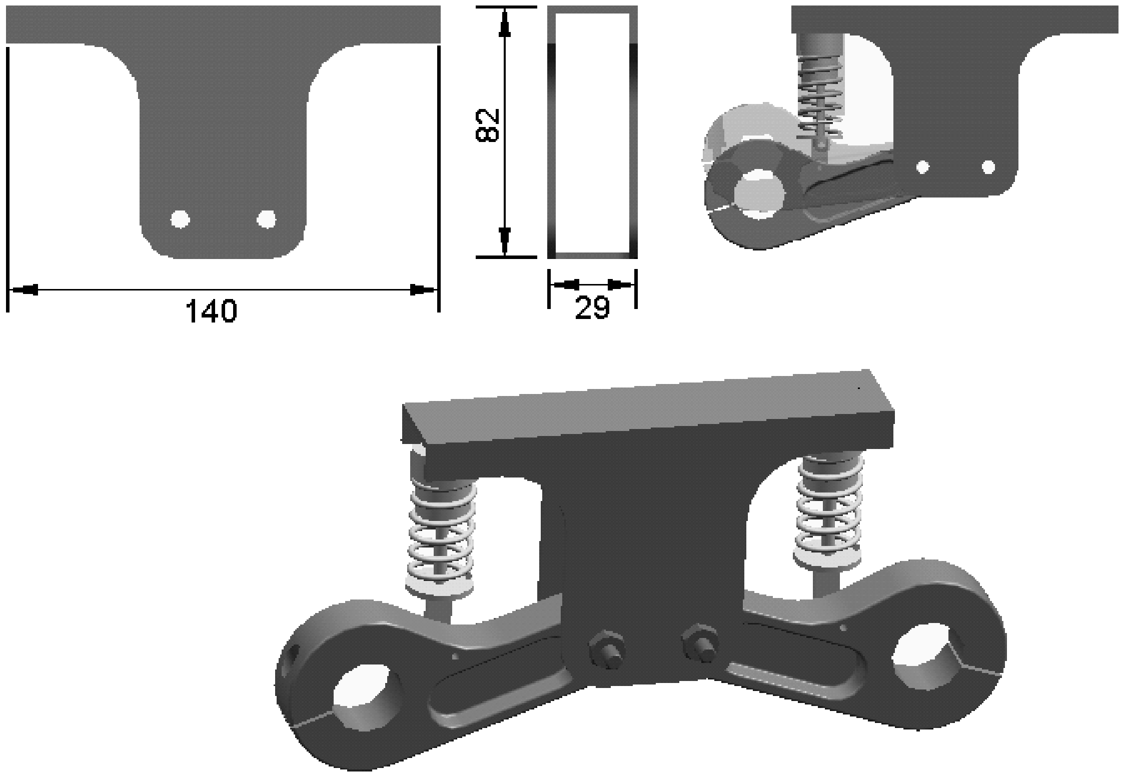


Figure 4.3.4

Figure 4.3.4 shows the final design, which came to be because of a unique piece of aluminium box section that came in precisely the appropriate length. The design still had the same features of the most recent design decisions, with the exception of the battery mount, but it had some added advantages. The section was high enough to mount the arms near-horizontally and the spring kits vertically. This meant that the springs would not rotate much between their fully extended and fully compressed states, thus preventing the spring stiffness from being affected by their orientation. Also, because of the near-horizontal arms, the wheels would be moving close to straight up and down, safeguarding against any kinematic difficulties that might creep in as a result of the movement of the suspension arms. The width of the box section happened to fit exactly the shank length of one of the shoulder bolts available on order, which was convenient, and this meant that the arms would be mounted in between the flanges with a spacer. Being made from aluminium, the design could be manufactured personally without commissioning the services of the Mechanical engineering workshop, saving manufacturing costs.

4.4 Assembly

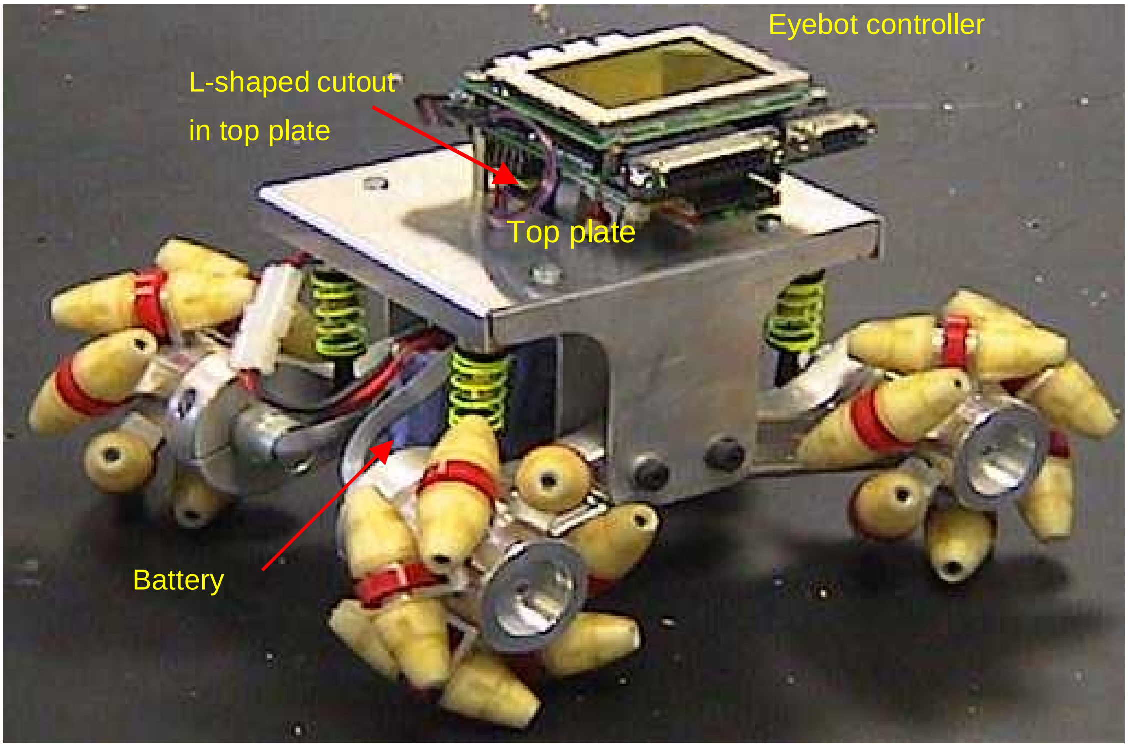


Figure 4.4.1 Finished assembly of the chassis with controller and battery fitted.

The final assembly of the chassis was very simple because all the complications of suspension and motor mounting were taken care of by the components already discussed. The flat plate that was discussed in the previous section is merely a way to join the central mounts, the battery holder and the central processing unit together. If there was a request to make the vehicle look sleek or stylish then this assembly would not win any awards, but since there was a need for versatility, and the ability to attach future apparatus that can not be foreseen at present, this was ideal.

In the corners of the top plate, holes were drilled for the central mounts to attach each side and one hole was made elliptical to allow adjustment of the parallel. The battery holder was a simple bent piece of aluminium sheet that is riveted to one of the central mounts. The battery is held in place by Velcro™, which stops it from sliding forward and aft. Some screw holes were drilled for two mounting pillars on the central processing unit to attach to, and an L-shaped cut out was made to provide access for the motor cords to plug in. The top plate was been bent over at the edges to give the plate some resistance to bending as well as giving the chassis a more pleasing appearance.

4.5 Modifications

Many modifications were made during the developmental stages of the various components, but there were some things that had to wait until the vehicle was constructed and tested before they were observed.

The Processor has a hardware testing function hardwired in to it, and upon testing the response of the four motors, it was discovered that one had a poor connection. Unfortunately this meant that the back of the motor had to be cut open and new wires grafted to the damaged ones. In hindsight the conclusion was reached that the process of fitting a sleeve to the outside of the motors is a very delicate process and should be done slowly and methodically to ensure the wires are kept safe at all times. Had this been done in the first place, a great deal of time and repair effort could have been saved.

In early photos a simple flat square piece of aluminium can be seen being used as the top plate. The aluminium came from scrap and was thick enough to provide stiffness to prevent sideways bending. This was intended to remain, but the location holes for the processor and the cut outs were placed in a bad position, which left too little room for attachments later. The Processor mounting position had been under scrutiny for some time because the centre distance of the mounting pillars was such that the holes in the top plate would not fit between the central mounts. The decision had been made to fit the processor with the readout screen at right angles to the forward orientation of the chassis and the holes and cut out were placed without proper consideration of other factors. A new top plate was made, this time out of thinner aluminium, with the edges bent over to increase stiffness and the processor located further aft for more room at the front. In order for the programmers to understand which motors are plugged in to which ports (front-right, rear-left etc.), the front of the robot was labeled.

During the final tests of the assembled robot, it was observed that the motors struggled with sideways movement. In this mode of movement, each wheel rotates in the opposite direction the wheel on the opposing side. This propulsion relies on the torque of the motors being transmitted as a sideways force via the rotation of the rollers, which involves a high proportion of transmission losses. To reduce these transmission losses some low friction washers were placed on ether side of the roller discs to reduce the rubber contact with the inner face of the aluminium clevis. This helped but the motors were still observed to struggle. It is an interesting case to study because the motors do not have trouble using sideways movement to rotate the robot on the spot, but it is beyond the scope of this project. This is mentioned in the performance evaluation.

5 PERFORMANCE EVALUATION

The main focus of the design was to produce a chassis that would in no way hinder or compromise the performance of the control system it was designed for. As a result the suspension system was perhaps over engineered, giving the wheels a lot more suspension travel than was necessary. Because the suspension system is so robust, the wheels can overcome a step size of around 15mm in longitudinal motion. The vehicle has already endured a heavy fall, which only bent one of the roller shafts. Fortunately there was a spare, so nobody’s work was hindered for too long, but the fact that nothing else broke speaks highly of the suspension system and needle roller bearing for absorption of motor shaft radial loads.

Testing of the performance has been done on a number of surfaces ranging from smooth surfaces (linoleum floors and tabletops) to rougher surfaces (carpet and bitumen) as well as uneven surfaces (tiles and pavers). The forward motion of the vehicle is unaffected by terrain, the suspension enables effortless handling of surface irregularities.

Transverse motion is more difficult for the robot to perform. On flat, smooth surfaces, the transverse velocity is around seventy percent of the longitudinal velocity, and on surfaces like carpet and matting this drops to about fifty percent. However, because the rollers are orientated 45 degrees to the wheel axis, theoretically there should be no reduction in velocity for transverse motion. Unfortunately the robot is slightly under powered, and this is evident in its performance on carpet. Also, the vehicle does not maintain a constant angular orientation during this movement, but this could be fixed with a little adjustment.

Diagonal movement involves the operation of only the diagonally opposite wheels and this has the effect of forcing the disengaged wheels to turn. Unfortunately the friction of the rollers causes too much of a moment on the contacting roller, and this tends to force the stationary wheel to turn. Hopefully this will be solved in the future by the use of a feedback control system currently being developed in CIIPS.

Rotational movement is performed with no difficulty at all. With the centre wandering about 4.5mm per revolution, the positional accuracy is reasonable, and hopefully will also improve with the addition of a feedback controller.

The specifications and performance characteristics are as follows:

Length	260mm
Height (without controller)	120mm
Height (with controller)	160mm
Width	220mm
Mass	2.85kg
Longitudinal velocity	0.27m/s
Transverse velocity	0.19m/s
Rotational velocity	1.46rad/s

6 CONCLUSIONS

Overall the construction of this chassis was a success. Testing proved that its operation on a range of surfaces was satisfactory, thus, far outperforming the previous model. Some forms of motion presented problems, but there is room for adjustment and development of software to overcome them. As well as improved performance characteristics, this robot has a smaller wheel diameter, and is more compact and lighter than the first design.

7 RECOMMENDATIONS

The successful completion of this project has produced a reliable, robust foundation for further research to take place CIIPS. Although it is a vast improvement on the vehicle before it, there is much room for future improvement.

Firstly, the vehicle has some metal components that are heavy. If the Wheel hubs, the clevises and the suspension arms were manufactured from a polymer, the overall mass reduction would be around 1.2 kg[1], almost half the existing mass. A considerable improvement in performance is likely to be observed as a result.

Secondly, the roller shafts can be made with a retaining head at one end so that the number of fasteners on the wheels is halved. This would make the vehicle cheaper and less tedious to assemble and maintain.

Thirdly, grub screws were used to lock the shaft in place. A more sound method of locking the motor shaft to the wheel hub would increase longevity and reduce maintenance time.

Finally, an analysis of the roller friction should be performed to determine if the Teflon coated bushes are necessary.

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[1] Unigraphics solutions Inc. *Solid Edge* Computer Program calculations

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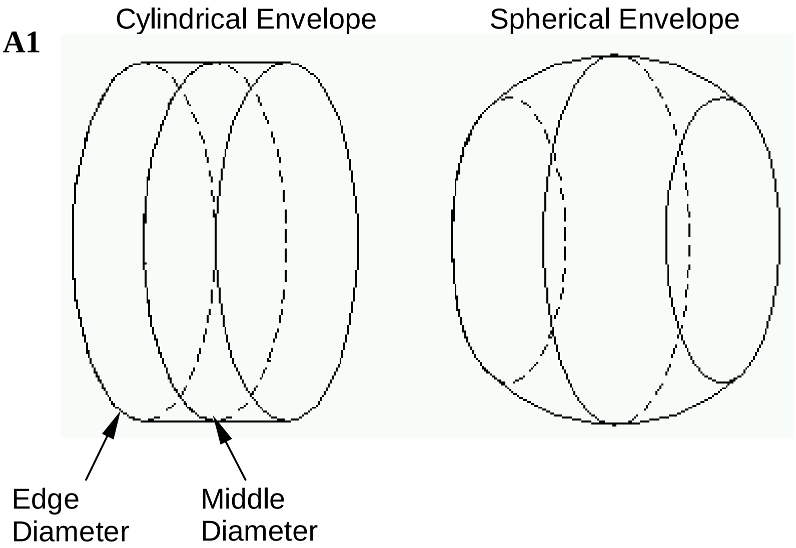
APPENDIX A

Proof of Cylinder-Based Roller Profile

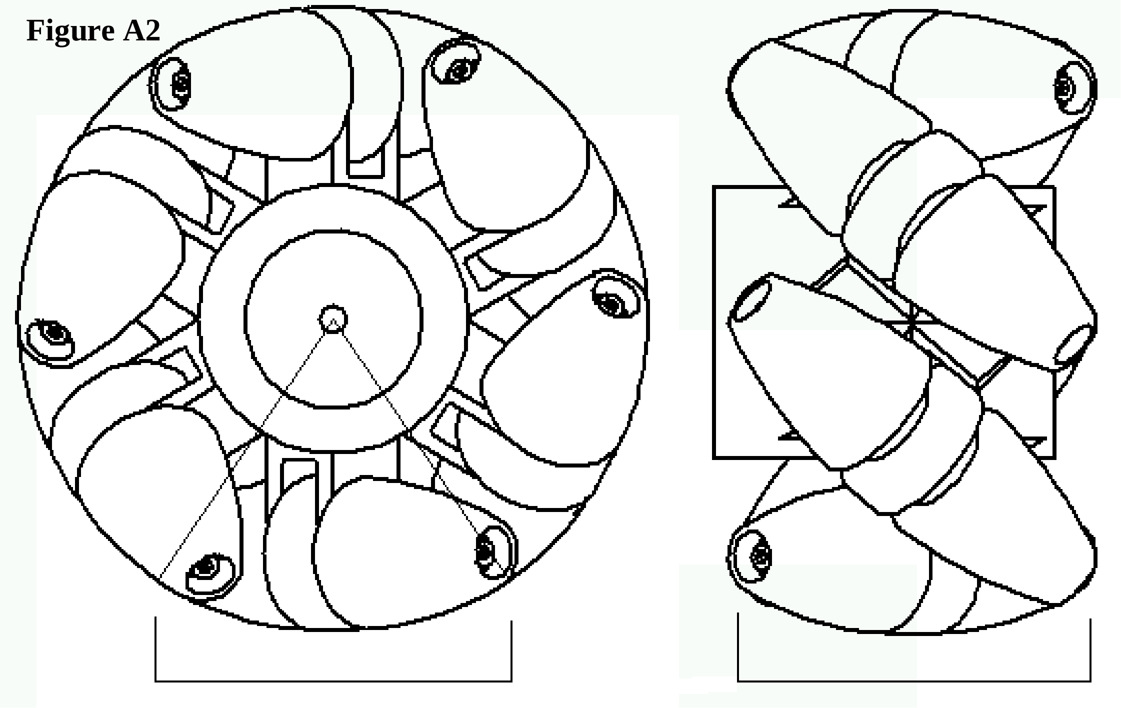
In Section 2.2, the roller profile is said to be based on the envelope of a cylindrical wheel. For mechanum wheels of this type it is a necessity, otherwise the frontal projection of the wheel is not a circle and the wheel does not roll smoothly. Consider two different wheel envelopes: one cylindrical and the other spherical.

Figure A1



For the purpose of this study, we define the two terms shown above: *Edge Diameter* and *Middle Diameter*. Obviously they are the diameter of the wheel at the edge and at the middle respectively. With a cylindrical envelope, these diameters are the same, whereas with a spherical envelope they are not.

Figure A2



As shown in Figure A2, when Mechanum wheels use rollers orientated at any angle other than 90 degrees, the roller length spans the width of the wheel envelope as well as spanning a segment of the wheel diameter. If the rollers span the width, then the surface of the middle part of the roller is some distance, equal to the radius of the *Middle Diameter*, from the wheel axis. Likewise, the surface of the ends of the rollers is the distance equal to the radius of the *Edge Diameter* from the wheel axis.

Now, if the rollers are spanning the circumference of the wheel, then the <u>whole roller profile</u> must coincide with the wheel diameter, otherwise the wheel will not roll smoothly.
This can only be done if the *Edge Diameter* is the same as the *Middle Diameter*.
Thus, the roller profile must be made to suit a cylindrical envelope.

APPENDIX B

Rubber Moulding Process

After days of developing the moulding process, it was put into a number of steps in order to achieve a consistent result and produce more rollers at a time. The most moulds that could be filled with rubber compound from the same batch was three because any more would mean that the compound would be starting to set during the pouring of the final mould. There were, however, five moulds completed by the mechanical workshop, so two batches were done per moulding session. Before beginning it is important to make sure that the are is clean, all the utensils and substances are all within arms reach and the mould components are adequately coated in release agent. Once the reagents are combined, the clock starts ticking, so anything that can be done prior to the mixing should be completed.

When it is time to begin, the first task is to measure out the reagents. The ratio is fairly critical, so a mass balance accurate to 1/100 of a gram is used. Because the amount of compound required per mould is around 4 ml, this apparatus enables a level of three significant figures, which is adequate. The mass of resin and hardener is calculated to meet the prescribed 35:100 ratio and then the calculated amount of resin is poured into the zip lock bag. The resin is by far the more viscous liquid, similar to honey. Being the more difficult to measure accurately, it is put in first so that time can be spent getting the right amount in. The hardener is thin enough to be administered using a syringe, making it very quick and easy to add the precise amount. Figure 3.2.1 shows this being done.

Figure 3.2.1

Once the correct amounts of resin and hardener are added, the air is carefully coerced out of the opening, as shown here in figure 3.2.2, and the bag is sealed. The bag is then vigorously kneaded and squeezed to mix the two reagents together. If any air is left in the bag then it is of no consequence because it is broken up into tiny bubbles and dispersed throughout the mixture by the kneading process. Particular attention is paid to the corners where unmixed reagent tends to dwell.

Figure 3.2.2

Once the reagents are mixed the compound is neatly pushed into one corner and the bag is folded over to form a neat little parcel (see figure 3.2.3). The corner of the bag is cut and the compound is squeezed out in a manner similar to that of a piping bag.

Figure 3.2.3

The core insert and locating pin are already placed in the mould and the compound is poured down the gap located at one of the milled channels of the core (recall section 3.1.1). This, as mentioned previously, is made easy because the liquid is squirted from the bag, getting it into the mould faster than it normally would under gravity alone. This task is illustrated by figure 3.2.4.

Figure 3.2.4

The rubber coating occupies around 2.7 ml of volume so when the mass balance reads more than 2.8g, enough has been added. The balance is zeroed with the empty mould beforehand so this can be measured. To complete the pouring, Figure 3.2.5 shows a bead of compound is laid around the top of the insert to safeguard against bubbles of air staying there when the cap is put on the mould. You can see from Figure 3.2.6 that the mould now contains 3.6g of rubber compound.

Figure 3.2.5

Figure 3.2.6

Figure 3.2.7

Figure 3.2.8

The top cap is fixed to the locating pin, covering the very back of the insert so the compound does not collect there, and the core and top cap are lowered slowly into the compound reservoir using the wing nut on the bottom (Figures 3.2.7 & 8).

The excess liquid flows out the sides and the escape holes as the wing nut is tightened (Figure 3.2.9), and this is wiped off with a paper towel (Figure 3.2.10). Paper towels are very important for wiping away any spillage and it is advisable to have a good stack of around 15 to make sure they do not run out in the event of any spectacular fumbles.

Figure 3.2.9

Figure 3.2.10

In Figure 3.2.11 the puddles on top of the escape holes have been left until after the compound has set. This is because some fluid is sucked back into the mould during shrinkage and if this is wiped away before setting, then air is sucked back in.

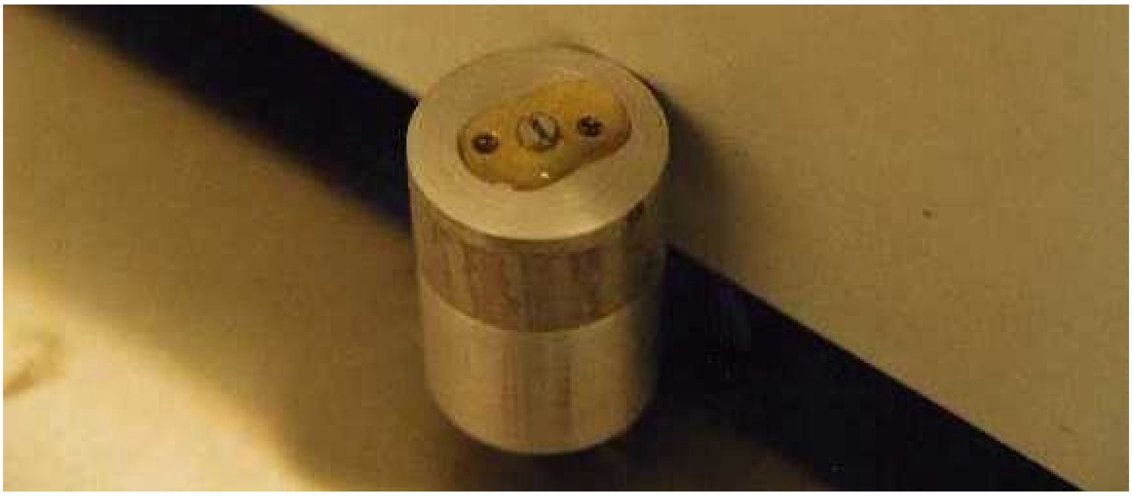


Figure 3.2.11

Once the process was perfected then the roller segments were produced much more reliably and they were very easy to extract from the moulds. If a roller segment moulding process were to be industrialised, then it would most likely bear very little resemblance to the process formulated here. However, since there was a low output of fifty units to be made quickly and cheaply, this crude and hobby-like solution was both effective and fulfilling.

APPENDIX C

Mechanical Design Drawings

C1 **Mechanum Wheel Hub**

C2 **Roller Clevis**

C3 **Roller Segment Core**

C4 **Mould for Roller Tyre**

C5 **Locating Pin**

C6 **Roller Disc**

C7 **Roller Axle**

C8 **Suspension Arm**

C9 **Central Mount**

C10 **Top Plate**