THE UNIVERSITY OF QUEENSLAND

Foot Design for a Humanoid Robot

By

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and Electrical Engineering

Submitted for the degree of

Bachelor of Engineering (Honours)

In the division of Mechatronics Engineering

October 2004

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27 October 2004

Professor Paul Bailes
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Dear Professor Bailes,

In accordance with the requirements of the degree of Bachelor of Engineering (Mechatronics), I present the following thesis entitled

"Foot design for a humanoid robot."

This work was performed under the supervision of Dr Gordon Wyeth. I declare that the work submitted in this thesis is my own, except as acknowledged and has not been previously submitted for a degree at the University of Queensland or any other institution.

Yours faithfully,

Michael G. C. Davis

To all students who understand the importance of the weekend

Acknowledgements

In the preparation of this thesis I am most grateful to the following people for their contributions and assistance.

Dr Gordon, for his guidance, humour and sense or reality.

Damien and the robotics postgraduates, for their unknowing advice in the direction of my life and all the little pointers along the way.

Associate Professor Carlos Caceres and Graeme Rhule for their assistance in material selection and testing.

I am eternally thankful to have had many wonderful people influence me through my life and through the course of my thesis, in particular, my family who provide refuge and motivation. For my mother’s trusty advice, wonderful cooking and unwithering support, my Father’s inquisitive nature, reliable scepticism and desire to see me do my best, and my sister’s empathy and sense of fun. Finally, I thank all of my friends for making my final year of university so much fun!

Abstract

This thesis describes the design of sensate feet for a humanoid robot. The robot, GuRoo, is capable of basic walking but lacks the ability to sense its interaction with the surrounding environment. The aim of this thesis is to redesign GuRoo's feet so they can measure ground reaction forces that will aid in active and static balance.

The redesigned foot incorporates two groups of sensors that together gather the information about the ground's surface most relevant to walking. The first sensor is a contact grid sensor that checks for contact at each point of a grid and delivers a series of binary data representing the contact points with the ground. Collating this data allows the robot's support polygon to be calculated. The second set of sensors are capacitive sensors that measure the deflection of a series of leaf springs held between two rigid plates. As the springs behave linearly, measurements of the plates' separation at each corner is sufficient to calculate the normal force and pitch and roll moments through the foot. Combining these two sensors, GuRoo can ascertain both the shape and reaction force distribution of an object under foot.

Although the mechanical construction of the foot is not complete, preliminary simulations show predictable and reliable functionality of the foot. The integration of the redesigned foot will allow GuRoo to make comparisons between its calculated and actual ZMP (zero moment point), resulting in a closed loop gait. Furthermore the redesigned foot brings the capability to walk on a variety of uneven surfaces.

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Chapter 1 – Introduction

This thesis describes the design of sensory pads to be fitted to the University of Queensland's humanoid robot, GuRoo. The pads perform two functions. Primarily, the pads are designed to return useful information about GuRoo's ground reaction. This information combined with calculations of the zero moment point (ZMP) will drastically improve static and dynamic stability. The pads' secondary function is to minimise vibrations caused by contact with the ground. This will improve GuRoo's gait by maintaining joint and link integrity during the loading cycle.

1.1 GuRoo

GuRoo is a humanoid robot designed and developed by members of the University of Queensland's robotics team. GuRoo stands at 1143mm and weighs approximately 40kg – similar proportions to a young child. The name GuRoo stands for Grossly Under-funded Robot. GuRoo was created to participate in the international RoboCup [3] competition. The vision of the RoboCup organisation is "By the year 2050, develop a team of fully autonomous humanoid robots that can win against the human world soccer champion team." GuRoo's current functionalities include elementary walking and vision. This thesis is intended to further improve GuRoo's interaction with its surroundings by the use of sensitive feet. With further development, it is planned that GuRoo will be capable of playing soccer in an interactive environment with humans.

1.2 Problem Statement

Currently, GuRoo has a limited array of sensors. The existing sensors include motor encoders, to measure the angle of the robot's joints and the IMU (Inertial Measurement Unit) to measures body and gravitational forces. These two sensors allow open loop control, but cannot account for internal imperfections (in the form of gearbox backlash and link deformation), external disturbances (such as an uneven surface or inclined walking platform) or externally applied forces (such as being hit by a soccer ball) acting upon the robot.

Large vibratory oscillations are generated in GuRoo's gait as a leg undergoes rapid deceleration when it makes contact with the ground. The underdamped nature of GuRoo's structure allows these force impulses to resonate throughout the robot's structure.

1.3 Design Requirements

The requirement of this thesis is to redesign the existing foot with the ability to sense ground reaction forces and absorb force impulses generated by the robot's gait. The existing foot provides a platform capable of supporting the robot in its normal modes of operation. As such, it is desirable to make modifications and additions to the existing foot rather than redesign the entire foot. It is forecast that the modifications to the foot will take the form of pads fitted to the underside of the existing foot.

1.3.1 Design limitations

The rules and regulations set by the RoboCup Organisation [2] govern certain critical specifications of GuRoo. Whilst there are many rules, only a few have implications for the proposed addition of GuRoo's sensory pads. Firstly, there is a restriction on GuRoo's height – 1200mm. As GuRoo currently stands at 1143mm, this is not a problem, however as a new head is being designed, the remaining 57mm may well be required elsewhere. As such, thinner pads are desirable. Secondly, the total surface area of the two pads is to be less than 800cm^2. This is not currently a problem as the feet have a surface area of 600cm^2. Extra surface area might prove useful as a larger platform to increase stability; however this would require a redesign of the entire foot. Finally, in keeping with its name, GuRoo is not accustomed to extravagantly expensive equipment. This will undoubtedly be reflected in the final design of GuRoo's sensory pads.

1.3.2 Desired improvements

The addition of contact and pressure sensors in the feet will provide GuRoo data on ground reaction forces as well as a basic knowledge of the ground's surface. The pressure sensors are responsible for collecting information about the net ground reaction force and its line of action. Whereas the contact sensors are responsible for identifying points of contact that can be used to determine the robot's support polygon.

The addition of sensory pads will increase the sprung and damped nature of the robot. However, in creating a critically damped gait, large amounts of power would be lost through damping mediums. In order to reduce impulse forces generated during walking, modifications will need to be made to the gait. Such modifications will allow the various joints of the lower body to absorb ground reaction forces and reduce the magnitude of impulse forces. In this way the robot's gait would be made smoother and more efficient.

1.3.3 Projected design

Given the limitations and desired improvements set out in this section, an overall concept of the redesigned foot can be proposed. A successful design will take the form of a thin layer that extends below the existing foot and measures important ground reaction forces. Due to the time and resources allocated to this thesis, a simple, but effective design is sought.

Chapter 2 –

Existing Technology and Designs

2.1 Existing GuRoo Foot Design

GuRoo's existing feet were designed and constructed by Wagstaff [6] in 2001. The initial design allowed basic bipedal function without force feedback or padding. Position feedback was achieved through reverse kinematics of the motor encoders.

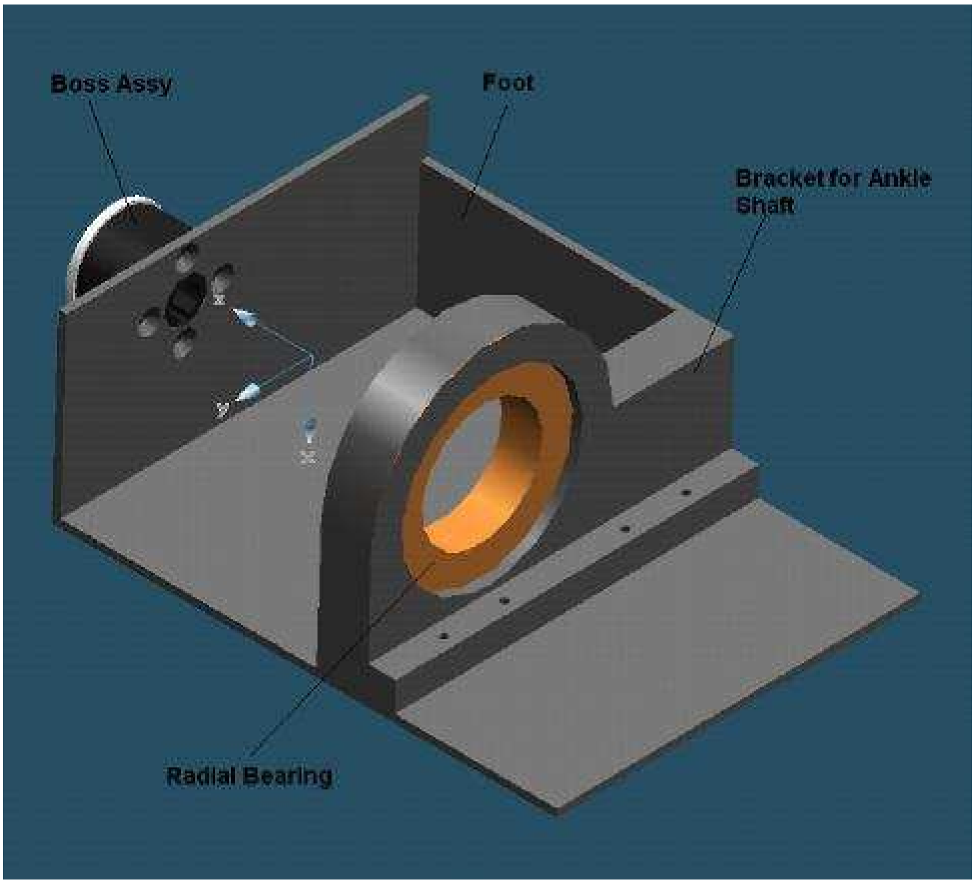


Fig. 2.1 Existing foot design [6]

2.2 Other Designs

There are few humanoid robots with foot padding and sensory feedback and the most detailed information about this technology is not usually disclosed. However, the information that is available provides guidance in achieving the design requirements set out in 1.3. Detailed in this section are two other humanoid robots, ASIMO and the SDR-4X. Both of these robots show advanced balance control, however, they achieve this through different means.

2.2.1 Honda's ASIMO

Honda's ASIMO utilises six-axis force sensors in each foot of the robot [1]. These sensors measure forces and moments in all three directions as seen at the ankle. In addition to this, ASIMO uses accelerometers and inclinometers to measure the overall orientation of the robot. To reduce vibration through the robot, Honda implements unidirectional rubber bushes and a rubber sole to the base of the foot.

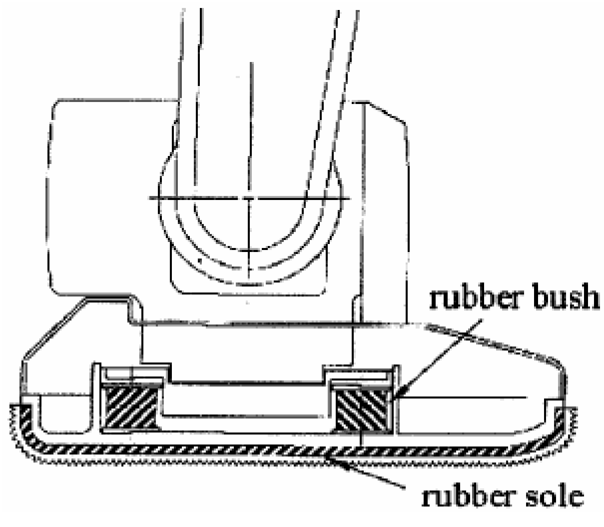


Fig 2.2. The padding and sensing configuration of Honda's ASIMO [1]

2.2.2 Sony's SDR-4X

Sony's approach is to fit both the sensing and vibration dampening hardware to the bottom of the foot. In 1994, Yamaguchi [7] implemented four linear potentiometers placed at the corners of the foot to measure the compression of the padding medium. The padding medium itself was a layered composite of acryl, urethane foam and memory foam. Composite stoppers were used to limit the maximum compression of the padding foam and to reduce deformation due to sheer. While there is no documentation of Sony's latest humanoid, it is suspected that a similar design is still used, but with the addition of contact sensors on the four corners of the sole.

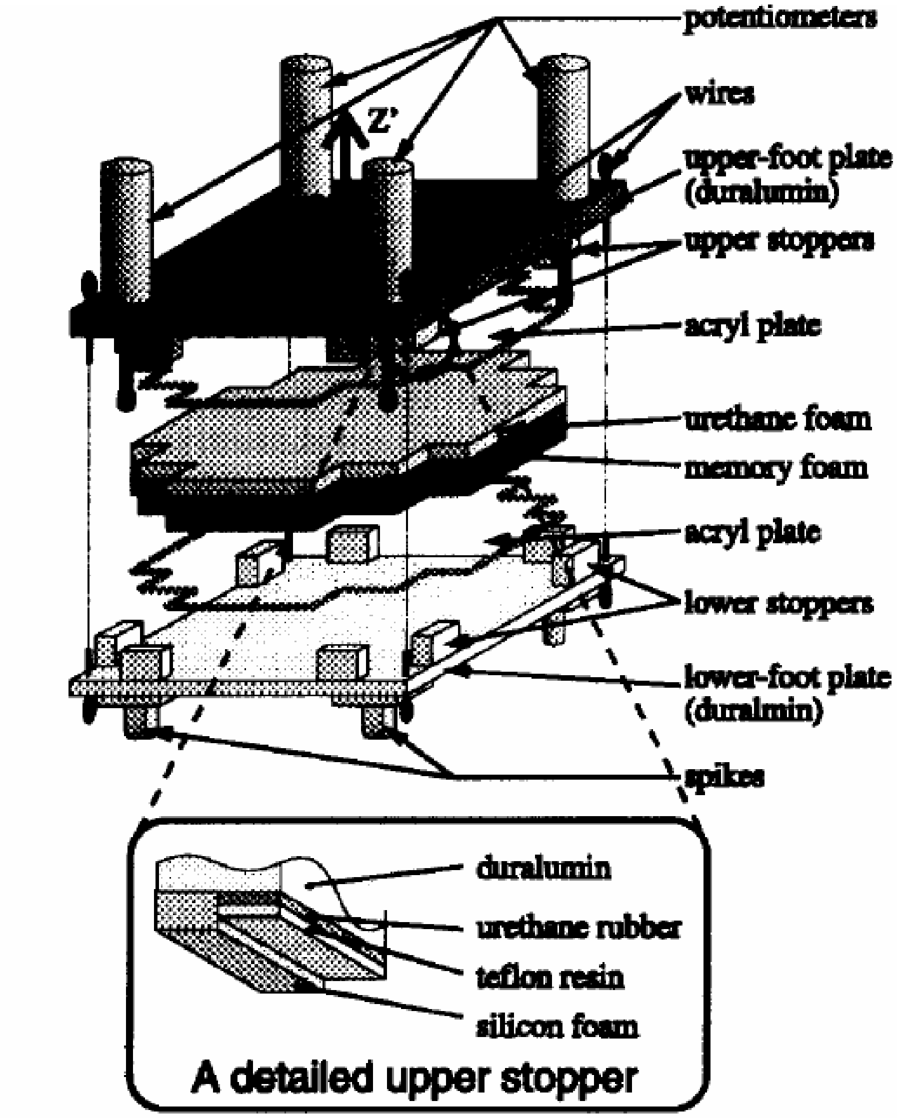


Fig 2.3 The composite materials used for padding in Sony's SDR-4X robot [7].

2.3 Existing sensing devices

There are many sensors designed to sense a uniaxial force. Among the more common are capacitive sensors, force sensitive resistors (FSRs), linear voltage differential transformer (LVDTs), touch pads and piezoelectric sensors. This section examines some of the more suitable of these sensors to the requirements of the design.

2.3.1 Capacitive sensors

Capacitive sensors measure the distance between two plates via the capacitive effect of the two plates [4]. The relationship between the capacitance and the separation of the plates can be described as:

$$C = \frac{\varepsilon A}{x}$$

Where C is the capacitance between the two plates in Farads, ε is the Permittivity of the dielectric, A is the area of the plate and x is the separation between the two plates. As the values for ε and A remain constant, the capacitance across the two plates can be used to calculate the distance between the two plates. To work accurately, the sensor must be shielded from electromagnetic radiation and the two plates must remain parallel [5]. This type of sensor functions best with small values of x (typically less than 10mm) as this gives capacitances within a more readable range.

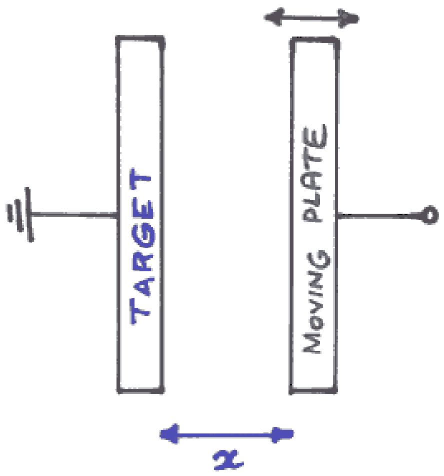


Fig 2.4 Configuration of capacitive sensor [4]

2.3.2 Force Sensitive Resistors

Force sensitive resistors measure the elongation of an elastic conductor through its change in resistance. The relationship governing this change is given as:

$$R = \frac{\rho L}{A}$$

Where R is the resistance of the conductor, ρ is its specific resistance, L is its length and A, its cross sectional area. These sensors are generally suited to measuring large forces through small deflections [4].

2.3.3 Piezoelectric sensors

Certain materials generate an electric charge when deformed by an external force. Such materials, like quartz, form the basis of piezoelectric sensors. As the sensor only produces a small current and generates no charge under constant compression conditions, they are not suited to static or low frequency systems [4].

$E \propto \dot{x}$ Generated electrostatic charge as a function of rate of compression

2.4 Existing methods of padding

Both of the examined robots utilise padding in their foot design. The primary source of padding is in the form of rubber and foam. These materials exhibit both spring and damping characteristics, which are desirable in the design of a robot foot. However, they also exhibit other non-linear characteristics such as creep (continuing compression under a constant load), relaxation lag (time to return to initial shape once a load has been removed) and hysteresis (different loading and unloading responses).

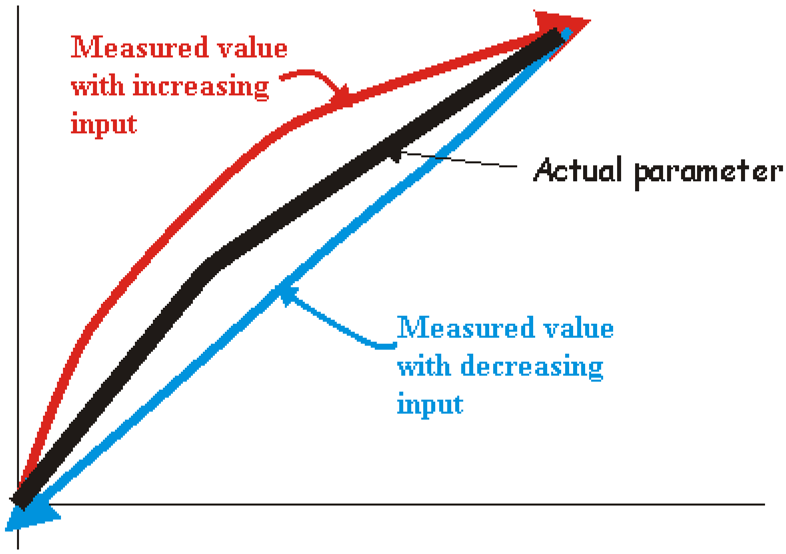


Fig 2.5 Graphical representation of hysteresis [4]

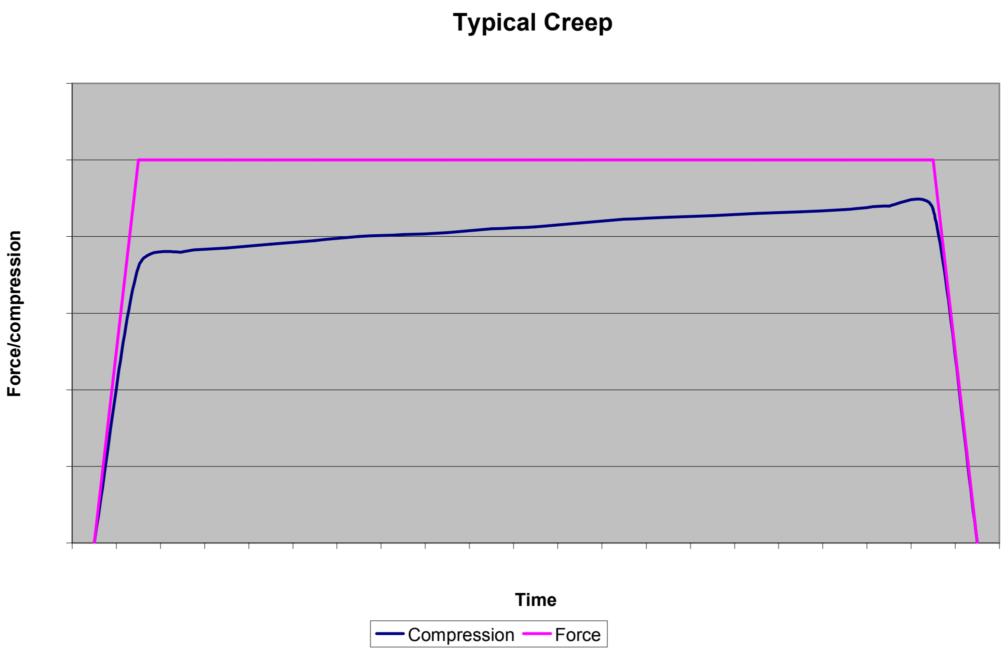


Fig 2.6 Graphical representation of creep

Chapter 3 – Design Solution

3.1 Design concepts

In order for the redesigned foot to reach the level of functionality set out in chapter one, means of force sensing, contact sensing and padding are all required. This section details the concepts underlying each of these aspects of functionality and the following section (3.2) details the integration of these concepts into the final design.

3.1.1 Force sensing

In selecting a method of sensing force, each of the methods mentioned in chapter two were considered. However, as the research of Nick Undery [5] focused upon the use of capacitive sensors to sense force in the context of a humanoid robot, this method proved most applicable. Undery's [5] capacitive sensor gave useful outputs over a range of 0-5mm. This small range of compression would suit the foot design well as larger local compressions would lead to a less rigid (and therefore less stable) support platform.

To utilise the capacitive sensor as a force sensor, rather than a linear distance sensor, a compressible medium must separate the plates. Undery [5] found that if the separating medium was placed between the plates, its volume (and more importantly, its dielectric properties) changed as the plates were compressed. To remedy this it was suggested that air be used as the dielectric, as its properties aren't affected by the sensor's internal volume. This leads to the use of the compressible medium being implemented external to the plates.

In choosing a separator for the capacitor's plates, it is most important that its elastic properties are understood and predictable. As the capacitive sensor is to be used to measure force as a function of the plate's separation ($F = f(x,\dot{x})$) it is desirable that the medium exhibits purely elastic or elastic and damping characteristics only.

$F = kx$ Force of compressing purely elastic medium

$F = kx + c\dot{x}$ Force of compressing medium with elastic and damping properties

($\dot{x}$ represents the velocity at which the medium is being compressed)

Introduction of non-linear characteristic will increase the error of these functions.

3.1.2 Force sensing layer

The role of the force-sensing module is to resolve the foot's ground reaction into one linear force and two moments. All other forces (remaining linear forces, shear forces and moment) are superfluous and should not affect the integrity of the foot. As the method of sensing force is through compression, a layer with specific rigidity and compressibility in specific directions has been conceived.

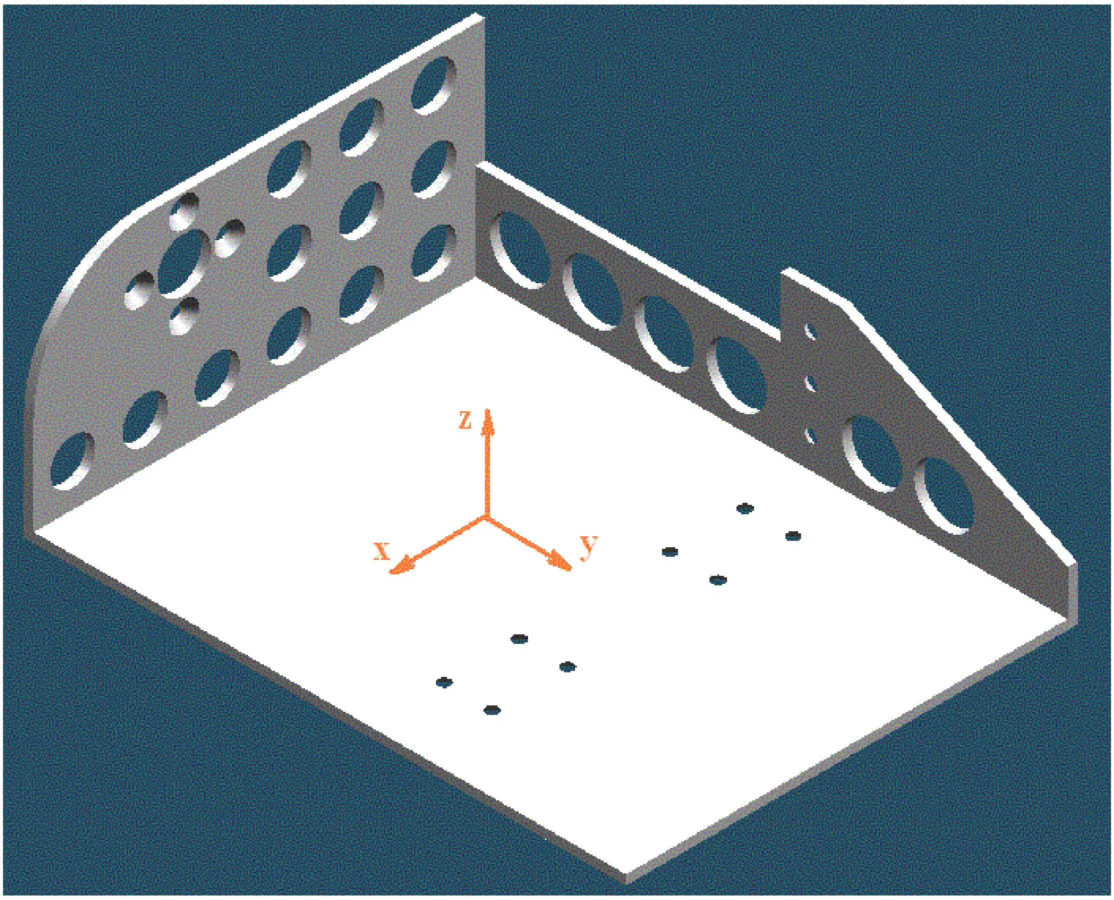


Fig 3.1 Sign convention used throughout thesis

The force-sensing layer is a thin layer that fits to the bottom of the existing foot. It has the same length and width as the robot's foot and has a thickness of approximately 10mm. There are several attributes that this layer requires. Firstly, the top and bottom layers must remain planar under all combinations of loading. Secondly, the layer is compressible in the normal (z-axis) direction, but not compressible in the x or y direction. Thirdly, the layer will deform due to moments about the x and y axes, but not about the z-axis. Finally, the layer does not deform due to shear forces applied to its top and bottom surfaces.

By placing a capacitive sensor in each of the four corners of the layer, the normal force and moments of interest can be measured. If the compressible medium is used to separate the top and bottom planes of the layer (other constructs will be required to limit other modes of deformation), then the elastic modulus in the z-axis (Ez) and moment of inertia about the x and y axes (Ix, Iy) can be calculated. Breaking down the superposition of compressions in the capacitive sensors allows simple equations to resolve the normal force and two moments.

$\sigma = \mathrm{E} \cdot \delta$ or $F = k \cdot x$	Equations used to derive normal force through compressible medium
$M = I \cdot y$	Equation used to derive moments about x and y axis of compressible layer

3.1.3 Contact sensing layer

The purpose of the contact sensor is to derive the support polygon of the robot. Since contact is a binary property, it is logical that its sensor should operate upon that principle. The resolution of the support polygon is directly proportional to the resolution of the contact sensor's nodes.

As this contact sensor operates in a similar manner to a keyboard (detects contact at specific points on its surface) its design also mimics a keyboard. The contact sensor has two layers of wires, the top layer running in the lateral (x-axis) direction of the foot and the bottom layer, which run along the y-axis of the foot.

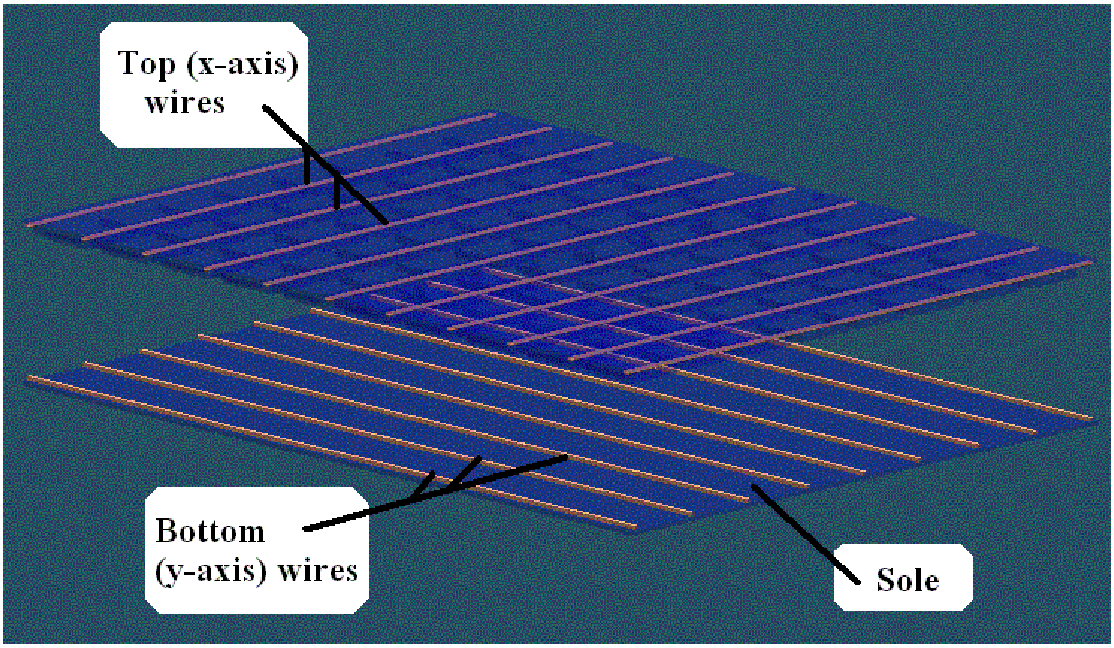


Fig 3.2 Contact sensor

In the relaxed state, the each wire is separate and insulated from every other wire. As local pressure is applied, nearby wires in the bottom layer rise to contact wires in the top layer. As the wires make electrical contact, a physical contact node is detected.

Electrical contact is detected via a scanning process. To start the scan, a voltage is applied to one of the y-axis wires. Then a scan of the x-axis wires detects contact nodes along that y-axis line. After that scan is complete, the voltage is disconnected from that y-axis wire and applied to the next. This sequence is looped continuously to maintain an updated array of contact nodes.

The calculation of a support polygon is a simple process. Once the array of contact nodes has been attained, the outermost contact nodes are joined by straight lines. In this way, all of the contacted nodes are encompassed within this polygon. There may also be several nodes within the polygon that have not made contact, however this will not affect the calculation or use of the support polygon. The purpose of the support polygon is to define the bounds of the robot's support such that pressure is only applied within a stable support platform.

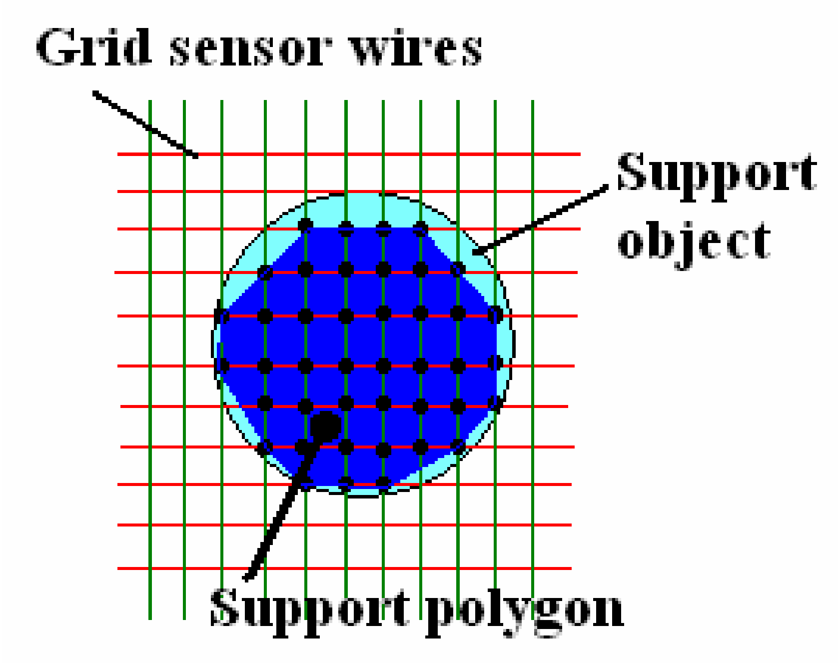


Fig 3.3 Calculation of Support polygon from grid sensor data

3.2 Final design solution

In attaining the final design, each module - force sensing, contact sensing and padding - needs to be brought together such that it can perform its individual task without hindering the other modules. As each module requires the robot's ground reaction force to pass through it, they were arranged as a series of layers. In this way, each layer would experience the force exerted by the robot and layers above it, whereas the response of the robot would be the sum of the individual layers' responses.

In choosing components for the final design, rigorous tests and calculations were used to select the most appropriate materials and layer configurations. This section details the component selection process and explanation of each selection. It also highlights the important properties and function of each component in the final design. The performance of the final design is assessed in chapter five.

3.2.1 Leaf springs

In choosing a suitable material to separate the two plates of the force-sensing layer, simple compression characteristics were paramount. Various materials were considered for this task, including EVA foam, rubbers of various densities and spring steels. In order to understand the compression characteristics of these materials a series of tests were performed. Each test was performed under load conditions representing various aspects of GuRoo's gait.

Each test was designed to represent a different mode of GuRoo's operation. The first test was a single cycle, maximum compression test (normalised to 2.5 times GuRoo's mass). This simulated the largest conceivable impact that GuRoo would transmit through the force-sensing module. The second test involved ten cycles of loading (normalised to twice GuRoo's mass) at frequencies between 0.2 and 1Hz. This test simulated GuRoo walking. The load was increased to twice GuRoo's mass to account for the impact force associated with foot placement as well as uneven foot placement. The final test was a creep test. Each material was compressed under a constant load (normalised to GuRoo's mass) for a time of one minute. This test simulated GuRoo standing stationary.

The tests were performed with the aid of an Instron stress-strain apparatus. The apparatus allowed compression of the test material at various rates and measured the compression of the material as well as the force exerted on it. The point of contact with the material was two parallel plates. The configuration of the tests can be seen in the following figure.

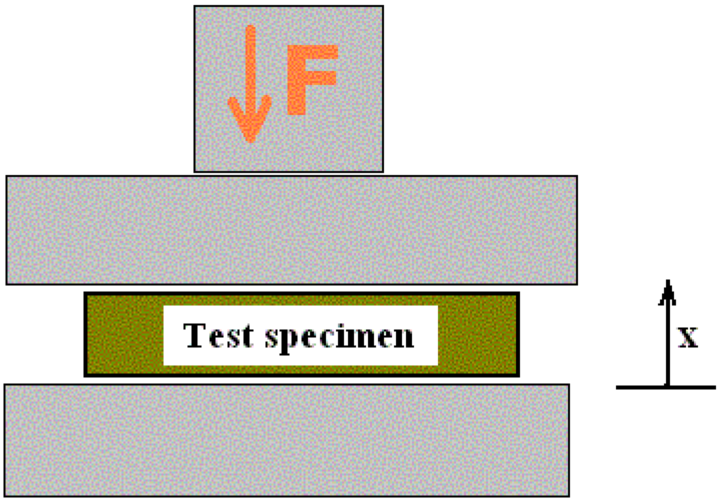


Fig 3.4 Instron apparatus setup

Test type	Test methodology	Simulated behaviour
Max compression	Compression to 2.5 times GuRoo's normalised weight	Maximum potential impact generated by GuRoo
Multi-cycle test	10 cycles at twice GuRoo's normalised weight (frequencies of 0.2-1Hz)	Normal walking
Creep test	Constant compression of GuRoo's normalised weight applied for one minute or longer	Prolonged standing

Table 3.1 Material tests

The results of the tests were varied. Whilst the foam and rubbers displayed good elastic and damping characteristics, their properties were hard to characterise. It was not possible to model their behaviour by either the $F = kx$ or $F = kx + c\dot{x}$ function. These materials also performed poorly in the creep test, showing continual compression under a constant load.

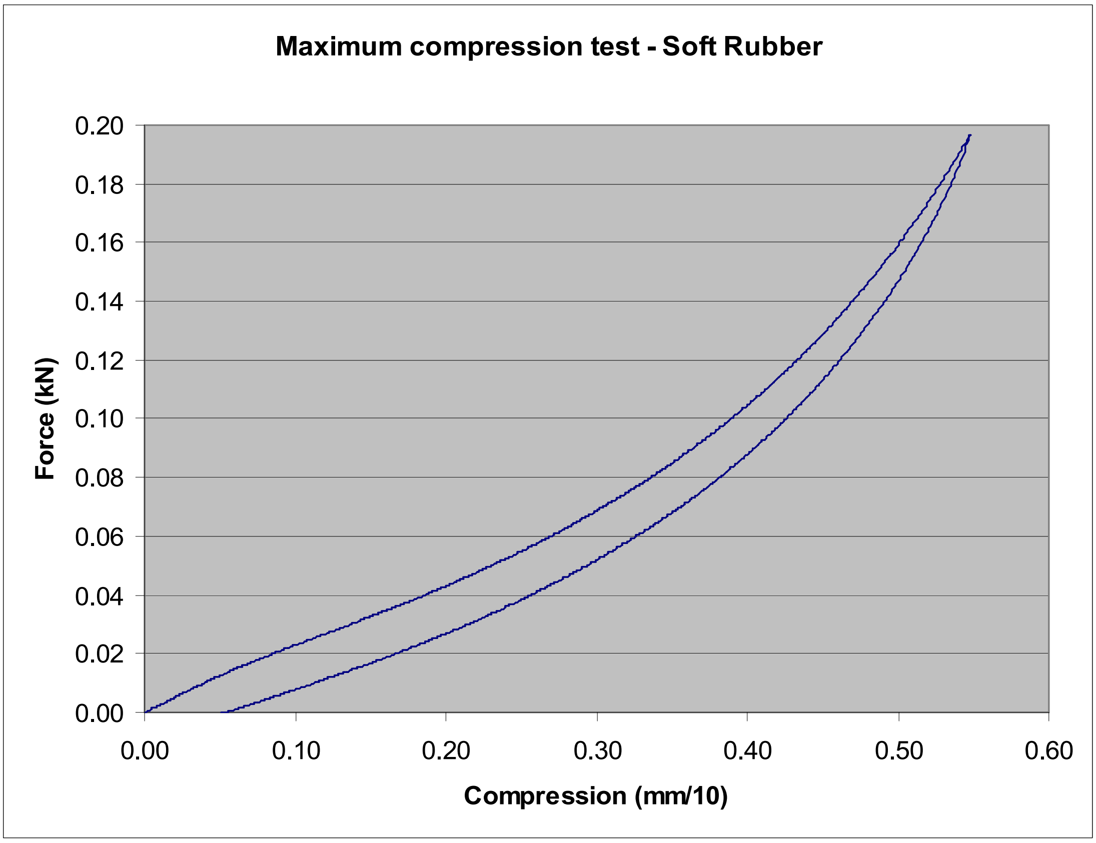


Fig 3.5 Typical maximum compression test for rubbers and foams

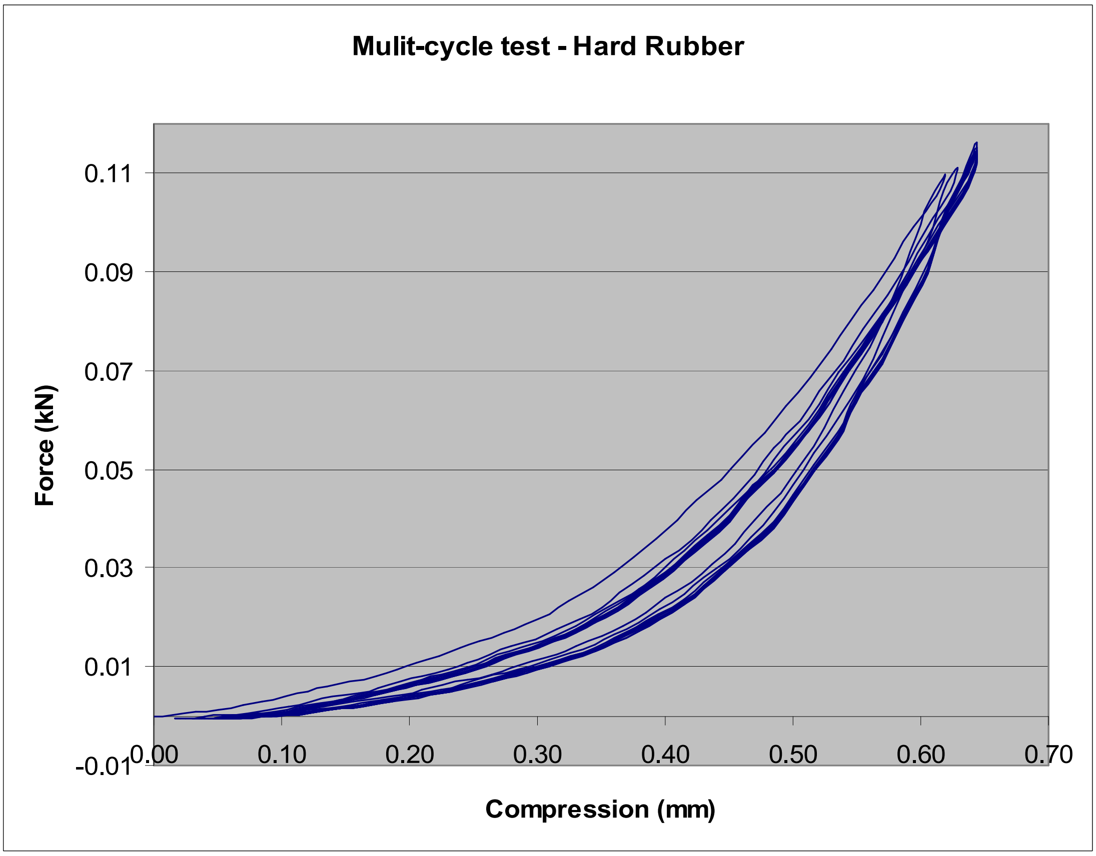


Fig 3.6 Typical multi-cycle test result for rubbers and foams

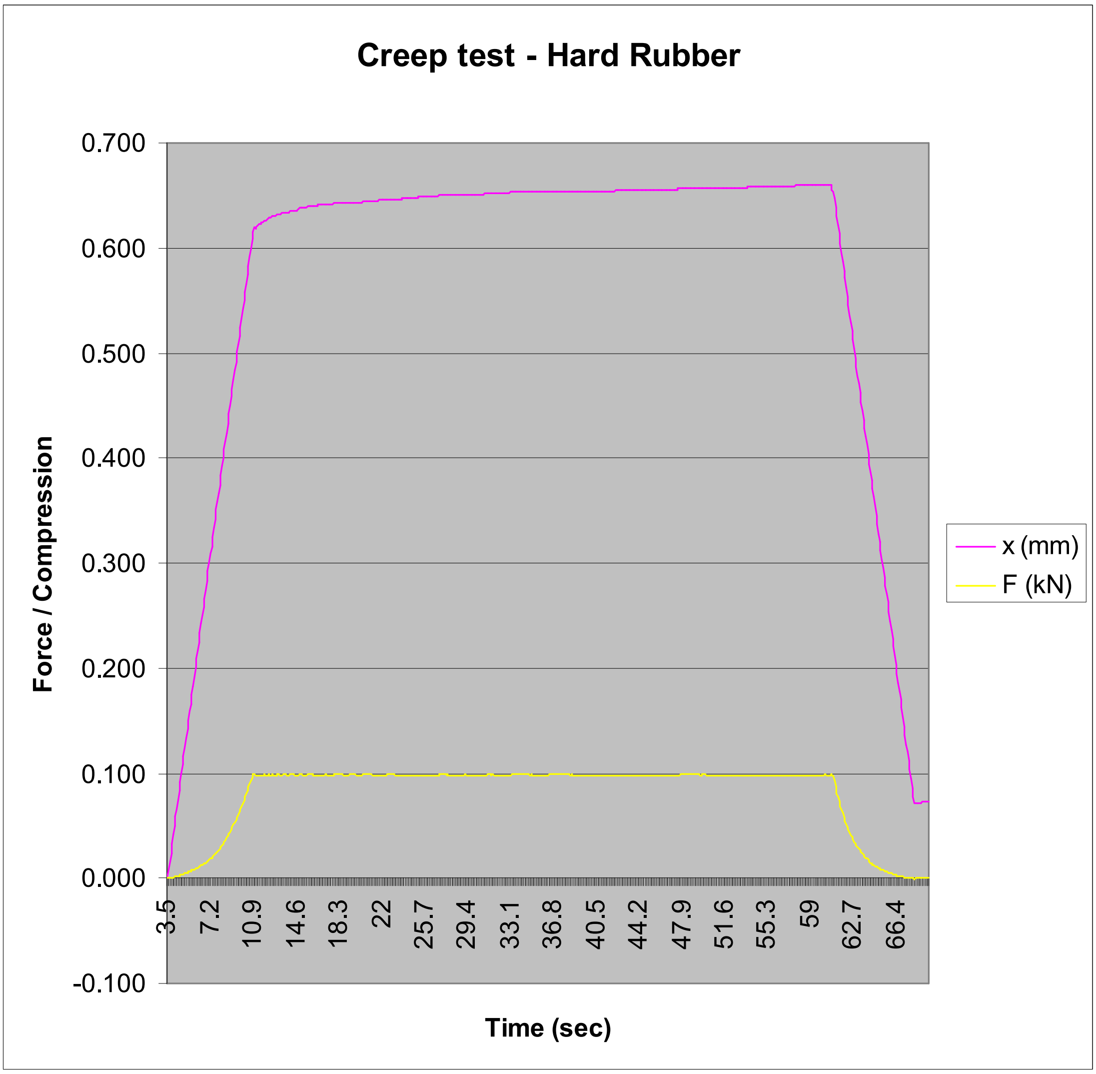


Fig 3.7 Typical creep test results for rubbers and foams

In contrast to the foams and rubbers, the spring steels displayed simple elastic behaviour (with little damping or non-linear characteristics.) Each of the spring steels behaved according to the function $F = kx$ within the capabilities of the testing equipment. The spring steel also performed well in the creep test, showing minimal effects due to prolonged loading. The graphical results of the tested spring steel can be seen in section 4.1.2

Given the above findings, spring steel was chosen as the medium to be used in the force sensor module. As the spring steel displayed no damping characteristics, modifications have been made in the contact sensor to incorporate damping effects there. To utilise the spring steel, a leaf spring was designed.

Fig 3.8 Designed leaf spring

The leaf spring has been designed to be the sole method of separating the two force-sensor planes. Several of these leaf springs are distributed between the upper and lower planes of the force-sensing module to create a compressible medium. Using leaf springs allowed the force-sensing module to remain relatively thin, thus satisfying one of its design criteria.

3.2.2 Middle foot

The layer connected to the base of the existing foot is the force-sensing layer. Its design is based upon the principles set out for the force-sensing module, detailed in section 3.1.2. To stop deflections due to shear forces, non-normal forces and moments about the z-axis, two pins have been located on the stiff plate (lower plane of the force sensor layer) that insert into pin guides fixed on the existing foot (upper plane of the force sensor layer). The pin guides allow axial movement of the pins as well as minor alignment discrepancies (due to rotation about the x and y axes). There are also another two bolts, located at the front and back of the foot that maintain slight compression of the springs between the two planes. Twelve leaf springs hold the two plates of the force sensor layer apart. Their locations are chosen to maintain maximum stability. The figure below shows the configuration of the middle foot.

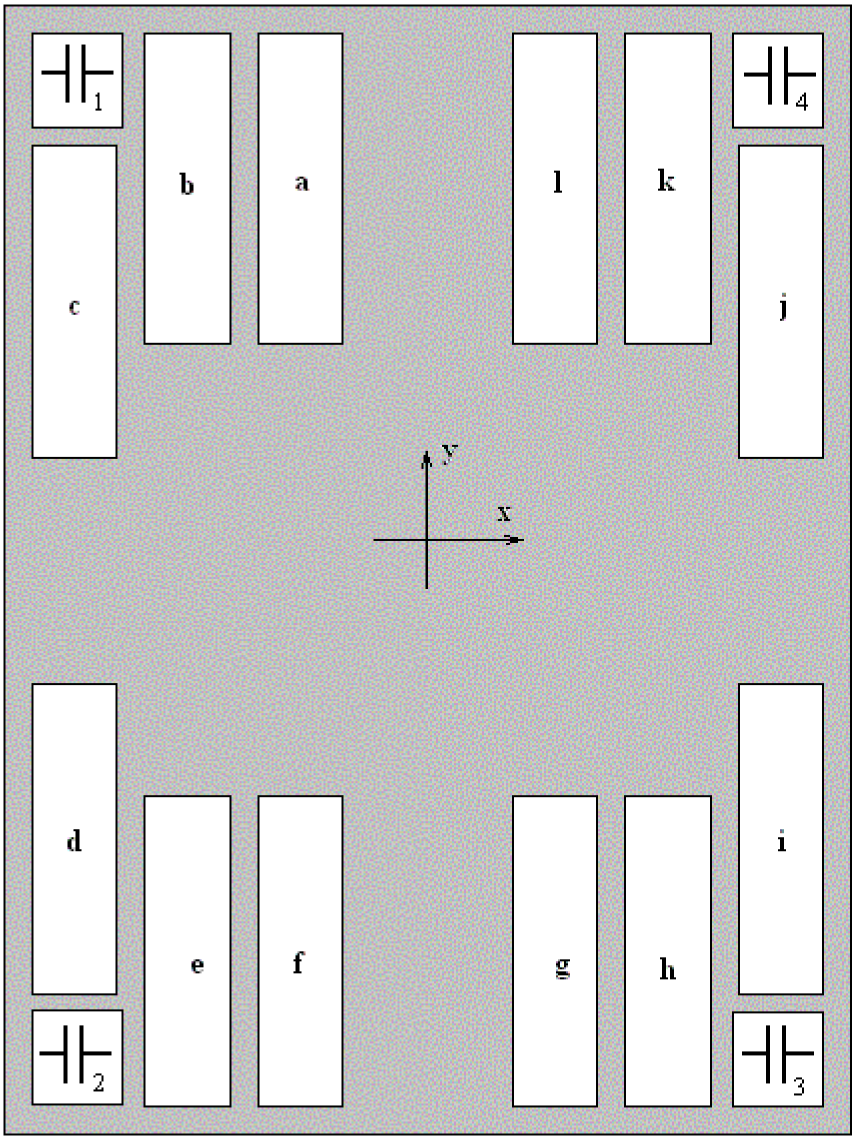


Fig 3.9 Schematic layout of middle foot projected onto the stiff plate.
Letters denote the placement of the leaf springs,
Numbers denote the placement of the capacitive sensors.

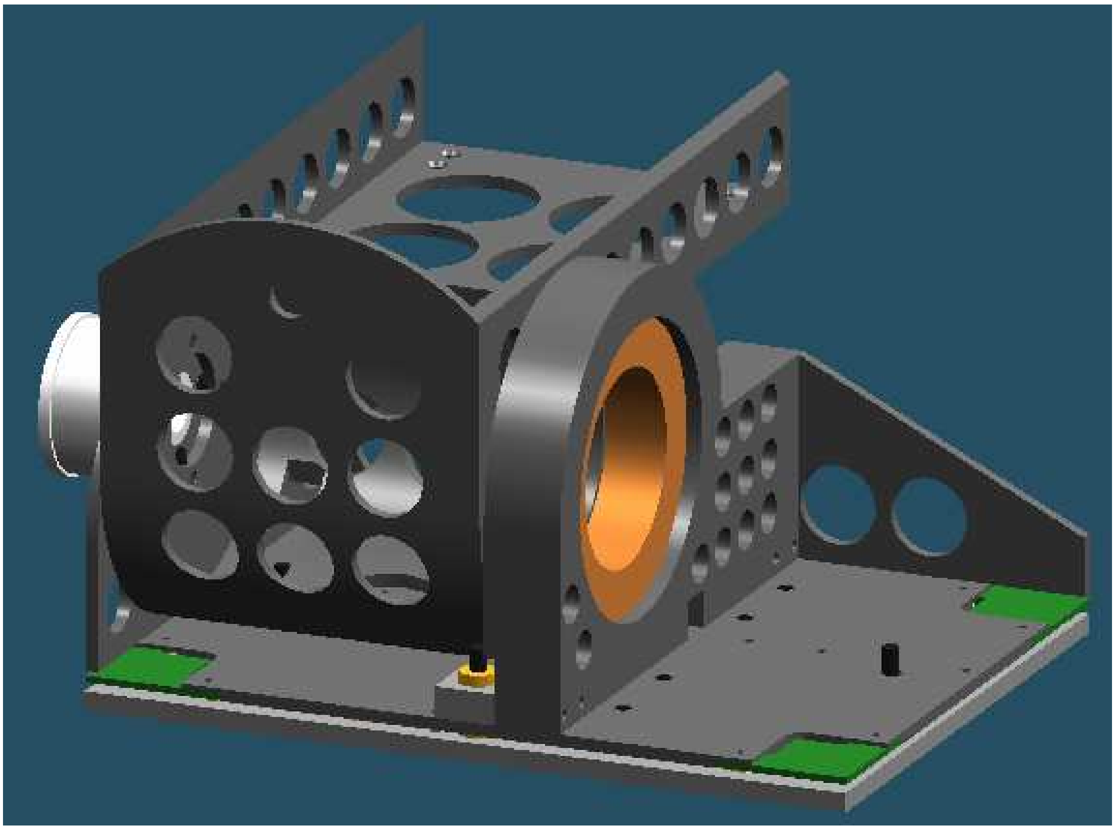


Fig 3.10   Assembly of the upper and middle foot

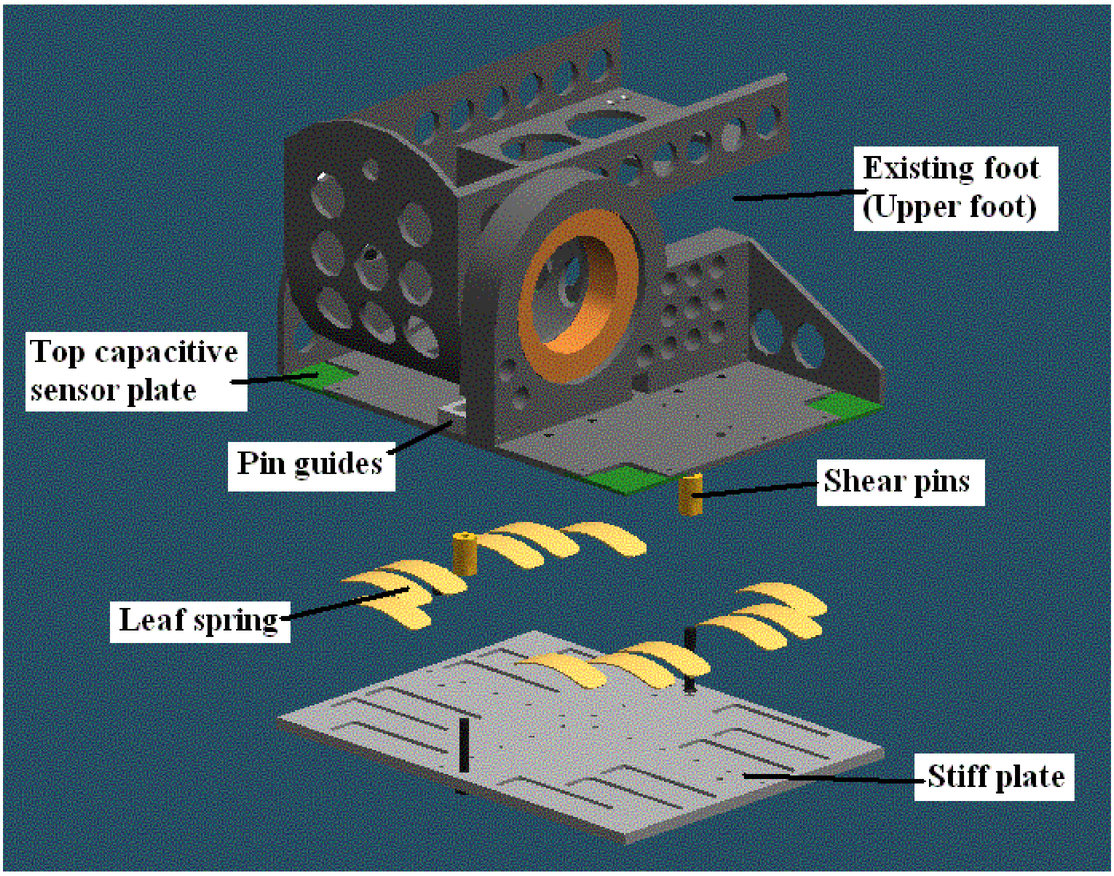


Fig 3.11   Exploded assembly of the upper and middle foot

3.2.3 Lower foot

The foot's contact sensor and padding is incorporated into a layer below the middle foot that is the robot's contact with the ground. This lower foot is predominantly constructed of compressible rubber (similar to the rubber tested in 3.2.1) and the contact sensor's wires. Between the underside of the stiff plate and the top layer of the contact sensor's wires (x-axis wires), a thin plastic layer is placed to insulate the contact sensor from the rest of the foot. As described previously, the two layers of the contact sensor are separated by a compressible medium. This compressible medium takes the form of rubber cords that run between the wires of the top (x-axis) layer of the sensor. The cords are thicker in diameter than the sensor's wires, but compress into the sole under local pressure, allowing the contact sensor to register a point of contact.

The dimensions for this sensor are based upon its performance requirements. The major dimensional consideration for the contact sensor is the grid size of its wires. As it is intended that most of GuRoo's foot will be in contact with the ground under normal operation, there is little need for high resolution contact sensing. As such, the grid size of this sensor is 20mm. This allows calculation of the support polygon's perimeter to within 10mm.

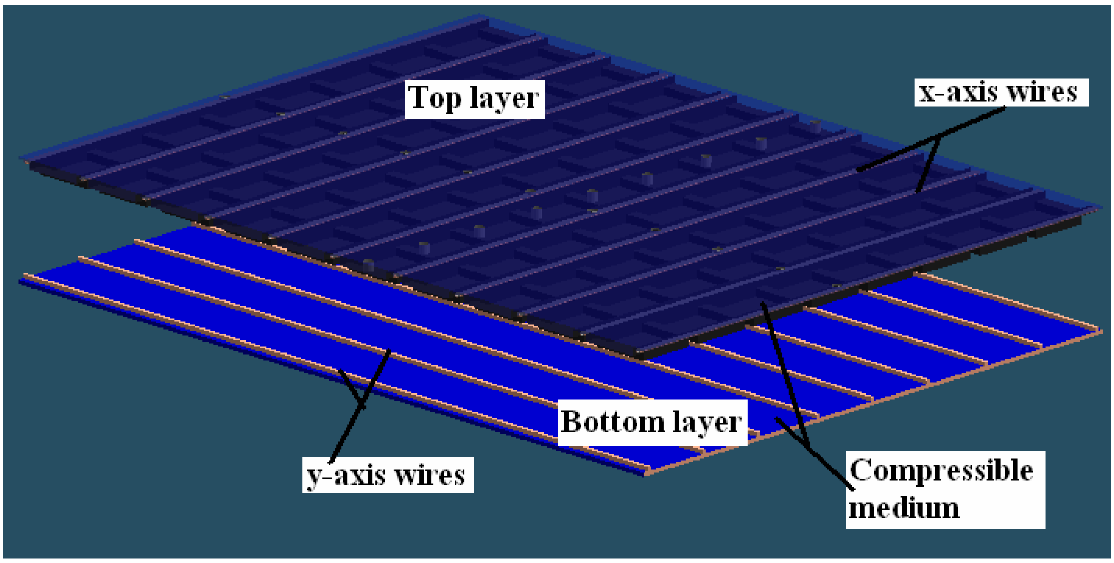


Fig 3.12 Exploded diagram of lower foot

The sole is the foot's means of contact with the ground. The sole is a thin sheet of rubber displaying elastic damping characteristics. The use of rubber as tested in section 3.2.1 is adequate for this purpose. Although this rubber displays non-linear characteristics, they will not affect the function of either of the sensors. This is achieved as the two sensors rely upon compressive force - which will transmit through this layer – rather than the response of the layers below them.

3.2.4 Overall design

This subsection illustrates how the various parts of the foot are assembled.

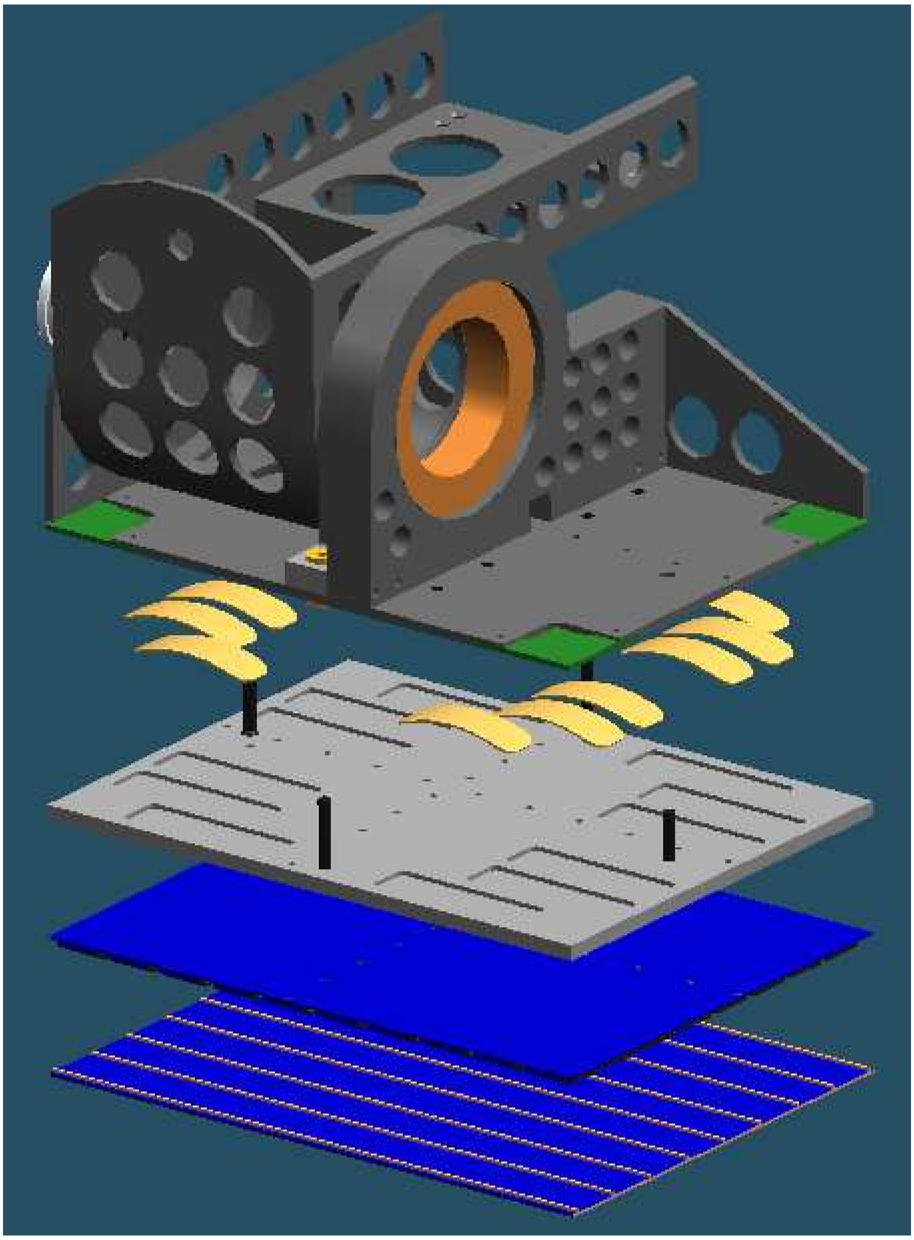


Fig 3.13 Exploded view of redesigned foot

Fig 3.14 Colour scheme used throughout all CAD drawings

Chapter 4 – Simulation and testing

Having redesigned GuRoo's feet, a series of tests need to be performed to evaluate the proposed design. This list should reflect the design criteria set out in section 1.3. This list takes the form of a checklist, assessing the design for required levels of performance. In order to prove some of these levels of performance, simulations or tests have been devised. This chapter reflects upon the design criteria set out in section 1.3 and the design's ability to achieve those objectives.

4.1 Middle foot

The primary function of the middle foot is to resolve the foot's ground reaction into a net force and point of action. It is designed to do this through measuring the relative movement of two plates (the bottom of the existing foot and the stiff plate) whose position is governed by the ground reaction force and the array of leaf springs between them. As such, assessing the middle foot's functionality relies heavily upon its ability to resolve ground reaction forces.

4.1.1 Desired performance

In creating a list of performance levels for the middle foot, it is important to asses both internal component performance as well as overall performance. Assessing the internal components leads to an awareness of the overall mechanics of the structure.

There are several internal components that need to meet certain performance objectives. It is important that the designed leaf springs behave in a predictable, linear manner. Likewise, it is important that the capacitive sensors developed by Undery [5] can be adapted to suit the proposed design. Finally, the mechanical design of the middle foot must be structurally sound.

4.1.2 Simulated performance

Each aspect of the middle foot requires different means of validating its ability to perform. The table below gives a summary of the various required levels of performance and the simulated or calculated performance of the design.

Component	Required LOP	Test	Simulated/ calculated LOP
Leaf spring	Repeatable, linear, easily characterised behaviour	Max compression	Max compression: 4.8mm Max load: 150N
		Multi compressions	Linear response, repeatable
		Creep (const. load)	No creep
Capacitor sensor	Adaptable to design	Modification tests	Modifiable
		Quantisation	Error of 1% to 25%
Structural analysis	Maintains characteristics of middle foot	Stiff plate analysis	Sufficiently rigid
		Shear pin analysis	Structurally sound
		Range of motion	Sufficient

LOP: level of performance

Table 4.1. Required and tested levels of performance for various components of the upper foot.

To asses the behaviour of the leaf springs, the material selection tests were repeated. There are three main tests that together characterise the behaviour of the springs. A maximum compression test gives an understanding of the limitations of the spring, as well as its loading characteristics over its range. The multiple cycle compression test evaluates the reliability and repeatability of the spring's characteristics. The creep test is a measure of the spring's response to prolonged compression. Creep indicates a time dependant response that is hard to characterise in the model of the foot.

The various graphs below show the testing results for the leaf spring. The same apparatus was used here and in material selection.

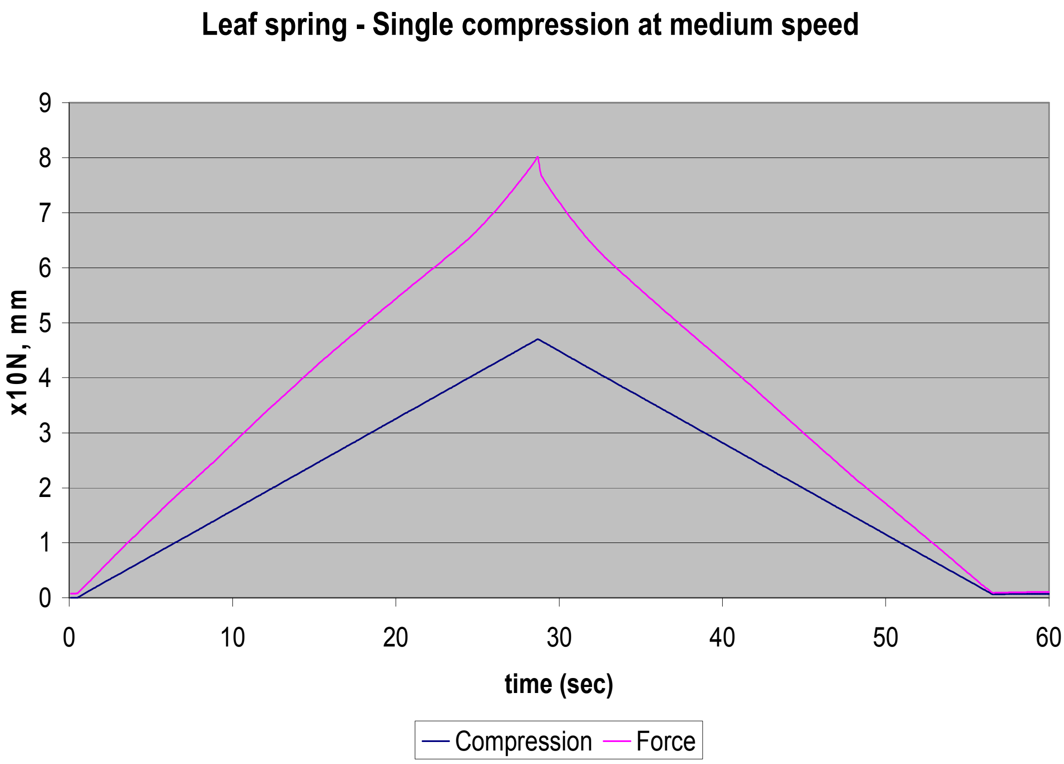
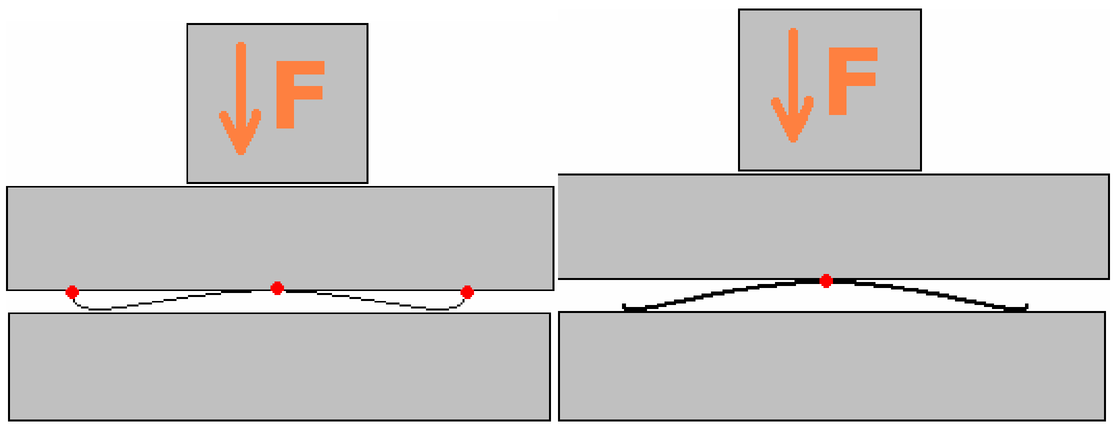


Fig 4.1 Results of leaf spring's maximum compression test



(a) (b)

Fig 4.2 Setup for leaf spring absolute maximum (a) and standard (b) compression tests

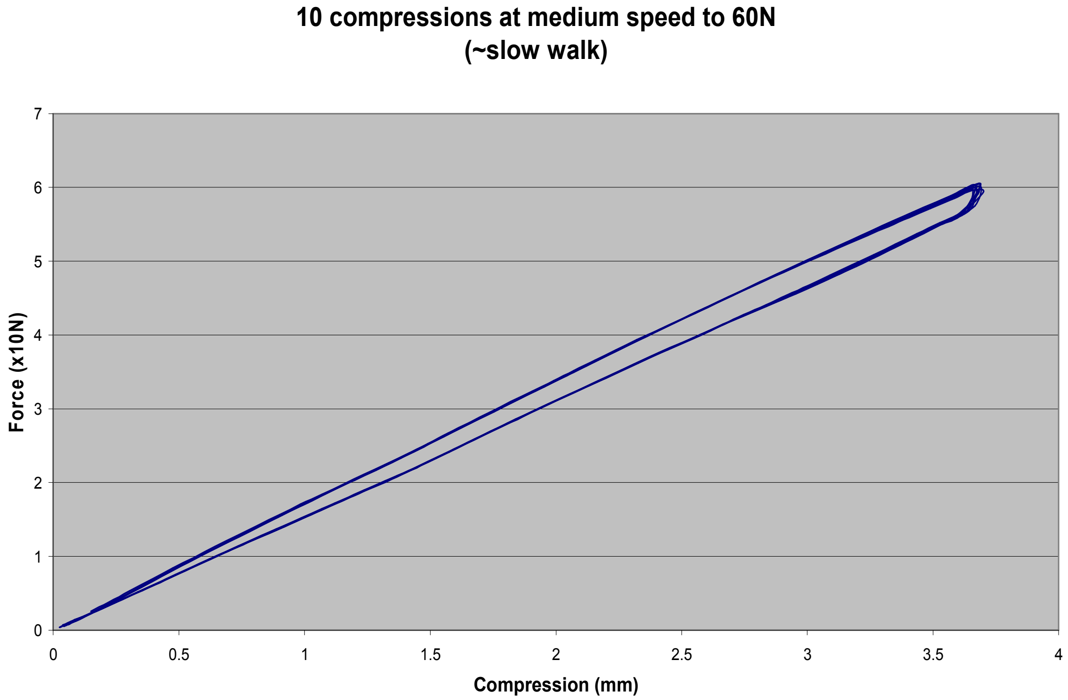


Fig 4.3 Results of leaf spring's multi-cycle test

Fig 4.4 Results of leaf spring's creep test

As the above figures and graphs show, the leaf spring performs well within the desired specifications. Its maximal compression of 150N is far in excess of any conceivable loading situation. Its max deflection of 4.8mm is sufficiently close to the desired deflection of 5mm. The multiple loading graph shows a consistent spring constant that is not affected by its loading history. The non-identical unloading line (seen in Fig 4.3) can be accounted for by slight relaxation of the compression apparatus' joints. Finally, the creep test (shown in Fig 4.4) demonstrates the spring's compression to have no time related dependencies.

In modifying the capacitive sensors several major modifications had to be made. The first of these was the size of the sensor plates. The existing capacitor plates had an area of $2500mm^2$ whereas the middle foot only allowed for square plates of $400mm^2$. This can be accommodated easily, with the only noticeable effect being the output capacitance of the sensors. Where the range of Undery's [5] sensors was 5-45pF the new sensors will have a range of 0.7-7pF. The second modification needed was the removal of the dielectric. Undery [5] performed some research into this and found that air performed well as a dielectric medium. The third modification to the sensors required implementing a common ground for multiple sensors. As Undery [5] connects one of the capacitor's plates to ground in his design, the stiff plate shall be used as the common ground to all four sensors.

In order to understand the capacitive sensors' ability to interpret the relative position of the upper foot and stiff plate as ground reaction forces, a simulation model was devised. The model involved a Microsoft Excel spreadsheet that interpreted various ground reaction forces, applied them to the middle foot and calculated the various separations of the capacitive sensors' plates. From these plate separations each sensor's capacitive value could be calculated. However, these capacitive values needed to be truncated to an 8-bit value (0-255) to keep in alignment with GuRoo's processing ability. After truncation, it could be seen that these values displayed errors between 0.8% and 25%. The largest errors occurred in association with small ground forces (errors greater than 15% were only found with a ground reaction forces less than 150N). In the region of 100%-200% of GuRoo's weight, quantisation errors were typically less than 3%.

To assess the structural performance of the middle foot, various calculations were applied to the design.

- As it is important that the upper foot and stiff plate remain planar, a maximum allowable deflection of 1mm was implemented. Deflection calculations were performed with a worst case scenario approach - applying a load of (three times) GuRoo's weight to the foot at the centre of the foot. This caused a deflection of the stiff plate of 0.74mm and an insignificant deflection of the upper foot.
- The shear pins were also assessed for their ability to maintain the middle foot's integrity under maximal loading conditions. The shear strength of the pins was calculated to be 3.5kN, which is beyond the loading capabilities of the robot's actuators. This is also in excess of the friction coefficient of the sole and is proof enough of the pins' structural integrity.
- Finally the range of motion of the middle foot was assessed. The middle foot's range of motion in the z-axis direction extends the full range of the leaf springs and is only limited in extension by the top-out bolts (seen at the front and back of the foot). In rotation about the x and y axes, the foot was capable of rotation by 1.9^{o} about the y-axis and 1.4^{o} in the x-axis. These capabilities are the result of the relationship between the pin guides and the shear pins.

4.2 Lower foot

The primary function of the lower foot is to provide a means of calculating the support polygon for the robot. In assessing the lower foot's functionality, the ability to determine a support polygon is investigated as well as ground reaction properties of the sole.

4.2.1 Desired performance

In assessing the lower foot, only the external functionality need be examined. This is possible as the internal workings of the contact sensor are basic and it is more important to ascertain the effects that different soles have upon the resolution of the support polygon. An important characteristic of the contact sensor is the ability to accurately detect contact points at the resolution required and derive the support polygon from that information. A secondary requirement of the sole is that it has a coefficient of friction greater than 0.5. This will allow the robot a maximum instantaneous acceleration of $4.8m/s^2$, which is in excess of current gait capabilities.

4.2.2 Tested performance

As the concept of the lower foot is relatively simple, it was possible to create a prototype contact sensor and test its functionality. The prototype was constructed with thicker wires than intended; however separating the wire layers with soft foam counteracted the effect of the stiff wires. This contact sensor was used for the below tests.

Specification	Required performance	Tested performance
Contact point resolution	50mm	20mm
Contact switch force	≤5N per contact point	~2N per contact point
Accuracy of point reading	Reliable, no false positives	No false positives
Sole padding	Damping behaviour	Damping & elastic behaviour
Sole coefficient of friction	0.5 Coefficient of friction	~0.6 Coefficient of friction

Table 4.2. Required and tested levels of performance for various components of the lower foot.

The prototype was designed with a grid size of 20mm. This was smaller than required but proved to give additional accuracy without compromise of reliability. The soft foam produced a low contact switch force; however a similar result would be achieved with higher density foam of lesser thickness. The material tested for the sole was the hard rubber from the initial material tests. It displayed good damping and frictional characteristics.

Chapter 5 – Results and Discussion

This chapter evaluates the findings of the tests from chapter four and analyses their implications to GuRoo. In general, comparing the desired functionality to the test results gives a good understanding of the design's ability to satisfy its purpose. However, further analysis of the results shows how important the individual functionalities are.

5.1 Evaluation of testings

The results of the simulations and tests from chapter four have been redisplayed below for reference.

Component	Required LOP	Test	Simulated/ calculated LOP
Leaf spring	Repeatable, linear, easily characterised behaviour	Max compression	Max compression: 4.8mm Max load: 150N
		Multi compressions	Linear response, repeatable
		Creep (const. load)	No creep
Capacitor sensor	Adaptable to design	Modification tests	Modifiable
		Quantisation	Error of 1% to 25%
Structural analysis	Maintains characteristics of middle foot	Stiff plate analysis	Sufficiently rigid
		Shear pin analysis	Structurally sound
		Range of motion	Sufficient

LOP: level of performance

Table 5.1 Required and tested levels of performance for various components of upper foot.

Specification	Required performance	Tested performance
Contact point resolution	50mm	20mm
Contact switch force	≤5N per contact point	~2N per contact point
Accuracy of point reading	Reliable, no false positives	No false positives
Sole padding	Damping behaviour	Damping & elastic behaviour
Sole coefficient of friction	0.5 Coefficient of friction	~0.6 Coefficient of friction

Table 5.2 Required and tested levels of performance for various components of the lower foot.

Each of the two tables show that the proposed design meets the desired levels of performance set out in 1.3 These desired levels of performance were attained by defining the role of the redesigned foot in association with the forecast operation of GuRoo for the life of the feet.

Perhaps the result with most potential for improvement is the quantification of the capacitor sensors. Converting any continuous range into a discrete set will produce rounding errors. However in this design, the errors are unevenly distributed. The errors produced when the capacitor plates are uncompressed have a large effect upon the ground reaction force calculations. These rounding errors could be reduced by using a non-linear look up table instead. A look up table that resembled the $^1/_x$ characteristics of the capacitor sensors would spread the rounding error evenly over the full range of the capacitor sensor. These errors in small force measurements will have less effect on GuRoo's current gait as its stride length is short. As GuRoo's stride length increases, these small errors will be multiplied by their distance from the robot's ZMP. In doing so, they will create more pronounced errors in the robot's derived ZMP.

In achieving all of the required levels of performance, the underlying concepts of the design have been proved. Although problems may arise from unforseen relationships or secondary physical effects, the solid foundations of these concepts will allow the product to overcome its unforseen obstacles. The next development of the design is the construction and testing of the physical product.

5.2 Performance implication for GuRoo

The redesigned feet have been designed with the aim of improving GuRoo's static and dynamic balance. These improvements were sought through providing additional sensory information and modified ground response of the robot. However, in producing this additional information and modified ground response, certain resources would be required of GuRoo and ground stability would be altered.

In calculating the ground reaction force and support polygon, additional processing power will be required. This is planned to be facilitated by a separate processing unit that will calculate the net ground reaction force and line of action, as well as the support polygon. This information will then be sent to the robot's main processing unit as pre-calculated information. As such the design will only require power for processing and facility in the main processor to utilise the additional sensory information.

As a result of incorporating elastic and damping effects into the foot, the stability of the foot platform itself is compromised. Due to various loading conditions, relative movement of the upper foot to the ground create a reduction in stability. The existing design of the foot (a rigid platform) provided a sturdy stance on the ground, provided the robot's ZMP remains within the support polygon. Although the robot has no means to validate its ZMP calculations, it can usually assume the sole of its foot to be parallel to its walking platform.

As the redesigned foot is designed to deflect under normal operation, the upper foot no longer bears relation to the support platform below it. However, using support forces instead of joint angles to drive the robot's control loops, the benefit of the redesigned foot can be realised. Although this design allows for greater understanding of the robot's reaction to its environment, a higher performance requirement will be placed upon the robot's control system.

Chapter 6 – Conclusion

This chapter evaluates the project as a whole and assesses its relevance to the GuRoo project in general. It assesses the work completed on the foot and outlines future work in implementing and extending this design.

6.1 Evaluation of project worth

Unfortunately, due to time restrictions, the extension to the existing foot was not built. However, construction of the leaf springs and a prototype contact sensor were useful in proving several of the concepts that the design relies upon. The redesigned foot is projected to be built within the next few months and can then be tested and implemented in the context of the robot. Until then, the various tests and simulations of the redesigned foot are presented as proof of concept.

Assuming there are no unforseen problems in the construction and implementation of this design, the redesigned foot will extend the capabilities of GuRoo. The purpose of this project was to increase GuRoo's ability to sense its surroundings. This is an important requirement for humanoid robots as they strive to liken human functionality. While ground reactions are a simple interaction between a robot and its environment, they provide a source of important information that aid in balance of stance and gait.

While this foot design is simple in its nature, it provides the basic and vital ground sense feedback that human feet offer. Of the sensory ability of human feet – touch, force, pain (an overload of local force), proprioception and temperature – this design is capable of measuring all except temperature, which bears little meaning to a robot. In this way the design is in keeping with its application to a humanoid robot.

6.2 Future recommendations

Despite achieving the design requirements set out in this thesis, there are substantial improvements that could be implemented in this redesigned foot. Although the proposed redesign of the foot allows the extended functionality desired, a series of improvements would facilitate easier integration of the sensors and extended capability and functionality.

Perhaps the largest hindrance of this redesign is the creation of a non-rigid walking platform. The deflection of the middle and lower foot require a certain level of compression to facilitate force and contact measurements as well as producing the required damping response. However, if the sensors used in the middle foot were capable of sensing smaller deflections accurately, then a limit could be place upon the compressibility of the middle foot. The padding associated in the lower foot is largely to absorb the impact of rapid foot deceleration due to foot placement. If this impact force were reduced through modifications to the walking gait, less damping would be required in the lower foot, also creating a more solid walking platform.

The choice of sensors used in the middle foot has a large impact on its rigidity. With the recent improvement in accuracy of small scale FSRs (force sensitive resistors), a very rigid middle foot could be created. FSRs have traditionally been used in measuring large forces as this produces a greater range in output resistance, however if a suitable sensor could be found it would greatly improve the performance of the middle foot.

The configuration of the proposed redesign allows the capacitive sensors to register a force overload of the middle foot. As an excessive load would cause the stiff plate of the middle foot to make contact with the upper foot, it would also cause the two plates of the capacitive sensors to make contact. By sensing the resistance between the two plates of the capacitor, an overload of the middle foot could be sensed. This ability would be useful in interpreting the outputs of the four capacitive sensors.

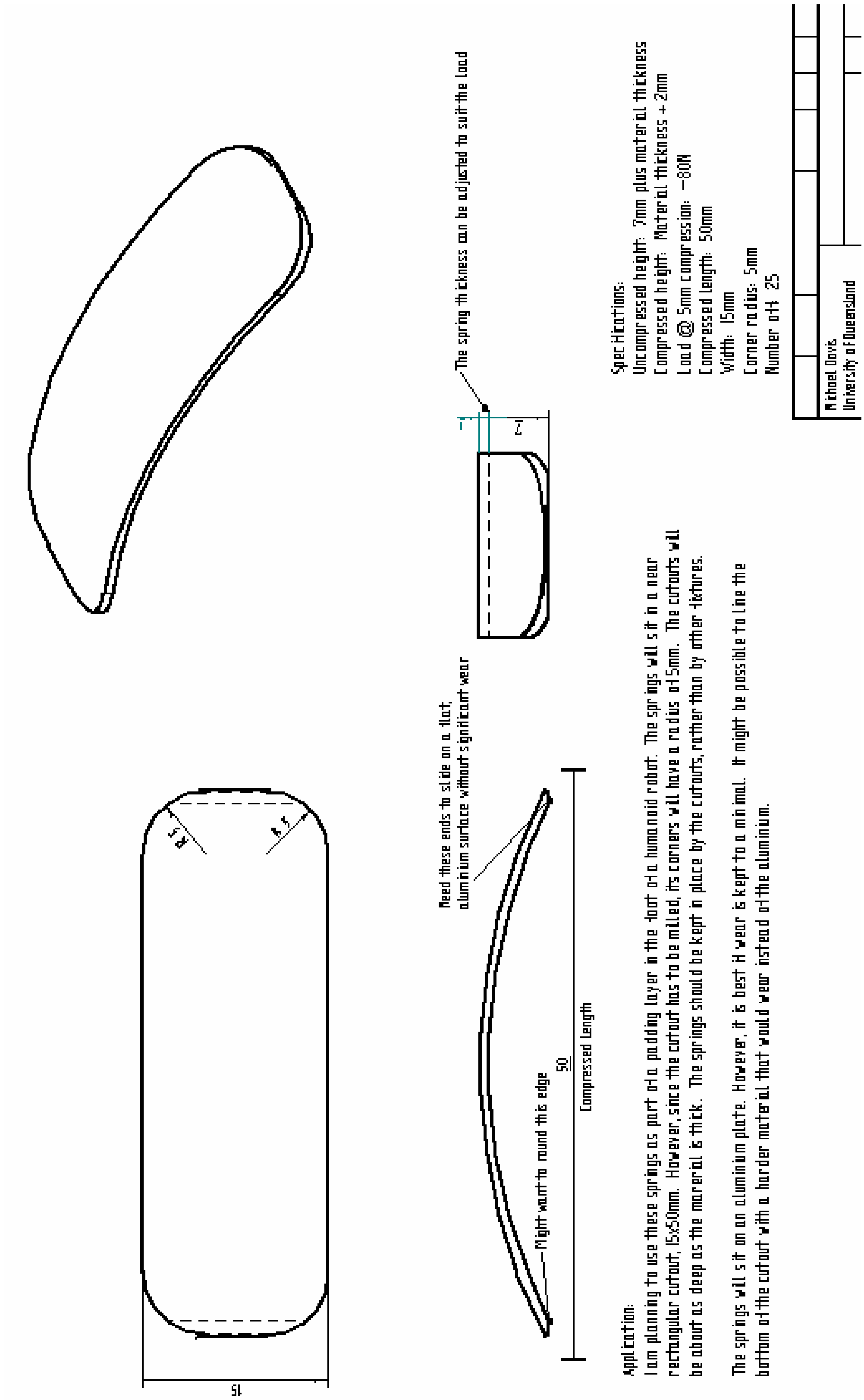
As GuRoo ventures onto uneven walking platforms, the role of the contact sensor will become increasingly evident. Although only the outer bounds of GuRoo's ground reaction affect its support polygon, the grid size of the contact sensor dictates the minimum size of a contact point. The grid size of 20mm was chosen as it represented the smallest conceivable area of contact and remained in manageable proportions. A finer grid size could be implemented if it was found that increased resolution was needed.

As GuRoo's feet begin to interact with other elements of its environment, rather than just the ground, additional sensory input might be required. When GuRoo progresses to kick a soccer ball, it would prove useful to measure where and when the foot struck the soccer ball. This would require at least a contact sensor to locate the point of contact and time of impact. The addition of a force sensor would allow the robot the ability to estimate the trajectory of the ball.

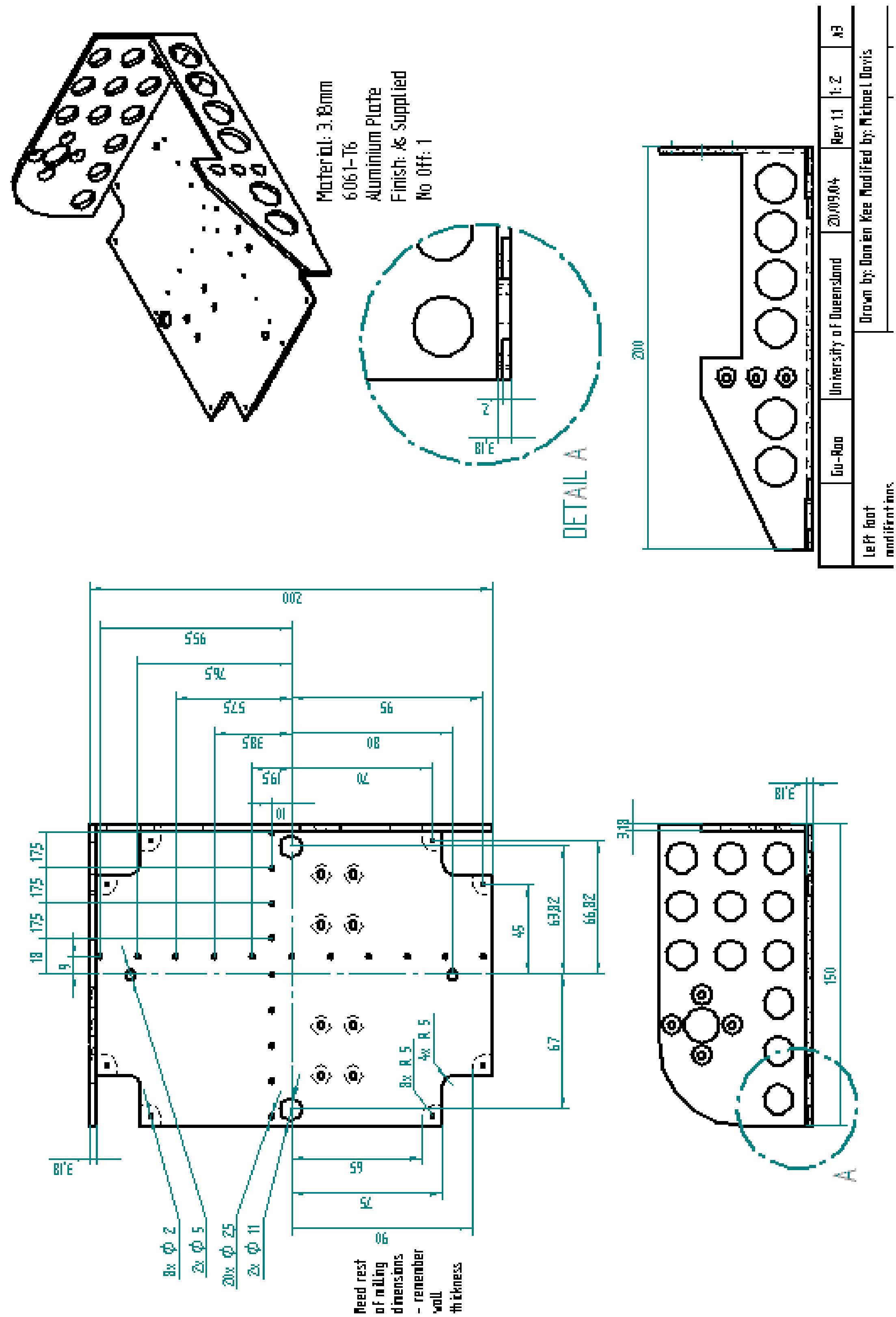
With the realisation of the proposed foot and possible future improvements detailed in this section, the foot will become a highly functional addition to GuRoo.

Appendix A- Solid Edge Drafts

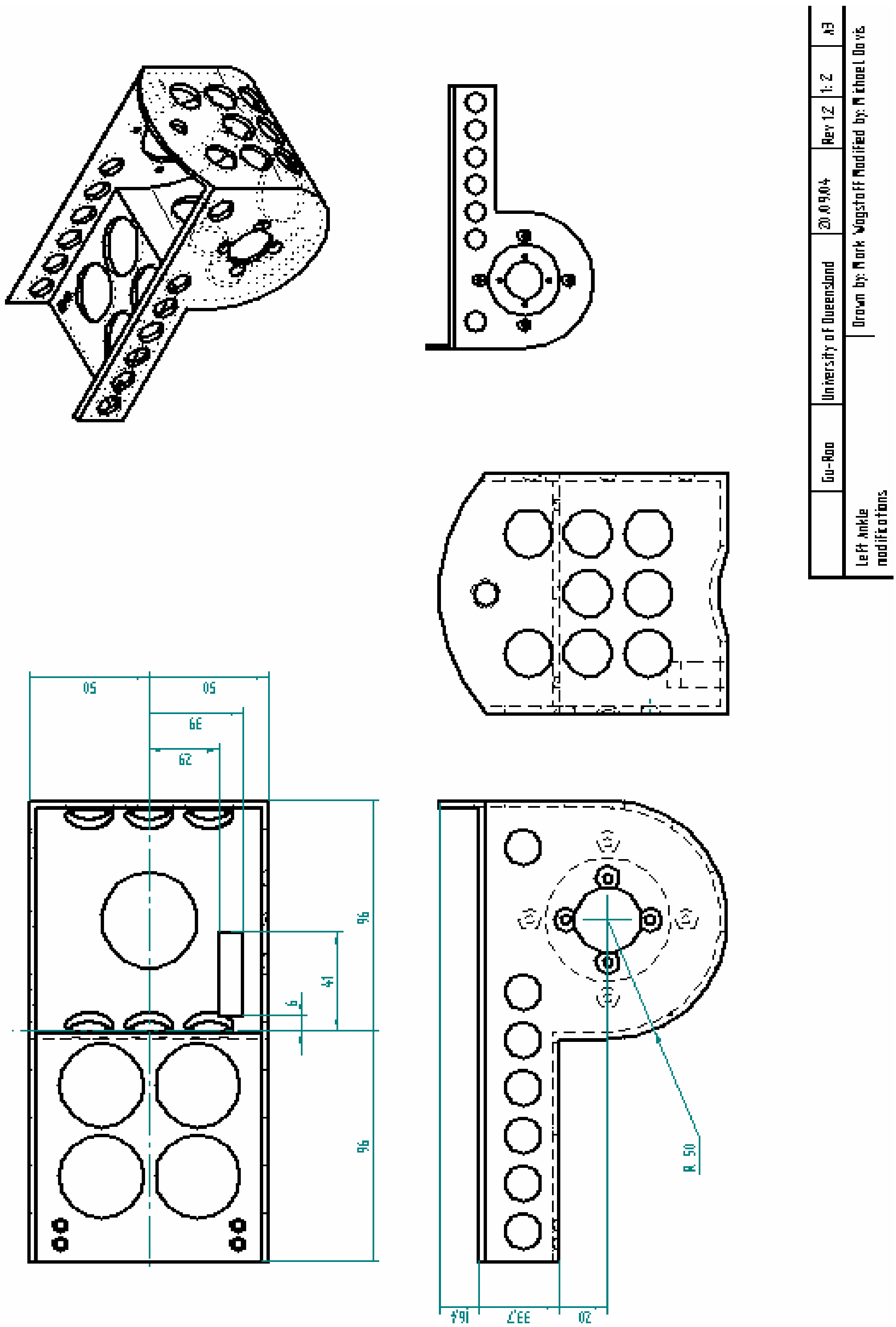
A.1 Leaf Spring



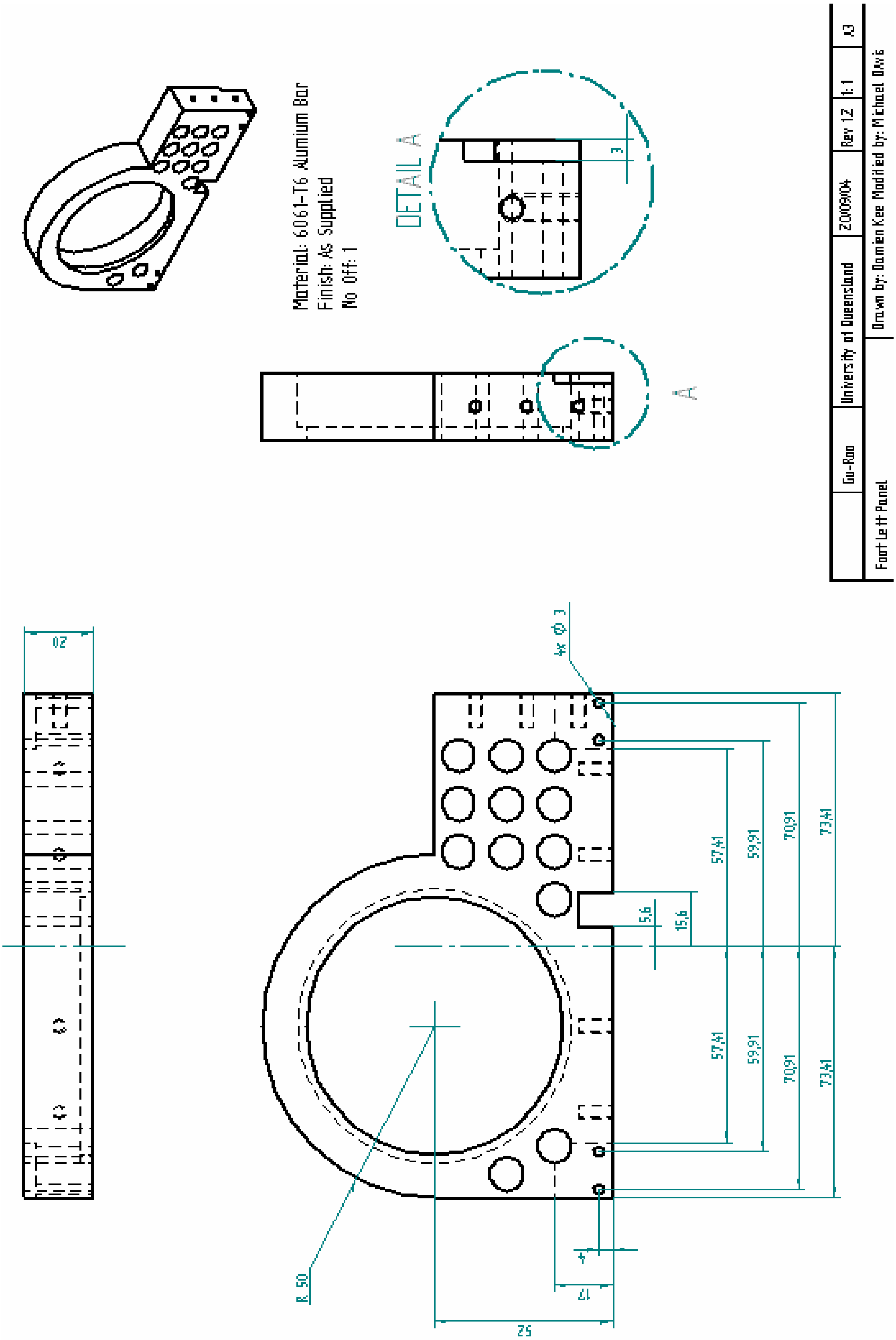
A.2 Upper foot modifications



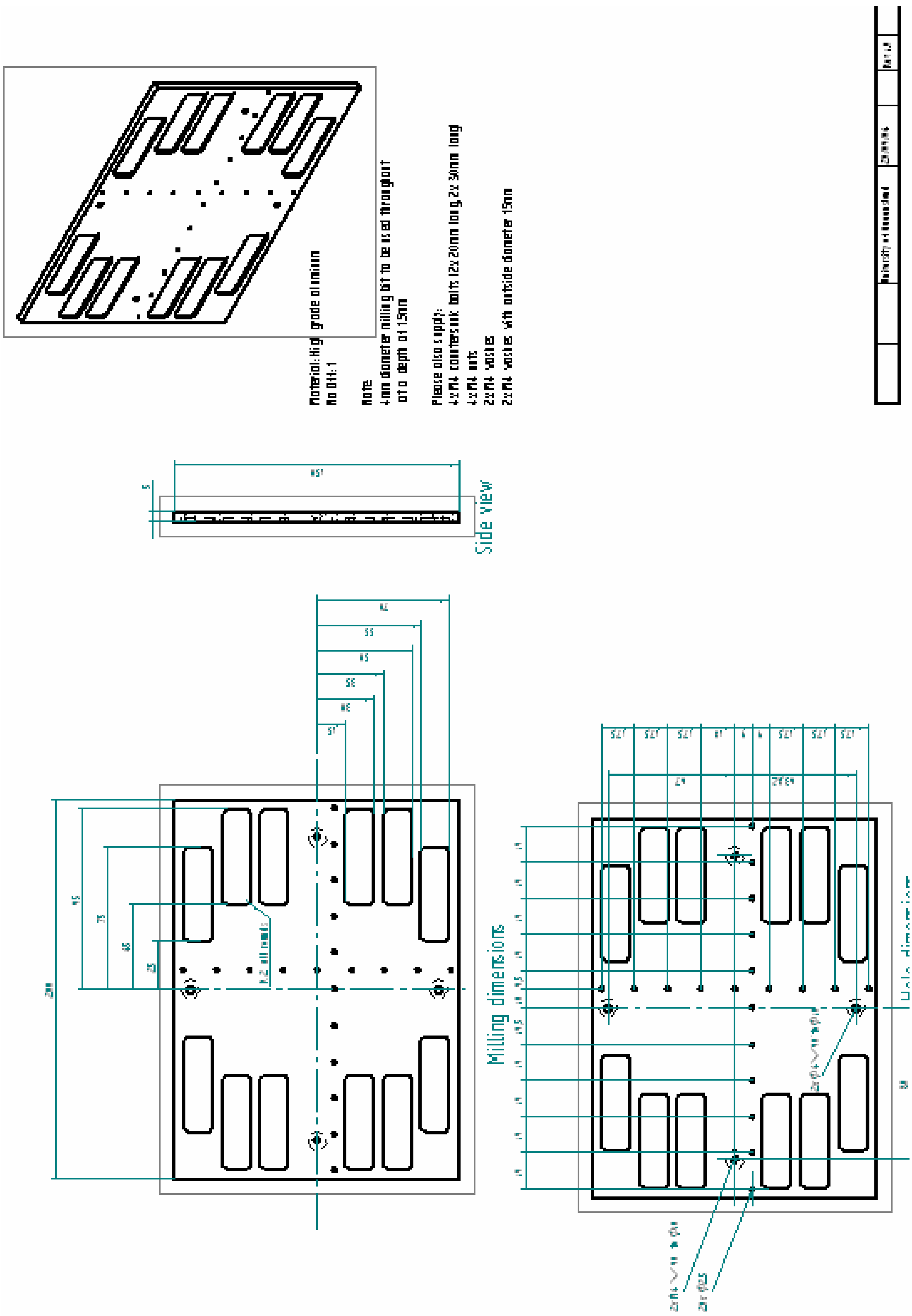
A.3 Ankle modifications



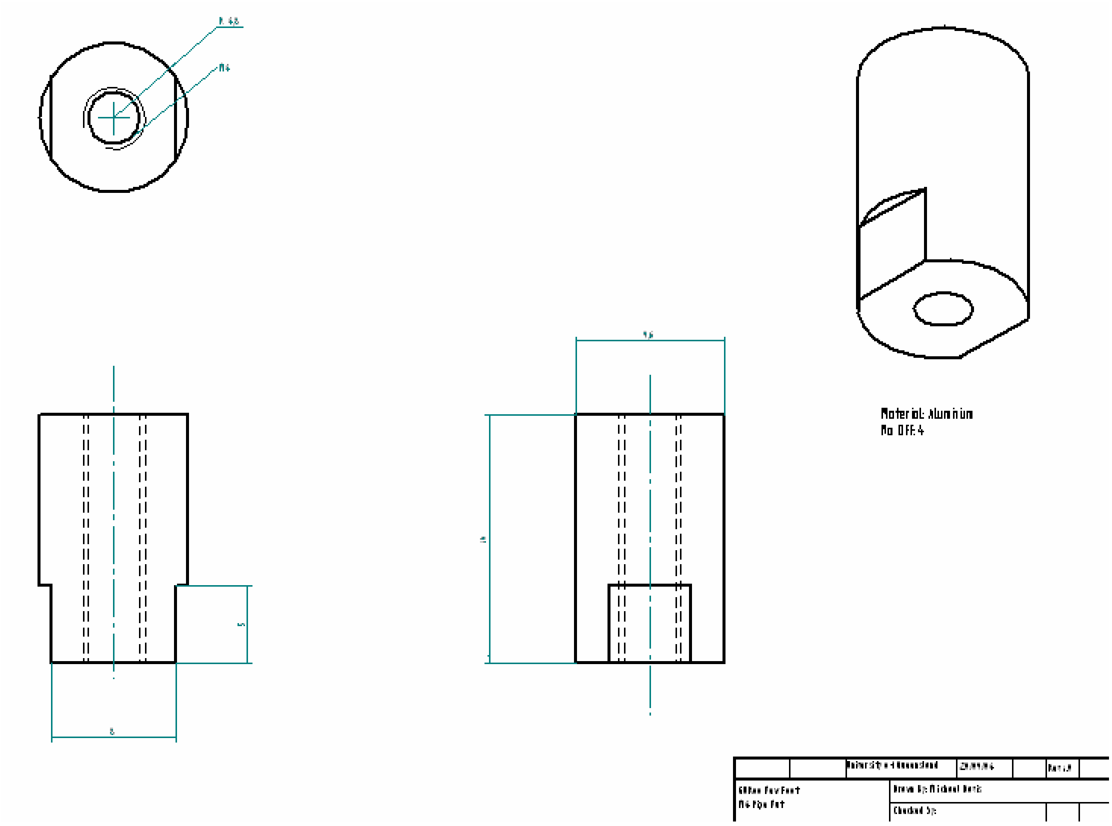
A.4 Foot panel modifications



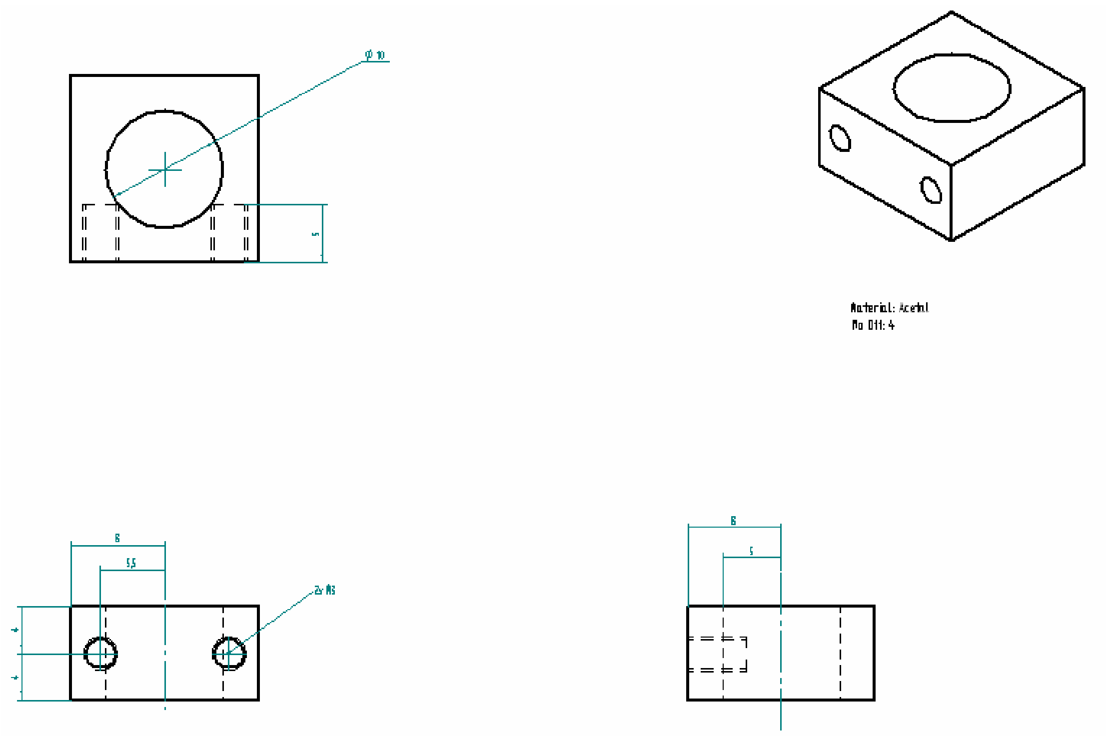
A.5 Stiff plate



A.6 Shear pin



A7 Pin Guide



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