University of Southern Queensland
Faculty of Health, Engineering & Sciences

Design of a Rig for Automated tissue discrimination in beef striploin during trimming operations

A dissertation submitted by

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Abstract

In this project, an automated three-axis cartesian robotic positioning Rig has been designed, built, and performance tested. The test Rig is to place sensors for evaluating the location of tissue interfaces within a beef striploin primal cut. The results will inform the future approach and parameters for machine perception, where robotics will be used to carry out high value trimming tasks in production. For beef striploin, the automated discrimination of fat thickness for trimming is an important factor to achieve. An understanding of red meat industry production and literature on advances in the automated processing of natural mediums has provided a good foundation to design, build and test the machine.

Design of the Rigs, working requirements came from customer specifications, while supported by engineering models, met performance and application requirements. A full computer model was created for the detail design stage, which helped to size critical parameters and components. The Rig was then constructed systematically beginning with the mechanical structure and mechanisms. Electrical components were integrated into the second stage of the build, followed by the addition of software programming functions that were written to drive and control the Rig in testing performance and sequencing the placement of sensing devices. The system was tested for accuracy with results varying. Performance tests demonstrated sensor placement accuracy and repeatability errors of less than 2% of FSD. This is well within performance requirements

The tested ability for simultaneous measurements was achieved in rapid succession in contrast with manual approaches. This important factor avoids errors resulting from relaxation in the meat between measurements. These coordinated characteristic measurements will be used to build models describing norms and variation of expected tissue interface position with respect to the overall size and shape of pre-processed primal. The models will form the baseline for robot path planning, guiding cutters relative to tissue interfaces. The new capability will enable automation of complex high-value industrial meat production operations.

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Limitations of Use

Certification of Dissertation

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

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

Benjamin Owen Cooney

[redacted]

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I would like to start by acknowledging everyone who has helped and supported me during my studies to get me to this point. At times it has been the people working behind the scenes who have made it possible.

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Chapter 1 Contents

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Acronyms

Australian Red Meat Industry	(ARMI).
Australian Meat Processor Corporation	(AMPC)
Light Detection and Ranging	(LiDAR)
Power Supply Unit …	(PSU)
Centre of Agricultural Engineering	(CAE)
Computer Numerical Control	(CNC)
Meat and Livestock Australia	(MLA)
industry value add	(IVA)
Duel-energy X-ray absorptiometry	(DEXA)
dual energy computed tomography	(DECT)
Meet and Livestock Australia	(MLA)
National Sanitation Foundation	(NSF)
Peripheral Intravenous Catheterisation	(PIVC)
Intravenous	(IV)
Smart Tissue Autonomous Robot	(STAR)
Partial Least-Squares Discriminate Analysis	(PLS-DA).
Laser Induced Breakdown Spectroscopy	(LIBS)
Support vector machine	(SVM)
Pulse Width Modulation	(PWM)
Micro controller Unit	(MCU)

Chapter 1 Introduction

1.1 Aim

In this project, a three-axis Cartesian positioning test Rig has been designed and built that automatically positions sensors simultaneously within a three-dimensional cartesian space. This will be utilized in evaluating the location of tissue interfaces within a striploin beef primal cut. This will produce parameters for machine perception, where robotics will be used to carry out high value trimming tasks in production. The customer's required design, construction and measured performance have been met. Positional accuracy is less than 2% Full-Scale Deflection (FSD) repeatability 1 mm have been achieved.

The RIG has been designed for use, with high-value striploin. Its purpose is focused on the collection of data so that models can be created that will improve processing quality, accuracy and speed of the processing chain in meatworks. This will Industry value add (IVA)to the product, by providing international customers with their tailored requirements, at a highly competitive rate.

The Australian red meat industry is moving towards process robots that trim and cut relative to product tissue, with a specific focus on high value trimming tasks. With striploin, the trimming process separates the fat and tissue to leave a specified margin from the invisible interface. The automation of this process will improve the performance of highly skilled manual operators.

The Rig design utilises a mechatronic system that will be explicitly designed for striploin study. This first section will be devoted to the objectives, background, driving factors and benefits that the design provides.

One area of development that is vital to the growth of the industry is automation. The meat processing industry is highly profitable to the Australian economy, and this value has been created through continued investment into research and development. The report will now discuss the Rig and its details. The design of the Rig as a robotic device will fulfil each of the objectives.

1.2 The Rig

The Rig's design is based on a computer numerical control (CNC) type system. It has been designed and built to suit the unique requirements of the Centre of Agricultural Engineering (CAE). The system integrates mechanical, electrical, and software elements.

Chapter 1 Introduction

The mechanical system has used v-slot rails with their accompanying component. The x-axis rails have six wheels each side of the gantry. The x-axis rails utilise timing belts, gears and motors for the drive of the system. V-slot rails are used for each of the system rails (Figure 1.1). The 40mm x 40mm x-axis rails run 1500mm, which is the length of the system. The 20mm x 40mm y-axis and 20mm x 40mm z-axis rails are 500mm and 170mm respectively. The outside dimensions of the Rig are defined by these measurements.

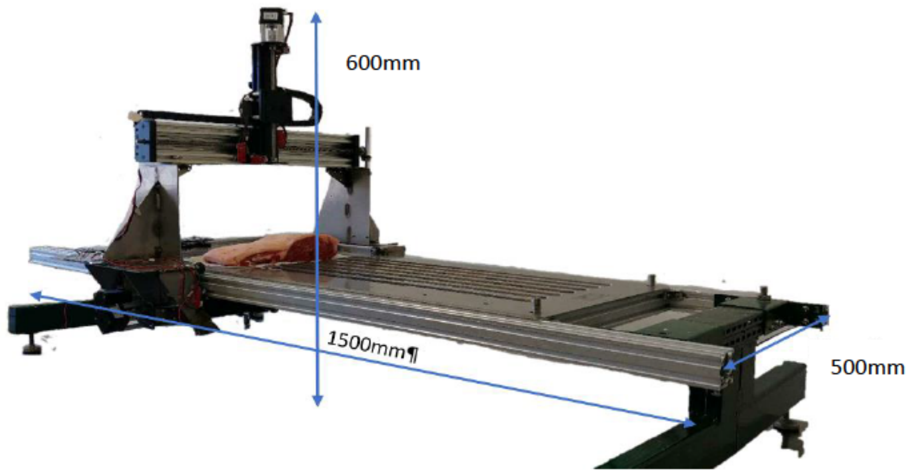


Figure 1-1 The Rig

The systems electrical components compose of the power supplies, motors, ultrasound solenoid and control system for the Rig. The motors of the Rig are open-loop stepper motors and consist of NEMA 17 and NEMA 23 motors. These motors where selected based on torque requirements of the system. The NEMA 23 was selected as the actuator for the x-axis and has been designed to push or pull the 2kg set force.

The stepper motor drivers are used to provide the pulses to the steppers. Each motor has a motor driver. Two of which are on an Arduino shield that drives the NEMA 17 steppers and one standalone driver for the NEMA 23. Each drive provides the ability for the step size (resolution) to be uniquely set.

The system uses two power supply units (PSU). The unit's output 24v DC and 12v DC. The requirement for two different power rangers is based around the stepper motor requirements. The NEMA 23 stepper motor requires 24v DC to work to its full potential. The rest of the electrical system makes use of the 12v PSU.

The Arduino microcontroller has been used. It incorporates the ramp 1.4 stepper motor shield, that is specifically designed for use with 3D printers. The Ramp 1.4 directly drives the two NEMA 17 motors, lighting, and solenoid. The microcontroller also sends signals to the NEMA 23 motor driver.

The code has been written to drive the stepper motors down the x-axis while allowing the implemented sensors to take measurements as forces are manipulating the meat. The code is set to take 17 measurements down the x-axis and do this seven times across the y-axis. At each fixed position, the solenoid will engage, pushing the ultrasound sensor into the underside of the striploin and signalling the Light Detection and Ranging (LiDAR) sensor, to take its measurement. This will provide a measurement of fat thickness.

The Rig has been specifically designed to incorporate Lidar, ultrasound, machine vision and incorporate purpose-built test sensors to work with striploin.

The CNC system provided an excellent foundation to incorporate a mechatronic design. The design was built, tested and provides accurate movements along the rails. The Rig has been designed specifically as a research tool.

1.3 Background

The use of robotics has been present in the meat processing industry for the last 40 years. Up to 2000, the automation of boning and cutting was a fixed operation with little allowance for size (Clarke et al., 2014). In the paper by Clarke (1986), he discusses the need for automation concerning the future viability of the industry. This is matched by Meat and Livestock Australia (MLA), who has the vision to see automation increase in every stage of the process (MLA, 2015). The development of automation will continue until full automation is achieved.

The Australian Red Meat Industry (ARMI) presently processes carcases into manageable parts using bone as the point of reference. There can be a high degree of accuracy due to the stiffness provided by the bones. This is where technology has peaked. The ability for automation to work with the dynamics of meat has proven quite challenging and has not yet been achieved.

The need for automation is also backed by the continuing increase in production worldwide, as can be seen in Figure 1-2. The continual increase in global production shows the insatiable demand for red meat. This is also matched by the demand for high quality proccing to be available at an ever-reducing price.

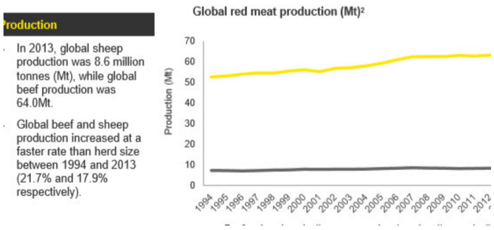


Figure 1-2 Global Red Meat Production Overview (Ernst & Young, 2017)

Once production demands have peaked, the market leaders will be controlled by quality and price. This can only be met with the continual trend of technology implementation into the industry. This will reduce cost and improve quality. This leads us to the challenges faced within the ARMI.

1.4 Challenges of Red Meat Processing Automation

There are three main challenges faced by the ARMI, which help to drive the advancement of automation. These challenges are:

1) Technological ability to work with the product.
2) Labour shortages
3) International competitiveness and cost of production

The main challenge is the technological ability to work with meat. This next stage of development in meat processing will require the knowledge for the teaching of robots to work with more complicated cuts. As pointed out by Border et al. (2019), ‘The processing of high value primal is a manual task of cutting, trimming and deboning.’ Presently, only highly skilled operators can achieve these operations. These processes will be separating mussel and muscle, bone and muscle, fat and mussel, and bony joints. When the meat has forces applied, every point around that force will change, the fat and meat will change shape and thickness. These processes require highly skilled operators to achieve these quality outcomes.

The second challenge that is faced by ARMI is associated with labour. This means that the industry requires a considerable labour force to fulfil these roles. As stated above, this contributes to one of the most significant challenges faced by many food processing industries, the constant turnover and retraining of workers. Table 1 shows the diverse roles that make up a process chain within an abattoirs Clarke (1986).

Table 1 Overview of steps in primary Production of Meat Producing Animals

- Live animal supply (catching, hauling, unlading)
- Stunning (bolt, electrical, CAS)
- Bleeding
- Removing hair/fathers/hide/scales
- Electrical stimulation
- Evisceration
- Inspection
- Chilling
- Aging
- Portioning cutting
- -Trimming of product to fit consumer requirements
- Packaging and distribution

The meat processing industry finds it hard to recruit staff due to working conditions. These conditions are reported to produce musculoskeletal disorders and accidents (Guire et al., 2010). This is creating risk in terms of selling Australia's ideas and skill set to the overseas market and sending the local dollar in the same direction.

Meat and specifically beef is Australia's 4th largest manufacturing sector and industry export sector. It relies on overseas labourers who are here on temporary working visas. This is creating risk in terms of selling Australia's ideas and skill set to the overseas market and sending the local dollar in the same direction. The need for automation has been compounded by worldwide events like Covid-19, that prevents international labour from even entering the country. This adds to the last major problem of international competitiveness.

The food industry is growing rapidly in conjunction with population growth (Egan 2017). With this consideration, the rate of growth in third world countries is among some of the greatest, which in turn means they hold the keys to greatest competitiveness through low labour costs. The ARMI is worth 23 billion annually, with international competition as its biggest threat (AMPC, 2020). A cut of meat can be produced at up to 50% cheaper in Brazil and 20% cheaper in India, than that of Australia.

The Quality of the meat produced by Australia is much higher than that of overseas markets. This is changing as our international competitors are starting to match this quality. This needs to change so those producers can cater to the domestic needs from within Australia while profiting from international consumers.

Many challenges are facing the meat industry like present technological ability, labour problems, and international competitiveness. As discussed, the meat industry is pushing forward with automation and automated processing chains, which provide a growing need for greater automation technology. This Rig will help to provide solutions through understanding. Many benefits arise from automation development that will provide solutions to the above problems.

1.5 The Benefits of Automation in the Australian Red Meat Industry

The primary benefit of implementing automation advancement within the meat processing industry would be to solve the three problems suggested in section 1.4. This will improve productivity, reduced labour and reduce productions costs while creating an environment that is safer and more rewarding (Clarke et al., 2014). The following considerations will reflect those mentioned in section 1.4:

- Development of tools to advance technological ability
- To solve labour shortage problems
- Compete internationally by implementing automation

Each of these points provides a just cause to progress the knowledge and capabilities of the industry through automation.

1.5.1 Development of Tools to Advance Technological Ability

This development involves the study of developing tools to work with processing high-quality cuts of meat. The development of Rig's, as proposed, is a forward step within the meat processing industry and will allow for a greater understanding of the development of meat processing. The Rig is not the advancement, but it will allow easy ways to study the reactions of high-value products like striploin.

As described by Border et al. (2019), variation and deformation add to the complexity when using automation to process meat. This proves the need to model the reaction better and to be able to use real-time recognition to determine machine response and change cutting strategy during processing. With the capability of pinpointing different mediums within the meat, as well as being able to combine this with understanding the reactions of the workpiece, substantial development in quality will occur.

One of the catalysts for the development of automation has been advancement in sensor technology. Sensor technology has improved the ability to work with dynamic sizes and shapes within the meat industry. These developments are present in carcase processing while requiring little to no human involvement (Templer et al., 1999).

Technology advancement will provide the ability to automate complex processes. This advancement will use Rigs and modern sensor technology to draw information from the workpiece in real-time to build models that will be eventually implemented into industry. Automation then leads to solving labour problems.

1.5.2 To Solve Problems of Labour Shortage

Ernst & Young (2017) discuss how, "Australia's red meat and livestock industry IVA was $18b in 2015-16, increasing by 34% year on year". This IVA can also be diverse in where it takes place. One area that provides IVA is through automation of processes which reduce labour and increase productivity. Some of the present automation devices have replaced 2-3 operators per shift and can cut 240 head/hour continuously (SCOTT 2020).

Robotics in the meat industry is something that is required due to labour shortages and expense in labour costs (Purnell et al., 2013). It has been proven that automation brings cost savings and constant efficiency, which far outweigh that of humans. This has primarily been described by Mitchell (2016) when describing that robots can be 2 to 3% more efficient than humans in accuracy and don't need retraining in jobs that have 100% turnover of workers. This means that robotics can IVA $3+ million a year through their use.

This justifies the requirement to develop solutions to reduce labour dependency. As labour is sought internationally, the labour and skills solution that the industry has adopted will eventually encounter problems during international travel bans. The labour costs include the cost of not being able to get labour, the cost of 'sickness and stressfulness' of the job, the cost of 'lack of skill', when people's health is not 100%; all will affect the work quality.

1.5.3 Compete Internationally by Implementing Automation

One of the main ways Australia is battling this lack and near impossibility to compete with these cheap labour countries is through automation. The development of greater technology and computational processing power, along with a greater cohort of input, means that Australia can rise to fulfil this competitive void. This is important for the Australian economy to be able to IVA to our resources and make it count to the Australian economy. Automation within the food processing industry is increasing as robots are much more efficient and cost-effective than that of human labour (Mitchell, 2016).

As indicated by (Ernst & Young, 2017), “Australia’s red meat and livestock industry turnover were $62b in 2015, increasing by 11% year on year.” For this to continue, greater advancements in technology are required to provide a competitive edge. Figure 1-3 presents the leading international export countries for red meat, such as beef and veal. Australia’s closest competitors are India and Brazil, who have the advantage of lower labour costs. Its higher market share displays Australia’s ability to produce higher quality, but as the international quality is improving, Australia is required to develop ways to reduce production costs.

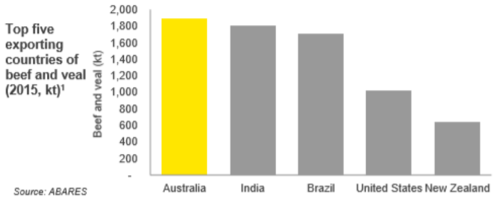


Figure 1-3 Australian Export Compared to other Countries (Ernst & Young, 2017)

International trade is vital to the success of ARMI. By gaining a competitive advantage over international competitors, the industry will continue to grow. Automation will also bring benefits to the labour problems that the industry faces.

1.6 Objectives

This section will review the objectives of this study by providing a list of outcomes that the report will accomplish. The aim is to design a robotic Rig that will aid in the collection of data. This was a CAE supported project. As a part of their support, they set down specific requirements that they wanted to be accomplished as a part of the project. The outcomes of this project will be:

1) To design and build a Rig within the specification provided by the (CAE). The Design will work from the customer specification that describes functions and operating criteria needed.

- The Rig needs to be stiff
- The Rig needs to fit on a stainless-steel table that is provided while maintaining a lightweight and the ability to transported.

- The Rig needs to incorporate LiDAR, ultrasound and machine vision sensors while incorporating their limitations.
- The Rig needs to provide sensor accuracy within 2mm of a designated spot. Horizontal and vertical.
- The Rig needs to operate with a 20N working force along the x-axis.
- The investment needs to be around $1000

2) The Rig must be incorporated safely into the provided environment and provide operational safety during use.
3) The technical specification derived will reflect customer requirements and the technical parameters to be met to achieve the aim for the machine.
4) To Design the configuration and produce detailed design assembly and elements
5) The motors and drives will be selected to provide a torque/ speed ratio enough for accurate collection of data.
6) The accuracy of movement and positioning of sensors will be within two %FSD with repeatability of .5% FSD.
7) To set up a test procedure by developing control algorithms to integrate the mechanical and electrical component into a mechatronic design for use as a R&D tool and present test results.

Working to the objectives will deliver the aim for the project

This Design project is developed explicitly around the purpose of studying a striploin fillet. This system will help the CAE explore the interface point between the muscle and the fat and to measure these points under different working conditions accurately. The choice of the mechatronic system will be a low-cost yet practical way to develop the models required to take the measurements and collect the data

1.7 Section Overview

Section overview will discuss the Dissertation by outlining Sections 2-8. The reader will be able to quickly refer to the sections associated with literature, design considerations, the physical Rig and the components that make it perform, data gathered from this and lastly the conclusion and recommendations.

1.7.1 Overview of the Dissertation

This dissertation is organised as follows:

- [Chapter 2] **Literature Review**: Considers the research previously undertaken concerning discrimination of red meat, Robotics and Automated Systems, Meat Industry and Medical

Industries. The Literature Review will also consider sensors like Machine Vision, Topography and ability to use force and torque as a form of sensor. A brief discussion on the relevance of the state of the meat and Industry food standards. The conclusion considers the information and the viability of a tool to study striploin.

- [Chapter 3] **Design Methodology** – In this Section, the projects method and pathway have been developed. The technical specification developed from customers requirments has been presented. Each section will describe a different element and break that element down into itemised requirements for each section. The selection of parts requirements will be outlined within the methodology. The methodology will also describe what has to occur.

- [Chapter 4] **Selection of Components and Physical Design Consideration—**This chapter describes the selection process of the components of the Rig and also present why specific designs have been selected. It shows the motors and drives, microcontrollers, sensors and sensor carriages that have been selected. Different models are presented like the Rig, base, alignment of sensors, and sizing of bevel gears.

- [Chapter 5] **Analysis of Crucial Component**—The analysis of critical components and computational models of the Rig has been presented. The build will systematically go through each crucial component of the mechanical and electrical system. The results that will be presented are main beam analysis, shaft analysis, motor sizing and stability of bench.

- [Chapter 6] **The build and Programming of the RIG**– This will discuss the build process and considerations during the build. It will consider the procedures followed as the mechanical components where constructed. Discuss the electrical implementation onto the system. The programming of the Rig This will discuss the Arduino program and discuss the development and aim of the program. The installation of the sensors is discussed.

- [Chapter 7] **Accuracy Results of RIG Positioning** —The results gathered from the performance of the Rig will be discussed. There have been two tests completed, and they have focused on repeatability and accuracy. Graphs have been built as visual representations of what has occurred. The Raw data has been added to Appendix G.

- [Chapter 8] **Discussion of the Dissertation and Objectives**– This section discusses the overall results of the project. The discussion considers what each section offers and delivers to the outcomes. It shows how the technical specifications have been met through references to sections that fulfil the requirements.

- [Chapter 9] **Final Conclusion and Recommendations**—This presents the conclusions of the report. It briefly describes the outcomes of each of the objectives. This chapter then offers suggestions as to what further work may be considered and what direction this project may head.

- [Appendix A-H] presents extended data that adds to what is provided in the text.

Chapter 2 Literature Review

This study has been commissioned to design, build and test a Rig for use in studying the effects of fat trimming on the whole striploin. Currently, automation technology is not available to interact and adapt to deformable meat workpieces, where the highly variable properties and behaviour can be perceived and responded to automatically in both planning functions, and real-time corrective control strategies.

This literature review will consider the following elements. This will include research previously undertaken concerning discrimination of red meat, robotics and automated systems, meat industry and medical industries. It will consider sensors like machine vision, topography and data from force and torque measurements.

The Literature will provide insight into the industry requirements while shedding light on advancements that can be implemented into the industry. This will give a detailed overview of the developments and research that relate to the focus of this dissertation. It will also provide insight into the development of a Rig for researching striploin beef.

2.1 Techniques Available to Interact with Soft Tissue.

When considering the discrimination and interaction with soft tissue, the study has turned to industries already involved with the interaction of meat. This enables Rig design to build on what has already been developed while helping to develop methods to grow the knowledge and understanding of how to best interact with striploin. The literature that is most relevant to this study considers areas such as:

- Industry Tools that Already Exist within the Meat Processing Industry
- Development of Medical Processes that are used to Interact with Soft Tissue
- The Development of Automated Systems and their Ability to Work with Dynamic Materials
- Different Methods Already Developed to Discriminate Between Different Mediums.
- Striploin Processing Timeline
- Industry Food processing standards

The investigation of these five areas provides a greater understanding of what developments have been established. This also provides a greater understanding of the development of processes to discriminate between different elements of a striploin.

2.2 Industry Tools that Already Exist within the Meat Processing Industry

By understanding the level of tool development within the meat processing area, a narrower focus can be developed concerning the gaps that need to be filled to provide a high level of automation. By investigating the manufactures of meat process equipment, level of development can be shown. There are several companies involved in the meat processing automation industry, and two of the leading companies will be discussed here. These will be MARELL and SCOTT.

The investigation will describe what processes are available, what sensors and technology are used, and lastly a discussion on their actual ability. The report will start at tool capabilities.

2.2.1 The Tool Capabilities within Meat Industry

Many of the automation processes that exist in the meat industry are processes that work with rigid materials and not the dynamic reactions experienced with striploin. This means the tools are able to work on a medium that has very little change in shape like meat with the bone (Guire et al. 2010). The processing of meat is exceptionally hazardous, especially as companies speed things up to increase yield (Demetrakakes 2019). These processes split the full-size carcase into smaller segments, which then get passed on to a human worker. Low-level automation and high impact human interaction is the present case.

What are the benefits of the automation that is already implemented? According to SCOTT, (2020) who produces a robotic beef rib cutting robot (Figure 2-1), indicates that there are many advantages to this advancement. The following list is a consideration of the benefits of these systems (SCOTT 2020):

- Labour efficiency and safety reduces band-saw risk to the workers in the industry.
- Reduced ‘Sawdust’ caused by the cutting action of band saws and through the use of circular saws.
- Cut Accuracy which increases the weight of the usable product.

This means they are precise and very efficient.

Figure 2-1Automated Rib Cutter/Scriber (SCOTT, 2020)

Marel is another leader in animal processing equipment, and their machines are moving towards robots that cover every step of the process. This includes (MARELL, 2020):

- Live animal control, slaughter, scalding, de-feathering and washing
- Cut-up deboning, filleting and trimming, skinning, inspection, portioning and slicing
- Preparation, forming, coating, frying heat treatment, sausage making and freezing

- Marel also has several automated machines used to recover meat from the pig heads and the finer pieces of meat and bone.

Their machines also cover portion slicers and every machine to take the product from A to B. Many of their machines involve human interface and add to the efficiency of the human operator.

The development of the Rig will help build on the machines that companies have produced. It will also help to take away the human interaction, provide safety and improve work conditions. To do this, an understanding of meat dynamics and movement must be developed. The Rig will need to work with non-rigid workpieces.

2.2.2 **Technology Already Present in Meat Processing Industry**

Within some of the animal processing industries, line speed can be up to 1200 beasts/h for pigs and up to 400 beasts/h for beef (Barbut 2014). This could include automation in hide pullers, man lifts, automatic saws and pneumatic shears, computer-controlled systems and laser-guided pork cutting robot.

Kinea Design and Scott Technology were at the forefront of developing technology to de-bone beef (Hook Assist co-robot) (Robotics Tomorrow 2011). This bit of technology succeeded in producing a piece of equipment that works collaboratively with a worker by improving pull strength up to 10 times. It is suggested by SCOTT (2020), that this robot has the following qualities which ultimately lead to better product and greater profits:

- Yield gain
- Greater safety
- Improved working conditions, staff retention and better recruitment
- Workload more manageable
- Ease can be implemented into most boning rails
- Efficiency improvement

This again points out the limit of automation. This is one of SCOTT's premier bits of equipment and still involves human interaction. Where there is high powered machinery, there are safety concerns. Scott also indicates some of the benefits that will undoubtedly be multiplied with greater automation. The main industry sensors will be discussed next.

2.2.3 **Main Industry Sensor**

Dual Energy X-Ray Absorptiometry (DEXA) is one of the primary sensors used to determine the structure of the meat and will create a 3D map of the bones. DEXA is used in conjunction with 3D scanners, colour camera, laser guides and computer-controlled systems. It is an X-ray machine that scans every beast, producing accurate images for accurate cuts. These sensors match together to be able to create information suitable for the process. The X-ray is ideal for mapping a rigid specimen but has health issues with radiation.

Many great systems have been developed in the industry, but still limited to human interface. The accuracy of the primary industry sensor is based on a pre-scan, and no real-time scanning is available yet. What little amount of automation there is, it provides safer working conditions and more significant gains. The development of a Rig will require real-time sensor information during the interaction, great use of autonomy, and better adaptability during the process with real-time sensing information.

2.3 Development of Medical Processes that are used to Interact with Soft Tissue

When comparing the meat processing industry and human medical fields, it could be considered that there are many similarities. Automated devices like Smart Tissue Autonomous Robot (STAR), which boasts of being able to react to uncertain, dynamic landscapes of soft tissue surgery, is vital to this study (Bushak 2016). As with many industry tools, medical robots are more accurate than that of the human surgeons (Strickland 2017) and have greater dexterity and vision compared to humans (Svoboda 2019). The focus of this project is on striploin beef which has many similar attributes to that of the human body. This means that many techniques in surgery could be transferred from medical science to the meat processing industry. The following will consider some of these processes:

- The Use of Force and Torque Within Surgery
- A Venepuncture Detection System
- Pattern Recognition System

Each process is unique. To understand what is available in other industries, like the medical industry, will provide a greater picture of what is possible. This will also help to design a Rig that can better incorporate a broader range of possibilities. The report will consider force and torque as ways to interact with soft tissue.

2.3.1 The Use of Force and Torque Within Surgery

This process was successfully used in surgery as a way of predicting what lies ahead by using torque and feed force as orthogonal sensory data transient coupled through tissue. The technique was implemented in a drill used for cochlea implant surgery. As stated by Brett et al. (2018), “The information is extracted by the drilling system to describe the state of the process relative to deforming tissues, the state of the tissue, and drill bit”. As it is further explained by Brett et al. (op.cit.), that as the drill approached the edge of the cochlea (and other materials such as rock and steel), the force suddenly reduces and torque increases, signifying the approaching tissue interface. (see Figure 2-2)

Force is a crucial factor in many surgical processes. The Smart Tissue Autonomous Robot requires force to prevent exaggerated movements in soft tissue which tends to deform when pressure is too great. (Svoboda 2019) This force is being modelled on haptic feedback, which is the sense felt by skin, muscles and joints, and such a sensor has been developed by Sensible Technologies Corporation (Hu et al. 2019).

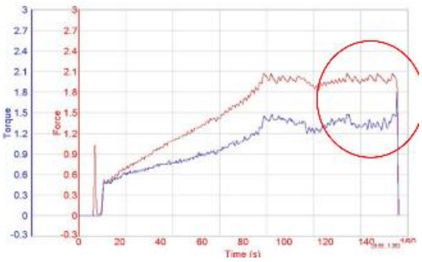


Figure 2-2 Force vs Torque – Tissue Discrimination (Brett et al. 2018)

This type of sensory information could be implemented through different forms of sensors developed for the Rig. The Rig will need to be stiff enough to provide accurate reading at the point where force and torque information is gathered. Another interesting development within the medical field is the use of Impedance in a device like the venepuncture detection system

2.3.2 A Venepuncture Detection System

This method is used to assist, not replace, the process of giving an Intravenous (IV) catheterization, which has a high failure rate of close to 30% (Zhuoqi et al. 2016). As the needle goes into the patient, the system can detect the different tissue layers, including when the needle hits the bloodstream. The device used in Peripheral Intravenous Catheterisation (PIVC) has a plastic tube over a needle. The needle is used to puncture the skin and vein, and when in the correct position, the needle is removed, leaving just the plastic tube. As stated by Zhuoqi et al. (2016), "…different types of tissue present different electric impedance". Figure 2-3 shows the impedance level of some of the soft tissues from pig samples showing a very accurately detectable range.

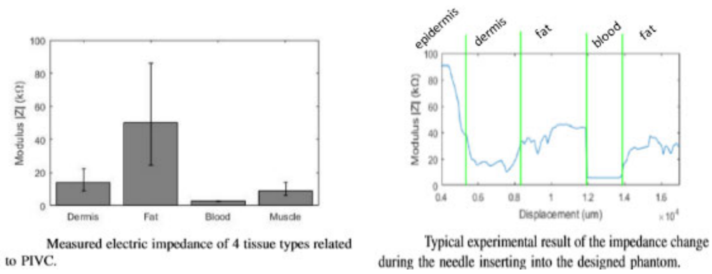


Figure 2-3 Impedance results from different pig tissues (Zhuoqi et al. 2016)

The Kalv et al. article (2009) considers the use of impedance to determine needle position within muscle, sub-dermis and fat.

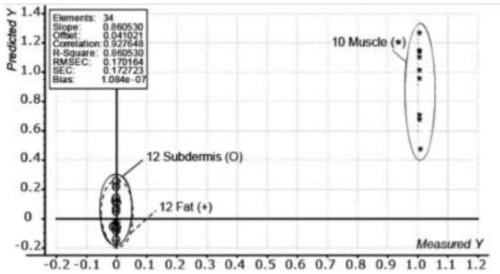


Figure 2-4 Results from Impedance-based tissue discrimination for needle guidance (Kalv et al. 2009)

The results in Figure 2-4 and Figure 2-3 show that the different groups of soft tissue can easily be discriminated using statistics, and in this case, Partial Least-Squares Discriminate Analysis (PLS-DA). This uses needle-like probes that penetrate the meat around the cutter. This aims to determine, through an impedance, the type and depth of material. A vector can then be created for knife direction. It may also be used to back up what is being seen through other methods of discrimination. This would need to be averaged so that the cut would not take a dramatically new path.

So where is the ability to add to common knowledge within this sector? All the methods to discriminate between different parts of the product concern stationary interaction. What needs to be developed is interaction with the product in a dynamic situation, mid-process or in real-time. Pattern recognition in surgery will now be considered.

2.3.3 **Pattern Recognition System**

One of the common ways that automated machinery is being taught to perform tasks is through patterns set by human operators or as simple as lines drawn on a subject. This is seen in the use of the STAR. With its near-infrared camera and other sensors, it visually tracks tiny digital marks placed on the tissue before surgery (Strickland 2017).

The medical field is highly regulated and has substantial government funding and private funding in many countries. It must be highly scrutinised and anything developed has to be perfect. It is a good place to seek information concerning what is available to interact with soft tissue and to transfer ideas to the meat processing industry.

2.4 **The Development of Automated Systems and their Ability to Work with Dynamic Materials**

There are no machines that have been developed to very accurately work with dynamic materials outside of the medical field. The former way of identifying cut locations was to stretch the meat or use mechanical means. This is now being replaced with sensors, software and algorithms like an x-ray.

A lot of the automation equipment that is used is high-speed machines that are programmed for high output. These same machines are designed to work within a set size limit. It is suggested that some of the challenges are because the automation machines are not sensitive to variation in size (more common to the larger red meat animals) and quality which may require unique sensors and control systems (Barbut 2014).

Guire et al. (2010) indicate some of these processes mimic that of the human operator and are shown in Figure 2-5 below. It demonstrates how an operator uses a Z pattern cut. This is now mimicked by a robotic arm.

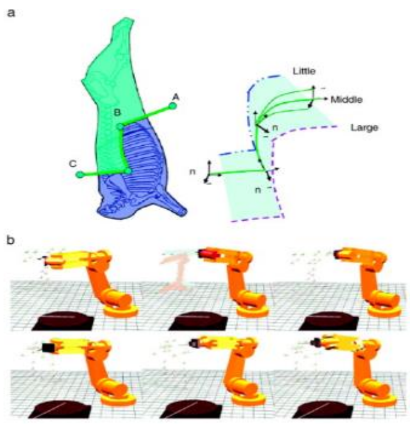


Figure 2-5 Process developed from mimicking human processor (Guire et al., 2010)

This section reveals the need for greater understanding of soft tissue like striploin, that requires high accuracy and a greater understanding of how the meat reacts to interaction. Other methods of discrimination will now be discussed.

2.5 Different Methods Already Developed to Discriminate Between Different Mediums.

There are many ways developed to discriminate between different mediums, and the following will be considered:

- Laser-Induced Breakdown Spectroscopy (LIBS)
- The Use of Topography Methods to Find Interface Points
- Machine Vision

For these methods to be useful in determining interface points in soft tissue, they need to have the ability to determine the invisible and visible points of interest in real-time.

2.5.1 Laser-Induced Breakdown Spectroscopy (LIBS)

One of the primary studies done concerning soft tissue discrimination has been through the use of LIBS. This type of analysis has been used to investigate things from soil, carbon, fish bones, explosives, to cancer and more. In the article by Li et al. (2018), the discussion is how this technology can be used to tell the difference between various sections of skin, fat and muscle tissue from other cuts of meat, with a very high rate of success.

Li et al. (2018) also have discovered that, "…tenderloin muscle tissues can also be discriminated with acceptable performances." The best discrimination performances are achieved with Support Vector Machines (SVM) classifiers using Gaussian Kernel Function, with an accuracy of 76.84%, sensitivity of over 0.742 and specificity of over 0.869.'

This method does not happen in real-time environment. It relies on the ability to analyse over a set time period. It also indicates that it is a destructive analysis. Lastly, its ability to describe anything but the surface of what is being studied makes this option not feasible for cutting operations, unless the laser and sensor can be positioned right at the cut.

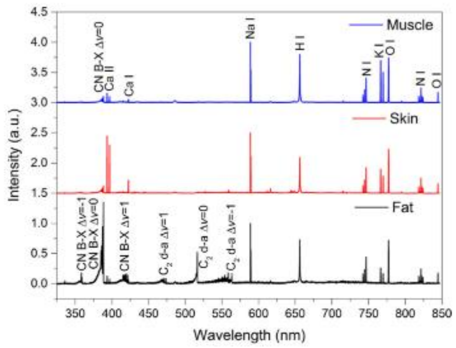
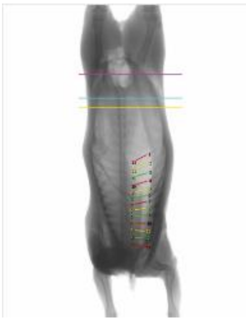


Figure 2-6 Normalised average LIBS spectra of fat, skin and muscle tissues-source: (Li et al. 2018)

As can be seen in Figure 2-6 there is a visible difference between the testing of various soft tissue members in the LIBS process. The report will now move on to topography methods that may be used to determine interface points.

2.5.2 **The Use of Topography Methods to Find Interface Points**

Studies have been made using tomography technology. These include investigations in the use of "dual-energy computed tomography" (DECT) or for DEXA. See (Figure 2-7 for scanning and being able to discriminate between different soft tissue (Zachrisson et al., 2010). As can be seen, the less dense material shows up lighter, and bones come up darker. This cannot be applied to striploin, due to its deformation during working producing incorrect addresses (Border et al. 2019).



(Figure 2-7 X-Ray of a carcass showing marker points (SCOTT 2020)

Even though this is possible, the CT solution is costly. There are cheaper topography methods like those of ultrasound. Ultrasound technology has been used within the food industry for many years for the cutting or sieving of products and food quality (Du and Sun 2004). At a frequency of 20kHz – 15 MHz, the ultrasound is able to pick up different medium densities and is presently used in pork processes (Border et al. 2019).

Other forms of tomography that have been considered are image processing techniques like-charged coupled device camera, ultrasound, magnetic resonance imaging, computed tomography and electrical tomography.

2.5.3 Machine Vision

Machine vision camera can be used to differentiate the meat from the fat. A machine vision system is only useful on the surface of the medium and can be used to segment the meat and fat (Du and Sun 2004). Machine vision has been used to classify fish species by using the information on colour and texture features, all on mobile phone cameras (Hu et al. 2012).

Within the industry, machine vision is spreading to the use of smartphones as a possible use for quality and discrimination (Hosseinpour et al. 2019). Meat quality is assessed through colour assessment and marbling while producing some form of a score which may be assigned for differences in fat colour (Du and Sun 2004).

Chen et al. (2010) in an experiment using a boundary tracking algorithm in conjunction with the logical operator ‘AND' of the mask image, optimum threshold, image is binarized, flecks of fat are removed, and the fat portion is isolated. A similar objective has been acquired through homomorphic filtering to remove unwanted noise created from light to emphasise marbling (Pang et al. 2014).

Machine vision is growing in every industry and provide valuable data. It can differentiate colour, change in size, real-time interaction, and could definitely be used to determine how the change in shape relates to internal structural change.

2.6 Striploin Processing Timeline

Another interesting point to be considered is the point at which the process should happen. When an animal is killed, the beast will go through different stages to rigor-mortis (stiffness of meat) which reduces to a pliable form after some time. It is explained by Barbut (2014) that what is happening at a cellular level is crucial when designing equipment and processes. Some of these processes can be utilised, such as electrical stimulation and maturation chilling to enable better interaction with the meat.

When a beast is cooled too quickly after slaughter, it produces a tougher cut of meat, and that is why electrical stimulation was developed and is now used in most animal and fish slaughter processes (Barbut 2014). The methods reduced pH levels by 0.5 units which would typically take 3 hours by conventional means.

This is critical when developing machines such as a Rig to work with meat as the meat relaxes quickly. The measurements taken initially will be different after some time due to the beef settling under gravity. So the speed of testing will be crucial and also consistency in environment essential. The Rig will need to take measurements quickly and consistently.

2.7 Industry Food processing standards

Wherever there is food processing, there are standards that must be met to maintain a level of sanitation. This means that the automation process must be done in a way that provides a high level of health standards, and this also applies to the equipment being used (FastCasual 2018). There are more than 20 standards imposed by the National Sanitation Foundation (NSF), that cover location and ability to clean and access. Manufacturers are also self-implementing cleanliness into their processes (Riley 2018). All automated devices are being engineered to maintain a level of sanitation and washability.

This is vital to the development of a Rig. The Rig may be required to be taken into a food processing environment for research. Under that condition alone, it will need to be developed with food-safe materials and be able to comply with food-safe standards and sanitation.

2.8 Conclusion

This research discusses the limited ability presently for interaction with soft tissue in the meat industry. Most automated devices have been developed with human interaction in mind and pose as an extension of the person. The use of robotic arms and gantry-type systems are used widely within the ARMI and can be adapted to the small scale required what fully automated devices that are used provide little adaptability to dynamic workpieces and work from rigid and constrained states.

The ability to fully automate is available, as already seen, in the medical industry and already exists in some parts of the meat processing industry. Sensors are well developed and provide the ability to take important information and combine that information into useable data. The implementation of any number of sensors that can be utilised safely and used in real-time would be invaluable.

The state of the meat has been shown to be crucial during operations, and methods need to be developed to take measurements quickly and accurately while maintaining consistency.

Food standards are an essential aspect of the development of any tool that could ultimately be used alongside consumable products.

The development of a tool to study reactions of the meat would provide greater ability for processes to be developed and models to be created.

Chapter 3 Design Methodology

3.1 Introduction

The methodology provides a written pathway from start to finish for this design project. The methodology will critically consider the steps required for successful completion of the project and outline specific consideration of the elements that need to be discussed. The methodology then presents the design and build of each area of the mechatronic unit.

The following sections will be considered

- Time Management of this Project
- Research and Background of Automation in the Meat Industry
- The Meat Considerations (striploin)
- The Mechanical Outline of the
- The Electrical Hardware requirements
- Equipment and Software requirements during Design and Build
- Safety and Risk Assessment
- Conclusion

The methodology considers the decision requirements that will be needed for the build of the Rig. This will have to cover each of the required Rig components. A successful result will be achieved through following the pathway (considerations) that is succinctly set out in the following section. The project started with an outline of a plan and the need for research in all relevant areas through a literature review (chapter 1).

3.2 Time Management of this Project

A systematic plan has been developed as a road map for this design project. A Gantt chart has been produced and presented in Appendix A2. This Gnat presented is a refined plan developed from a much more detailed plan. It shows critical assessment dates and achievement benchmarks that are vital to the success of the project. The original plan also included travel dates, due dates of assessments and goals to attain concerning different parts of the research. This plan will remain unless something unprecedented happens, and plans must be altered.

Now that time management of the project has been discussed; the report moves on to the Literature review and its requirements for successful understanding of where the ARMI processes presently stand.

3.3 Research and Background of Automation in the Meat Industry

The Literature review show's that the processing of high-quality primal cuts is a process yet to be developed. It reports on the significance of robots within the meat processing industry. Present tools and physical ability are there to advance the industry, and it is a matter of developing these tools to suit application requirements. The literature review will discuss what factors are driving this project and what tools and systems can be used to expedite industry advancement.

The literature review has used information from MLA, current industry leaders like Scott and Marel, scholarly articles and medical industries advancement to develop an understanding of the next step forward. This will provide a well-rounded view on where this technology state is at present.

3.4 Breakdown of Critical Considerations with Questions.

A selection of considerations has been presented in Table 2 that provides direction into the further development of the Literature Review and project overall.

Table 2 Background and Research Considerations

Section	Questions
Project statements	What problem will be solved through this project? What will need to be implemented to form the solution? How will this project add to what is already available?
Industry	What machinery is available in the industry? What technology is available in other industries that can be implemented? What are the barriers that have prevented further development? Where is the push for advancement coming from?
Meat	What makes up a striploin? What benefits will striploin process automation provide? What will the final result look like?

Mechanical	What can mechanical devices be used in this project? What must be built in this project? What are the restrictions? What are the requirements? What is the speed at which the Rig has to move?
Hardware and Electrical	What will the development board be used? What motors will be used to manoeuvre the Rig? What sensors will be required? What power will be needed? How will the information be transferred to the computer?
Software	Will the software be required in the development of the project? Will the software be needed in the solution?
Applications	Where will this system be implemented? Can the solution be used in any other processes? Will the solution be fully automatic or involve user interaction? Who will have access to the solution?
Further development	Will this solution be a part of the final answer or just a conduit?
Required resources for the project	What will be required for the build? What software will be required for the build?
Safety and Moral Effects	Who will be affected by this development? What negative implications will arise? What safety measures will need to be incorporated into the design? What are the implications of power being used around this space?

By asking the questions below a greater scope of answers will be considered, which will help develop a result with greater accuracy. The projects focus is on striploin, and this will be regarded as next

3.5 Technical Specifications

The technical specifications have been developed for the Rig from the requirements set by the CAE. The specifications can be seen in Table 3. The size of the Rig is set by internal and external constraints. Accuracy has been determined by the CAE. The Rigs weight has to be manageable. The speed of operation has to provide accuracy under a 20N load.

Table 3 Technical Specifications

Component/action	Technical specification
Size of the Rig	External (set by bench) 1500mm x 700mm x 600mm Movement over platform 800mm x 330mm x 160mm
Accuracy Horizontal	Error 2% full-scale deflection repeatability 0.5%
Weight	Under 30kg
Working force	20N
Horizontal accuracy.	2mm
Rig Speed	Full run under 3 min.

3.6 The Meat Considerations (striploin)

Meat is a very dynamic material and acts in uncertain ways. Without the development of test equipment to study reactions, it is impossible to build models due to this uncertainty (Border et al. 2019). This will allow the development of automation equipment to be based around information over theoretical data. The Rig, as a tool, provides the ability for quantitative research processes to take place that will focus on the cause and effect of Striploin. This completed Rig will collect data through experimentation, followed by statistical analysis (Borrego et al. 2009).

The build will revolve around the striploin, especially the upper-end size of the striploin. The development of the Rig is to work with a high-quality product, and everything done is to IVA to the end product.

The following issues will need to be considered:

- What is the size range of the meat portions?
- How close do the sensors and meat have to be?

- What effects if any, will the meat have on the Rig?
- The weight of the meat will have to be considered when developing the Rig.
- The striploin is made up of a number of muscles which will affect sensing in different ways.

It is necessary to understand the result expected from the process and from that, form a method of how the process needs to occur. The structure of the meat will obviously be different for every specimen. The result expected by other customers will also be varied. The solution will need to be adaptable in both what the Rig sees and how the Rig reacts.

A striploin portion can be as large as 600mm long x 250mm wide x 90mm high (LWH) (Khodabandehloo, 2018). The striploin mass can be as large as 12kg. Knowing these dimensions will allow the design to be built around the striploin. The sensor carriage will need to be designed so that every part of the striploin can be analysed.

The mechanical part of the design is now be considered in conjunction with the CAE requirements. This will now be presented.

3.7 The Mechanical Outline of the Rig

The Rig will have some essential fundamental requirement concerning the mechanical part of the design. The Rig's design will use the meat as the critical element to consider. Components will be investigated and, using decision techniques; parts will be selected. The structure of the Rig can be separated into five main parts:

- The Striploin Process Area
- The Design of the Sensor Carriages
- The Design of the Base
- The Platform
- The Mechanical Components that Form the Drive System

The decision process relies on modelling software to create physical 3D shape and sizes, engineering models and calculations to test component capabilities and the CAE requirements as the foundational base. These results will help to develop the technical specification. The ability for accuracy is vitally important to the successful outcome of the project.

The meat has set the internal work area required for the project, and the striploin process area will determine the outer dimensions of the project. The impact of this area will now be discussed.

3.7.1 The Striploin Process Area

The Bench

The position of the Rig is on a rigid bench, sturdy enough not to collapse under its weight. The bench must also have a centre of gravity that will not promote the tipping of the table during operation of the test Rig. The rigidity of the table affects overall measurement accuracy. The bench requires adjustable feet for platform stability and to counteract unevenness on the floor.

The bench will be stainless steel. The use of stainless steel and other non-corroding materials is standard practice in the food processing industry, as stated in AS4674-2004 standards (Australian Standard, 2014). This standard will be continued throughout this project. A stainless steel table has been provided by the CAE (Figure 3-1) to be used as a bench for the Rig. It will be placed in a refrigerated room. The dimension for a table would be 1500mm long (X) x 700mm wide (Y) x 900mm high (Z) (LWH).

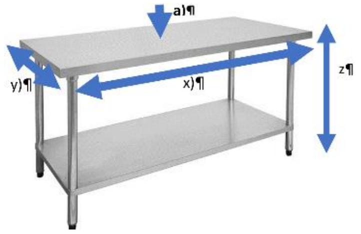


Figure 3-1 Stainless Steel Bench to Hold the Rig

The bench will be placed in a room that is appropriate for processing food.

The Room

The room is refrigerated as it is dealing with a food product. These Australian Standards provide criteria on design and construction which will assist with compliance with Standard 3.2.3 for new buildings and alterations to existing buildings. Specifically, this Standard aims to ensure that premises: (Safe Foods Australia 2018)

(a) Are easy to clean and maintain clean.

(b) They have enough space, facilities and suitable equipment to produce safe food.

(c) They are provided with services such as potable water, adequate sewage disposal and enough light and ventilation for the food handling operations.

(d) Provide facilities for staff to maintain standards of personal hygiene and equipment.

(e) Cleanliness that will protect food from contamination and are proofed against entry by and harbourage of pests.

The room must be set at a temperature that provides an atmosphere that promotes longevity of test specimens.

The Methodology will now consider the use of sensors carriages on the Rig.

3.7.2 The Design of the Sensor Carriages

The design of the Rig requires efficient measurement of the interface between the lean and fat of striploin steak. Sensor carriages will be used to carry the sensors to the required position and need to have access to every point of the striploin. The following criteria will need to be considered:

- The sensor carriages need to be sufficiently rigid to reduce bending of components and inaccurate movements during operations.
- The sensor carriages will need to have sensors mounted accurately on them. Sensors required will be Cameras, LiDAR, Ultrasound, Linear scale, and a way to duplicate test results.
- The sensor carriages require adaptability, to allow the workspace to be a multiple-use area. This may include the easy removal of the top part of the Rig to allow a robotic arm to be used in its place.
- The sensor carriages will be used to study principles for cutting and sensing of the meat.
- The sensor carriages will need to provide a clear view of the process area during testing operations.
- The sensor carriages will have to integrate into the platform provided by the CAE.
- The Rig will have to allow the sensors to be in line for accurate measurements.

It is essential that the sensor carriages are designed accurately. The sensor carriages will be formed from pre-developed carriages. The system will be required to move smoothly and accurately in the 3D space. The final selection of components will be based on their suitability for a task.

Safety will be considered as the sensor carriages will have moving parts. This brings the next stage of the report. This is the design of the base.

3.7.3 The Design of the Base

The Base will be the structural component on which the sensor carriages will be mounted. This will need to comply, once again, with food-safe materials. Its design criteria will have many similar attributes to the sensor carriages; it should:

- be rigid
- be easily modified so that it can be repurposed (use many bolted joints)
- provide easy removal of the Rig

- have adjustable feet to provide solid footing on the bench
- be able to mount the platform (a surface that will carry the meat)
- be designed to be extremely solid

The design of the base will utilise modelling software and developed engineering techniques to determine part suitability. The platform will be easily attachable to the base. It is now considered.

3.7.4 The Platform

The platform will be the component that will hold the test piece (striploin). This will be made from food-safe materials. Its design will have the following attributes:

- The platform will have to be designed to allow sensors to access the test piece.
- It will have to be rigid enough to prevent deflection under the weight of a test piece (test pieces can be up to 12kg).
- The platform will be simulated through software to determine the ideal mounting method.

The platform has been provided by the CAE to be used in the project (Figure 3-2). The platform is 316 stainless steel. The dimensions can be found in Appendix E.2.6 Platform. The striploin will sit on the platform, and the Rig will need to move around the platform. The holes in the platform provide access for the ultrasound to interact with the meat.

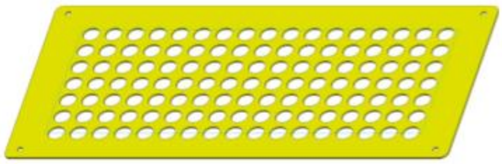


Figure 3-2 RIG Platform

The design of the Rig will need to consider the platform deflection and the associated error. A visual representation of this item can be found in Figure 3-2. The results of a simulated deflection can be seen in chapter 5.2. The drive components of the Rig will now be discussed.

3.7.5 The Mechanical Components that Form the Drive System

The moving parts in this project will interface with the hardware. This will involve special consideration as to what is required from the system. These components will also be off-the-shelf components that are pre-designed to fit the application. These mechanical components may involve elements like:

- gears and drive pulleys
- belts, screw drives, and shafts
- couplings, spacers, bolts and nuts
- bearings
- rails, wheels, brackets

Due to the lightweight application of the Rig, a lot of standard components will be able to be matched to critical components; for example, bearings can be matched to shafts.

3.7.6 Conclusion of the Mechanical System

The mechanical system sets the platform for the electrical system and the operation required for the study of striploin. Its design will need to consider each of these things throughout the plan. Components will be mathematically considered by engineering models to confirm suitability. The mechanical system parts will be ordered. Then the mechanical system will be constructed before any other system is attached or developed.

3.8 The Electrical Hardware requirements

The hardware comprises of the electrical components of the Rig. A risk assessment needs to be considered prior to commission. This will include several different sections. They are:

- The Microcontroller
- the motors
- sensors
- other parts

The microcontroller is an electrical component that utilises 12 volt PSU. A 12 volt PSU may also be used if components require it. This is a low voltage device. It will provide safety to persons using the equipment as well as to prevent damage to the equipment itself. The hardware will be used in an environment that is subject to corrosion and maybe a wet area.

The following will need to be considered during the selection process:

- Will the component be suitable for the task?
- How will the different components communicate?
- What voltage will the components require?
- How will the components be mounted into the design, and will they require an enclosure to protect them against the elements?
- Is the system safe

The microcontroller manages the operations of the system and will be considered first.

3.8.1 The Microcontroller

The microcontroller controls the movement of the sensor carriage around the 3D workspace of the Rig. The MCU will also store and processes information for further use in the real-time process of the Rig. It will be the 'brains' of the operation and will connect all the other hardware components into the one system.

The microcontroller selection will allow for full automation of the Rig. A development board should be considered, as this allows for the greatest flexibility for the interchange of different devices that may be tested during development. This would need to be compatible to interface with the requirements of the hardware but also be a suitable price.

The microcontroller will be mounted during the electrical installation stage. The hook up will be done in segments to assure correct component placement. A waterproof housing will be used to maintain the safety of parts and limit human contact. The microcontroller will control the movement of the motors around the system, and crucial characteristics of the motors will now be discussed.

3.8.2 The Motors

There will be three motors required to drive the system. Each axis of the system will require its own drive. The motors operation signals come from the microcontroller. The position of each motor needs to be continually known. The motor needs to have some form of feedback or ability to step or interface with some linear measurement device. During the selection of the motors, the following considerations will need to be considered:

- What size motors will be required to drive that component?
- What will the motor drive, to move a sensor carriage?
- How accurate will the motors need to be?
- How will the drive position be recorded?
- How fast will the motors need to drive?
- How will the motor work and interface with the microcontroller?

The motors will be used to position the sensors and interface equipment with accuracy. The Rig will be designed with the motor position in mind. The Rigs motors will be mounted on the Rig during the installation of the electrical system. They will be tested for accuracy and their ability to perform the required task. The sensors will now be discussed.

3.8.3 The Sensors

There will be three primary sensors required for this project, and one is a sensor used to check the accuracy. They will be ultrasound, LiDAR, camera, and inductance measuring device. Together these four sensors will discriminate between the fat and the lean and confirm that what is determined is correct.

The following information about the sensors will need to be considered:

- The sensors provided will be sought out for suitability and the specification aligned with requirements.
- The output of the sensors will need to be considered (analogue or digital information). This will need to line up with the selected microcontroller.
- The sensors will be mounted on the sensor carriages. Suitable brackets will need to be made or sourced. The brackets will need to be adaptable to changing circumstances.
- The interface between the sensors will be looked at so that the information can be brought to one spot.

The impedance sensor will be developed as a check to the accuracy of the other sensors. Two of these devices have been predetermined by the CAE and will now be considered.

3.8.4 LiDAR Performance Specs and Required Data from Reading.

The LiDAR is a device that measures distance. This project will use the LiDAR to determine the distance from the meat to the table. The LiDAR has been supplied by the CAE. This system is stand-alone and will provide its own power and data collection method. The system could provide digital information to the data collection Arduino, but this is outside the scope of this project.

There are several important features shown in Table 4. The measurement range starts at 60mm, which requires the mounting position of the sensor to be at least this distance from the largest striploin. Also mentioned under repeatability is the error of $30\mu m$. This will form a part of the overall error expected from the system.

Table 4 Specifications for Laser

Model	OD2-P120W60U0	
Supply voltage	18v – 24v	This device will have its own power supply

Warm uptime	≤ 30 min	This will need to be an allotted time prior to use
Measurement range	60mm—180mm	Set at least 60mm above larges striploin
Repeatability	$30\mu m$.	An error of 30 microns
Measure frequency	2kHz	
Output time	≥0.5ms	Will need an allotted 0.5ms for data acquisition
Laser class	2 (IEC 60825-1:2014) EN 60825-1:2014)	This is a class 2 laser and is safe - it consists of visible light higher than level 1 (arpansa, 2020)
Typ. Light spot size	1mm-1.5mm (120mm)	This describes the area being sensed
Digital output	PNP ≤mA	This is based on the transistor used and is a sourcing output, connecting to the positive supply
Analogue output	0v-10v ≥10,000Ω	Analog will produce a signal between 0v and 10v

The following text refers to Figure 3-3. The mounting of the LiDAR sensor will need to line up with that of the ultrasound device (Line A and C) so that the measurements are vertically accurate. Once information is gathered, an output distance will be taken (Line A) and subtracted from the overall length (Line B) to the bench providing a height of the top of the striploin. The information will then be gathered from the ultrasound (Line C), and the LiDAR's information (Line D) will be subtracted, indicating the thickness of fat (Line E) from the top of the striploin to the start of the lean. This process will take place along the whole length of the striploin (Line F) at equally selected increments. The process will do this many times across the width (line G).

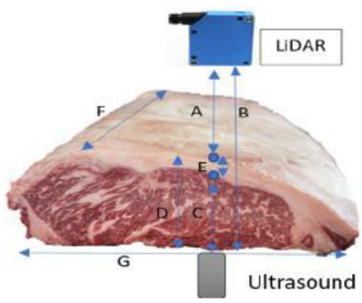


Figure 3-3 Striploin Sensor Measurements

The LiDAR and Ultrasound will work together to determine the required information.

3.8.5 Overview of Ultrasound

An ultrasound uses a transducer to send soundwaves into a body, providing density information about the different layers of the primal. The technology can cause cell death at power levels of $10 - 1000\ W/cm^3$ (MLA, 2019). This item has been pre-selected by the CAE and is a stand-alone item. It is a part of equipment lent from Attec Denmark. The item is highly accurate. The ultrasound uses Piezo technology and utilises B-mode ultrasound.

Table 5 General Specifications of Ultrasound

Sound Wave	20kHz- 15MHz
Sound wave Penetration	1450-1580 m/s
Type	B-Mode
Realtime	Yes

Ultrasound is becoming more popular in many of the food processing industries to determine the quality and internal information. What is to be achieved here is using the technology in real-time to work with high-end products. For the useful collection of data, there is a requirement for a way to test the results at the point of discrimination.

3.8.6 Conclusion of the Electrical System

The Rig will be designed with sensor accuracy in mind right from the start of the project design. The Rig sensors design will need some level of adjustment so their position can be fine-tuned. The sensors will be mounted once the Rig is built. Adjustments will be made to tune the Rigs sensors to the required accuracy accurately. They will be used to test the accuracy of positioning during final tests.

This concludes the design methodology of the electrical hardware and brings the report to the next section covered. This will be the software considerations.

3.8.7 The Software

The requirements concerning the software of the system will be essential for the accuracy of the project and used during the operation of the Rig. There will be the code that runs the motors and the code that runs the software elements. The following will provide considerations for software:

- The software will be needed for the sensors and motors.
- The software will need to be stored (on the microcontroller or PC).
- What language will be used for coding the tasks to the microcontroller?
- The selected language must be capable of performing the required tasks.
- Will any programs need to be written for this task?
- What information will be sent to the software?
- How will the software process information that will be useful to output back to the Rig?

The software will need to interface the sensor results to Rig position.

3.8.8 Conclusion of the Software Element

The software will be tested after all the components have been installed. The software will be built from the bottom up so that the program is fully controlled and understood. Once the software is completed, and the Rig can complete a full run over the platform, the code and Rig will be tested for accuracy. This will include setting movement size and adjusting the step size between measurement sights. The accuracy will be required to fit the 2% FSD set by CAE.

3.9 Equipment and Software requirements during Design and Build

The development of this project will require some essential equipment, tools and analysis software to produce the Rig. This list is not definitive and will be broad in nature.

The use of available tools will be required to build the mechanical parts of the Rig. This will need items like welders, measuring devices like Vernier callipers, marking equipment, taps and dies, cutting equipment and personal safety equipment.

The use of modelling software will be needed to test different mechanical aspects of the Rig to ensure that the strength of specific components will be satisfactory.

A laptop with windows ten will be used to interface with the development board and run the modelling software. The computer will have to have enough USB ports to handle modelling software and possible Bluetooth.

There will be several sensors used that have already been purchased by the research sponsor (Centre of Agricultural Engineering).

A supplier of parts will also have to be sourced.

3.9.1 The Analysis of Information

The information put out by the sensors will be directed to a central point. The data will need to be computed and set to a value that is useful for a final process. The idea is to provide information on the point where the fat and lean intersect so that a cutting device can trim the meat to a set height, without cutting into the muscle. Measurement will be suggested so that some form of analysis can be simulated.

3.10 Safety and Risk Assessment

Safety is the number one driver in most engineering products and processes designed today. There are many safety concerns when it comes to machinery. In Table 6, the major risk areas are assessed and discussed.

Table 6 Risk Assessment and Acknowledgement

	The Build	The Operation	Others, Investors and Guests
Duty of care	A requirement that protective equipment is used. The device made with full planning	During the operation of the Rig, the operator must have full training on the device	Distance from the Rig must be stated and physically marked
Environment	The build must take an environmentally friendly attitude utilising and disposing of waste appropriately	Clean up waste, and the use of chemicals must make use of food-safe practices and disposal. Chemicals used must be suited to food practices	The system must be developed and to a standard that has nothing to hide and be able to be presented to others.
Product (meat)	During the build, the final product must be considered. Meat is a wet product. Any chemicals used during build must not contaminate the workspace	The workspace must always be cleaned down and left in a way that is ready for reuse of a food product.	The meat is the backbone and will be what the investors want to look at. This must be available without risk of slippage or danger from the Rig.

Design	The Rig has to be rigid without being excessive. Every component must be selected and designed with an engineered method and common sense	The Rig must be designed appropriately for interaction with an operator. The operator will need access without having to climb near the Rig, and the operator should be well informed of the design specifications	All others should be kept from interaction with the Rig with signs
Electrical	The Rig must be designed to be electrically safe with high voltage housed correctly	The operator must be informed that electricity is used on the Rig. There is a degree of resistance components must have to water and wet splash. Proper usage of high voltage switches	Signs must be placed on electrical housing and barriers in place (like locks on boards)
Mechanisms	Designed with safety, bearing in mind that moving parts cause hazard	Guards must always be on, and the risks explained to the operator	Others must not interact with the Rig
Cleanliness	The Rig must be designed with cleanliness and food-safe material	The operator must clean the Rig workspace after use. Certain materials and wet waste cause a severe health hazard	Others must be encouraged to enter the space with clean hands and footwear

The two major risk/hazards are the electricity and mechanisms which have to be considered on every level of the build and use of the Rig.

3.11 Conclusion

The development of the Rig will need to carefully considered ergonomics, safety, and the CAE's requirements. Each section has outlined in detail processes and requirements for each level and section of the build. The methodology will be referred to when making a final assessment on the direction for each component.

This methodology has discussed crucial elements such as the meat, the working space, parts supplied by the CAE, all of which set some restrictions to the build. The methodology has also considered the main requirements around the mechanical, electrical and software systems of the Rig. Lastly, the methodology has discussed when each system will be implemented.

The next section within this report will discuss the selection of components (chapter 4) and then detail the necessary calculations and models concerning critical components of the Rig (Chapter 5).

Chapter 4 Selection of Components and Physical Design Considerations

This chapter takes the requirements of the project and matches them to components suitable for the design. Each section sets aside a critical element of the system, and a solution has been considered and selected. The following sections will be discussed:

- Confirm Decision to Use Off-the-shelf Components (Chapter 3.5.5)
- The Carriage Design will Affect the Structure and Stress on Components
- Rails that will Provide Rigidity and Reduce Deflection
- Drives to Produce Adequate Force Response
- Determination of Suitable Actuator for the Application
- Stepper Motors Types and Torque Requirements
- Sensors, Accuracy and Positioning Requirements of the Sensor Carriages
- Matching a Microcontroller Unit (MCU) with Application Requirements
- Further Sensors that have been Integrated into the Project
- Model of the
- Conclusion

The Rig is a research tool, and it has been designed to a high standard so that it can interact with food products. The CAE has provided a number of components, sensors and workspace for the implementation of the Rig. These factors, as mentioned in chapter 3, will need to be considered during the design stage, especially when components are being selected.

The methodology (Chapter 3) has set down the steps and consideration to proceed with the design. Chapter 4 will discuss the selection of components based on the requirements and practical assessment of the need. Chapter 5 will determine the suitability of critical components through the use of Engineering calculations and models. The report will now discuss the decision to use of the shelf components.

4.1 Confirm Decision to Use Off-the-shelf Components (Chapter 3.5.5)

The aim of this section is to decide on the suitability of using tailored parts or to use off the shelf components. This does not encompass parts where there is no option other than to get them fabricated. The choice of how the parts are acquired or made will affect the quality and operational performance.

There are several possibilities when considering how to proceed with the component selection and build of the sensor carriages. The Rig could use off-the-shelf components or have purpose-built rails. An experiment was performed to see how a purpose-built Rig, Figure 4-1, with workshop-built rails, might perform. This was also done to get a direction for the design. The product was sourced from a local hardware store. When developing this system, it was quickly realised that the movement of the rails was amateur, and components would need to be sourced.

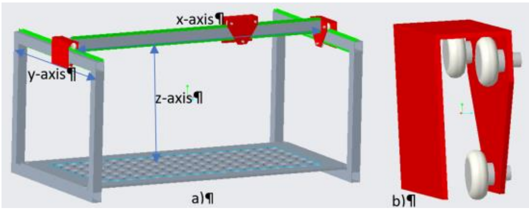


Figure 4-1 Initial Rig Design to test the suitability of hand-made rails.

The components will be-off-the shelf components that have been proven to work for other applications. There are many types of structure that could be used, and this will now be considered.

4.2 The Carriage Design will Affect the Structure and Stress on Components

The structure needs to be designed with the CAE requirement of 20N force (chapter 1.6) that will be applied to a vertical axis (z-axis). This section will discuss:

- Consideration to use One or Two Support legs
- Platform Position will Reduce Force and Torque while Providing a Better Utilisation of Space.

By reducing the amount of twisting and bending applied to the overall structure, the unknowns caused by moments and stresses have been reduced.

4.2.1 Consideration to use One or Two Support legs

Two possible solutions will be considered. The Rig could be built with one or two support legs. As shown in Figure 4-2, when a basic simulation of 20N force is applied, there are different reactions experienced by each model. This structural decision has been made to reduce unknowns associated with twisting and excessive forces produced in the simulations.

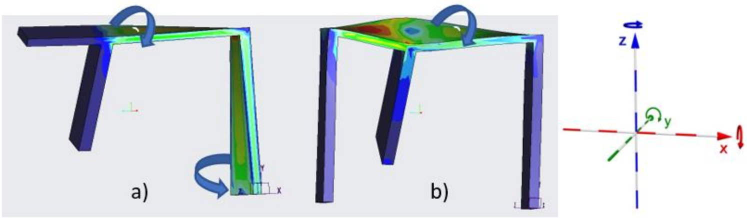


Figure 4-2 Simulate of single and double leg supports

There are adverse effects produced by a Rig frame, such as that in Figure 4-2 a), which has opposing moments around each axis. Larger rails would be required to produce the same level of rigidity in figure a) compared to that of b). There would be a greater degree of vision. As shown in Figure 4-2 b), there is only one main twist. This will maintain the requirements set out in the methodology to retain rigidity and accuracy. The ability to provide a clear line of sight will remain in both configurations.

The design in Figure 4-2 b) will be used. This option provides greater accuracy during measurements and reduced unknowns caused by twisting around the Z-axis. The next section will decide how the double leg support frame will be incorporated into the Rig design.

4.2.2 Platform Position will Reduce Force and Torque while Providing a Better Utilisation of Space.

The aim of this section is to practically consider different arrangements of the platform with reference to the sensor carriages. This consideration will be the placement of the Rig, in relation to the platform that holds the striploin and where the movement of the carriages occurs. The platform and carriages will provide for all sensors to interact with the striploin, as stated in the methodology 3.7.4. There will also be access to the platform from above and below.

As shown in Figure 4-3, the rails could be mounted above, partway down or below the platform, respectively. In Figure 4-3, both a) and b) restrict the mounting of the sensors to above the platform and Figure b) will produce much greater torque on the wheels. Torque will increase linearly, the further from the pivot point. This was a part of the work of Archimedes, Equation 1, on levers which state that:

$$Force(f) \times radius(r) = torque(T) \qquad (1)$$

This quickly rules out Rigs a) and b). Rig c) has been selected as the best platform mounting position as it will reduce the amount of torque on the wheel. The requirement to mount a sensor under the platform will be fulfilled. There will also be less overhead restrictions in c) compared to a).

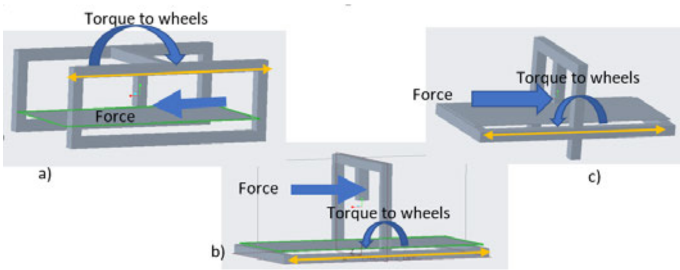


Figure 4-3 Platform position to rails

The use of a structure like that of Rig c) is most practical for the required application. The focus will now turn to the platform that holds the striploin.

4.3 Rails that will Provide Rigidity and Reduce Deflection

The aim of this section is to choose rails and running gear that provides the structure with rigidity and overall usability. This is vital to the project as this will fulfil the requirement to be rigid, to run smoothly and accurately. The selection has to consider chapter 3.6 of the methodology. The different parts will be selected by considering application and requirements. This section will discuss:

- Determining Suitable Rails that Will Benefit the Design of the Rig
- Selection of the Wheels, their Material and Overall Placement

The report will now discuss the choice of the rails and analyse the rails that have been selected.

4.3.1 Determining Suitable Rails that Will Benefit the Design of the Rig

The aim of this section will be to consider the different rails available on the market and to decide what rails would best suit the project. The rails selected will be rigid and provide support to the structure. They will have the ability to handle heavy loads while performing a smooth and accurate operation.

The selection of linear rail on the market is endless, so the more commonly used ones will be briefly discussed (Figure 4-4). Many of these devices can be used as stand-alone rails, whereas others require existing infrastructure to attach to. When referring Figure 4-4, many rails have parts that would collect and be clogged with fat and parts of by-product produced by the process. Possible solutions a), c) and d) appear to be more light-weight solutions for a similar price to that of b).

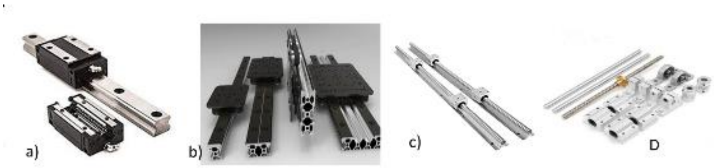


Figure 4-4 Different forms of linear rails

Figure 4-4 b) has greater strength than the other options. Option b) can be used as a stand-alone option and can easily be scaled in size. V-slot rails, Option b), is presently used in CNC machines which have similar characteristics to the Rig design that has been selected.

The V-slot rails are made from aluminium. The galvanic series (Table 7) explains how stainless steel can be both passive and active. In the initial construction, there will be two different metals on the Rig. This must be considered due to stainless steel and aluminium being dissimilar metals. Salas et al. (2012) explains that meat is a low corrosive material and that stainless steel is an obvious choice for food machinery. There is a concern in this article that must be considered, and that is the use of salt as a preservative which is common within the meat and fish industries. This means the possible creation of the perfect environment for galvanic corrosion, and this must be considered in the final development.

Table 7 The galvanic series (William D. Callister and Rethwisch, 2012)

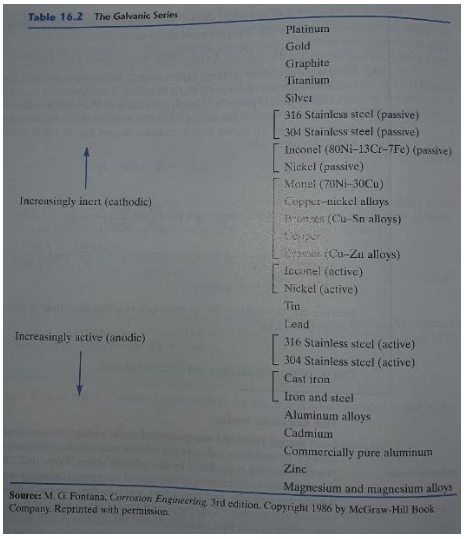


Table 16.2 The Galvanic Series

	Platinum
	Gold
	Graphite
	Titanium
	Silver
	316 Stainless steel (passive)
	304 Stainless steel (passive)
	Inconel (80Ni–13Cr–7Fe) (passive)
	Nickel (passive)
	Monel (70Ni–30Cu)
Increasingly inert (cathodic)	Copper–nickel alloys
	Bronzes (Cu–Sn alloys)
	Copper
	Brasses (Cu–Zn alloys)
	Inconel (active)
	Nickel (active)
	Tin
	Lead
Increasingly active (anodic)	316 Stainless steel (active)
	304 Stainless steel (active)
	Cast iron
	Iron and steel
	Aluminum alloys
	Cadmium
	Commercially pure aluminum
	Zinc
	Magnesium and magnesium alloys

Source: M. G. Fontana, *Corrosion Engineering*, 3rd edition. Copyright 1986 by McGraw-Hill Book Company. Reprinted with permission.

There are many variations of V-slot rails for what will be required for the Rig up to industrial sizes to suit more extensive applications. V-slot rails are the obvious choice for this type of Rig, but care will need to be taken using dissimilar metals. The report will now consider the stress and moments associated with the selected rails.

4.3.2 Selection of the Wheels, their Material and Overall Placement

This section determines, through experiment, the suitability of different material wheels. The correct choice of wheels will provide a more accurate running carriage that will not succumb to jamming or interference. The wheels provide smooth movement along each axis, and the selection of the wheels will be selected to maximise performance.

The wheels for the V-slot system come in stainless steel or polyoxymethylene (Figure 4-5). Polyoxymethylene (acetal) is a thermoplastic used for precision parts that require shape stability, high rigidity and low friction (Chandran et al., 2014). An experiment was performed on some V slot rails with the two types of wheel.

The stainless-steel wheels, under the same conditions as the acetal wheels, showed extremely high rigidity with no room for play. The stainless wheels required noticeably greater force to move the sensor carriages. The acetal wheels (Figure 4-5a)) had a smooth operation on the without compromising rigidity. This acetal wheels have a greater ability to adapt to by-product on the rails.

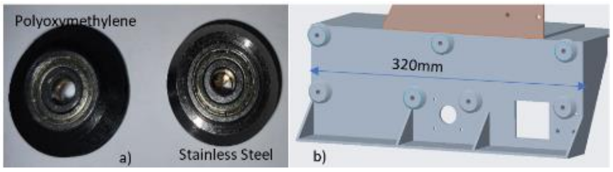


Figure 4-5 a) Acetal & Stainless Wheels b) placement of wheels

Wheel spacing has been considered. It has been determined that the greater the wheel spacings, the less chance of the RIG's movement twisting or jamming. The spacing of the wheels has been spread over 320mm. With the wheels spread (Figure 4-5 b)) and one shaft that propels both sides (Figure 4-7), it has been determined that the risk of jam has been mitigated.

The acetal wheels have been selected as the best fit for the purpose required. For the number of wheels, it has been decided to have three on top and four underneath. This is because the wheels form part of the belt drive that will be considered in section 4.4.4. The next section will look at the drive system and the requirements for each axis.

4.4 Drives to Produce Adequate Force Response

This section will look at different drives for the Rig. The focus of one of the drive systems will be on torque while the other will focus on speed of movement over the platform. Both drives need to provide

2% FSD accuracy. The drive system includes shafts, gears, belts and lead screws. This section will look at:

- System Requirements of the Drives Required for Each Axis
- Different Belt Efficiencies for use on X-axis
- X-axis Drive Selection
- Y-axis Drive Section and Configuration
- Determination of Bevel Gear Size Requirements for Use on Y-axis
- Z-axis Drive Choice

These sections will start by looking into types of drive systems.

4.4.1 System Requirements of the Drives Required for Each Axis

The drive systems will be selected and matched for the required purpose. This will be important as accuracy, speed and torque form the requirements. When choosing parts, the environment of the system and its application must be considered.

The drive possibilities suitable for V-slot rails are few. The best fit solution for each axis will be selected. These components may include timing belt and gear (Everman Belt Drive System), lead screw drives and rack and pinion.

Once again, the solution must consider that meat is the product being studied. Meat overspray can spread and cause build-up on components. Cleaning is always going to be the secondary preventative measure. The drive system will need to remain as clean as possible. This will not affect the higher drive system parts as much as those sitting lower than the striploin.

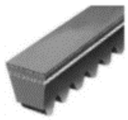
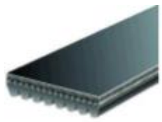
With the above consideration, a rack and pinion will not suit this operation without extensive guards being built to protect from off-spray building up and compressing in the tracks. The same applies to the screw drive. The screw drive has the added benefit of being able to transmit torque through to other components and is worth considering as one solution. The timing belt and gear have some downsides. They are harder to align, and there is more significant wear on the belts (Maker Store, 2020). The belt can provide greater speed and is very accurate when used with a stepper motor. Its motion is directly related to the timing gear.

The timing belt and the screw drives are best suited to this project. Their implementation in to the project will be considered in the following sections. This will start with the X-axis.

4.4.2 **Different Belt Efficiencies for use on X-axis**

This section will point out the different efficiency of belts, particularly that of the timing belt. This is important as low efficiency will reduce the overall performance.

Table 8 Nominal efficiency per type of Belt (Dereyne et al., 2012)

				
type	Wedge belt (SP) or V-belt	Cogged wedge belt (SP) or cogged V-belt	Poly V- or ribbed belt	Synchronous or timing belt
Efficiency according to manufacturer	Up to 97%	Up to 97%	Up to 96%	Up to 98%
measured	Up to 97%	Up to 98%	Up to 97%	Up to 98%

The X-axis will use a timing belt system that will mesh with the GT3 timing pulley. Timing belts have high efficiency, as shown in Table 8, with up to 98% efficiency. The table also shows the efficiency of other belt-driven systems. The timing belt has the highest measured efficiency. The next section will investigate the configuration of the X-axis drive.

4.4.3 **X-axis Drive Selection**

This section explains the use of the timing belt and gear as the drive for the sensor carriages along the X-axis. As the Rig is in early development, the speed of operation is not so important. The Rig is required to be able to carry out tasks and take measurements.

The X-axis is the main working direction and will also have the 20N working forces applied. It would be beneficial for greater speed to be available for this axis due to the travel distance. For these reasons the timing belt, with matching gear will be used (Figure 4-6). This system will reduce the effect of splatter on the belt as the teeth are facing down. The belt is attached to each end of the X-axis and travels under the wheels. At a predesignated spot, the belt will fold over the timing gear as shown in Figure 4-6.

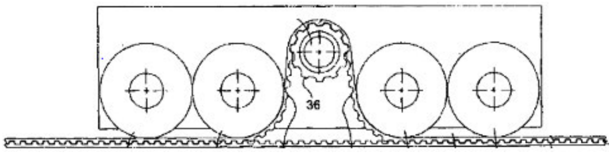


Figure 4-6 Positioner utilizing engaged toothed gear belts, one static and one dynamic (Everman, 2009)

By visibly considering Figure 4-7, it is obvious that the system could be driven by one or two motors. It will be belt driven, and there will be a shaft that runs between the two-timing gears. This will enable the system to drive uniformly. The timing belts have two size options and a broad range of gears. The larger size will be selected due to the industrial nature of the application.

Figure 4-7 System being designed

The GT3 timing Pulley with 20 teeth and 8mm bore has been selected. This will provide aggressive teeth compared to the GT2. The Diameter (d) of the pulley is 18.2mm, and by solving for its circumference (c) (Archimedes), we can find the approximate length of travel per revolution to be 52mm. The y-axis will now be considered.

4.4.4 Y-axis Drive Section and Configuration

The Y-axis provides one solution for both the y-axis sensor carriages. This means the one actuator will drive both the carriages simultaneously. The purpose for doing this is, so the carriages move from the same actuator, they will move together. The design will have to incorporate methods of transferring torque around the Y-axis system.

The Y-axis utilises the screw drive. This is done to transmit the power around the system and maintain accurate movement for the sensors. As shown in Figure 4-8, both the y-axes are manoeuvred by the one motor. The Ultrasound and LiDAR are used to determine measurements at a single point at the same interface. The system will have to be built around this requirement. Such a system will maintain a uniform movement of the top and bottom carriages. This is important that they line up and move in unison to keep the sensors in line.

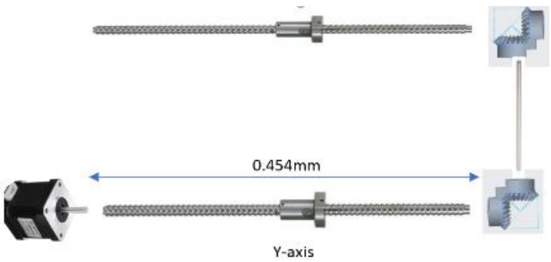


Figure 4-8 Y-axis design

The screw drive analysis and selection of stepper motor are dependent on one another. The sizing of the motor will be considered in chapter 5.

The lead screw selected is a 2mm pitch x 4 start. This lead screw will move a carriage 8mm/revolution. The nut that runs on the lead screw will prevent backlash The Y-axis Shaft Concept to Provide Accuracy in Sensor Movement

As the vertical alignment of the shaft is essential, so is the movement of the shaft along the Y-axis. As seen in Figure 4-9 a)**Error! Reference source not found.**, the Y-axis shaft system can be run off one motor. This will allow the two sensors to remain in line and move in unison. The two sets of bevel gears have a requirement to turn the two Y-axis shafts in the opposite direction.

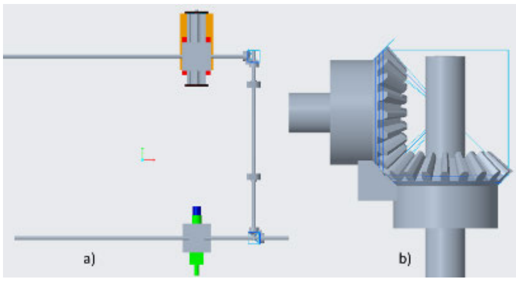


Figure 4-9 a) Y-axis Shaft Arrangement b) view of bevel gears

Modelling characteristics required for the bevel gears shown in Figure 4-9 b) can be seen in Appendix B.5. In this situation, industrial bevel gears where selected and needed to be modelled for accurate system representation. . The next section will determine the size of the bevel gear required to transmit torque.

4.4.5 Determination of Bevel Gear Size Requirements for Use on Y-axis

This section decides on the dual bevel gear pair which provide the torque between the y-axis lead screws. Its design reduces the power need of the system and provides an easy way to keep the carriages inline. There is very little torque and force applied to the gear. The maximum radius of the bevel gear needs to be less than the distance between the lead screw it is mounted on and the V-slot beam that the carriage runs on. The space between the V-slot beam and the lead screw is adjustable but will be set around the 15mm mark. This means that the maximum radius with clearance will need to be 12.5mm.

A Creo drawing of a possible bevel gear has been created to determine the fit Figure 4-9. The calculations can be found in Appendix 2a.

The gear selected is 20 teeth, 1.5 moduli, 1:1 ratio, bevel gear pair. Its maximum diameter is 27mm which fits within the specified range above. There will be two sets of gears used. The next section will briefly cover the Z-axis, and it will hold many similarities with Y-axis.

4.4.6 Z-axis Drive Choice

The Z-axis will also make use of a lead screw. This will provide accuracy in the vertical direction. This carriage will be much shorter than the Y-axis. The movement of the carriage will be the difference in height between the front and back of the striploin. To maintain the ability of the Rig to be adjustable, the Z-axis will be given a range of movement of 150mm. The same lead screw specification of the Y-axis will be used. The z-axis can be utilised for pneumatic cutters, tools attachments, and sensors

This concludes the selection of the drive. The drives will now need to be matched with actuators which will occur within the next section.

4.5 Determination of Suitable Actuator for the Application

This section selects actuators to be used on the drives. This will help determine what motor will best suit the application and provide accurate positioning within a reasonable price range. This section will build on what has been suggested in Chapter 3.7.2.

This system selects actuators to drive the systems which have already been established. The motors will be required to move accurately. This could be done with motors using linear scales or through motors that measure rotation. This section will consider motors on the whole, and we will choose a motor that best suits the operational requirements.

The motors that will be considered are 12v and 24V DC motors. A low voltage system has been selected for the following reasons. Firstly, to keep the Rig as cheap as possible. Secondly, a low voltage system will provide safety from any unexpected electrical hazards during development. This will allow for the system to be trialled in its working environment without considerable risk to the user from electrical hazards. The environment will be a moist environment.

The motors that will be considered are:

- Consideration of Brushless and Brushed Motors
- Consideration of Direct Drive Motors
- Consideration of Linear Motors
- Consideration of Stepper Motor

The basis of all motors can be found in the theory of Lorentz Force which indicates that the force (F) on a section of a length (L) of wire which carries current (I) through a magnetic field (B) can be determined.

$$\vec{F} = I\vec{L} \times \vec{B} \tag{2}$$

4.5.1 Consideration of Brushless and Brushed Motors

Brushless motors rotate a shaft by using rotating magnets that spin around a permanent coil of wire. They can use both AC and DC current (with use of controller) that produces a magnetic field which turns the motor.
With brushed motors, a magnetic field is generated around the armature when power flows through the motor coil. This pushes the shaft against the opposing magnet, which is drawn towards the opposite magnet (Motion Control, 2017). There is nothing built into these motors to provide controlled turning. A controller will be required. A brushed motor can be customised and is simple to control, whereas a brushless motor has greater efficiency, is smaller and makes low noise. One of these motors could be used, except it would require a complex system of feedback from sensors, and controller to keep the speed constant. As the torque rises, the speed will drop so the motor will require more current by a power amplifier controller. These motors will not fit the requirements of an early build system because of complexity and price.

4.5.2 Consideration of Direct Drive Motors

As the name suggests, this motor drive system has no gearbox or other components that contribute to the final output. The direct-drive motor would be larger than a motor for the same size job with less noise (Hughes et al. 2019). With high efficiency, low wear and increased acceleration, these motors provide a possible choice for an initial build. Once again, further equipment would be required to accurately measure the position of the Rig and rotation of the motor.

4.5.3 Consideration of Linear Motors

The linear motor is highly efficient, quick and would suit the application of the Rig. The system works on similar magnetic principles to all motors. The system uses an unrolled stator and motor, which produces linear force instead of rotational force incorporating two ends with a flat active section (Motion Control, 2017). This type of motor and system is very expensive. It would be ideal for further generations of the Rig.

4.5.4 Consideration of Stepper Motor

Stepper motors provide precise positioning unless slippage occurs. This means it is an asynchronous move that allows exact steps (All About Circuits 2020). It is a standard motor used on CNC machines and other devices that require high precision. The motor is controlled by Pulse Width Modulation (PWM) or pulses per second. The system involves the motor, a potentiometer and a control circuit. The price of a stepper motor in the 12v or 24v range is within project specifications. For these reasons, the stepper motor is selected.

There were four types of actuators examined, and the most appropriate one was the stepper motor. It provided accuracy within a price that is suitable for the project. The next section will add to this by determining the type and size of the stepper motors that will be used.

4.6 Stepper Motors Types and Torque Requirements

The aim in this section is to look at the various stepper motors and decide on the best choice of motor to use. An analysis of the stepper motors will be done in chapter 5.5 so that the selected stepper will meet the requirements set by the design of the Rig.

4.6.1 Background of Stepper Motors

This section will develop a greater understanding of the stepper motor. This will provide a general view of the stepper motors and provide a greater working knowledge of them so that an informed decision can be made towards the exact suitability of a stepper motor.

There are several stepper motors available such as permanent magnet, variable reluctance and Hybrid synchronous with either 2-phase bipolar or 4-phase unipolar. The hybrid stepper motors are the most common and will be used. (Electrical Technology, 2020)

The core consists of 4 magnet types, [North South] [North South] creating two pole shoes. Each one has precisely 50 teeth per sprocket, but they do not line up with that of the other three sprockets. The stator of the stepper motor also has one set of 50 teeth but will not be magnetised until one of the two coils (2 coils make eight coils) gets current. This will create a magnetic attraction between the stator and the sprocket. By changing the combination current between the four motor wires (two ground and two VCC), different poles will become the magnet and force the teeth to realign, creating movement. There are 4 steps per combination. This will give us the number of steps per revolution.

$$50\ teeth\ \cdot 4\frac{steps}{tooth} = 200 steps\ per\ rotaion \tag{3}$$

There will be stepper motors with different configurations of teeth and lead number. An Individual stepper motor will now be selected for each axis.

4.6.2 Stepper Motor Selection

The stepper motors have been selected to provide motion to the sensor carriages. There are many stepper motors that range from industrial through to printer size applications. In this section, a stepper motor will be selected based on the required application. The stepper motor is ideal because:

- There is no controller required as they are pulse driven.
- A stepper motor will provide a constant velocity.
- The motion will be constant.
- The price will suit the budget requirements.

As the NEMA motors are much the same with small variances in max current,

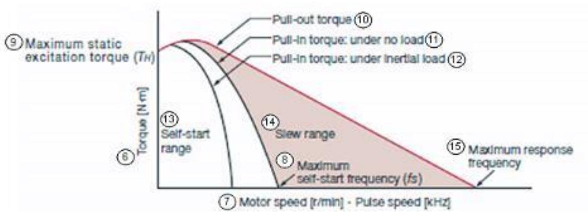


Figure 4-10 Generic Torque-Speed Curve (Orientalmotor, 2020)

As described in figure 4-9, stepper motors performance is based on speed and torque. The stepper motor's torque-speed changes over the range of motor uses, which is described by the lines enclosing the shaded area. Each torque speed curve is suited to a motor and driver. The greater the speed, the less the torque. Also, the higher the resolution, the less the torque. When the torque requirements of the motor exceed its ability, the motor will slip.

As the motor-use changes, so do the unique speed curve. The following will describe the terms mentioned in Figure 4-10 (OSMTEC, 2020):

- As can be seen on the chart, the motor can even produce torque when not moving (0 rpm). This is described by the detent torque (not energised) and holding torque (has current but no movement) shown by table in Appendix B1.
- The pull-in torque curve describes where the motor can start, stop and reverse with a maximum value of speed and torque. The pull-out torque is where the motor stalls at those values of torque and speed. The slew range is the area where the running of the stepper wants to remain to maintain synchronisation.

The following section will consider the background of the stepper motors and lay some foundational knowledge about those motors.

4.6.3 Stepper motor selection conclusion

The NEMA stepper motors have models through every power range. This system will incorporate both 12v and 24V. The 12 volts system will be used to drive the NEMA 17 motor which has been selected. The NEMA 17 is at the top end of the 12-volt systems, and there are various motors with a variety of torque and speed ranges.

The 24-volt system will be used to run a NEMA 23 stepper. The NEMA 23 has much greater torque and will be more suited to the x-axis and the movement with force. The stepper motor usage calculations can be seen in chapter 5.5.

4.7 Sensors, Accuracy and Positioning Requirements of the Sensor Carriages

Accuracy is a feature of this project that is integral to its success and to assure consistency. This section will show how this will be achieved and follow on from the requirements set out in Chapter 3.7. The need for consistency arises from the need to repeatedly take measurements at the same locus so that data can be collected and collated. End stops will allow the sensor carriages to be set at a predefined position.

The Rig will eventually hold a cutting device which is where the 20N force is assumed. If this cutting device fails or clogs for a small amount of time, the torque may rise above the capabilities of the motor, and the carriage position will be disjointed. The following sections will consider:

- End Stops used for Calibration of Position in Case of Stepper Motor Slippage
- The Benefits of an Encoder in Future Builds

These solutions will enable the stepper motors to re-centre and calibrate on each run. Future generations of the Rig will be able to implement real-time accuracy measures. Alignment of the Sensors for Accuracy of Result

The design of the Rig allows the LiDAR and the Ultrasound to line up. The point being investigated needs to have measurements read from both sensors at the same time. In Figure 4-11 sensor alignment is visually explained. This configuration also needs to be adjustable so that if there is any misalignment, it can be easily fixed.

The position of the LiDAR bracket will be behind the Y-axis V-slot beam. The ultrasound will be attached through brackets to an electric solenoid. When activated at its correct position, the solenoid will push the transducer into the lean of the meat.

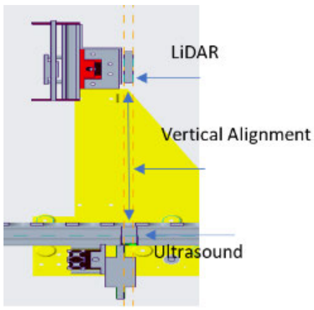


Figure 4-11 Alignment of the Sensors

The sensors development will be discussed further in chapter 6. The report will now consider end stops.

4.7.1 End Stops used for Calibration of Position in Case of Stepper Motor Slippage

The system will require some means of detecting the limit of movement. This will provide safety to the machinery and equipment in the development stage. It will also provide one means of calibration during the operation.

If the motor slips due to unexpectedly high torque, the machine will be put out of synchronisation. During operation, these sensors will be used as much as possible to reset the X-axis direction (axis of the 20N force) and at completion will allow the system to be positioned back on an origin point.

The sensor will be a simple limit switch that is suited to the required MCU. The switch will be set to N/O so that when the machine reaches this point, the switch will close to create a circuit, indicating the motor has reached its limit. The Limit Switch in Figure 4-12 has been selected.

Figure 4-12 Limit Switch

This limit switch has working voltage/current: 300V/2A with a temperature resistance of 80˚C. The limit switch will be wired to a normally open (NO) position. When the track hits this switch, a small voltage will be applied to the MCU, resetting the position counter.

There are also other ways that can record and measure accuracy. The next section further considers accuracy through the use of sensors.

4.7.2 Further Sensors that have been Integrated into the Project

The use of an impedance analyser has been considered for this project. The project requires a method to test the accuracy of results and to test areas in front and behind the point being determined. Impedance analysation will allow this testing to take place during operation. The method needs to be non-destructive and allow for the test sample to be re-tested. This will make it possible to create information and models on what is happening at the cut point. There are many methods that can discriminate between mediums, but there are limited processes available when time is a factor.

To create an impedance analyser sensor, the following components will be required:

- Evaluation Board
- Needle Coated except for Right at the end
- Coated wire

The evaluation board has the AD5933 high precision impedance converter system, which takes impedance and converts it to a digital signal. Table 9 shows the specifications for this Evaluation Board

Table 9 specifications of the AD5933 (Analog Devices, 2017)

Frequencies	≤100kHz
Frequency resolution	27 bits (≤0.1 Hz)
Impedance range	1KΩ to 10MΩ
Capacitance	100Ω to 1kΩ
Analog to digital converter	1MSPS
Voltage	2.7v-5.5v

Figure 4-13 provides a visual model of the proposed system. The evaluation board will be attached to the probe (needle). The voltage-in will connect to the needle. The voltage-out will connect to the coated wire that runs down the shaft of the needle and stops at the tip. The AD5933 will be attached to the Arduino via SDA and SLC Pins. When the needle penetrates the fat and hits the lean, the Arduino will tell the linear actuator to stop, and a value of the depth will be recorded as steps of the stepper motor.

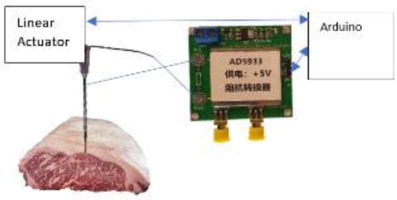


Figure 4-13 AD5933 Impedance Converter Network Analyzer Module 1M Sample Rate 12bit Resolution Measurement Resistance

This is one of many sensors that can be integrated into the system.

4.7.3 Sensors that can be Integrated into Further Models of Rig

Further on in the development of the Rig, there will be a requirement for more sensors. Some of these sensors could incorporate current (A), monitoring and torque on some of the working motors or even pneumatic cutters as indicated in the work of Brett (2018). The Rig will also make provisions for a High Definition machine vision camera. These are considered outside the scope of this project.

The following section will considerer the use of a linear encoder which will allow for an inaccuracy to be detected during the process.

4.7.4 The Benefits of an Encoder in Future Builds

The need for greater accuracy during movement of the sensor carriages will advance future refinements. This will allow for real-time detection of any errors that occur.

To increase accuracy and reliability, the system will initially make use of linear encoders. This allows the system to know its exact position throughout the entire process. To remain focused on a strict budget, the encoder will be developed from cheap equipment. An optical encoder makes use of a printed scale and optical reader. The optical encoder will be aligned with the stepper motor pulses. This will be mounted on the Rig along each axis, enabling the code to cross-reference actual position with the perceived position. It provides the ability for a DC motor to be eventually trialled.

To run the hardware that has been previously discussed, the use of a microcontroller will need to be implemented

4.8 Matching a Microcontroller Unit (MCU) with Application Requirements

An appropriate microcontroller needs to be selected for the early development of the Rig. This will need to align with budget requirements and be able to perform the required tasks. A development board provides the best option.

The system has electrical components that will require controls. This will include the stepper motor which relies on getting pulses supplied by a controller. A microcontroller will be required to orchestrate the movement of the system and the data acquisition from some sensors. The use of a development board will be required. This will allow the system to be built from scratch instead of trying to modify existing code from CNC programs. The development board will need to support stepper motors and other requirements such as limit switches and modern computer interface. There are purpose-built boards and methods that can facilitate this. These purpose-built boards can become quite expensive.

To drive and control stepper motors, the following components are required:

- micro-stepping driver (by how many motors)
- stepper motors
- a breakout board that will support the required number of motors
- power supply (can require multiple sources)
- purpose-built software

Many stepper motors for smaller applications can consolidate all this onto one board, like the TB6560 Driver Board, GRBL laser controller board or Arduino with CNC Ramp Shield.

Many of these driver boards are application-specific and make it hard to develop software outside of that application. For this reason and in consideration of price, an Arduino Mega will be used with a Ramp 1.4 shield (Figure 4-14), that is designed to run up to 5 motors. The board also supports limit switches. There is a large support community for Arduino (https://forum.arduino.cc/) and also for the Ramp 1.4 (https://reprap.org/forum/list.php?219).

The next sections will consider the following:

- Arduino Mega 2560 Specification
- The Ramp 1.4 Shields - Suitability for System Requirements
- The Requirement for Limit Switches Compatibility
- Ampere Requirements from a Power Source

These sections will provide the necessary background and specification for the system. The Arduino is a commonly used device for early-stage development and small electronic projects. It will provide a great foundation to the project. The report will now consider the specifications of the Arduino Mega.

4.8.1 Arduino Mega 2560 Specification

This section looks at the performance capabilities of the Arduino Mega and how they align with the system requirements.

The Arduino Mega is an open-source development board used for medium-scale electrical projects. It houses an ATMega2560 Microcontroller. In the future, there may be the requirement for 2 Arduino Mega to be used in this project. One will run the hardware requirements for the project. The other will be used for the data collection and transmitting from any purpose-built sensors. Table 10 the general specifications have been shown.

Table 10 Arduino mega Specifications (Arduino, 2020)

Specifications Arduino Mega	
Operating Voltage	5v
Input voltage	7-12v
Input voltage limits	6-20v
Digital I/0 pins	54 (14 provide PWM)
Analog input pins	16

Serial Ports	4
DC current per i/o pin	40mA
DC current for 3.3V pin	50mA
Flash Memory	256KB, 8KB used by bootloader
SRAM	8KB
EEPROM	4KB
Clock Speed (crystal Oscillator)	16MHz

As stated in the specification, the voltage is limited to 12v, which will be able to be incorporated from the power supply of the Ramp 1.4.

The clock speed is 16MHz which provides sufficient capabilities for the pulse rate required to run the three stepper motors while monitoring the other switches. The use of all the motor slots will not need to be used, providing digital pins as a way of communicating with other Arduino, Bluetooth or data storage.

The Arduino Mega has the required clock speed, pins and memory to fulfil the requirements for the project. Once the project moves on to a different level of development, a customised circuit board would be more practical. The board connects easily with the ramp shields.

4.8.2 The Ramp 1.4 Shields - Suitability for System Requirements

This section provides information on the suitability of the Ramp 1.4. The Ramp 1.4 shield slots onto the top of the Arduino and through the Printed Circuit Board (PCB) redirects these pins to specific motors (Appendix D1.1, D1.2, D1.3) and parts of the Ramp. This board can incorporate five stepper motors.

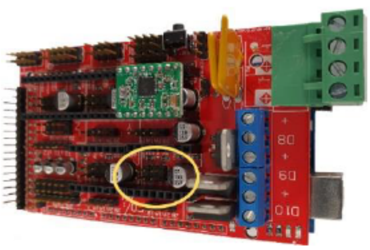


Figure 4-14 Ramp 1.4 and Arduino Mega development board

The ramp has two 12-volt inputs that produce different Amps. This provides the ability for two extra steppers or motors to be used. It also provides the ability to supply voltage to other 12v devices. The motor resolution will now be considered.

4.8.3 Motor Resolution Effect on Torque and Speed

The main purpose of the Ramp 1.4 is to provide control to the driver of the stepper motors - Appendix D1.2. The driver will provide pulses to the stepper motors in a number of possible ways. The different possibilities can be seen in Table 11. The greater the micro-step, the less torque with greater resolution. The ramp 1.4 can increase the resolution up to 3200 steps. This is achieved with a constant current that can be set to a different level on the two phases of the motor. For each step there will be different combinations of current, that will position the stepper either on the polls or slightly off the polls depending on the strongest and weakest current.

Table 11 Driver configurations available for the ramp 1.4

	Active coils	Steps per revolution	Properties	The jumper required for combination. **Error! Reference source not found.**
Wave	One coil active 4N or 4S			
Full step driving	Both coils active 4N and 4S	200 steps	Greatest Torque More noise	No jumper
Half step driving	8 coils active	400 steps	Higher resolution	1A only
Quarter step driving	8 coils and in-between steps	800 steps	Less resolution	1B only
One-Eighth step driving	So on	1600	Les resolution	1A and 1B
One-Sixteenth step driving	So on	3200	Greatest resolution least torque Least noise	1A ,1B and 0D

The jumper pins used to set resolution can be seen in Figure 4-15 a). In this figure, there are six pins within the yellow circle. When these pins are connected with a different configuration of jumpers, the resolution can be set. The jumper configuration can be seen in Table 11.

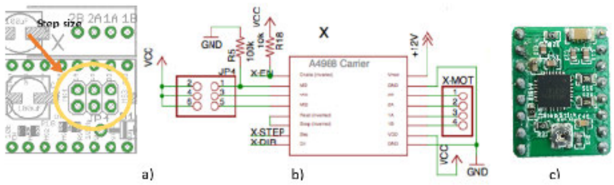


Figure 4-15 a)X-axis driver plug showing Appendix D1.1 b) X-axis driver schematic Appendix D2 c) A4988 Driver

An A4988 IC driver has been selected to control the steppers -Figure 4-15 b). The IC Figure 4-15 c) is basically a H-Bridge and its schematic can be seen in Appendix D4. Each motor will require its own driver.

4.8.4 The Requirement for Limit Switches Compatibility

The Ramp 1.4 provides the support for limit switches to be used on each axis. These limit switches will be positioned on the Rig at the required limit of each axis. This will allow recalibration after each run of the Rig along each axis.

4.8.5 Ampere Requirements from a Power Source

The Ramp 1.4 will require a separate source of power other than that supplied through the Arduino. The power supply will need to provide 12v with enough current for all the stepper motors and other equipment that may be attached.

Table 12 Apps required from Power

Device	Amps
Stepper Motors Appendix B1 and B2	4.4A if all used at once
Lights	1.2 A
Sensors	2A 1 sensor used
Peripheral	2A

Total	9.6A

Table 12 shows an exaggerated value of 9.6A would be required for the system. To provide for the unexpected, a 12v 20A power supply will be purchased. This will provide enough for any other experimental gear that may be required for this project.

The second PSU will be used for the NEMA 23 stepper motor driver and stepper motor. The NEMA 23 stepper motor will be the only draw on the 24v system. There will be ample power

4.8.6 Conclusion of the Microcontroller selection

The microcontroller selected is an Arduino with a ramp 1.4. This will provide control for the whole 12v and 24v system. The ramp 1.4 controls the 12v lights, solenoid, end-stops, motor drivers and cooling fan. The motor driver power will come from the 24v PSU. The PSU and microcontrollers will be housed in a waterproof electrical box.

4.9 Model of the Rig and Base Frame

The Rig design now takes all that has been decided and moulds it into a workable machine. A model of the initial design has been done on Creo Parametric. There was an evolution of models that went into the outcome.

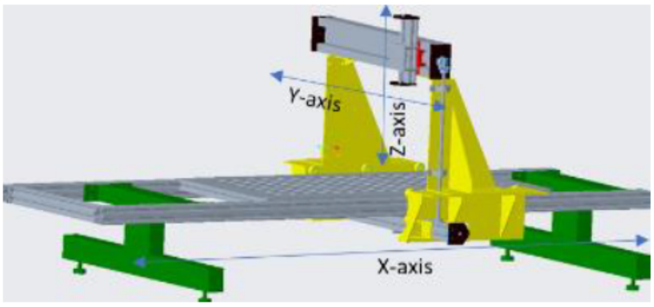


Figure 4-16 Final Design of the Rig

The Rig in Figure 4-16 Final Design of the is the first generation of the design. Its design incorporates simplicity and adaptability. The components can be modified and quickly shifted to better suit the application. In Appendix E1 There is an exploded view of this Rig along with the front, side and top views with dimensions. The design of the Rig must incorporate the purpose of mounting sensors which can be aligned promptly, moved, and pulled out.

The base and frame will eventually be one component, and the design has been created to fulfil this aspect of the requirements set out in the methodology (Chapter 3.6.3). The framework in Figure 4-17 Possible Second Generation of the Frame will be implemented in further generations of the project.

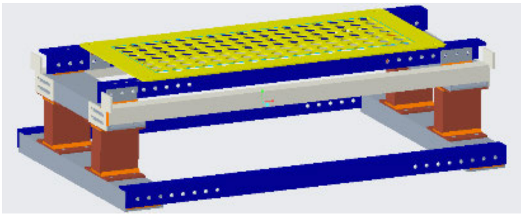


Figure 4-17 Possible Second Generation of the Frame

A detailed breakdown of the parts of the base can be seen in Appendix E.2. The base has not been manufactured in this project due to covid 19.

4.10 Conclusion

A wide variety of parts have been selected in this section that will ultimately provide a detailed pathway to ordering parts and towards a final build. This section has provided decisions that encompass the major mechanical and electrical components to be integrating it into a mechatronic system.

Chapter 4 started by deciding that a two-armed Rig with a lowered height that incorporates space underneath for sensor access is ideal. V-slot beams have been selected as they provide rigidity, engineered performance and can form part of the structure. The fact that the rails are aluminium presents the fact that galvanic corrosion will need to be considered. Actel wheels have been identified as the best solution for wheels, and when used with a widespread and duel shaft drive, twisting will not be a problem.

The Rig will make use of Screw and timing belt drives. An 8mm screw will be used on the z and y sensor carriages, and a timing belt used for the x-axis movement. The GT3 timing pulley and gear have been selected for the x-axis drive. Two sets of bevel gears have been selected to transmit torque between the top and bottom y-axis drives.

Stepper motors will be used to drive the system. 12V will be required for the NEMA 17 and 24V will be needed for the NEMA 23 steppers.

Accuracy is a requirement, and end stops have been selected as a way reset position after each run. This section also considers the use of a linear scale in future builds.

Selection of Components

An Arduino Mega has been selected for the control of the system. A ramp 1.4 shield will be incorporated. This will be suitable for the 12v system only and any larger voltage requirements sourced separately.

An impedance analyser has been sourced and integrated into the project as a method of testing the value output of the primary sensors.

Detailed models have been developed. There are a number of computer models created for the system, which convey that the requirements of the system have been met in design. These models included the final Rig, sensor alignment, y-axis system and a proposed base for the system.

. A detailed Parts list and pricing can be seen in Appendix F. The approximate price of the system came to approximately $1035, which is within the requirements set by the CAE.

Chapter 5 Analysis of Crucial Components

This chapter analyzes components that are mechanically critical to the success of the project. This analysis will use Engineering computational methods to determine the suitability of the components for the required task. The areas discussed in this chapter are:

- Stability of the Supporting Table to Assure Safe Operation
- The Error Deflection on the Platform Caused by the Striploin
- Analysis of Force Acting on the 1.5-metre V-Slot Rail
- ..Analysis of the Main shaft..Analysis of the Main shaft
- Analysis of the X-Axis Stepper Motor
- Z-axis Stepper Motor
- Conclusion Z-axis Stepper Motor

5.1 Stability of the Supporting Table to Assure Safe Operation

The aim of this section will be to determine the overall stability of the table presented first in chapter3.6.4. This is vital to provide a safe work environment as well as providing an understanding of how the possible weight of the Rig will affect the table. This weight will then be set as a constraint to the build. Some preliminary models were developed through Creo Parametric Modelling Software (CREO)

The mass of the Rig has been estimated by using the volume analysis capabilities on modelling software using preliminary designs. The mass will be set to approximately 30kg. For the initial prototype of the Rig, there will be no inertia forces large enough to cause it to tumble around the (Y) axis (Figure 3-1).

To find the stability of the table, "The First Moment and Centroid of a Composite Area" (Beer et al. 2009) will be used,

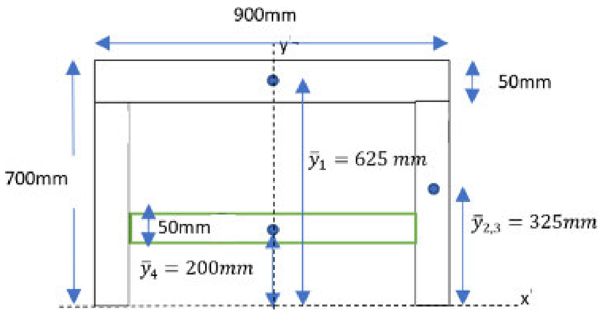


Figure 5-1 centroid of mass table

Step 1

Find the centroid of the mass

$y_1 = \ distance\ from\ the\ centre\ of\ table\ top\ to\ X - axis$

$y_2\ \&\ y_3\ is\ the\ distance\ from\ the\ centrr\ of\ the\ legs\ to\ X - axis$

$Y_4 = distancefrom\ the\ centre\ of\ the\ bottom\ shelf\ to\ X - axis$

$m = mass\ of\ each\ component$

Centre of mass on the narrow side.

$$y = \frac{\sum my}{\sum m} = 0 \tag{4}$$

The centre of mass on the narrow side will be in the middle

$$z = \frac{\sum mz}{\sum m} = \frac{m_1 z_1 + m_2 z_2 + m_3 z_3 + m_4 z_4}{m_1 + m_2 + m_3 + m_4}$$

$$= \frac{40 \cdot 950 + 5 \cdot 350 + 5 \cdot 350 + 10 \cdot 200}{40 + 5 + 5 + 10} = 741mm$$

This puts the centre of mass 200mm below the top of the table. It will require quite a large force to make the table and Rig tumble. For the table to become unstable, the centre of mass will have to pass the pivot point of one of the legs before it becomes unstable. The angle the table has to rotate on the narrow side will be:-

$$\theta = \tan^{-1}\frac{O_{pposite}}{A_{djacent}} = \tan^{-1}\frac{350}{741} = 25° \tag{5}$$

The table would have to roll 25˚ with a substantial force before it became unstable. To provide added safety, the table will be bolted to the wall.

5.2 The Error Deflection on the Platform Caused by the Striploin

This section will provide a computer-simulated result of the deflection expected from the platform when the largest striploin is placed on it. The error must be kept at a minimum as any error from the platform will carry through to the result. This will provide the most practical way to mount the platform to the body of the Rig so that this error is reduced. A small study of the different possibilities was considered. The platform could be mounted across the width, only at the 4 corners or around the entire perimeter of the plate. The simulate inferred that the plate was made from stainless steel. It also considered a 10kg striploin as the mass.

The first simulation was to support the platform across the entire width at both ends Figure 5-2 a)

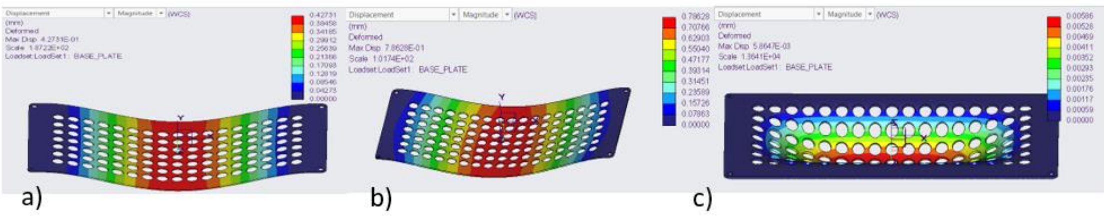


Figure 5-2 Displacement of the platform with 100N force caused by striploin a)constraints across the width (Y-axis) both ends b) constrained at mounting holes only c) fully constrained perimeter

The simulation showed that the maximum plate deflection (marked by red) was across the centre. The maximum deflection was 0.427mm.

Secondly, the platform was simulated as if it was constrained only at the mounting holes

Figure 5-2 b). The simulate affected the plate in a very similar way to that of the trial a). There was a difference in the deflection. The deflection was nearly twice as much, nearly 1mm error. The maximum deflection in this trial was O.786mm.

Lastly, if the bench has a fully constrained perimeter, as shown in Figure 5-2 c), the deflection is dramatically reduced. The displacement became so small that the error is negligible by itself. The deflection was 0.005mm, and the deflection was bowl-shaped with the significant deflection in the very centre.

Table 13 Results of deflection of a plate with 100N force applied

Type of constraint	Deflection (mm)
Across the width	0.427
At the 4 corners	0.786
A constrained perimeter	0.005

Each deflection is minimal, but due to the high-value striploin being studied, the error must be kept to a minimum to fulfil the exact requirements the end customer is requesting. The Rig build will use option Figure 5-2 c) as this option reducing the error to the smallest amount (Table 13). The next section will carry on the need for accuracy by examining the rails, their rigidity and deflection.

5.3 **Analysis of Force Acting on the 1.5-metre V-Slot Rail**

This section will analyse the V-slot rail and determine the stresses, moments and deflection associated with them. This is vital as a 1500mm span can manifest excessive deflection and stress if the selected V-slot is not adequate. The approach taken to determine the suitability of a 40x40 V-slot rail for the 1500mm run (X-axis) will use Newton's 3rd law. To every action, there is an equal and opposite reaction (Newton, 1962) This will resolve the horizontal and vertical forces.

$$\sum F_{x,y} = 0 \qquad (6)$$

The beam is simply held with pin support and roller support (This has been selected over fully fixed support, because as the beam deflects, it can roll) (Beer et al. 2009). The beam has several distributed forces acting on it, the first one being the platform (the area where the meat sits) and this has an approximate weight of 7.6kg unloaded (as weighted) or 20 with striploin, distributed over 80cm. The second distributed force is the Rig. The Rig has an approximate weight of 15kg. The weight is distributed over 32 cm. It will also be considered that there will be a 2kg mass acting on the cutting implement joint.

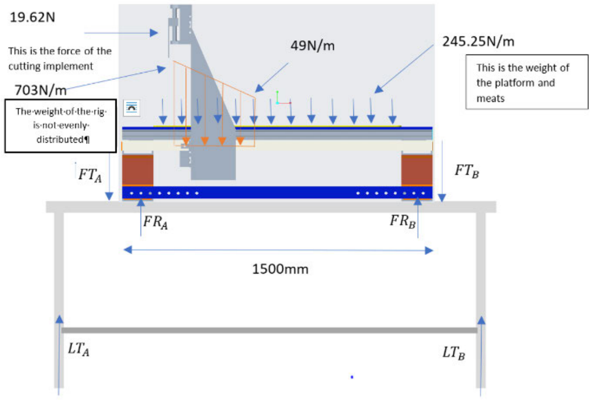


Figure 5-3 Forces of Rig transcending through table

The length of the beam is 1500 mm (AB) Figure 5-3. The V-slot beam is made from 6063-TS which has a modulus of Elasticity E of 68.9 GPa. The moment of inertia about the x-axis for a 40 x 40 V-slot beam is 81.407×10^{-9}

$FT = Force\ Table$

$FR = Force\ on\ Rig$

$LT = Force\ on\ Leg\ of\ Table$

5.3.1 **The Rig**

The greatest bending moment and deflection will be produced when the moving element is positioned at the mid-point on the V-slot rail. The following free-body diagram applies to this situation.

There will be a force of 2kg (19.6N) on the top of the Rig from either a cutter or other device. This will cause a moment about the centre of the beam. The force acts 60cm above the V-slot beam. This means that the moment will be:

$$Moment\ at\ the\ Centre = M_c = (19.6N)(0.6m) = 11.8Nm$$

The moment at the centre of the Rig caused by the cutter will be 11.8Nm. Equation 7 shows the sum of moments equals 0 Take the sum of moments about A:

$$\overset{\circlearrowleft}{+}\sum M_A = 0 \tag{7}$$

$$= C_y(1.5m) - 66.2(0.485) - (192.8)(.75) - 51.5(1.045) - 11.8N$$

$$\Longrightarrow C_Y = 161.54N \qquad A_x = 0$$

This will give the force at C_y of 161.5N and when the sum of forces is taken, they will equal zero (Equation 8) about the whole Rig, it is found that:

$$+\uparrow \sum F_y = 0 \tag{8}$$

$$\Longrightarrow A_y = 307 - 161.54 = 145.81N$$

The force at $A_y\ is\ 145.8N$

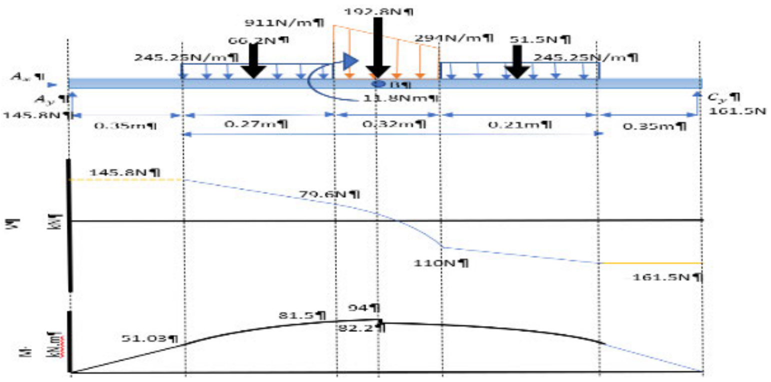


Figure 5-4 Freebody diagram of the forces on the Rig with associated stress and bending moment diagram.

Also described in Figure 4-8 are the stress and moment diagram. This shows the amount of stress distribution of the whole Rig and how the moment caused by the cutter will also be distributed (Figure 5-4). Creo simulate was used. The results from Creo simulate can be seen in Figure 5-5. This shows that the cutter force has been added as a vertical force at about the same height as the position of the cutter.

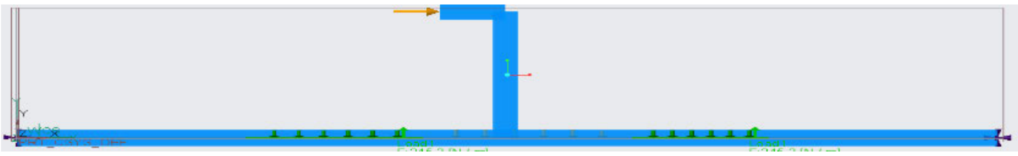


Figure 5-5 Freebody diagram set up on Creo Simulate

The stress and moment diagram (Figure 5-6) is comparative to that of the hand calculations.

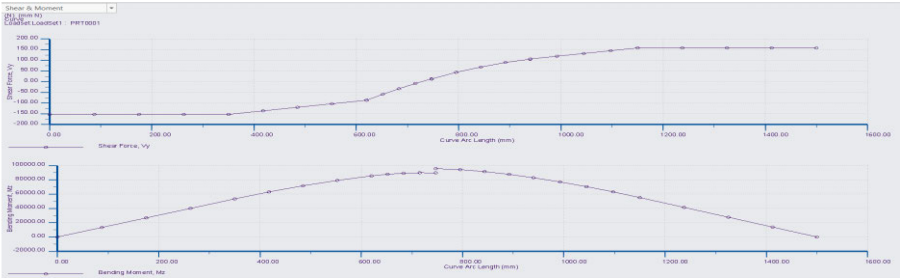


Figure 5-6 Stress and moment diagram from Creo Simulate

The deflection (Figure 5-7) is also an analysis that related directly to this project and is required to determine the overall error that the system may have. A simulation was done on the beam:

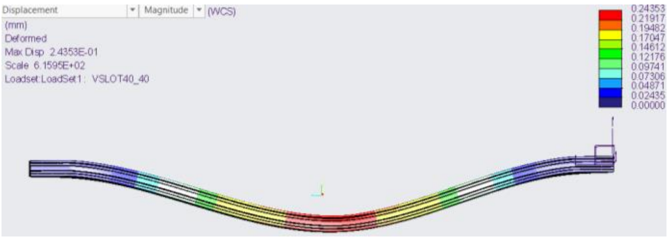


Figure 5-7 Deflection of 40x40 beam

Figure 5-7 shows the results of 118N being applied to the beam. This weight is around double the weight of the larger striploin. The simulation indicates that there will be around 0.24mm deflection. If a striploin is 150mm high and there is added deflection of 0.5mm. This will correlate to an error of around 3%. When considering that the platform has a greater rigidity, the FSD is dropped to a negligible amount.

5.4 ..Analysis of the Main shaft

The GT3 timing Pulley with 20 teeth and 8mm bore has been selected (chapter 4.4.3). This will provide aggressive teeth compared to the GT2. The Diameter (d) of the pulley is 18.2mm, and by solving for its circumference (c) (Archimedes) we can find the approximate length of travel per revolution:

$$C = \pi d \tag{9}$$

The circumference and one revolution of travel will be approximately 58mm/revolution.

The x-axis has a 2kg mass (m) that needs to be moved, which will be produced by a cutter or study mechanism. Using Newton's second law, we find:

$$F = ma \tag{10}$$

$$= 2 \times 9.81 \approx 20N$$

As the radius (r) of the gear is 9.1mm (0.0091m) we can find the torque (T) required to move the Rig.

$$T = Fr \tag{11}$$

$$= .0091X20 = 0.182Nm$$

The speed at this point is not an issue, but if a 2kg force is required to accelerate at 0.3m/s^2, this will require a torque of approximately 0.19Nm which will need to be matched with an appropriate motor.

The shaft must also be analysed in the event of a jam stop. The type of motors that will be discussed further on will produce a torque of $0.674Nm$. This will be the torque applied to the shaft in this situation.

This value of torque is relatively small even if it is doubled. The following analysis will consider the effects of a reasonable torque on the 8mm shaft. By increasing the torque (T) to 3.6Nm, much greater than expected and with a length (L) of 0.45m, a modulus of rigidity (G) of $77.2 \times 10^9 pa$ and polar moment of inertia (J), the angle of twist will be found.

$$J = \frac{\pi}{2}\left(r_o^4 - r_i^4\right) \tag{12}$$

$$\frac{\pi}{2}(0.004\text{^}4 - 0) = 4.02 \times 10^{-10}$$

$$(angle\ of\ twist)\theta = \frac{TL}{GJ} \tag{13}$$

The angle of twist is the angle at which the shaft rotates around its centre.

$$= \frac{3.6 \cdot 0.454}{77.2 \times 10^9 \cdot 6.3 \times 10^{-9}} = 0.0526°$$

The angle of twist will be minimal at 0.05°. This will, in turn, give the information required to find the sheer strain (γ)

$$Sheer\ strain\ \gamma = \frac{\theta r}{L} \tag{14}$$

$$= \frac{0.0526 \cdot 0.004}{.454} = 0.00046$$

The sheer strain is the deformation on the surface of the shaft as it twists. In this case, it is very small at 4.6×10^{-4}. To find the sheer stress, we modify the following formula (equation 10):

$$T = \int_0^r \tau\rho \, dA = \frac{\tau}{\rho} J \tag{15}$$

The modified formula becomes equation 11

$$sheer\ stress\ \tau_{max} = \frac{Tr}{J} \tag{16}$$

$$= \frac{3.6 \cdot 0.004}{6.3 \times 10^{-9}} = 2285714.3Pa$$

$$= 2.28Mpa$$

The shear stress is also very small, and this shows that the 8mm shaft will be sufficient for the requirements of the Rig.

The sheer strain is very small when considered with the yield strength of the stainless-steel shaft. A further analysis using Creo Simulate will be used to confirm the results. The forces and constraints can be seen in Figure 5-8. There are two bearings which provide linear constraints, and one of the cogs to the far right is fully constrained as if it is seized. The stepper drive is set up with a simulated torque. This will show if there is any other area that might be susceptible to sheer. The results can be seen in Figure 5-9. The stress and deformation are so small that the shaft is sufficient. The Yield strength of stainless is 215MPa. As can be seen, by the Creo analysis, the maximum stress occurs where the timing gear and shaft meet. This could pose a risk due to the timing gear being attached with grub screw over a key.

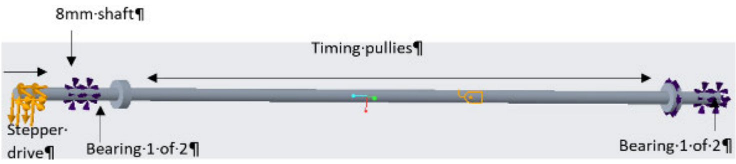


Figure 5-8 Showing the constraints and forces acting on the shaft in Creo Simulate

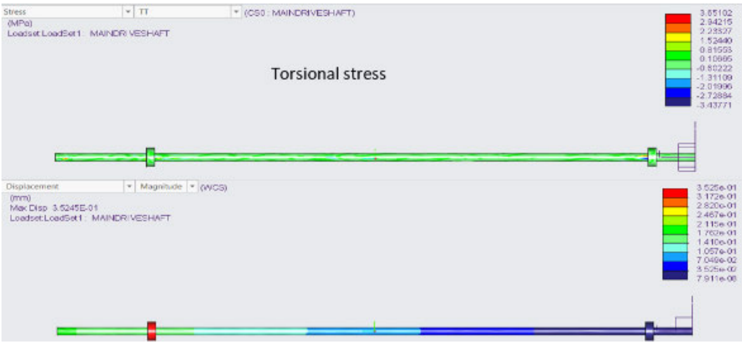


Figure 5-9 Creo stress and displacement analysis of.

The shaft will sufficiently handle the load even in the event of an immediate stop of one timing pulley. The next section will now determine the losses of belts in terms of nominal efficiency.

5.5 Analysis of the X-Axis Stepper Motor

This section will choose a stepper motor that has a torque range to handle the requirements for the X-axis. As previously mentioned, the X-axis will be where the major 20N force reacts. This implies that the stepper motor selected for this axis will need a greater torque than the other axis.

The size of the stepper motor will need to fit the required torque for the application. The torque has been established above in section 4.5.2 as 0.182Nm. When considering the efficiency of this system there will be some losses from the maximum output of the motor to the results achieved.

The losses of the system will come from the following possible points:

a) belt drive, 98% nominal efficiency (Section 4.4.2).
b) V-slot wheels will be assumed to have 75% nominal efficiency. (This is an estimate)

The efficiency of the belt-driven system will be set at 70% for this project. We then compute 70% of the full drive of the system.

$$\frac{0.182Nm \ \times 100\%}{70\%} = 0.26Nm$$

This will give us the required torque for the motor to overcome nominal efficiency.

The NEMA 23 motor is at the upper range of the 24V NEMA stepper motors. As can be seen in Appendix B1, a NEMA 23 motor has been selected.

$$Distance\ Travel/revoluiton = \pi d \tag{17}$$

$$= \pi \times 18mm = 56.54mm$$

The Stepper motor is a NEMA 23 ELEC-NEMA23-635-HT. All calculations were provided by All About Circuits (All About Circuits 2020)

Equation 15 determins the max speed of the stepper motor where applied voltage (v) is divided by $maximum\ current(I_{\max})$, stepper motor inductance(L) and steps per revolution (spr).

$$Max\ speed\ = \frac{v}{2LI_{max} \times spr} \tag{18}$$

$$= \frac{24}{2 \times 4 \times 3 \times 200}$$

Maximum speed =5.00 rev/sec

With the same information, the minimum time per step can be evaluated through equation 16.

$$Minimum\ time\ per\ step = \frac{2LI_{max}}{V} \tag{19}$$

$$= \frac{2 \times 4 \times 3}{24}$$

Minimum time/step: 1 ms

The maximum power is determined by current multiplied by voltage, as shown in equation 17.

$$P_{max} = I_{max}V \tag{20}$$

$$= 3 \cdot 24$$

Maximum power: 72 Watts

With the above information, we can determine the maximum torque of the stepper through equation 18

$$Torque = \frac{power}{speed} \tag{21}$$

$$= \frac{72watts}{5 \times 2\pi} = 2.291$$

Torque=0.674Nm

The distance travelled every revolution will be 56.5mm

Table 14 Performance calculations of X-axis stepper motor - Appendix B.1

Data Sheet (Appendix B.1)	
Rotational Speed	5.0Rev/sec
Minimum time/step:	1 ms
Maximum power:	72 Watts
Torque	2.291 Nm
Travel / revolution	56.5mm

Table 14 shows the calculated performance characteristics of the stepper motor when pushed to its maximum current. Also shown in Table 14, one revolution of the timing pulley produces a movement of 56.5mm meaning that the sensor carriages could move at 282.5mm p/s. The

The NEMA 23 motor that has been shown produces the required torque with extra play. With the 56.5mm/revolution and the motor set to a resolution of 1600stets/revolution, an accuracy of 0.03mm can be assumed The next section will discuss the requirements of the other two axes. These axes will not have a limitation on torque

5.6 Analysis of the Y-axis Stepper Motor

This section will determine a stepper motor that will provide greater speed and average torque than the requirements of the X-axis. The Y-axis stepper motors have minimal work-related force applied to. It does drive two sensor carriages though. The purpose of these axes is to position the sensor carriages along the y-axis.

These axes will use the NEMA 17 motor with less torque but greater speed. The benefit of a greater speed while using a lead screw is that one revolution travels much less (in this case 8mm Table 16).

17HS24-2104S **High Torque NEMA 17 Stepper Motor 65Ncm/92oz.in**

The Stepper motor is a NEMA 17 17HS24-2104S. All calculations were provided by All About Circuits (All About Circuits 2020)

The use of Equation 15-19 will help determine the y-axis stepper characteristics.

Stepper motor specs

$$speed_{max} = \frac{12}{2 \times 3 \times 2.1 \times 200}$$

Maximum speed =4.76 rev/sec

$$\min \frac{time}{step} = \frac{2 \times 3.2 \times 1.8}{12}$$

Minimum time/step: 1.05 ms

$$P_{max} = 1.8 \cdot 12$$

Maximum power: 25.2 Watts

$$Torque = \frac{25.2watts}{4.76 \times 2\pi} = 0.674$$

Torque=0.84Nm

Table 15 Performance calculations of y-axis stepper motor - Appendix B2

Data Sheet (Appendix B.2)	
Rotational Speed	4.76 Rev/sec
Minimum time/step:	1.05ms
Maximum power:	25.2 Watts
Torque	0.84Nm
Travel / revolution	8mm

Table 15 shows the calculated performance characteristics of the stepper motor when pushed to its maximum current. Also shown in Table 15, one revolution of the timing pulley produces a movement of 8mm meaning that the sensor carriages could move at 38.3mm p/s.

The analysis starts with certain requirements that the system wants to achieve and arrives at a figure of 3.7Ncm of torque required for the screw drive steppers. This was extremely small and probably unrealistic for even a drive that has no working force requirements. The NEMA 17 motor that has been shown produces the required torque with extra play. The next section will discuss the requirements of the z-axis. These axes will not have a limitation on torque.

5.7 Z-axis Stepper Motor

This section will determine the stepper specifications for the z-axis. Z-axis stepper motor has no work-related force applied to them. The purpose of these axes is to position the sensor carriages for the X-axis to do the work.

This axes will use the NEMA 17 motor with less torque but greater speed. The benefit of a greater speed while using a lead screw is that one revolution travels much less (in this case 8mm Table 16).

HANPOSE 17HS8401-S 48mm NEMA 17 Stepper motor 42 motor 42BYGH 1.8A 52N.cm 4-lead

The Stepper motor is a NEMA 17 17HS3401-S. All calculations were provided by All About Circuits (All About Circuits 2020)

The use of Equation 15-19 will help determine the z-axis stepper characteristics.

Stepper motor specs

$$= \frac{12}{2 \times 2.8 \times 1.8 \times 1.3 \times 200}$$

Maximum speed =8.24 rev/sec

$$= \frac{2 \times 2.8 \times 1.3}{12}$$

Minimum time/step: 0.607 ms

$$= 1.3 \cdot 12$$

Maximum power: 15.6 Watts

$$= \frac{15.6 watts}{8.24 \times 2\pi} = 0.674$$

Torque=0.301Nm

Table 16 Performance calculations of Z-axis stepper motor Appendix B3

Data Sheet (Appendix B.3)	
Rotational Speed	8.24 Rev/sec
Minimum time/step:	0.697 ms
Maximum power:	15.6 Watts
Torque	0.301Nm
Travel / revolution	8mm

As shown in Table 16, the travel of the stepper motor is 8mm per second with a rotational speed of 8.24 rev/sec. This means that every second the lead screw will travel 65.9mm. This speed will be more than adequate to fulfil the purposes of the Rig.

The NEMA 17 motor selected will provide a greater speed to be used in conjunction with the lead screws. One aspect of the stepper motor is its ability for high accuracy. The accuracy is directly related to the 200 step sizes per revolution. This resolution can be increased and the report will focus in on this topic.

5.8 Conclusion

The Analysis of different components in this chapter provided a detailed analysis of critical components associated with the successful build of the Rig. The analysis achieves two goals, firstly sizing components of the Rig that provide suitable solutions towards the build and secondly providing an understanding of the error that would be pass on from components. The following outcomes have been found:

1) The stability of the bench was considered, and it is determined that the bench would have to tip past 25˚ before becoming unstable. This was considered an unlikely large amount of inertia would have to be produced to rotate it past that point. It was concluded that the bench would be attached to the wall for added safety.
2) The platform was then analysed in Creo Simulate, and the amount of deflection was simulated. From the simulation, it was decided that the platform would be supported by the base around its full perimeter. The deflection would then be 0.00586mm.

3) A free-body diagram of the main beam was created and analysed. From that information, a shear and moment plot was produced providing information of the associated reactions. These plots where then backed up with results from Creo
4) The same beam was analysed for deformation under a maximum weight of 118N. The simulation shows that there will be around 0.24mm deflection. This would work out to about a 0.3 per cent error. This would be reduced even further because most deflection would be buffered by the platform. These results confirmed the ability of a 40 x40 slot beam to be sufficient.
5) An analysis of the main drive shaft was completed, and it shows that under current conditions the shaft would twist 0.05° and produce a shear strain of 0.00046 which shear stress of 2.28Mpa.
6) A figure of 0.26Nm was considered the torque required by the x-axis stepper motor to move the system. A NEMA 23 stepper was purchased which produced a theoretical torque of 2.3Nm.
7) The y-axis and z-axis stepper motors were rated at 0.8 and 0.3 respectively. This requirement was suitable as both these axes had no torque requirement required.

Chapter 6 The Build and Programming of the Rig

The Rigs construction revolved around the sequential order of the design. The Rig has been built, and the order of the build developed from the actual construction. The Rig was weighed at 28kg. The design of the Rig matched the design requirements set out in the project. The build will cover the four steps involved in the construction of the Rig.

- The Construction of the Frame and Drive System
- ..The Implementation of the Electrical system
- ..The Programing of the
- ..The Sensor Installation and Alignment
- Conclusion

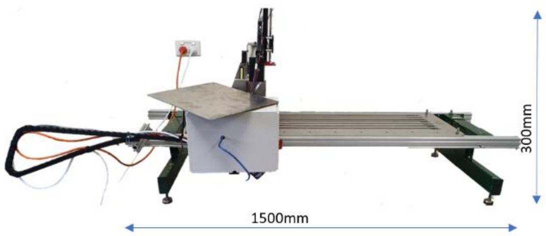


Figure 6-1 The completed mechanical aspects of the Rig

The process of putting the Rig together (Figure 6-1), incorporated the use of many tools, and each section will discuss the use of these. The build of the Rig will use those parts specified in Chapter 4 and 5. The Rig is made from stainless steel and other non-corroding metals. The build had to consider the safety of the users of the Rig and the Rig itself(chapter 3.9).

6.1 The Construction of the Frame and Drive System

The construction of the Rig started with the frame. This involved the rails, the gantry, and sensor carriages. The rails and sensor carriages were pre-developed parts, and it was a matter of bolting these parts together. These parts were all left oversized to allow for adjustments and future use in the evolution of the project.

The gantry arms were built from scratch. This involved the bending of plates and welding of stiffeners onto the gantry arms. These plates were purchased as scrap steel and where modified to suit the design. The arms where constructed as multiple parts to allow the ability to use with or without the top half of the gantree.

The gantry arms had many holes. All the holes had to be drilled for the wheels, frame attachments, motors and bearings. The holes were positioned with accuracy as many of them relied on the ability to be crucial to ±0.5mm. This accuracy meant that the holes, in some case, were drilled to allow some movement for exact positioning.

The use of special v-slot nuts where used to attach the rails together and rails to the frame. This system allowed the frame to be easily modified and positioned. All other fasteners were attached to the gantry through tapped holes with standard metric nuts.

The process of putting the mechanical part of the Rig together is shown inTable 17:

Table 17 The sequence of construction for the Rigs mechanical components

sequence	Part	fasteners	Notes
1	Base	This was the initial part	
2	2 x x-axis rails 40 x 40	16 x v-slot nuts M5 x 5mm bolts	Attached to outside edge of base
3	2 x platform mounts 1 x 40 x 40 1 x 20 x 40	8 x v-slot nuts and M5 x 5mm bolts 4 x M10 60mm bolts	These rails run between the x-axis rail. They support the platform, and the 4 M10 bolts provide quick attachment of the platform. The platform can be installed and remove quickly
4	Wheels (to gantry arms)	12 x wheels 4 x eccentric spaces 8 x standard spaces, 12x locknuts	The eccentric spaces used on the upper wheels allowed for fine adjustments onto the rails.
5	Lower gantry arms	The wheels	The wheels slide onto the 40 x 40 v-slot rails
6	Upper gantree arm	6 x M10 40mm bolts	The upper gantry arm was attached to a lower gantry arm.
7	Lidar Rail	8 x v-slot nuts with M5 x 5mm bolts	The nuts were attached to the top of the gantry arms and the liDAR rail slides onto the

			gantry arm, and the fasters are tightened. LiDAR rail is a complete package
8	Ultrasound rail	4 x M4 x 6mm bolts with nuts, 4 x v-slot nuts and M5 5mm bolts, 2 x right angle brackets	Two right-angle brackets that attach the ultrasound rail to the gantry arms. They link to the bottom gantry. The ultrasound rail slides onto the right angle brackets. Ultrasound rail is a complete package.
9	Bevel gear and shafts	6.2 2 x 8mm to 35mm Mounted Ball Bearings, 8x grub screw	Two bevel gears were placed on the ultrasound rail shaft and Lidar rail shaft. Two bevel gears attached to a vertical shaft. The shaft attached to the gantry arms with mounted bearings
10	Driveshaft and timing cogs	2 x flanged bearings, four by grub screws	The timing gears were placed on the shaft. The bearings are attached to the gantry arms. The shaft placed in the bearings
11	Timing belts	4 x v-slot nuts and M5 8mm bolts	The timing belt threaded as per section 4.5.2 and fastened to x-axis rails
12	z-axis	4 x M5 8mm bolts 4 x v-slot nuts	The nuts attached to the plate of the LiDAR rail and z-axis slides on and fastened.
13	Machine vision rail	4 x v-slot nuts and M5 5mm bolts	This attaches to the end of the Rig for the mounting of a stationary machine vision camera.

The movement of the system was tested with the use of a set of scales to confirm the efficiency of movement. The force to move the system was approximately 1kg. It was found that the timing belt tension was especially critical to the movement of the system, and if they were too tight, the force to move the gantry was dramatically raised to 3kg.

The easy flow of the Rig build was due to pre-design. There were some alterations that were required but were not substantial. The overall size of the Rig was 1500mm x 500mm x 600mm LWH. The sequence of putting the mechanical section of the Rig together was essential and if not followed, would need to be removed to put other parts on first. This leads the report to the implementation fo the Electrical system.

6.3 ..The Implementation of the Electrical system

Most of the electrical components have been placed in a waterproof housing. This is to protect these components from water and to protect the possibility of electric shock from the users. All external components draw power and control from this housing.

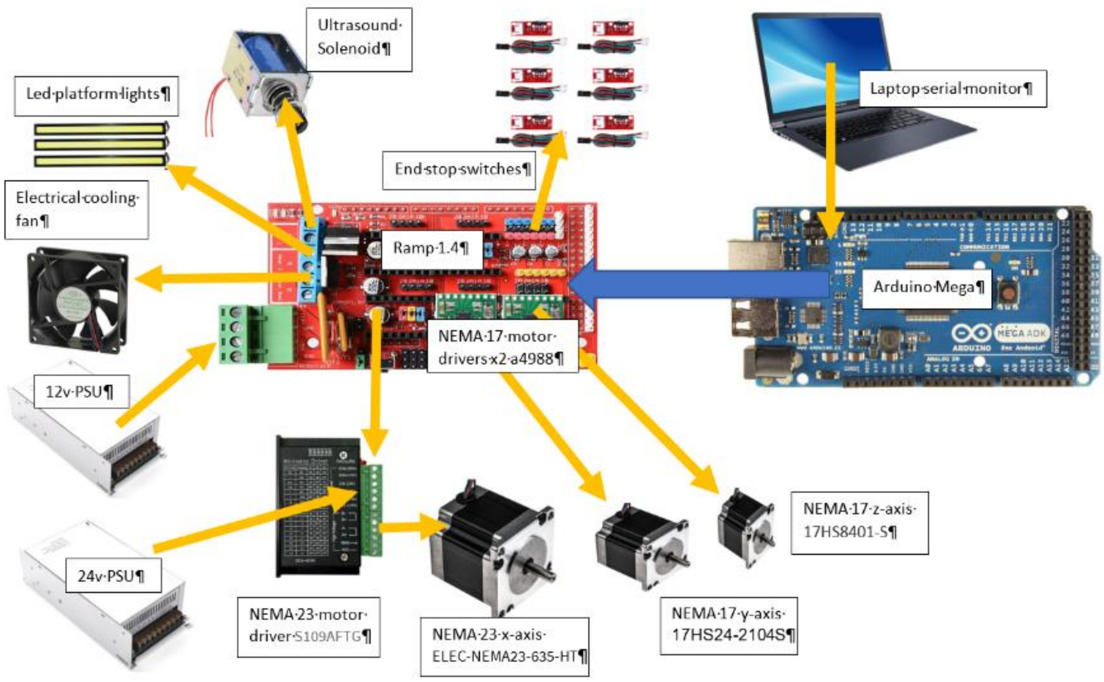


Figure 6-2 Model representing the electrical system

The electrical system (Figure 6-2) was less reliant on the sequence of attachment and more reliant on creating pathways for the cabling. The electrical system required three stepper motors, two PSU, three lights, Arduino, weatherproof box, and cable trays.

The Rig has three stepper motors, 1 for each axis. Two of these motors directly attached to the sensor rails (Figure 6-3 a) b)). The NEMA 23 attached to the gantries arms Figure 6-3 c) They are connected with by 60mm M3 bolts with nuts and 55mm spacers. The shafts of the motors are joined to the shafts of the Rig via flexible couplings. The wires are run to the waterproof housing where the Arduino, PSU and motor drivers have been placed.

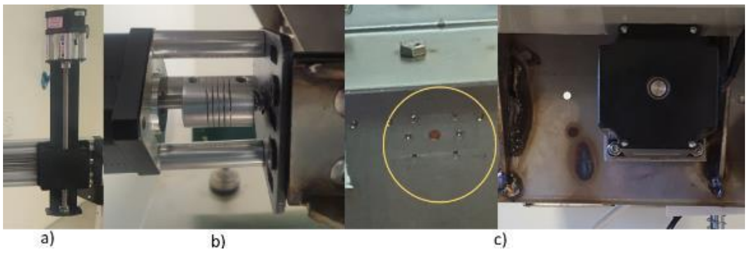


Figure 6-3 Motor attachment a) z-axis motor b) y-axis motor c) x-axis motor

There are three 12 volt LED rails attached around the gantry to light the work area. These lights provide a uniform spectrum for any future machine vision that might be used. The lights are wired to the Arduino ramp 1.4.

The PSU is powered by 240v. These were hard-wired by a professional electrician and where the wires attach, they were sealed to prevent possible bumping. The PSU supplied 12v and 24v to the motor drivers and ramp 1.4. The PSU was housed in the waterproof housing to prevent water damage and possible electrical hazards.

The ultrasound sensor required a method to be put in contact with the meat. This was done through the use of a 12v solenoid. The solenoid was attached to the ultrasound rail and when the power was turned on the solenoid would be pressed into the meat. The solenoid was wired to the Arduino. The report now discusses the programing of the Rig.

6.4 ..The Programing of the Rig

The program for the Rig is focused around the driving of the stepper motors and control of other electrical components. There have been three different programs written during the development of the system which can be viewed in Appendix C. All three codes will be discussed in this section while highlighting the parts of the code that focus on the accuracy. This section will discuss

- ..The Initial Test Code for Running Steppers on Ramp 1.4(Appendix C.1)
- ..The Full Run of the (Appendix C.2)
- ..Code for Rig Running to a Coordinate(Appendix C.3)
- ..Use of Code to Control other Electrical Components on the

The initial test code was to designed to test system and steppers while the other two codes were developed to be used on the system.

6.4.1 ..The Initial Test Code for Running Steppers on Ramp 1.4

The Initial test code (Figure 6-4) was vital to the development of the system as it helped to understand the Ramp 1.4. The Ramp 1.4 is a shield that sits on top of the Arduino and aligns the pins with the requirements of the motor drivers. The schematics and pins of the ramp 1.4 can be seen in Appendix D. The stepper motor steps, when sent a signal from the MCU that is triggered by the code. The flow chart in Figure 6-4 shows the basic requirements for the initial test.

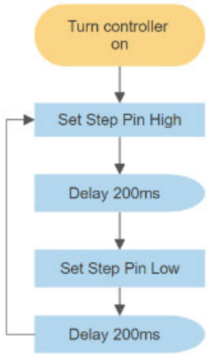


Figure 6-4 Initial test code flow diagram

The code is very basic and assigns the pins for only one stepper motor (which can be changed) and prompts the stepper to step buy signalling a high or low on the step pin of the motor driver. The speed of the stepper motor is set by delaying the transition from the high to low. This can be seen in the following segment of the code that is testing the x-axis stepper.

```
void loop () {

// the transition from high to low and back to high triggers the steps of the stepper
digitalWrite(X_STEP_PIN, LOW);
```

delay (200); //sets the stepper speed
digitalWrite(X_STEP_PIN , HIGH);
delay (200);
}

This helped to determine which stepper was assigned to a particular segment of the ramp 1.4 board and to eventually test and learn the system. The NEMA 23 had a separate motor driver who still used the ramp 1.4 pins as a signal station. This code help to determine pin assignment was correct prior to installation onto the Rig. Prior knowledge of the system and even steppers was extremely limited, and this provided a foundational step to the development of the system

6.4.2 ..The Full Run of the Rig

As it has been mentioned, the Rig has been designed to study striploin and take measurements accurately and in a reasonable time period. This program (Figure 6-5) has been designed to do a full run of the system. The code will run down the x-axis, stopping 14 times (if the full run is required), return, step across to next y-axis position and run down the x-axis again. The flow chart in Figure 6-5 describes the system code.

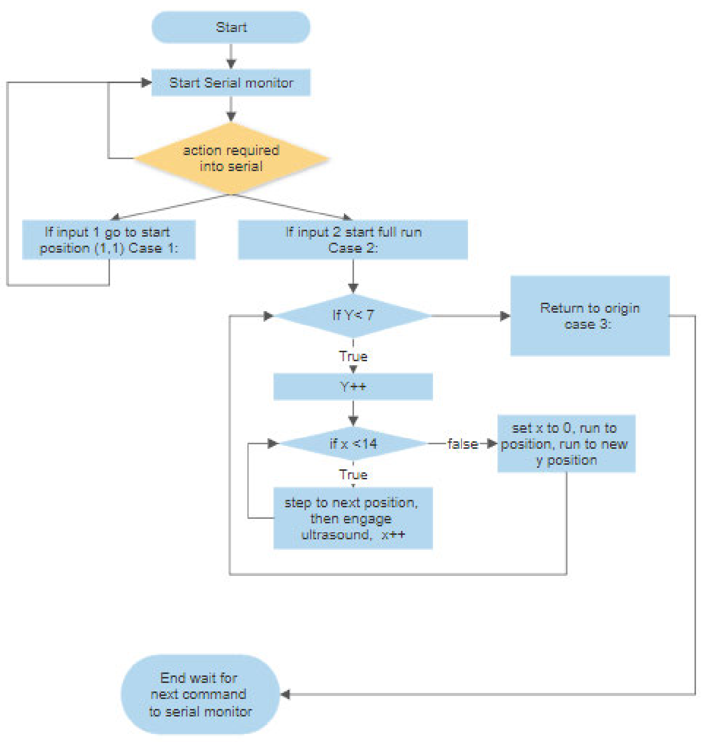


Figure 6-5 Flow chart of Full Run

Figure 6-5 explains that the system waits for serial input. If the input is a 1, then the system will proceed to the start position. If the input is a 2, then the system will go on the full run of the system. The system uses a basic nested if statement to increment the position. The size of the steps has been set in the code as a number of pulses. The start position (1,1) is set by the following code (Appendix C.2):

```
X_FROM_ORIGIN = -4254;        //stick  -459.46 the origin is 17mm from…….
                               centre of hole along x axis 1600 pluses

Y_FROM_ORIGIN= 1000;          //the origin is 40mm from centre of hole along
                               axis one revolution is 8mm 200 pluses
```

The start position, in this case, is set 4254 pulses in x-direction and 1000 pulses in the y-direction.

Equation 15 has been used to set the position in the nested if statement. This part of the code is dependent on the travel distance of the stepper and how many pulses/revolutions has been set.

$$postion = y_{postion} * constant * steps\ per\ revolution \qquad (22)$$

The constant in equation 15 has been determined by Equation 16. The Rig will move 53mm/revolution along the x-axis and 8mm/revolution in the y-axis. The constant can be determined by the ratio of the distance between sensor position and length travelled per revolution

$$constant = \frac{distance\ between\ sensor\ postion}{distance\ traveled\ per\ revoluiton} \qquad (23)$$

.

The size of the steps between sensor positions has been set by the following section of code (appendix C.2).

```
while (y<=7){;    //  7 stops along the y axis
```

```
int posy = (y*4.62*200)+Y_FROM_ORIGIN;    //4.62
```

and

```
while (x<=14){;

int posx = (-x*0.7*1600)+X_FROM_ORIGIN;   // 0.6757
```

The accuracy of the system can be tuned by changing the constant. Because the system can use up to 3200 pulses per revolution when set to 1/16 step size, the tuning can provide very accurate results. The full run has to be set to 200 steps/revolutions along the y-axis and 1600 steps/revolution along the x-axis.

The Arduino code has a number of library's associated for use with stepper motors. This project has utilised the <AccelStepper.h> which provides an easy implementation for acceleration, speed and position setting. The acceleration of the system provided some problems and was set to maximum to try to remove any acceleration in this project. By setting acceleration to 10000, the system performed a lot better and removed inaccuracies with some slipping of the motors, especially under load.

The code works and provides the results that were expected. Further work will be advantageous in the future, on this code, that could incorporate feedback to the system which will provide sensor readings that could determine the size of the run depending on whether there is a striploin present.

6.4.3 ..Code for Rig Running to a Coordinate

The last program designed (Figure 6-6) for the Rig was one that could be used to return to a single position quickly. This could be utilised to confirm a strange reading without the need to complete the whole run again. The following flowchart will explain the use of the code.

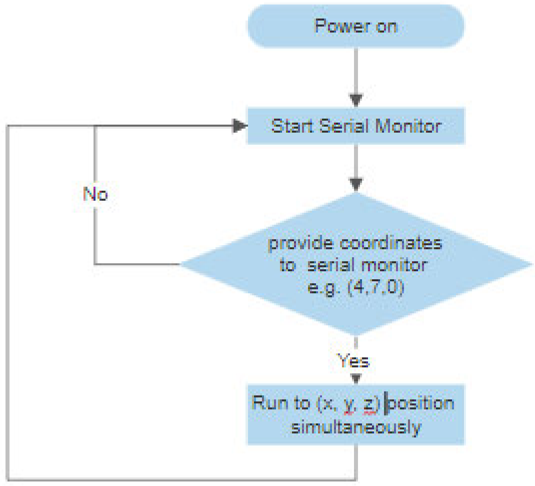


Figure 6-6 single position run

The code makes use of the serial monitor. The coordinates are input into the Arduino IDE serial monitor in the format of required sensor position, for example, 2,5,0. This will take the Rig to position two on the x-axis, line 5 on the y-axis and height 0 on the z-axis. The code moves each axis simultaneously and provides a high degree of accuracy when comparing it with a previous reeding. As mentioned in section 6.4.2, the use of <AccelStepper.h> library has been used.

6.4.4 ..Use of Code to Control other Electrical Components on the Rig

There are other electrical components on the Rig that are controlled within the program. The ramp 1.4 provides the ability to output 12 volts with the switch being controlled with code. The fan, solenoid, and lights are all run from this output source. Both codes represented in section 6.4.2 and 6.4.3 turn the lights and cooling fan on through the entirety of the Rigs use. In comparison, the solenoid is only an option in the full run mode at this point and has not been implemented into the programme used to run to a position. The end stops are also run from the ramp 1.4 but have not yet been integrated into the code.

The codes have been trialled, and all perform how they have been designed. The codes have also been used to test the accuracy of the system, and the results can be seen in the Accuracy results (chapter 7).

6.5 ..The Sensor Installation and Alignment

The last parts to be attached were the sensors. The two primary sensors are the ultrasound and LiDAR. Both of these sensors were connected to their own control systems which provide power. They are attached to their respective rails as represent throughout the text. The sensors required alignment so that they can take measurements of the same vertical point—this involved alignment of the top and bottom y-axis rail mounts and x-axis positions. The sensors were tested for alignment. The alignment matched the requirements both vertically and horizontally. The sensors have also considered Chapter 3.7.3 and instaled within the sensor limitations. They are able to take measurements vertically in the exact position.

6.6 ..Conclusion

The build was successful and matched well to the modelled design. There was some modification required to the Rig. This included:

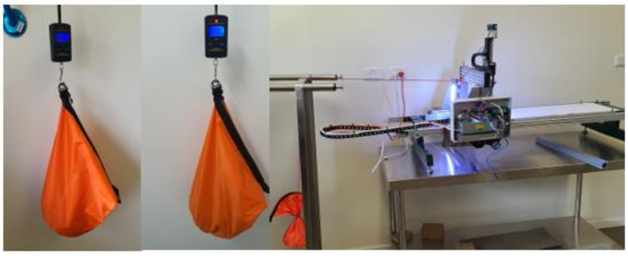
1) Longer v-slot beams from 1m to 1.5m
2) X-axis stepper motor size was taken from NEMA 17 to a NEMA 23
3) The Lidar had to be repositioned to raise the height.

This was a learning curve and provided a very important lesson as to what to check and how to go larger than small in initial builds. Otherwise, there were no major modifications. This was due to the system being very dynamic in the sizing of the components. The v-slot system made the construction easy and professional. The mechanical, electrical and computer systems all meshed well together and provided a very workable system.

Chapter 7 ..Accuracy Results of Rig Positioning

The results of the accuracy of the system were considered essential results. The system accuracy was focused on four main criteria. Firstly the sensors being placed within 1mm of a desired set of points, secondly doing so repeatably, thirdly do so under the 2kg required force Figure 7-1 a) and lastly the Rig returning to the point it started at. Figure 7-1 b) shows how the weight was attached to the top of the Rig, and as the Rig moved, the bag moved up and down. There was two tests done. They involved the Rig running through the whole process of 98 points and secondly the test of running to one point continuously then returning.

The procedure for this test involved the creation of position dots on an A3There where 98 dots placed on 2 A3 pieces of paper. These were used to represent test positions. A pointer has been attached to the Rig which will allow for accurate recording of positions. As each position has reached a position, a mark will be placed on the paper.



a) b)

Figure 7-1 a) measured weight at 1kg and 2kg b) weight attached to the Rig

Equation 15 subtracts the actual position from the desired position and divides that by the desired position resulting in a percentage change.

$$\%\ \text{change} = \frac{Acutal\ position - desired\ positon}{desired\ position} \tag{24}$$

7.1 ..Test 1

The test involved the accuracy of the Rig to do a complete run over the whole platform. The platform has seven rows and 14 measurements per row that will be considered. The Rig will be expected to position itself within 1mm of each position. This testing will be done with no weight, 1kg (appendix G1.2) weight and a 2kg weight(Appendix G1.1). The results of the 2kg will be recorder and tabulated and presented on a graph.

The objective is to determine the accuracy and repeatability of Rigs ability to position on the required spots over a full test run and return to its initial start position. This will intern allow for a quick rerun of the test prior to the meat deforming from gravity.

The paper was placed on the platform of the Rig. Due to the discrepancy of actual position compared to the printed version, the code was re-configured to the paper version. The Code can be seen in Appendix C.2. The user inputs command 1 through the serial monitor to make the Rig go to the first point, and user input command 2 and the process will start.

As the Rig moves to each position, a small mark was placed on the paper at its precise location. It would take 2 minutes to complete the full run. The results were derived as a percentage of error from the desired point.

The following method was used to determined error. The distance was measured from the centre of the desired position to the actual position. Each position was recorded and put into a tabulated version. The averages of the x-axis errors were taken across the y-axis and recorded. These averages were then turned into a percentage error and recorded as a plot.

Figure 7-2 shows the results of the error occurring along the x-axis. There was no drift error on the y-axis, and this was not presented here. There was 20 test recorded at four different weights with only the 2kg represent here.

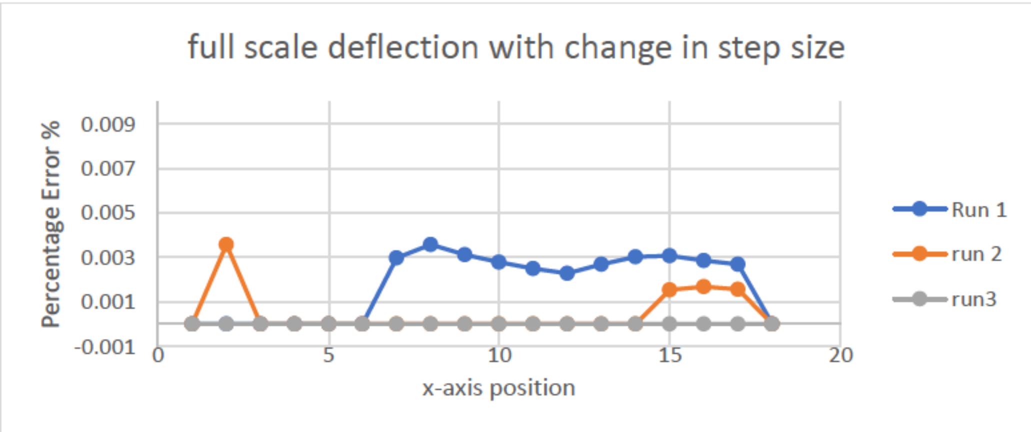


Figure 7-2 Results of the full run

Figure 7-2 shows the results of 3 runs with 3kg attached. The results indicate that the last position is situated with zero error or change from its starting position. As the step size was changed, the error was removed from the system and is indicated by run 3. The error resulted from the need to tune the system to the required position.

7.2 ..Test 2

Test 2 was done to test the error of the system as it travelled to one spot 18 times (Appendix G2). This was to test the drift of the system under load. The use of calliper measure equipment was used (Figure 7-3).

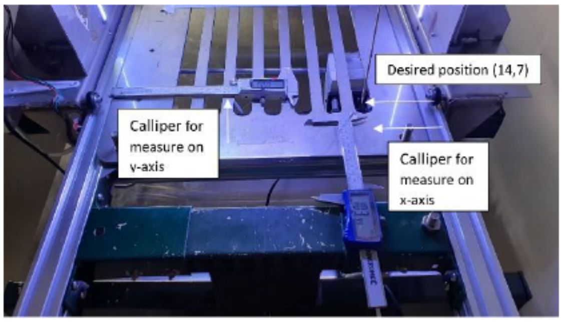


Figure 7-3 Test 2 calliper position and Rig position

The code used for this test can be seen in Appendix C3. The coordinate was input into the Arduino IDE serial monitor of the computer. This coordinate was (14,7), which is considered to be the extent of the system along both axes. Once the Rig had positioned the sensors at (14,7), the callipers were used to accurately measure the change of position. The results were tabulated. Once a trend could be established, an average was taken, and a percentage of error derived.

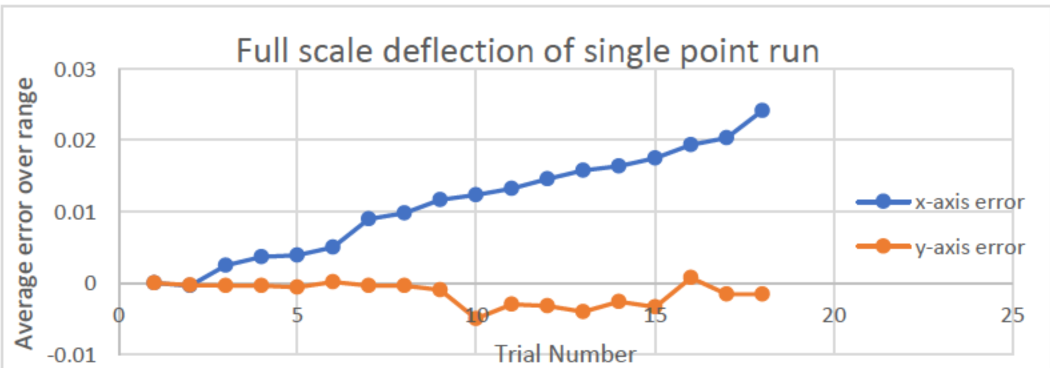


Figure 7-4 Average drift of system travelling to a single point

Figure 7-4 shows the average drift of the system in both the x and y directions. There is a slow drift of the system along the x-axis (-x direction). The y-axis shows there is no drift of the system and maintains a repeatable action. The non-linear state of the results is due to minute error in the operator's adjustments of the callipers and results can be considered linear. The accumulated error shown in Figure 7-4 was discussed, and the error was put down to 2 possible reasons

1) The error was a glitch in the code as the error was not present in Test one where there should have been an accumulated error over the 91steps. Due to the error being minimal, this may not have been evident and may have been there.
2) The error was caused by system settling and belt stretch.

The system has incorporated limit switches with the aim to recalibrate after each run. This would make any error present redundant due to a reset on the return of the sensor to the next starting position.

7.3 ..Conclusion

The results showed conflicting results. Test one showed that the system was accurate over the 98 stop-starts and returned to its initial starting position. Test 2 showed drift even after one stop-start. The accuracy of test 2 was much greater than that of test one, but there was up to 2mm drift after the 18 runs compared to 0 drift after what could be considered over 100 runs. The conflicting results occurred under the same conditions with the code being the only variable different. With limited long term results and the ability to change and retest the code, it has been considered to be the problem. The fact that test one resulted in a high degree of accuracy under the required 20N force test condition the Rig has to be considered to be able to perform to the required specifications and need.

The system has been designed to use limit switches for this reason. And if there is any drift in the system, it can be reset after each run down all axis if required.

Chapter 8 ..Discussion of the Dissertation and objectives

The CEA has commissioned the design of a three-axis Cartesian positioning test Rig that researches and discriminates between the lean and fat of a striploin (Chapter 1.6). The Rig has been designed (chapter 3, 4, 5), built (chapter 6) and tested (Chapter 7). This Chapter consolidates finding from the dissertation and objectives. This includes the significant findings of the literature review (chapter 2). Secondly, the objectives presented in chapter 1.6 have all be met and discussed.

8.1 ..The Impact of the Literature Review

In chapter 2, 'The Literature Review', research was conducted into the red meat industry. It reviled that there is a great need for automation equipment for the processing of high value primal and that equipment needed to be developed to study the reaction of the meat. Also, models and methods to interact with the product need to be developed. This dissertation provides the design of one tool that can accurately study meat reactions and provide a way to gather data efficiently. The literature shows that there is a big gap between what automation is available and what automation needs to be achieved for accurate trimming of striploin.

8.2 ..The Outcome of the Project and Objectives

The outcome of the project has provided positive results. The project progress was challenged due to the covid 19, and the ability to work on the Rig due to distance and lockdowns was challenging. All outcomes have been met and within budget (Table 20.12).

1) Safety was a significant factor in the build of the project. It was determined that Electrical system, moving components, and user awareness were the main hazard areas (chapter 3.9). The design of the Rig incorporated a waterproof housing (chapter 6.3) for the electrical system with a low voltage system supplying external components (Table 20.9). It has also been concluded that user awareness and training of anyone that would come in contact with the machine would reduce the mechanical hazards and user awareness problem (Chapter3.9).
2) The CAE requested that the Rig be industrial in nature (rigid and stiff). This has been achieved through the analysis and selection of critical components (Chapter 4,5). The decision was made to select suitable rails that provide rigidity (Table 20.4), and the sizing of the rails was determined appropriate through analysis of the 40mm x 40mm v-slot rails (chapter 5.3). The analysis shows that the maximum force on the Rig was 307N (Table 20.4). The models also indicate that the maximum deflection of the 1500mm beam was 0.24mm. Table 20.3 shows the maximum deflection of the meat platform was 0.005mm. This is the maximum deflection along the beam. The use of a dual-drive system (chapter 4.4.3) provided uniform movement along the x-axis. The

Mechanical system component selection (chapter 4.2 –4.4) all supported the formation of a structure with a high degree of rigidity.

3) This design and build research project provided positive test results (chapter 7). The machine has been designed and tested to be more accurate that the design objectives. There were two main areas identified for possible causes of inaccuracy. This concerns the; rigidity of the platform and slipping of the open-loop stepper motors. The rigidity has already been discussed, and the FSD is 0.3% maximum (chapter 3.3.1). The Rig has developed suitable control algorithms that both perform the run gear tasks, but also fulfil the required accuracy of the project (Chapter 6.4). Stepper motors resolution was another point highlighted for inaccuracies. Assuming no slippage, results of Test 1 (chapter 7.1), with 20N force and resolution of 1600 pulses/revolution, an accuracy of 0.03mm was determined (chapter 5.5). The accuracy is well within limits set by the CAE's requirements.
4) The design of the Rig incorporated the environment restrictions of weight and physical size. The Rig was designed and built to fit on a stainless-steel bench (table 20.11). The platform is a removable item and fits (chapter 6.1). The table is light enough to be able to be moved or even transported to a site. It is also designed around parts already selected by the CAE.
5) The design of the Rig considered the three main sensors and these sensors have been installed on the Rig (chapter 6.5). The sensors all can be adjusted for alignment in both the horizontal and vertical direction. The sensor positions have all been implemented with respect to their capabilities.
6) The physical design of the Rig used Creo parametric and Creo Simulate to create and test 3D models. The models were backed by hand calculations. The use of models was used to develop concepts and simulate reactions (table 20.13)
7) Some simple tests were completed (Chapter 7) with promising results. Test one was completed with a 20N force. Accuracy has been maintained throughout the whole run of the Rig. It returned to its starting position after 98 stops (figure 7.2). Test 2 under the same working conditions (Chapter 7) produced less perfect results (Figure 7.3) and inaccuracy where measured. The test record accumulated error over 18 runs. All test result fell within the accuracy limitation set in the objectives.

This section discusses the impact of the literature review and presents artefacts of evidence that all objectives have been met. There has been solid use of reference to this dissertation to confirm what has been established to produce the required results. A Technical specification table will now be presented.

Chapter 9 ..Final Conclusion and Recommendations

The study aimed to develop a Rig for use in the research of striploin. The study has achieved the design, build and testing of the mechatronic Rig. The Rig was built to specifications from a derive engineering technical specification. The Rig was constructed and then tested against the requirements outlined by the CAE.

- CAE requirements were incorporated into the design. The Rig build is stiff, has met budget requirements, complies to the environmental constraints and incorporates the required sensors. The size limitations of the Rig have been maintained. It fits within the environment while maintaining the ability to be portable and lightweight.
- Safety considerations of the Rig have been achieved. Electrical waterproof housings were used for electrical safety. Stability safety was achieved through a low centre of gravity and physical constraints. Mechanical safety was achieved by incorporating it into the design and limiting access to the Rig to experienced persons.
- The Rig met the technical specifications that were developed for the system. The technical specifications were implemented into the design and produced in the build.
- The detailed drawing was completed. Exploded views of the Rig were produced along with front, top and side views. Drawings of a base where created. Computer models of concepts and mechanical components were created and used for the build of the Rig.
- The motors and drives selected for the Rig, provide sufficient torque along each axis. It was decided that the speed of the Rig was not a critical aspect. The speed of operation was sufficient to do the task within an efficient time period for accurate collection of data.
- The overall performance requirements of the Rig have been achieved. The Rig achieved better position accuracy than 2% FSD and repeatability of 0.5% FSD while operating with a 20N force. The FSD was under 1% FSD and repeatability of o.1%FSD.
- Control algorithms were developed for the testing of the Rig. Three programs where written. One that helped with the initial test procedure and the second two for the final tests. The programs enabled the successful ability for a test to be carried out. The program enabled all system to be integrated into one system for use as an R&D tool.

9.1 Future Work

There will be a continual push for the development of Automation in the meat industry. The continual development of the rig is making the industry ready for Automation. This Rig has not been used as a research tool and needs to be commissioned to use. The control algorithms need to be further developed and incorporate sensor feedback. Sensor information has to be centralised. The Rig will then be able to be taken into abattoirs for testing of meat samples straight from the process line

Data gathered from the Rig needs to be consolidated, and models created that accurately represent how the meat reacts during processing. Future work will be able to discover meat reactions not yet known. This will inform the industry about their product and how to better deal with it. Through the use of the Rig collecting many samples, models will be created to reflect a normal.

This will then help develop methods and models to interact with other forms of meat product. Creating average maps of tissue interface, that can be developed for each type of meat the system researches. This will provide a risk analysis of exposing lean and provide tracks on where to best cut.

If and when the Rig concept is considered a viable option, more accurate mechanical structures could be incorporated. This may include machine cut components produced straight from drawings. Greater accuracy in part placement and development. The rig concept may even be transferred as an attachment to a robotic arm.

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Appendix A

A.1 **Project Specifications**

ENG4111/4112 Research Project Specification

For: Ben Cooney

Title: Food Robotics_2: Automated tissue discrimination in beef striploin during cutting.

Major: Mechatronic Engineering

Supervisors: Professor Brett, Fraser Border, and Professor Khodabandehloo

Sponsorship: Centre of Agricultural Engineering CAE

Enrolment: ENG4111 – ONC S1, 2020 ENG4112 – ONC S2, 2020

Project Aim: This research aims to design, build and examine a Rig for use within the meat processing industry that can provide support to sensors and mechanisms that fit a predetermined application for the study of high-Quality Striploin.

Program: Version 1, 18th March 2020

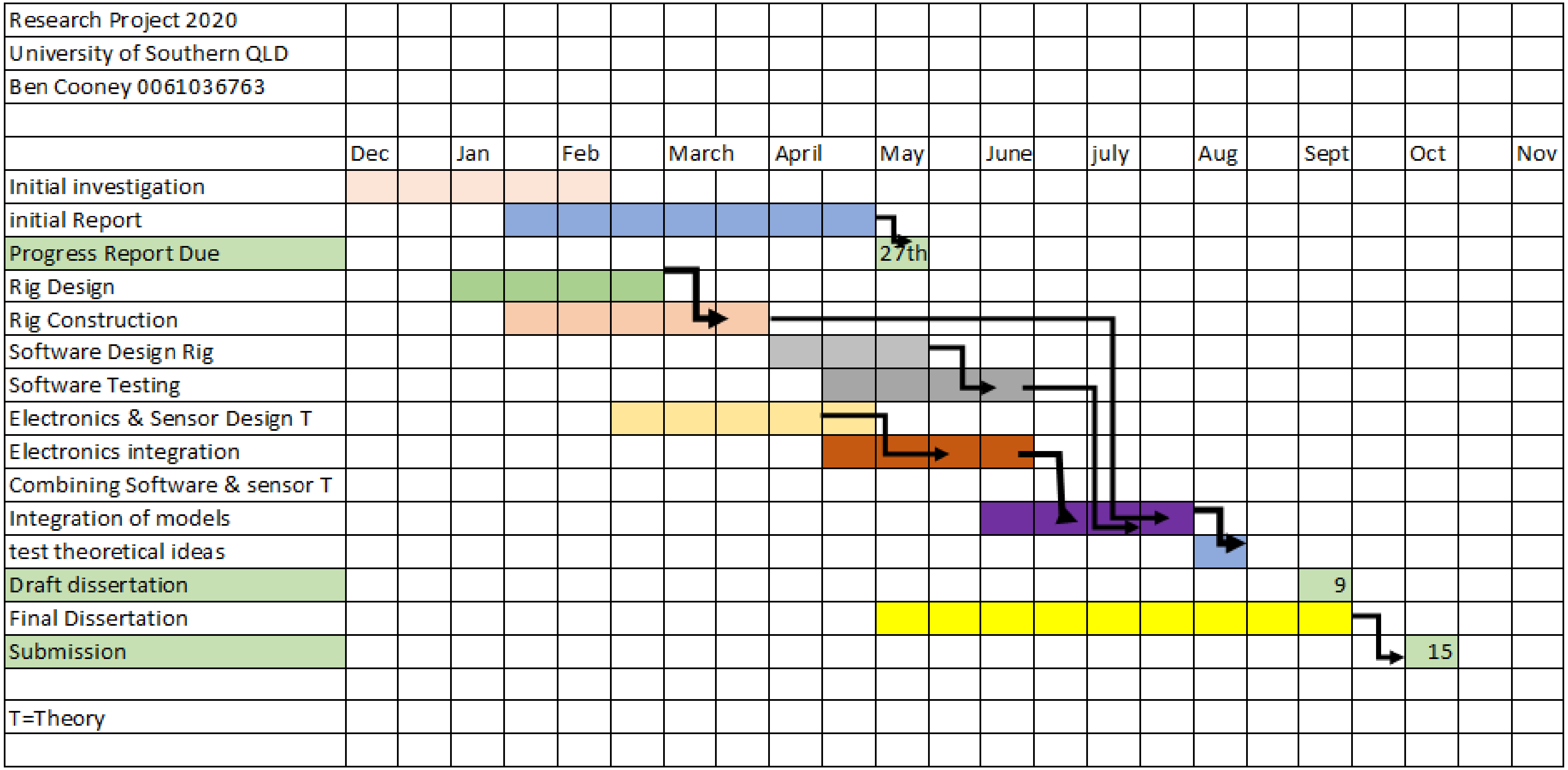
To add to the capabilities of automation within the beef processing industry and the devices that are already available, the following points will be considered in the research:

1) Report on the significance of robots within the meat processing industry
2) Design a Rig to discriminate between the fat and meat of a beef striploin.
3) Design a Rig considering the size requirements concerning space available and the product dimensions.
4) The design of the Rig will consider the requirements to be lightweight, rigid, and accurate.
5) Design a Rig to an engineering standard by considering the forces and moments that will be applied to it by cutters, rollers, and other mechanisms.
6) Provide calculations to show the performance of the Rig and how it fits the required applications.
7) The design of the Rig will be a mechatronic system and have structure, mechanisms, sensors and actuators.
8) Produce simple models to examine performance of specification (5).
9) Research the accuracy of the applied sensors considering the required performances across the range of operation.
10) To discuss the required sensors and their interface requirements. The sensors include LiDAR, vision system and ultrasound.
11) Consider the resolution of stepper motor motion and its required continual accuracy for positioning of the Rig.

If time permits.

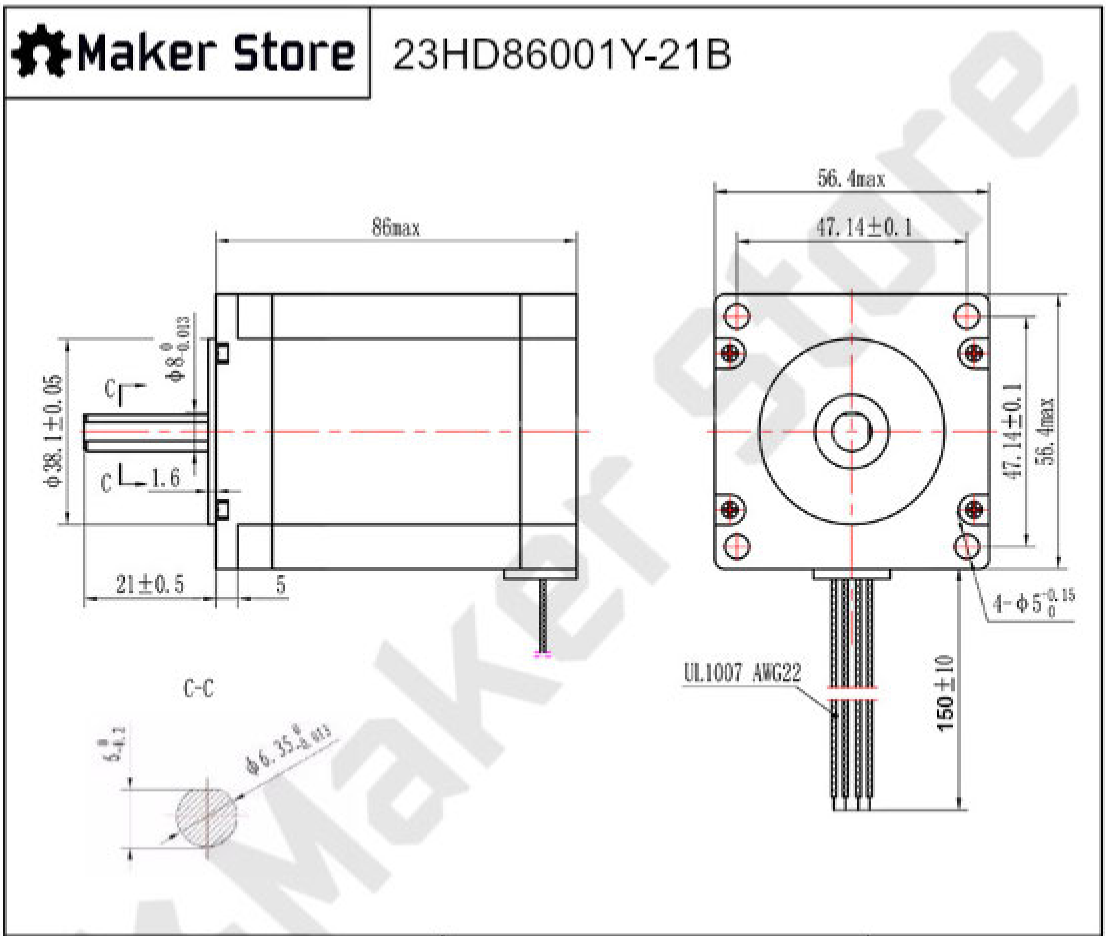
12) Write and test code for the operation of the stepper motors for the movement of the system.
13) Design and test a real-time way of testing the accuracy of the discriminated point.

A.2 Project Plan



Appendix B **Stepper Motor Data Sheets**

B.1 **The X-axis Stepper Motor Analysis**



General specification		Electrical specification		Wiring diagram
Step angle	1.8° ±5%	Rated voltage	3.6V	RED A, GREEN C, BLUE B, YELLOW D
Number of phase	2	Rated current	3A	
Insulation resistane	100MΩmin. (500V DC)	Resistance per phase	1.2Ω±10%	
Insulation class	Class B	Inductance per phase	4mH±20%	
Rotor inertia	600g.cm²	Holding torque	2.45N.m	
Mass	1.2kg	Detent torque	90mN.m	

Specification:

Model	ELEC-NEMA23-635-HT
Type	Hybrid
Phase	2
Step Angle	1.8˚
Motor Size	56.4 x 86mm
shaft	"D" shaft 21 xΦ6.35mm

Outlet way	"4" plug line
Motor Leads	Dupont line (1M)
Adapter drive	Two-phase step drive

Electrical Specifications:

Model No.	Step Angle	Motor Length	Rated Current	Resistance /Phase	Inductance /Phase	Holding Torque	Detent Torque	Inertia of Rotor	Lead
	(˚)	(L)mm	(A)	(Ω)	(mH)	(N.cm)	(N.cm)	$G.cm^3$	(no.)
17HS24-2104S	1.8	60	3.0	1.2	4	2.45Ncm	9	600	4

General Specification:

Precision angle step	±5% (full step, no charge)
Resistance accuracy	±10%
Precision inductance	±20%
Temperature Rise	??
Ambient temperature	??
Insulation resistance	100MΩ Min, 500VDC
Insulation Force	500VAC for a minute

B.2The Y-axis Stepper Motor Analysis

17HS24-2104S High Torque NEMA 17 Stepper Motor 65Ncm/92oz.in

The following specifications apply

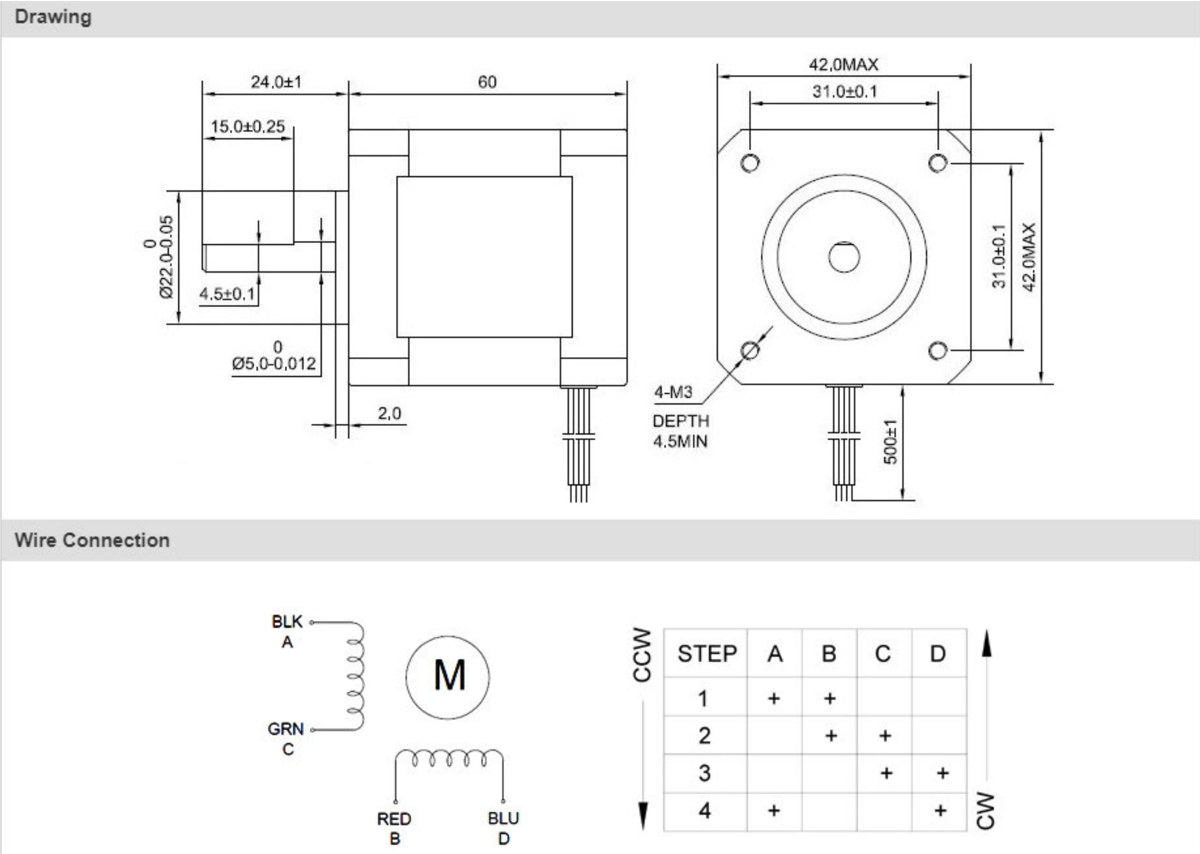


Table 18 Specifications for x-axis stepper motor

Specification:

Model	17HS24-2104S
Type	Hybrid
Phase	2
Step Angle	1.8˚
Motor Size	42 x 48mm
shaft	“D” shaft 21 xΦ5mm
Outlet way	“4” plug line
Motor Leads	Dupont line (1M)
Adapter drive	Two-phase step drive

Electrical Specifications:

Model No.	Step Angle	Motor Length	Rated Current	Resistance /Phase	Inductance /Phase	Holding Torque	Detent Torque	Inertia of Rotor	Lead
	(˚)	(L)mm	(A)	(Ω)	(mH)	(N.cm)	(N.cm)	$G.cm^3$	(no.)
17HS24-2104S	1.8	60	2.1	1.6	3	65Ncm	??	?	4

General Specification:	
Precision angle step	±5% (full step, no charge)
Resistance accuracy	±10%
Precision inductance	±20%
Temperature Rise	80deg Max (rated current, 2 phase on)
Ambient temperature	(- 20°)-(+ 50°)
Insulation resistance	100MΩ Min, 500VDC
Insulation Force	500VAC for a minute

B.3 The Z-axis Stepper Motor Analysis

The stepper motor is a NEMA 17 17HS3401-S

Table 19 Specifications for y-axis Stepper Motor

Specification:	
Model	17HS3401-S
Type	Hybrid
Phase	2
Step Angle	1.8°
Motor Size	42 x 34mm
Shaft	“D” shaft 21 xΦ5mm
Outlet way	“4” plug line
Motor Leads	Dupont line (1M)
Adapter drive	Two-phase step drive
Scope	3D Printers, Monitor Equipment, Medical Machinery, Textile Machinery, Packaging Machinery, Stage Lighting, Laser engraving, Automation Equipment, Non-standard Equipment, Placement machine etc.
Electrical Specifications:	

Model No.	Step Angle	Motor Length	Rated Current	Resistance /Phase	Inductance /Phase	Holding Torque	Detent Torque	Inertia of Rotor	Lead
	(°)	(L)mm	(A)	(Ω)	(mH)	(N.cm)	(N.cm)	$G.cm^3$	(no.)

17HS3401 - s	1.8	34	1.3	2.4	2.8	28	1.6	34	4

General Specification:	
Precision angle step	±5% (full step, no charge)
Resistance accuracy	±10%
Precision inductance	±20%
Temperature Rise	80deg Max (rated current, 2 phase on)
Ambient temperature	(- 20°)-(+ 50°)
Insulation resistance	100MΩ Min, 500VDC
Insulation force	500VAC for a minute

B.4 Stepper Motor

This section aims to work out the requirements of a stepper motor if speed were the requirement. It has been considered that 75mm every 1.5 seconds would provide quick enough movement.

How many pulses to move 3 inches in 1.5 seconds?

Screw pitch =2mm

1 rotation = 8mm

4 start

Tr8*8(P2)

The pulses / revolution can be set to 200, 400, 800, 1600, 3200 on the ramp 1.4 motor driver.

Step how many pulses to move 75mm:

$$75mm \times \frac{1\ revouliton}{8mm} \times \frac{800\ pulses}{revoluiton} = 7500\ pulses$$

The controller must do 7500 pulses in 1.5 seconds

$$\frac{7500}{1.5seconds} = 5000\frac{pulses}{second}$$

Positioning Accuracy:

$$\frac{8mm}{1rev} \times \frac{1rev}{1600pulses} = 0.01mm/pulse$$

Motor Speed required

$$75mm \times \frac{1rev}{8mm} = 9.375\ revoultions$$

Appendix

$$\frac{9.375revoultions}{1.5sec} = \frac{6.25rev}{sec} = 375rpm$$

Max Speed of the NEMA 17 stepper motors

$$\mathrm{Rev/sec} \ = \ \mathrm{V/(L * 2 * Imax)/(steps/rev)}$$

Minimum time/step

$$T = I \times \frac{L}{V} = 1.3 \times \frac{2.8}{12} = 0.607\ (milliseconds)$$

Max Power NEMA 17

$$pmax = I \times V = 15.6W$$

Account for speed up and Slow down

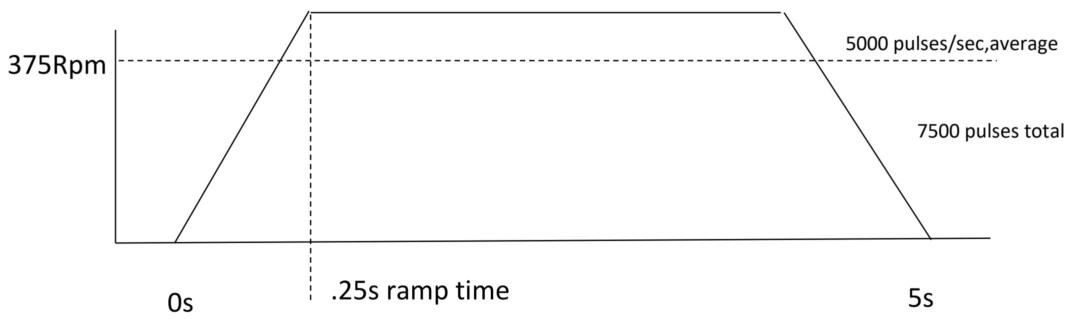


Figure 9-1 Account for speed up and slow down

Max rpm to account for speed up and slow down.

$$\max pulse\ per\ second = 750 \times 8 = 6000pulses/sec$$

$$\frac{6000pulses}{seconds} \times \frac{rev}{800pulses} = \frac{7.5rev}{s} = 450rpm$$

How much torque does stepper motor need?

$$Torque(T_{ttl}) = T_{run} + T_{accel}$$

$$T_{accel} = J_{ttl} \times \left(\frac{\Delta speed}{\Delta time}\right)$$

$$J_{ttl} = j_{motor} + j_{lead\ screw} + j_{carriage}$$

$$= 0.034Kg.cm^2\ + .03287Kg.cm^2 + 0.1172Kg.cm^2 = 0.18407Kg.cm^2$$

$$= .84 \times 10^{-5}Kg.m^2$$

$$T_{accel} = 84 \times 10^{-5}Kg.m^2 \times [\frac{8.24revps}{.25s}$$

$$= 0.00061kg.m.rev\ \times 2\pi\left(\frac{radians}{rev}\right)$$

$$= 0.0038kg.m = 0.03726527Nm$$

This value is very small torque. The screw drive has no weight as it moves along the Y-axis other than turning the bevel gears. The value could be up to double as it is moving two screw drives through the bevel gear configuration.

B.5 **Bevel Gear Calculations for Creo Design.**

P=pitch

D=pitch Diameter=25

N=number of teeth=20

P=pinion

G=gear

$$P = N/D \tag{25}$$

Pitch is Equal to 0.8

$Pitch\ angle = P_{\emptyset}$

$$P_{\emptyset} = \tan^{-1} N_p/N_g \tag{26}$$

The pitch angle is the angle between the axis and face of the pitch. In this case it is $45°\ as\ the\ ratio\ is\ 1:1$.

Calculate the Addendum= a

$$a = 1/P \tag{27}$$

The addendum is the difference between the outside diameter and the pitch diameter. This is also the difference the teeth gear extend past that diameter. In this case it is 1.25

Whole depth =h_t

$$h_t = \left(\frac{2.188}{P}\right) + 0.002 \tag{28}$$

The whole depth is the distance from the root diameter to the outside diameter =2.737

The dedendum=b

$$b = h_t - a \tag{29}$$

This is the difference between the root diameter and the pitch diameter =1.478

Base circle Diameter= D_b

$$D_b = D \cdot \cos{(20)} \tag{30}$$

=23.49

Root Diameter D_r

Appendix

$$D_r = D - 2b \tag{31}$$

$$= 22.044$$

Outside Diameter $= D_o$

$$D_o = D + 2a \tag{32}$$

$$= 27.5$$

The following involute curve equation was required.

r = 16.6116

ang = t * 90

s = (3.1416 * r * t) / 2

xc = r * cos(ang)

yc = r * sin(ang)

x = xc + (s * sin(ang))

y = yc - (s * cos(ang))

z = 0

Appendix C Code

C.1 Initial Test Code for Runnig steppers on Ramp1.4

Test code for stepper

```
#define X_STEP_PIN 54
#define X_DIR_PIN 55
#define X_ENABLE_PIN 38


void setup() {
pinMode(X_STEP_PIN , OUTPUT);
pinMode(X_DIR_PIN , OUTPUT);
pinMode(X_ENABLE_PIN , OUTPUT);
digitalWrite(X_ENABLE_PIN , LOW);
}

void loop () {
// the transition from high to low and back to high triggers the steps of the stepper
digitalWrite(X_STEP_PIN, LOW);

delay (200);                        //sets the stepper speed

digitalWrite(X_STEP_PIN , HIGH);
delay (200);
}
```

C.2 Code for Full Run of the Rig

```
#include <AccelStepper.h>

//define the enable pins for each axis

#define X_ENABLE_PIN 38

#define Y_ENABLE_PIN 56

#define Z_ENABLE_PIN 62


//define the pins to turn on 12v supply for D10, and D9

#define FAN_PIN      9   //define pin for cooling fan

#define Lights_pin   10   //define pin for cooling lights

#define USSoliniod    8   //define pin for ultrasound solinoide

#define stepsPerRevolution 200


AccelStepper stepperX(1,54,55);   //1= Easy Driver interface
```

```
                    //mega pin 2 connected to Step pin of A4988
                    //mega pin 3 connected to Dir pin of A4988
AccelStepper stepperY(1,60,61);   //1= Easy Driver interface
                    //mega pin 2 connected to Step pin of A4988
                    //mega pin 3 connected to Dir pin of A4988
AccelStepper stepperZ(1,46,48);   //1= Easy Driver interface
                    //mega pin 2 connected to Step pin of A4988
                    //mega pin 3 connected to Dir pin of A4988
//Stepper Travel Variables
long TravelX;         //Used to store the X value entered in the Serial Monitor
long TravelY;         //Used to store the Y value entered in the Serial Monitor
long TravelZ;         //Used to store the Z value entered in the Serial Monitor
int move_finished=1;      //Used to check if move is completed

int x = 0;
int y = 0;
int z = 0;
float X_FROM_ORIGIN = 0;  //To hold the distance from the origin to the x center of the run
int Y_FROM_ORIGIN= 0;  //To hold the distance from the origin to the y center of the run
int Z_FROM_ORIGIN= 0;  //To hold the distance from the platform to the Z start of the run
int inPut;
//int NEXTSTEP=0;
//String Fullrun;
//String Circuit;
//String UserInput;


void setup() {

  Serial.begin(9600);      //Start the serial monitor with speed of 9600 bauds
 // set enable pins on the ramp 1.4 to output
```

```
pinMode(X_ENABLE_PIN    , OUTPUT);
pinMode(Y_ENABLE_PIN    , OUTPUT);
pinMode(Z_ENABLE_PIN    , OUTPUT);
pinMode(FAN_PIN , OUTPUT);
pinMode(Lights_pin , OUTPUT);
pinMode(USSoliniod  , OUTPUT);

  //Print out Instructions on the Serial Monitor at Start
  Serial.println("Enter '1 ' to position sensors at start of run");
  Serial.println("Enter '2' for circuit run ");
  Serial.println("Enter '3' return to origin");
  Serial.println("Enter '4' reset origin");
  Serial.println("Please Enter decision Now: ");

String msg = "Enter Travel distance seperated by a comma:X,Y,Z";
String msg2 = " Please enter move now";

  //Set Max Speed and Acceleration of each Steppers
stepperX.setMaxSpeed(750.0);       //Set Max Speed of X axis
stepperX.setAcceleration(10000.0);    //Acceleration of X axis



stepperY.setMaxSpeed(500.0);        //Set Max Speed of Y axis
stepperY.setAcceleration(10000.0);   //Acceleration of y axis

stepperZ.setMaxSpeed(500.0);        //Set Max Speed of Z axis
stepperZ.setAcceleration(500.0);   //Acceleration of Z axis

//set 12v D8 D9 D10 on or off
digitalWrite(FAN_PIN    , HIGH);    //turn fan HIGH to cool motor driver y and z direction
digitalWrite(Lights_pin , HIGH);    //turn lights HIGH to light the bench
```

```
digitalWrite(USSoliniod , LOW);     //turn solenoidLOW so that only activates in program to push
ultrasound up

}

void loop() {

//This will detect if the user has imput a character into the imput and the imput will

//decide what the users selected decision will do:

if (Serial.available() > 0) { //dependent on value coming from serial imput

inPut = Serial.read();       // assignes the input to inPut


switch (inPut){


//  Case 1 is designed take sensors to postion start.

case '1' :

Serial.println("made it this far");

//call subroutine to position steppers at the

//x axis 1 revolution is 59.2mm and the holes are 40mm apart  and y axis is 37 mm apart

X_FROM_ORIGIN = -4254;        //stick  -459.46 the origin is 17mm from center of hole along x axis
1600 pluses

                          //       -4254.05                  157.4

Y_FROM_ORIGIN= 1000;          //the origin is 40mm from center of hole along y axis one revolution is
8mm 200 pluses

Z_FROM_ORIGIN= 0;

GotoORIGin(X_FROM_ORIGIN ,Y_FROM_ORIGIN,Z_FROM_ORIGIN);

Serial.println(inPut);

break;

case '2' :

//Circuit();

inPut =2;

break;


// case to recentre to starting point

 case '3' :
```

```
X_FROM_ORIGIN =0;       //the origin is 17mm from center of hole along x axis 1600 pluses
Y_FROM_ORIGIN= 0;        //the origin is 50mm from center of hole along y axis one revolution is
8mm 200 pluses
Z_FROM_ORIGIN= 0;
GotoORIGin(X_FROM_ORIGIN ,Y_FROM_ORIGIN,Z_FROM_ORIGIN);
break;
}}

//if (NEXTSTEP ==3){
//X_FROM_ORIGIN =0;       //the origin is 17mm from center of hole along x axis 1600 pluses
//Y_FROM_ORIGIN= 0;        //the origin is 50mm from center of hole along y axis one revolution is
8mm 200 pluses
//Z_FROM_ORIGIN= 0;
//GotoORIGin(X_FROM_ORIGIN ,Y_FROM_ORIGIN,Z_FROM_ORIGIN);
//}

if (inPut == 2){
Serial.println("step1");
delay(10);
while (y<=7){;   //  7 stops along the y axis
int posy = (y*4.62*200)+Y_FROM_ORIGIN;   //4.62

while (x<=17){  // 17 stops along the x axis
  digitalWrite(USSoliniod , HIGH);
  delay(500);
  digitalWrite(USSoliniod , LOW);
Serial.println("step3");

int posx = (-x*0.7*1600)+X_FROM_ORIGIN;   // 0.6757
int posz;
GotoORIGin(posx,posy,posz);
```

```
x++;
delay(1000);
}
y++;
x=0;
}
y=0;
delay(10);
}
//NEXTSTEP=3;
}
/*this will take the stepper motors to the origin. The origin will be a mark on the
 * stainless stell platform that will hold the striploin.
 */
void GotoORIGin (int X1, int Y1, int Z1){


stepperX.runToNewPosition(X1);
stepperY.runToNewPosition(Y1);
stepperZ.runToNewPosition(Z1);


 Serial.println("Please input 2 to continue");
}
void Circuit (){
//set oRIGon back to zero
stepperX.setCurrentPosition(0);
stepperY.setCurrentPosition(0);
stepperZ.setCurrentPosition(0);
Serial.println("Finished");
//take steppers to first hole
stepperX.runToNewPosition(100);
stepperY.runToNewPosition(100);
```

```
stepperZ.runToNewPosition(100);




}
```

C.3 Code for 'Rig Running to a Coordinate'

```
//Arduino Code for controling 3 axis stepper motor for Meat descrimination
#include <AccelStepper.h>
#define X_ENABLE_PIN 38   //set enable pin for stepper x direction
#define Y_ENABLE_PIN 56   //set enable pin for stepper y direction
#define Z_ENABLE_PIN 62   //set enable pin for stepper z direction
#define FAN_PIN      9   //fan pin D9 12v
#define Lights_pin    10  //light pin D10  12v
#define USSoliniod    8   //define pin for ultrasound solinoide D8
#define stepsPerRevolution 200

// confiugre stepper pins x,y,z
AccelStepper stepperX(1, 54, 55); //1= Easy Driver interface
                        //mega pin 2 connected to Step pin of A4988
                        //mega pin 3 connected to Dir pin of A4988
AccelStepper stepperY(1, 60, 61); //1= Easy Driver interface
                        //mega pin 2 connected to Step pin of A4988
                        //mega pin 3 connected to Dir pin of A4988
AccelStepper stepperZ(1, 46, 48); //1= Easy Driver interface
                        //mega pin 2 connected to Step pin of A4988
                        //mega pin 3 connected to Dir pin of A4988
//define stepper variables
long TravelX;           //Used to store the X value entered in the Serial Monitor
long TravelY;           //Used to store the Y value entered in the Serial Monitor
```

```
long TravelZ;                  //Used to store the Z value entered in the Serial Monitor
int move_finished = 1;         //Used to check if move is completed



void setup() {
  Serial.begin(9600);          //Start the serial monitor with speed of 9600 bauds
//configure pins and library commands
  pinMode(X_ENABLE_PIN , OUTPUT);
  pinMode(Y_ENABLE_PIN , OUTPUT);
  pinMode(Z_ENABLE_PIN , OUTPUT);
  pinMode(FAN_PIN , OUTPUT);
  pinMode(Lights_pin  , OUTPUT);
  pinMode(USSoliniod  , OUTPUT);

pinMode(X_START_PIN,  INPUT);
pinMode(X_END_PIN,    INPUT);
pinMode(Y_START_PIN,  INPUT);
pinMode(Y_END_PIN,    INPUT);
pinMode(Z_START_PIN,  INPUT);
pinMode(Z_END_PIN,    INPUT);

digitalWrite(X_START_PIN, HIGH);
digitalWrite(X_END_PIN, HIGH);
digitalWrite(Y_START_PIN, HIGH);
digitalWrite(Y_END_PIN, HIGH);
digitalWrite(Z_START_PIN, HIGH);
digitalWrite(Z_END_PIN, HIGH);
  //Print out Instructions on the Serial Monitor at Start
  Serial.println("Enter Travel distance seperated by a comma:X,Y,Z  ");
  Serial.println("Enter Move Values Now: ");
```

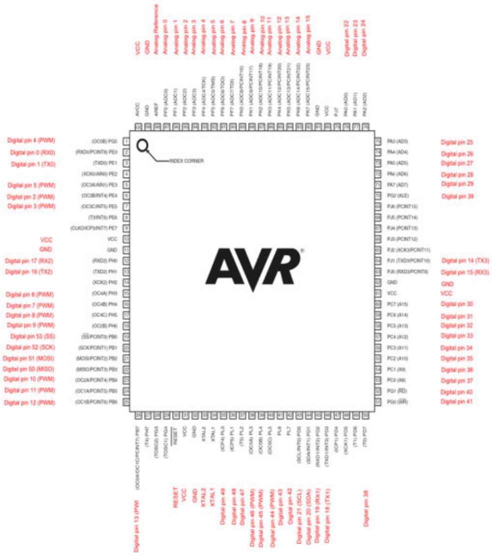
```
  //Set Max Speed and Acceleration of each Steppers
  stepperX.setMaxSpeed(750.0);       //Set Max Speed of X axis
  stepperX.setAcceleration(10000.0);    //Acceleration of X axis



  stepperY.setMaxSpeed(750.0);        //Set Max Speed of Y axis
  stepperY.setAcceleration(10000.0);   //Acceleration of y axis


  stepperZ.setMaxSpeed(500.0);        //Set Max Speed of Z axis
  stepperZ.setAcceleration(3000.0);   //Acceleration of Z axis


  //turn fan and lights on
  digitalWrite(FAN_PIN    , HIGH);
  digitalWrite(Lights_pin     , HIGH);
  digitalWrite(USSoliniod , LOW);     //turn solenoidLOW so that only activates in program to push
ultrasound up
}




void loop()  {


  while (Serial.available() > 0) {


    move_finished = 0;                //Set the variable for checking move of the Steppers


    TravelX = Serial.parseInt();       //Put First numeric value from buffer in TravelX variable
    Serial.print(TravelX);
    Serial.println("X Travel");
    //numrical value is steps between holes 1 revolution is 59.2mm with hole distance at 40mm
```

```
  //the motor is set to 1600 pulses per revolution  40mm/59.2mm  * 800pulses
  TravelX = TravelX * -541;


  TravelY = Serial.parseInt();       //Put First numeric value from buffer in TravelY variable
  Serial.print(TravelY);
  Serial.println("Y Travel");
  //
  TravelY = TravelY * 4.625 * 200;         //numrical value is steps between holes
  //4.75*200
  TravelZ = Serial.parseInt();       //Put First numeric value from buffer in TravelZ variable
  Serial.print(TravelZ);
  Serial.println("Z Travel");
  TravelZ = TravelZ * 10;           //numrical value is steps between holes




  stepperX.moveTo(TravelX);         //Set new move position for X Stepper
  stepperY.moveTo(TravelY);         //Set new move position for Y Stepper
  stepperZ.moveTo(TravelZ);         //Set new move position for Z Stepper



  delay(1000);                     //Wait 1 second before moving the Steppers
  Serial.print("moving Steppers into position...");
 }
 //Check if the steppers have reached desired position
 if ((stepperX.distanceToGo()  != 0)  ||  (stepperY.distanceToGo()  != 0) ||  (stepperZ.distanceToGo()
!= 0)) {
  stepperX.run(); //Move Stepper X into positon
  stepperY.run(); //Move Stepper Y into positon1
  stepperZ.run(); //Move Stepper Z into positon
 }
```

```
  //If move is complete display message on Serial Monitor
  if ((move_finished == 0) && (stepperX.distanceToGo() == 0) && (stepperY.distanceToGo() == 0) &&
(stepperZ.distanceToGo() == 0)) {
    Serial.println("Completed!");
    Serial.println("");
    Serial.println("Enter Nest Move values(0,0,0 for reset:");  //Get ready for new Serial monitor
values
    move_finished = 1;    //reset move variables
  }
}
```

Appendix D MCU

D.1 Arduino Mega 2560 Pin Diagram



D.2 Schematics for Arduino Ramp 1.4 shield {Reprap, 2020}

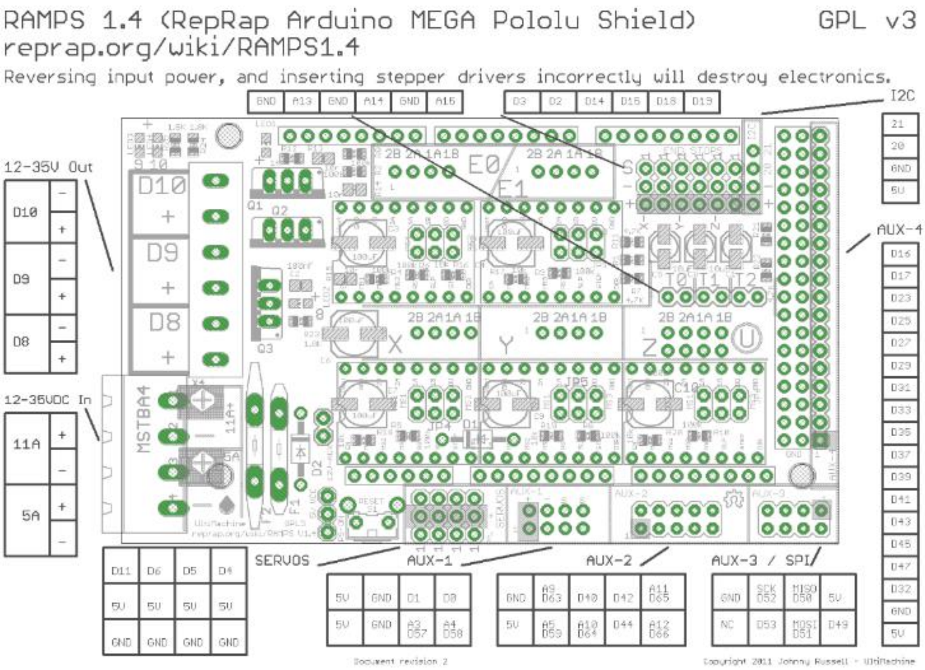


Figure 9-2 Pin Layout of Ramp 1.4

D.3 **Circuit Explanation**

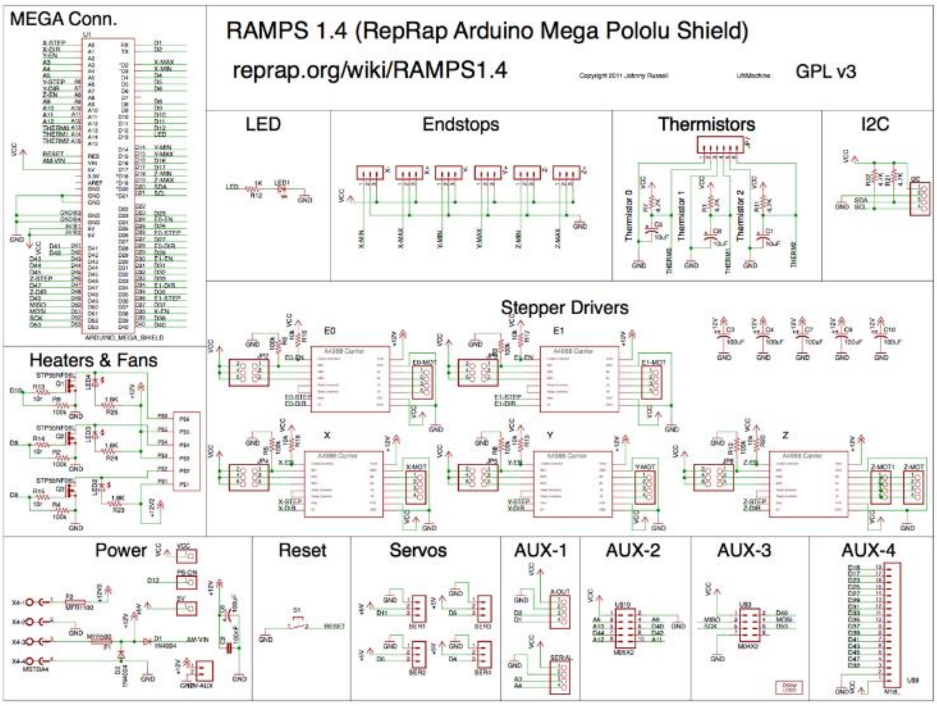


Figure 9-3 Circuit explanation of Ramps 1.4

D.4 **Circuit Diagram**

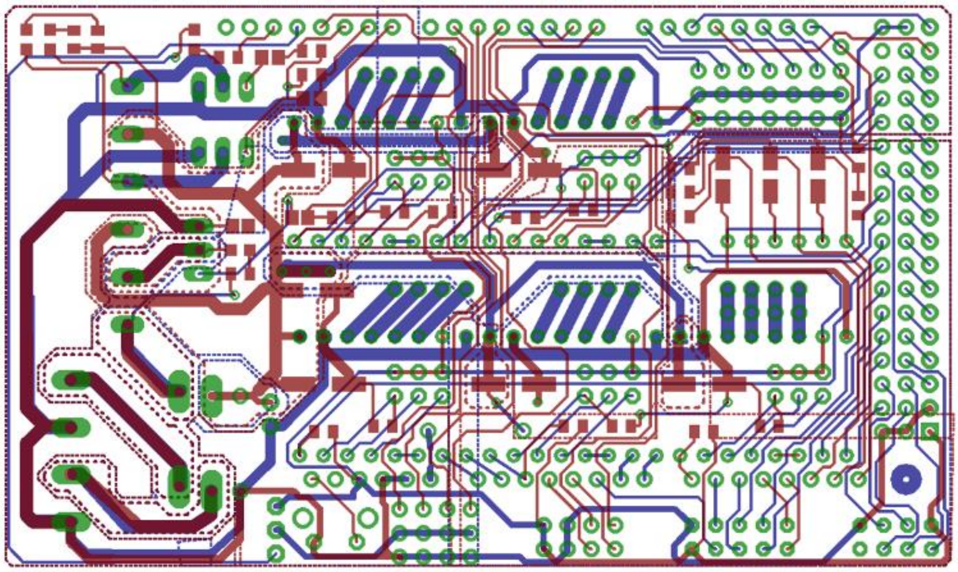
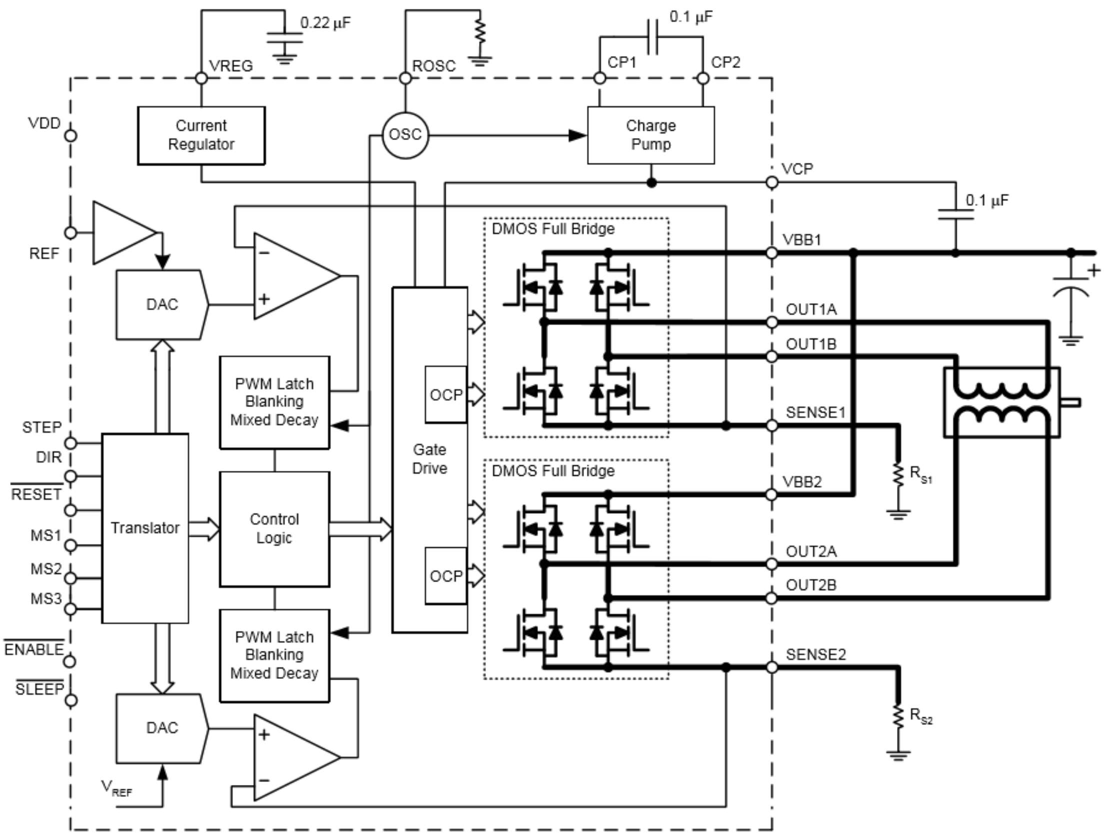


Figure 9-4 PCB circuit diagram of Ramps 1.4

D.5 A4988 Functional Block Diagram(Allegro Microsystems, 2020)

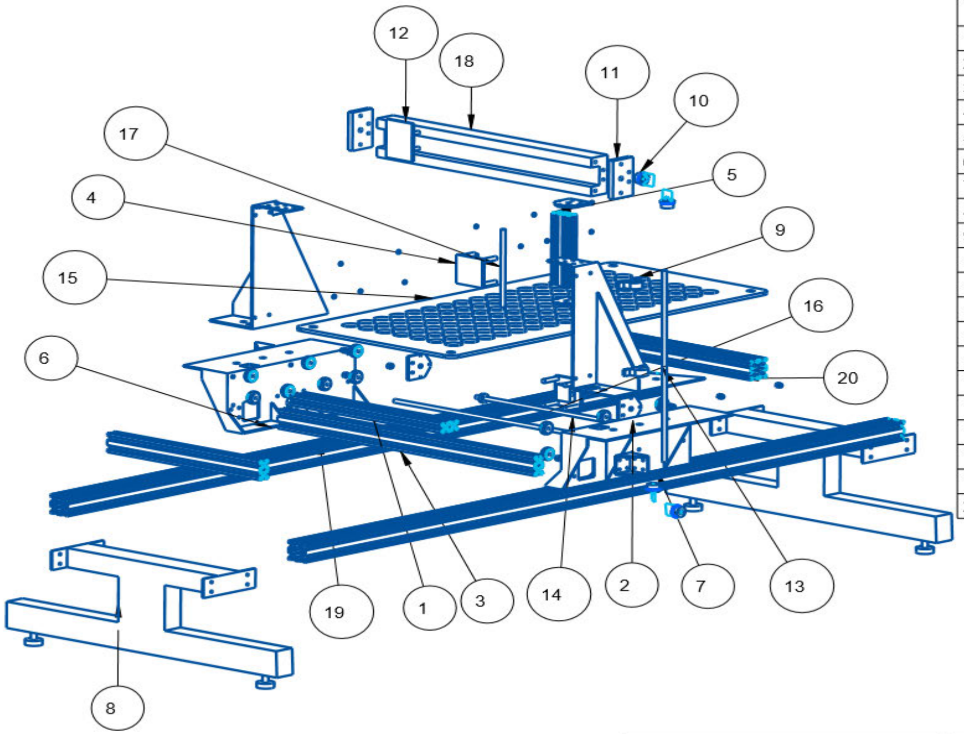
Functional Block Diagram



Appendix E **Models of Rig**

E.1 **Full Rig**

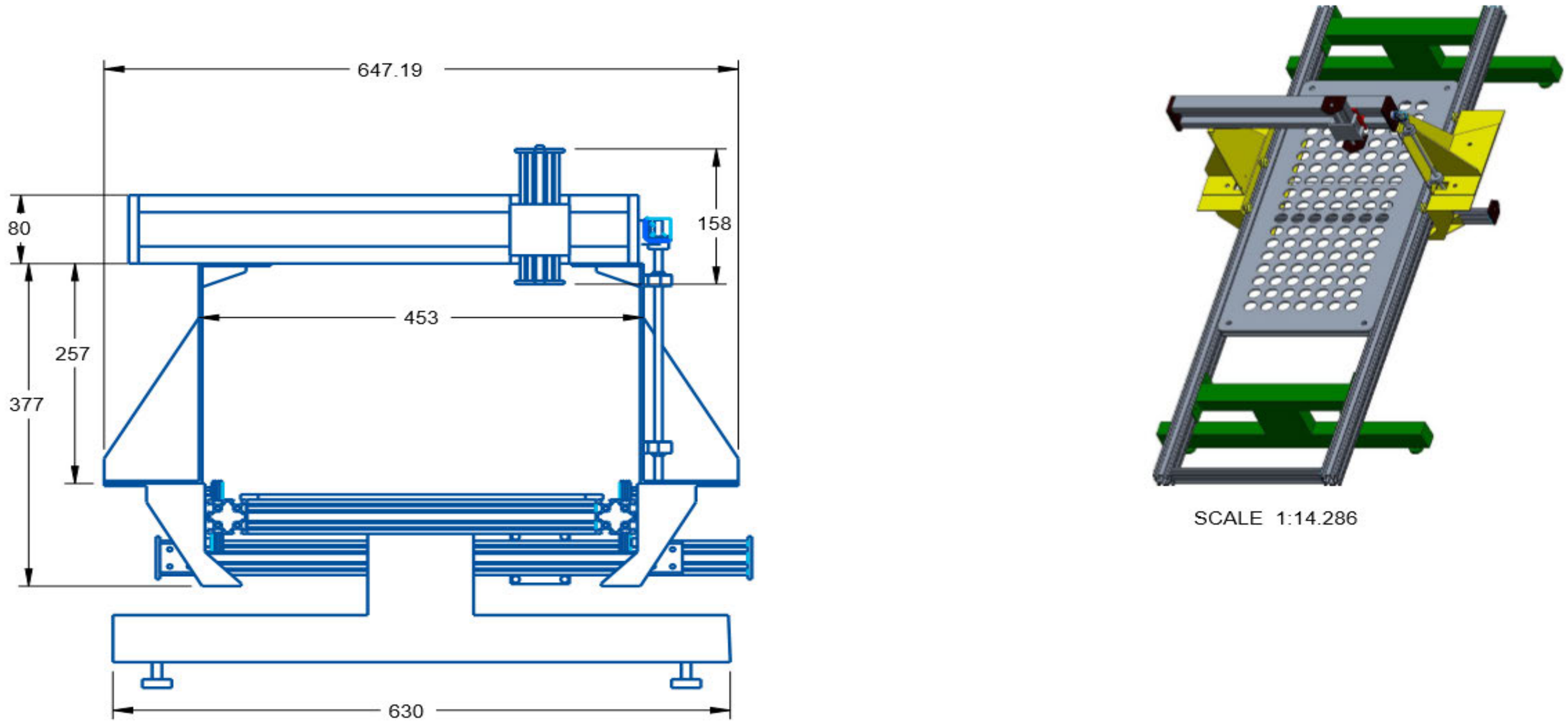
E.1.1 **Exploded View of the Rig**

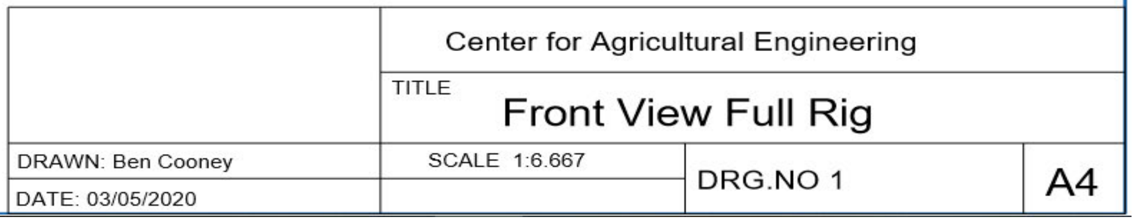


Index	component name	component type	quantity
1	2020	PART	2
2	2020BOTTOMEND	PART	4
3	2020BOTTOMESLIDE	PART	1
4	2020SLIDINGRACK	PART	2
5	2020VERTICAL	PART	1
6	ASM0001	ASSEMBLY	1
7	ASM0002	ASSEMBLY	1
8	BASE	PART	2
9	BEARING_FOR_SCREW	PART	2
10	BEVEL_GEARS	ASSEMBLY	2
11	CSLOT_SLIDER	PART	2
12	CSLOT_SLIDER_WHEEL	PART	1
13	GEARSHAFT	PART	1
14	MAINDRIVESHAFT	PART	1
15	PLATFORM	PART	1
16	SCREWBOTTOM	PART	1
17	SCREWVERTICAL	PART	1
18	TOP_RUNNER_CSECTION	PART	1
19	VSLOT40_40	PART	2
20	VSLOT40X40_357	PART	1

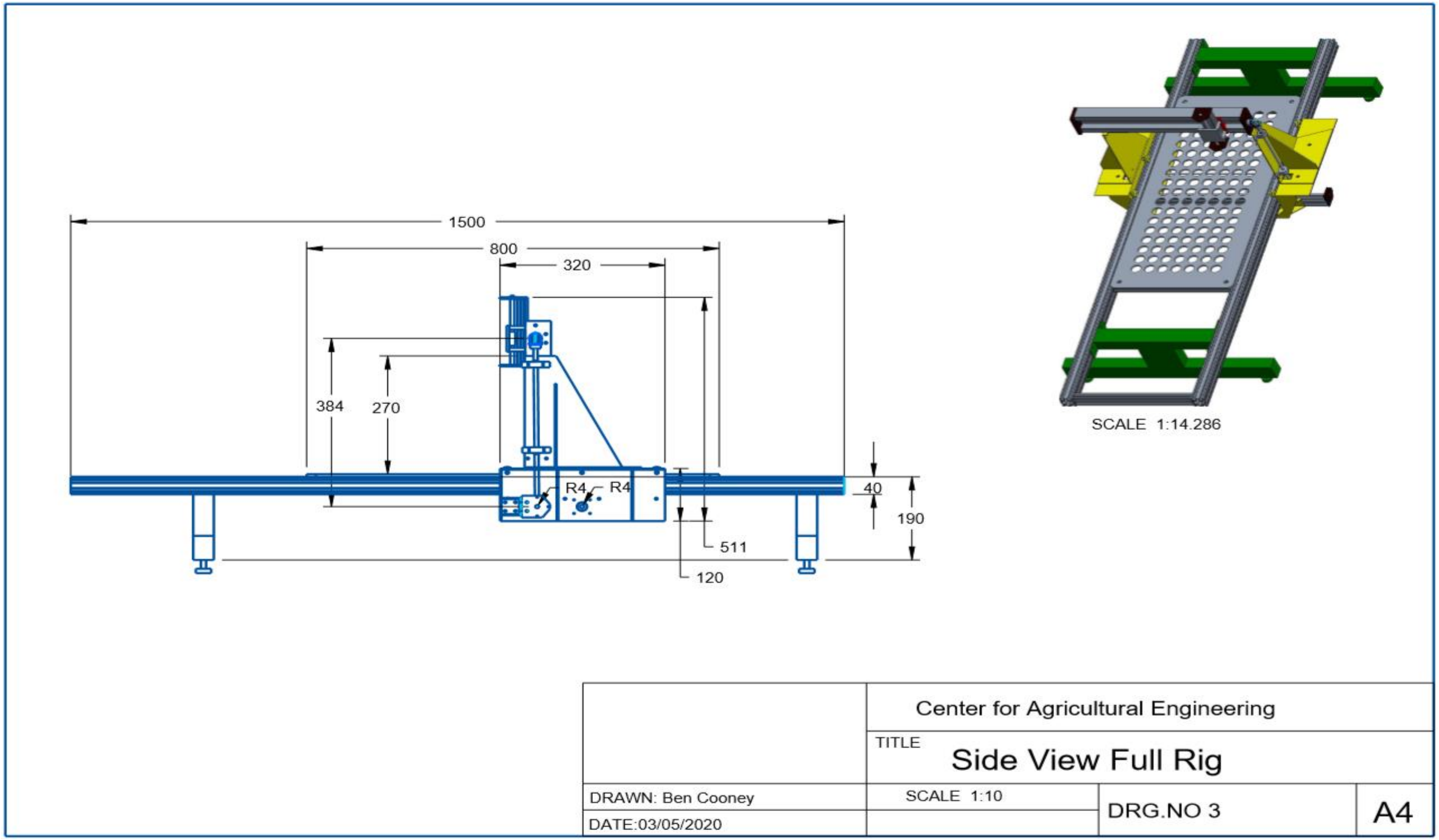
	Centre for Agricultural Engineering		
	TITLE: Exploded view of the Rig		
DRAWN:Ben Cooney	SCALE 1:10	DRG.NO 1	A4
DATE: 27/05/2020			

E.1.2**Front View of Rig**

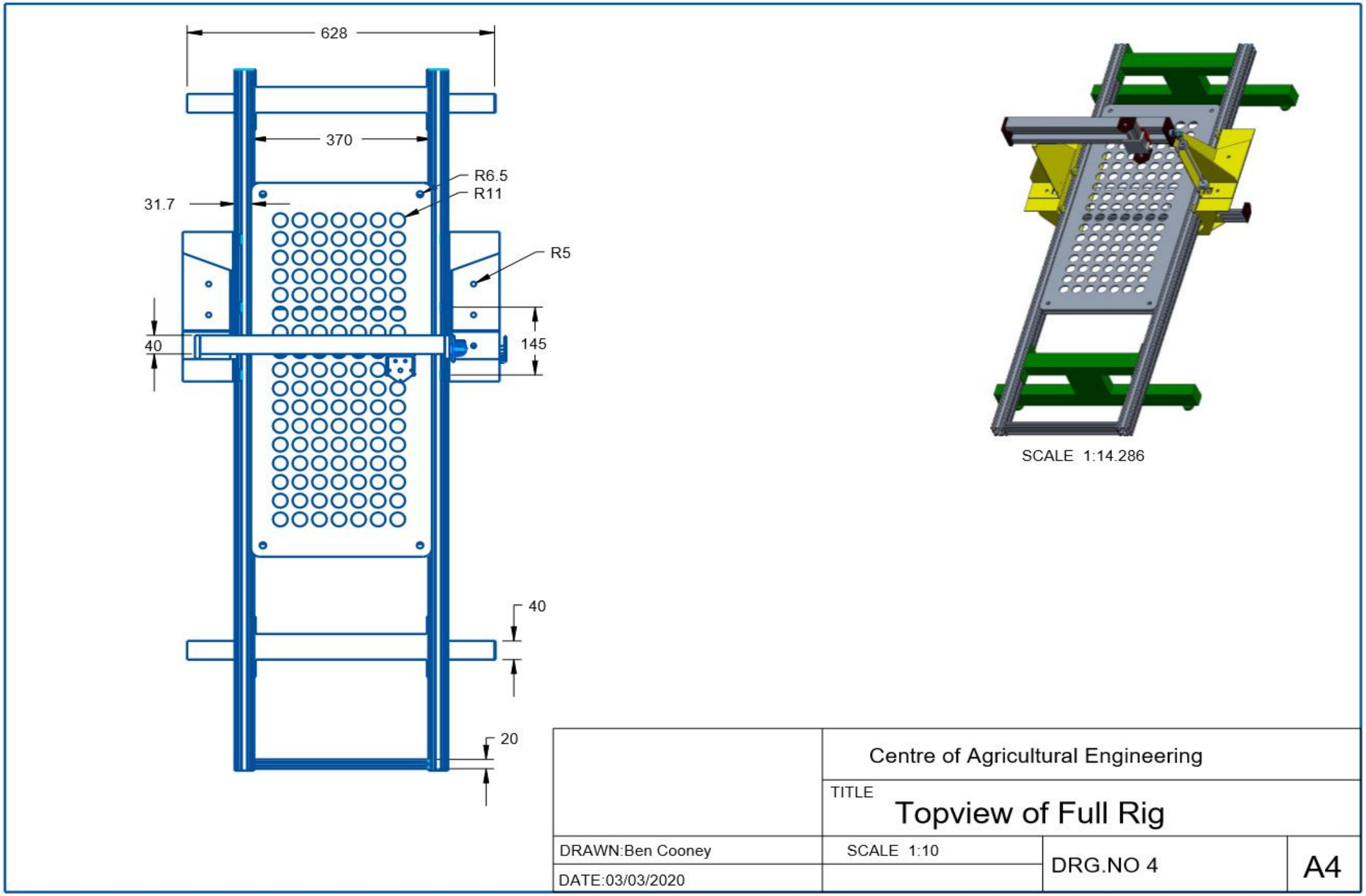




E.1.3 **Side View of Rig**



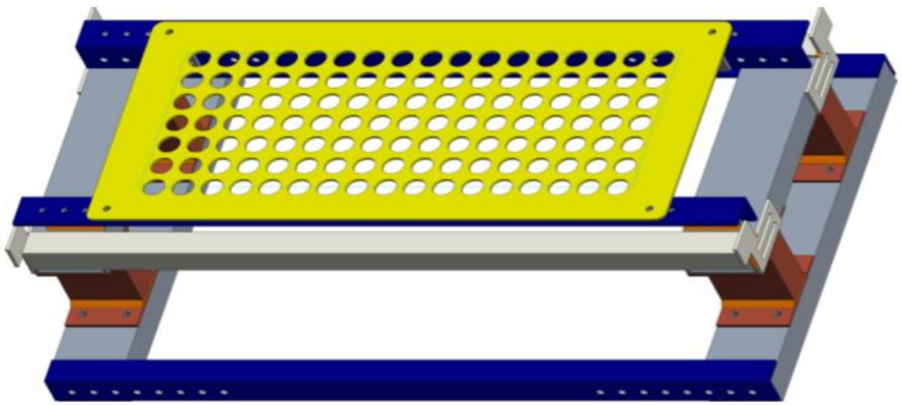
E.1.4 **Top View**


628
370
R6.5
R11
31.7
R5
40
145
40
20
SCALE 1:14.286
Centre of Agricultural Engineering
TITLE
Topview of Full Rig
DRAWN:Ben Cooney
SCALE 1:10
DRG.NO 4
A4
DATE:03/03/2020

E.2 Future Base

E.2.1 Full View

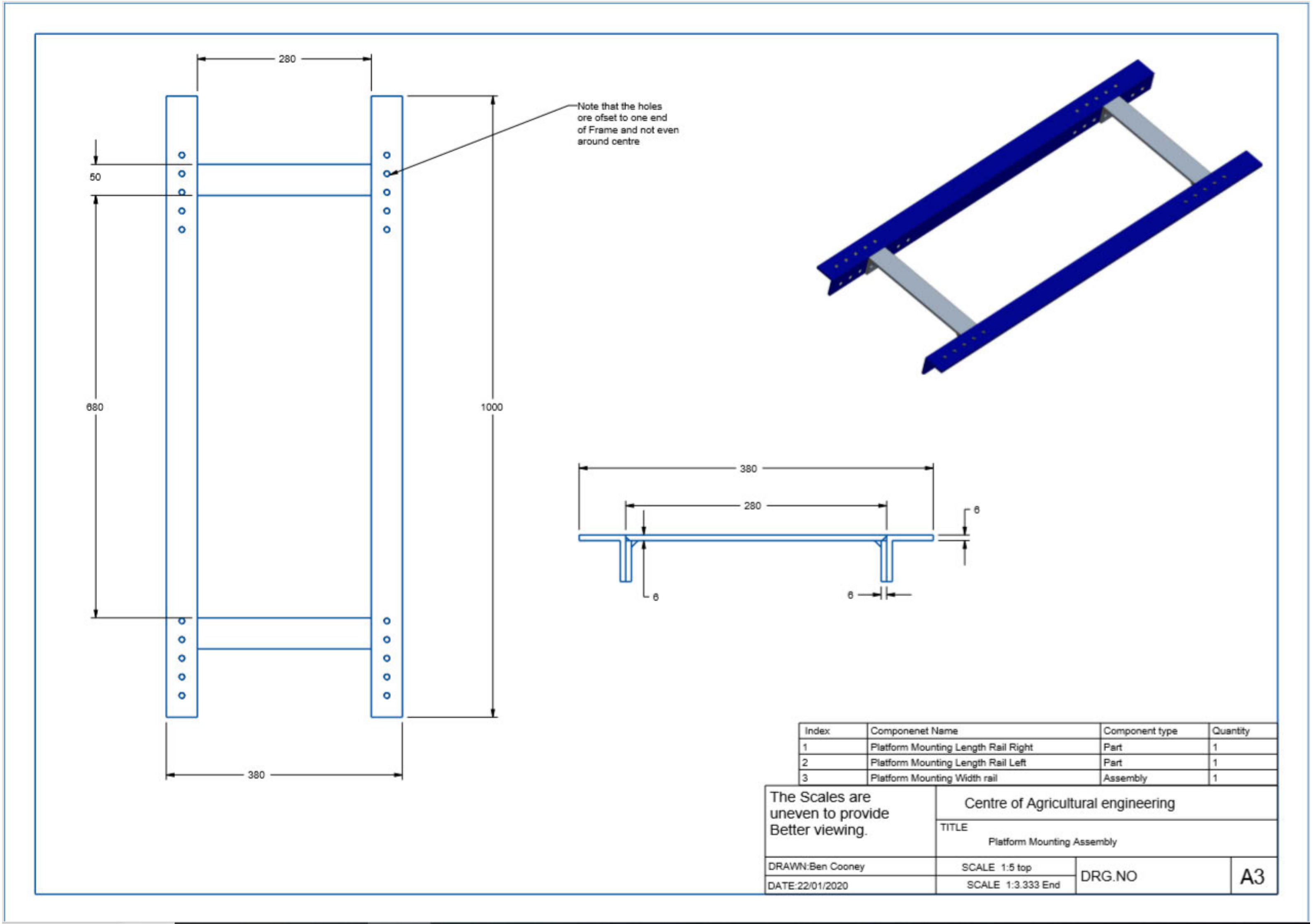
Index	Component Name	Comonent Type	QTY.
1	BASE_PLATE2	PART	1
2	BASEANGLEJOINER	ASSEMBLY	2
3	BASEENDASS	ASSEMBLY	2
4	PLAFORM_MOUNT_ASS	ASSEMBLY	1
5	RIGMOUNTASS	ASSEMBLY	2



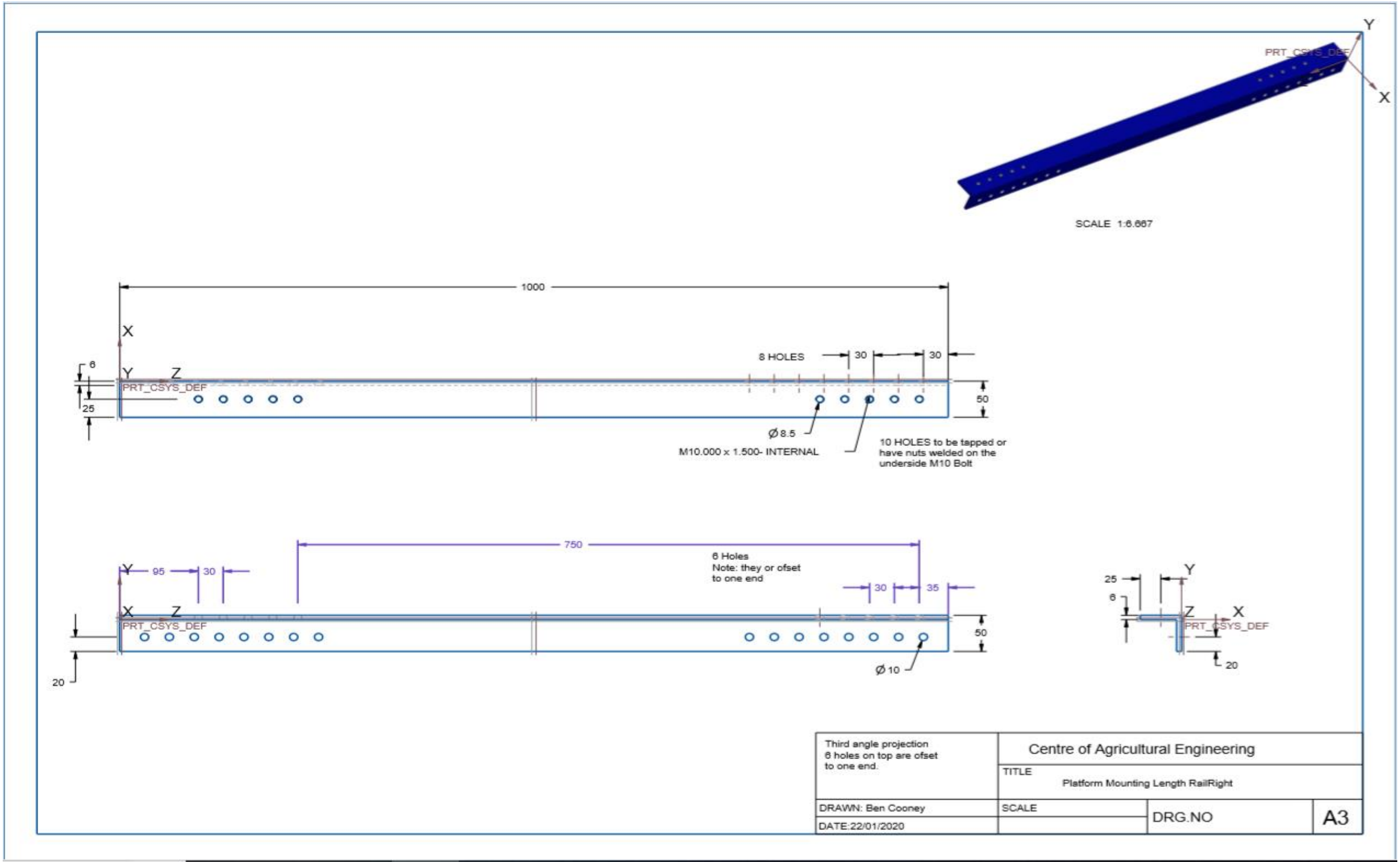
The Base will be Constructed out of 304 Stainless Steel	Centre For Agricultural Enginnering TITLE Full Assembaly Of Base		
DRAWN:Ben Cooney	SCALE 1:5	DRG.NO	A3
DATE:22/01/2020			

E

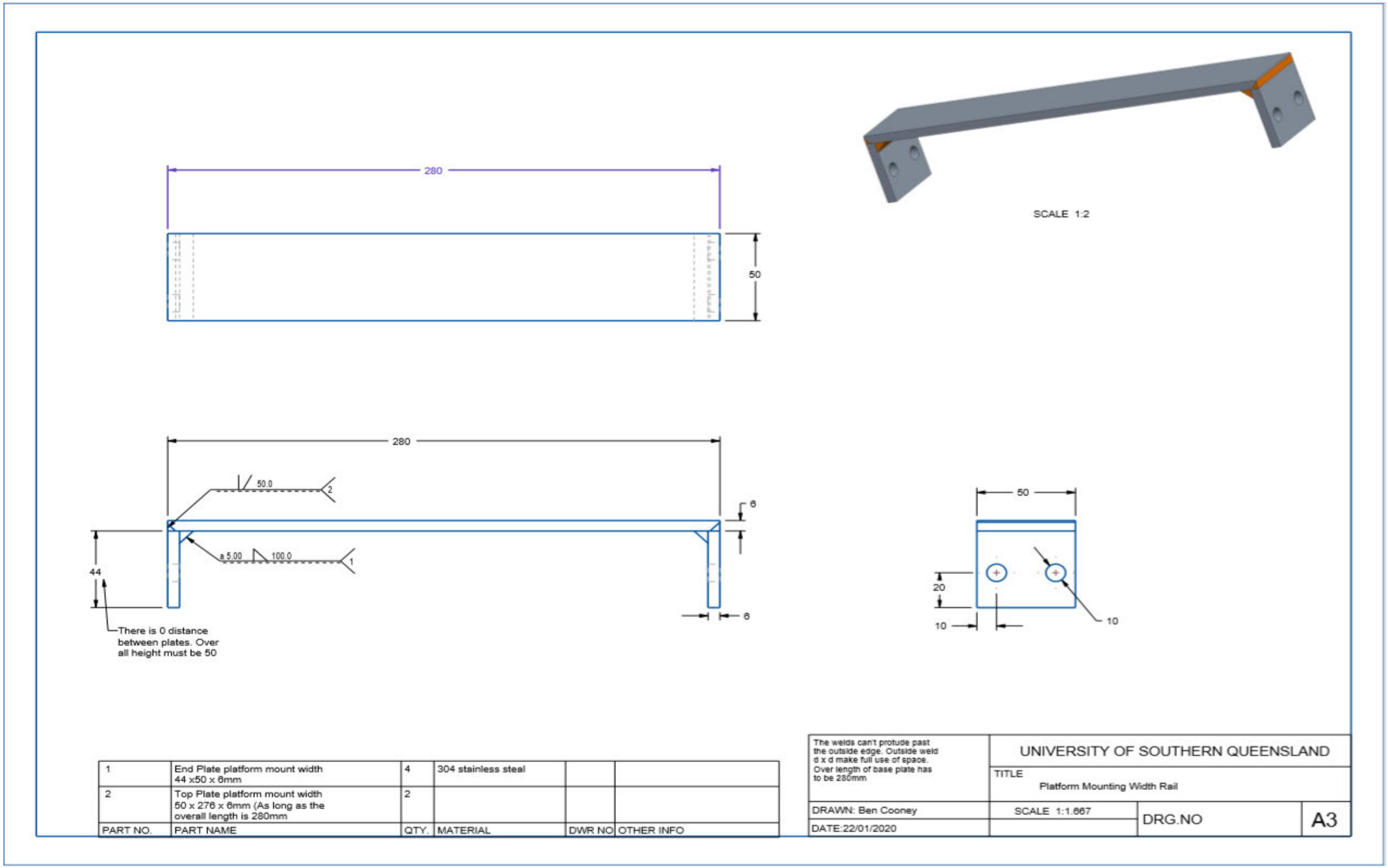
E.2.1.1 Platform Holder



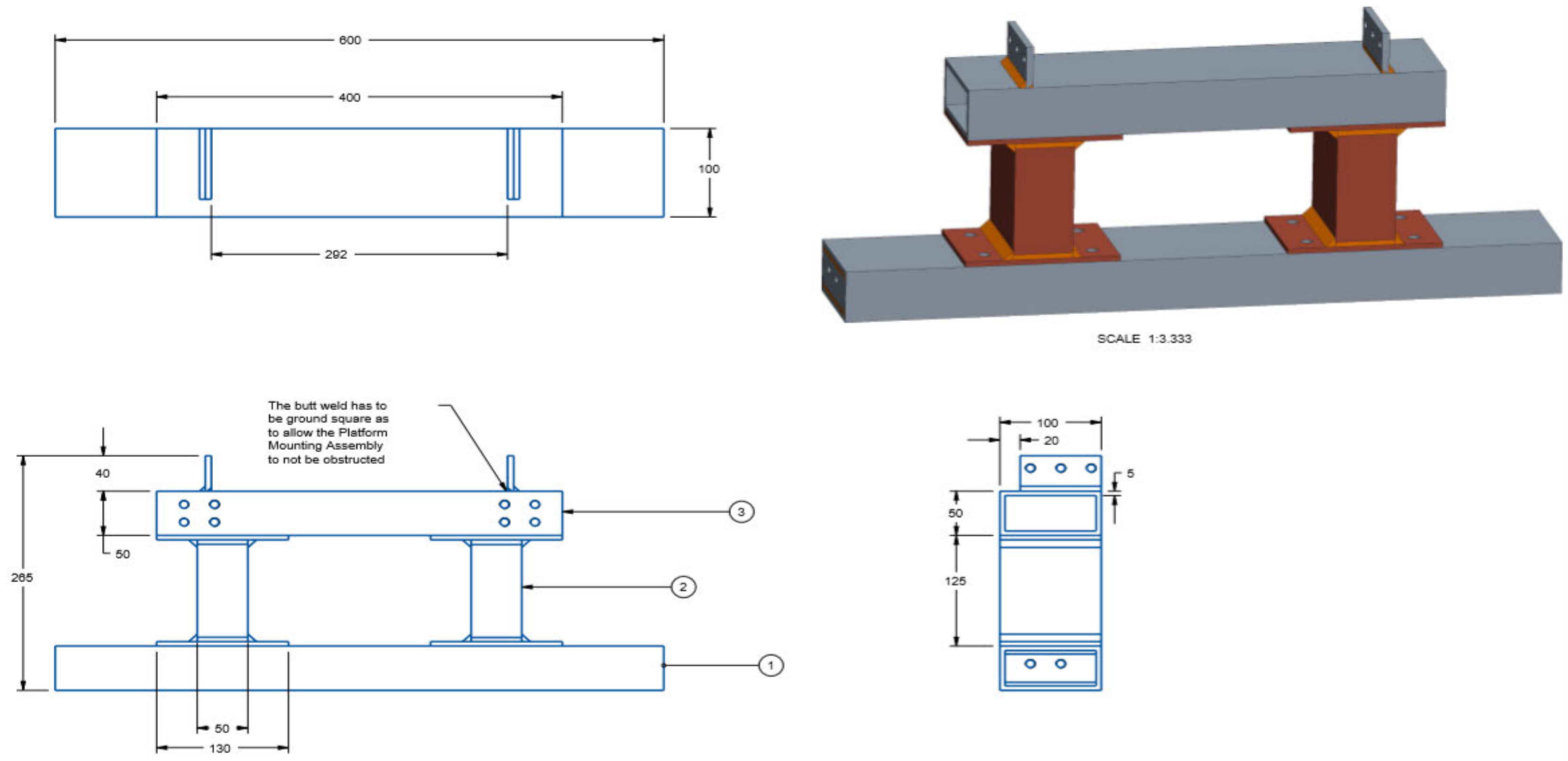
E.2.1.2 Platform rails



E.2.1.3 Platform width rail



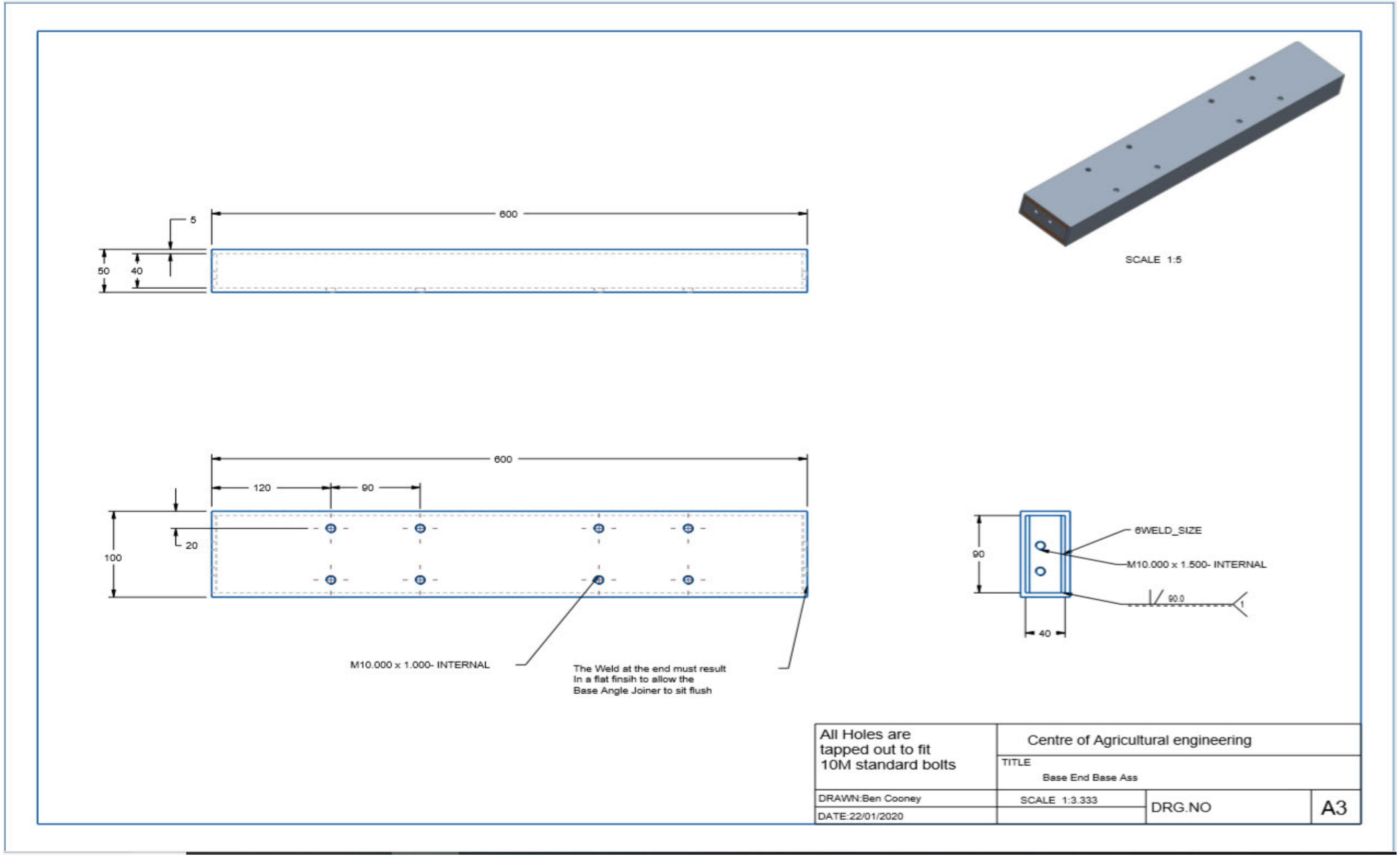
E.2.2 **Base End**



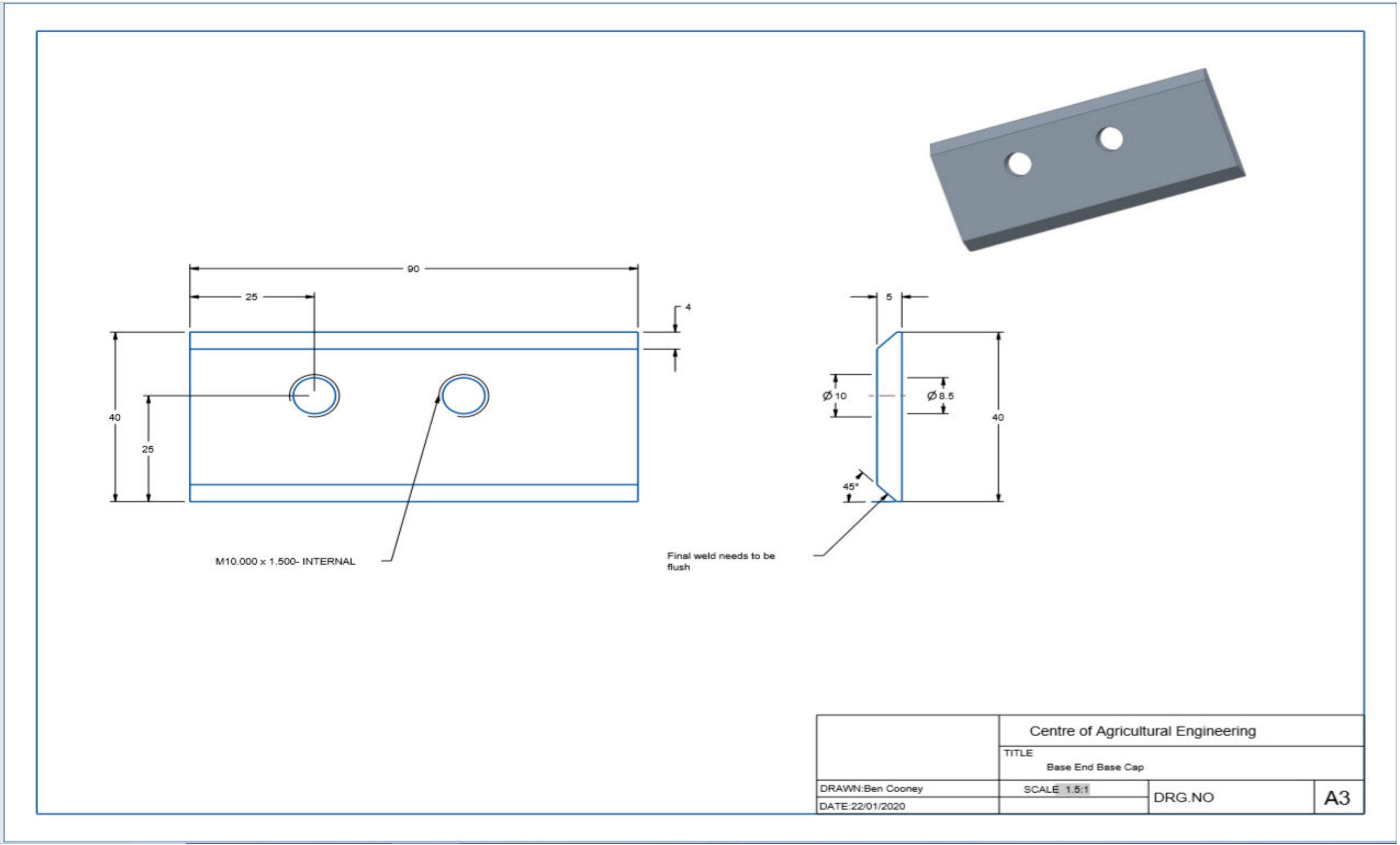
Index	Component Name	Component Type	Quantity
1	Base End Base Assembly	Assembly	1
2	Ass virtical Support Base End	Assembly	2
3	Base End Top Assembly	Assembly	1

	Centre Of Agricultural Engineering		
	TITLE Base End Assembly		
DRAWN:Ben Cooney	SCALE 1:4	DRG.NO	A3
DATE:22/01/2020			

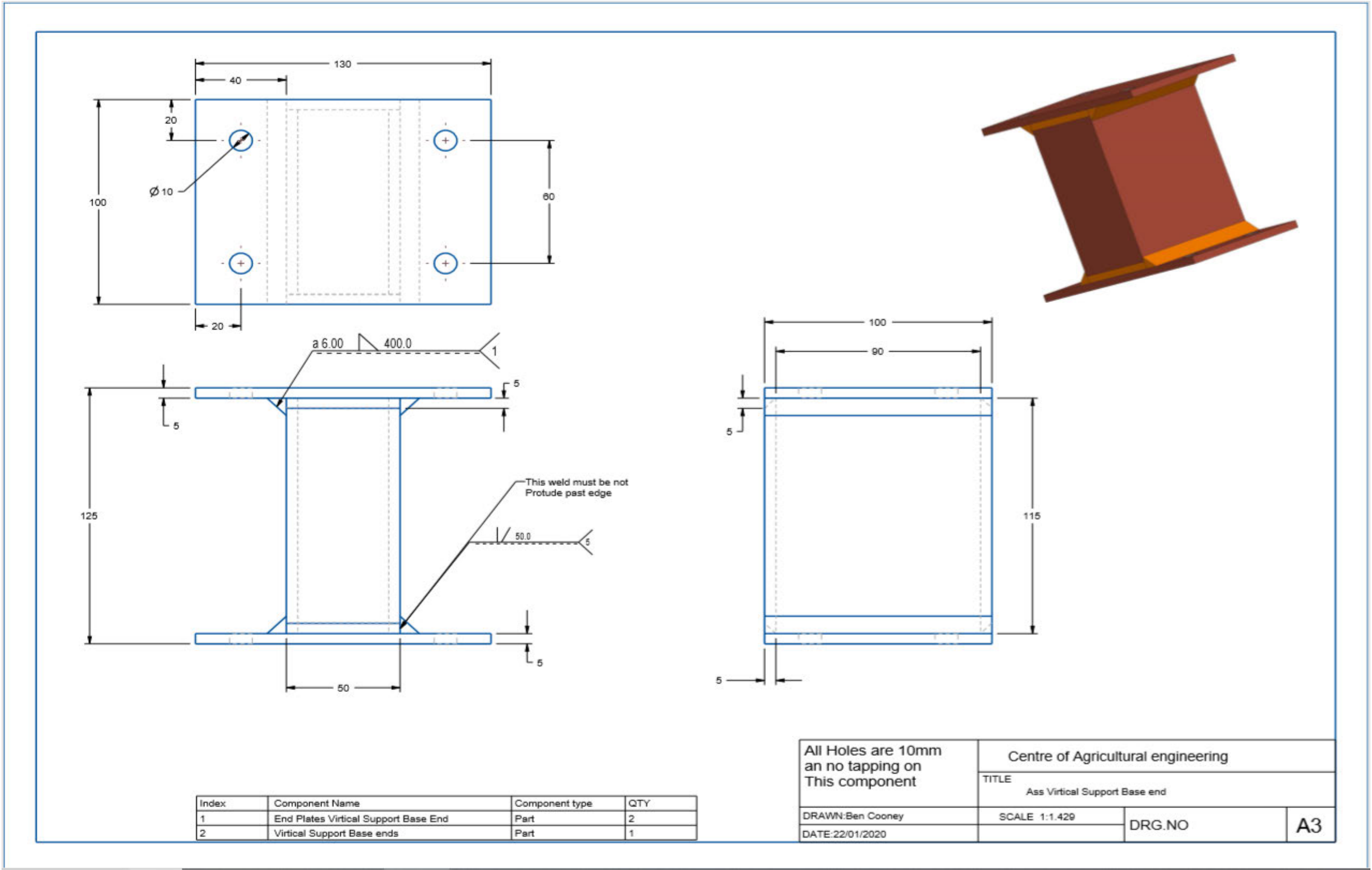
E.2.2.1 Base End Base



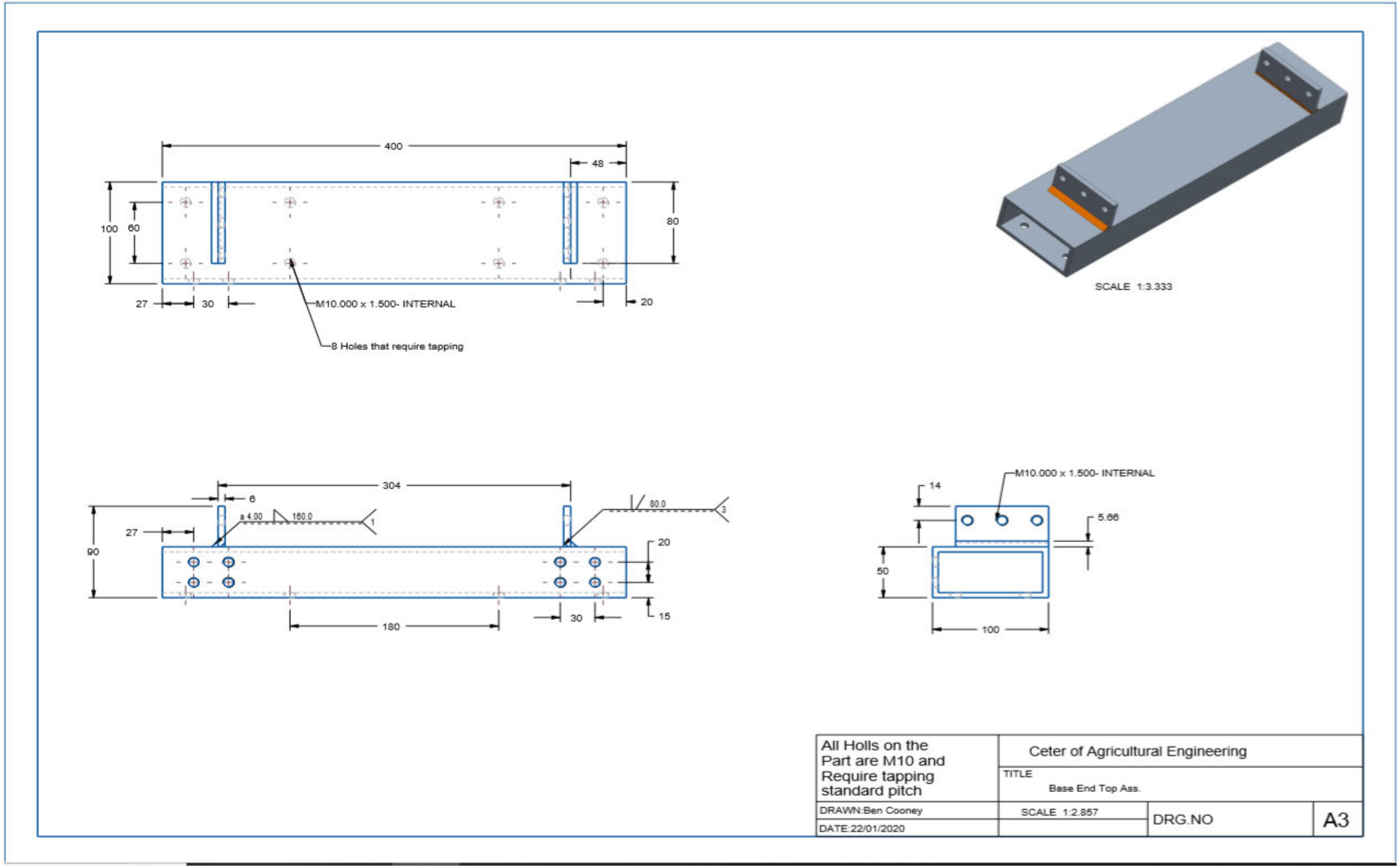
E.2.2.2 Base End Cap



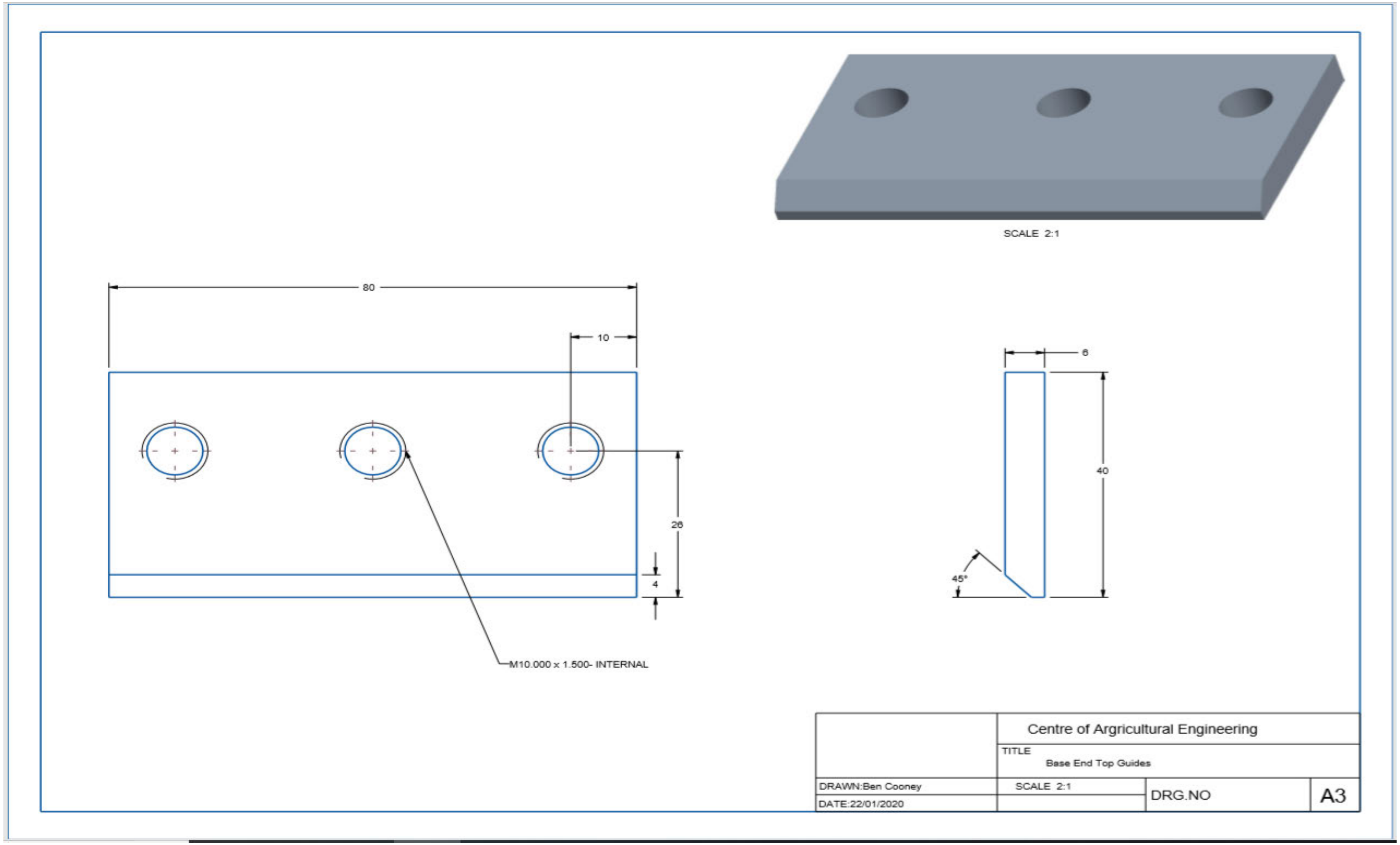
E.2.2.3 Base End Vertical



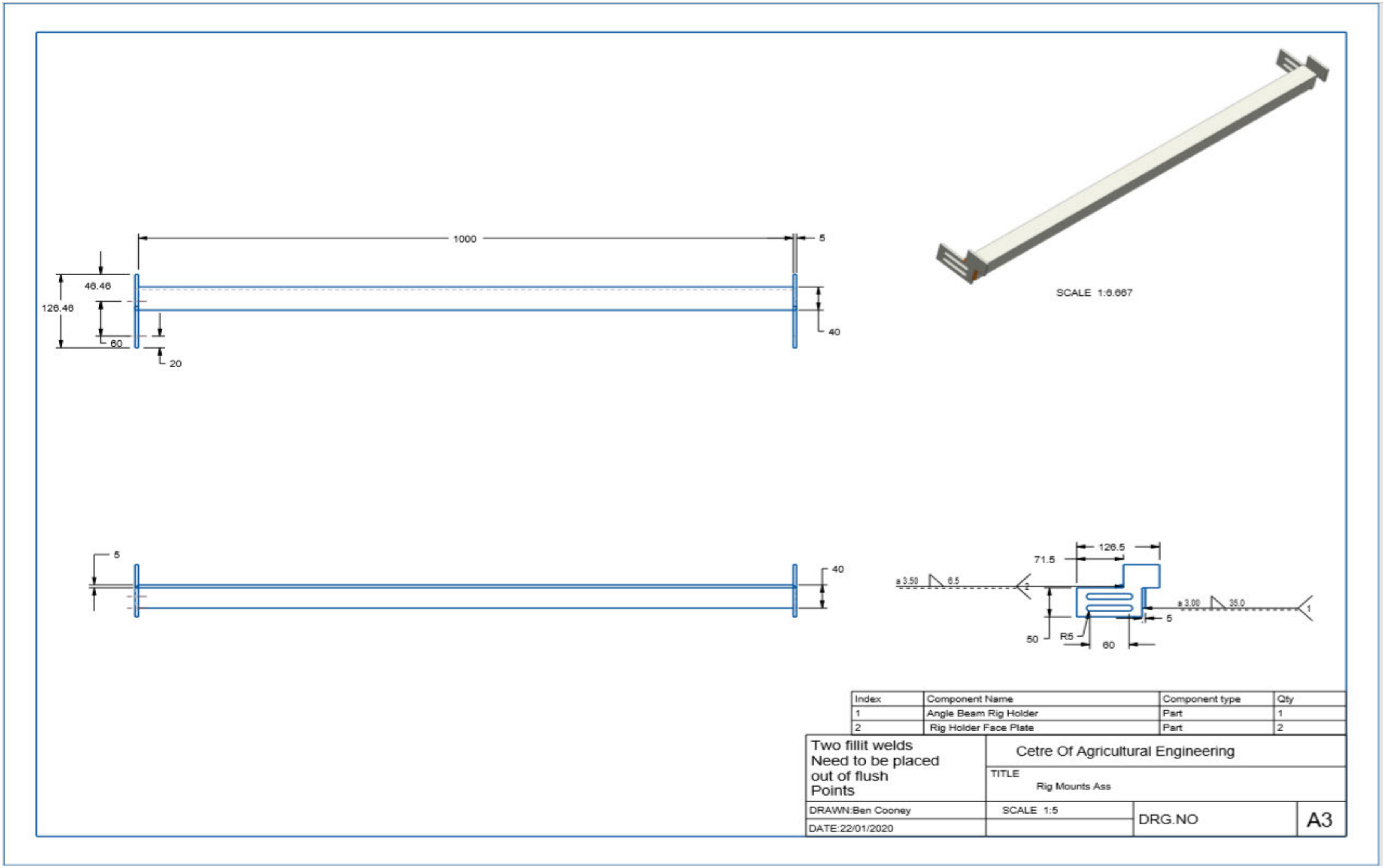
E.2.2.4 Base End Top



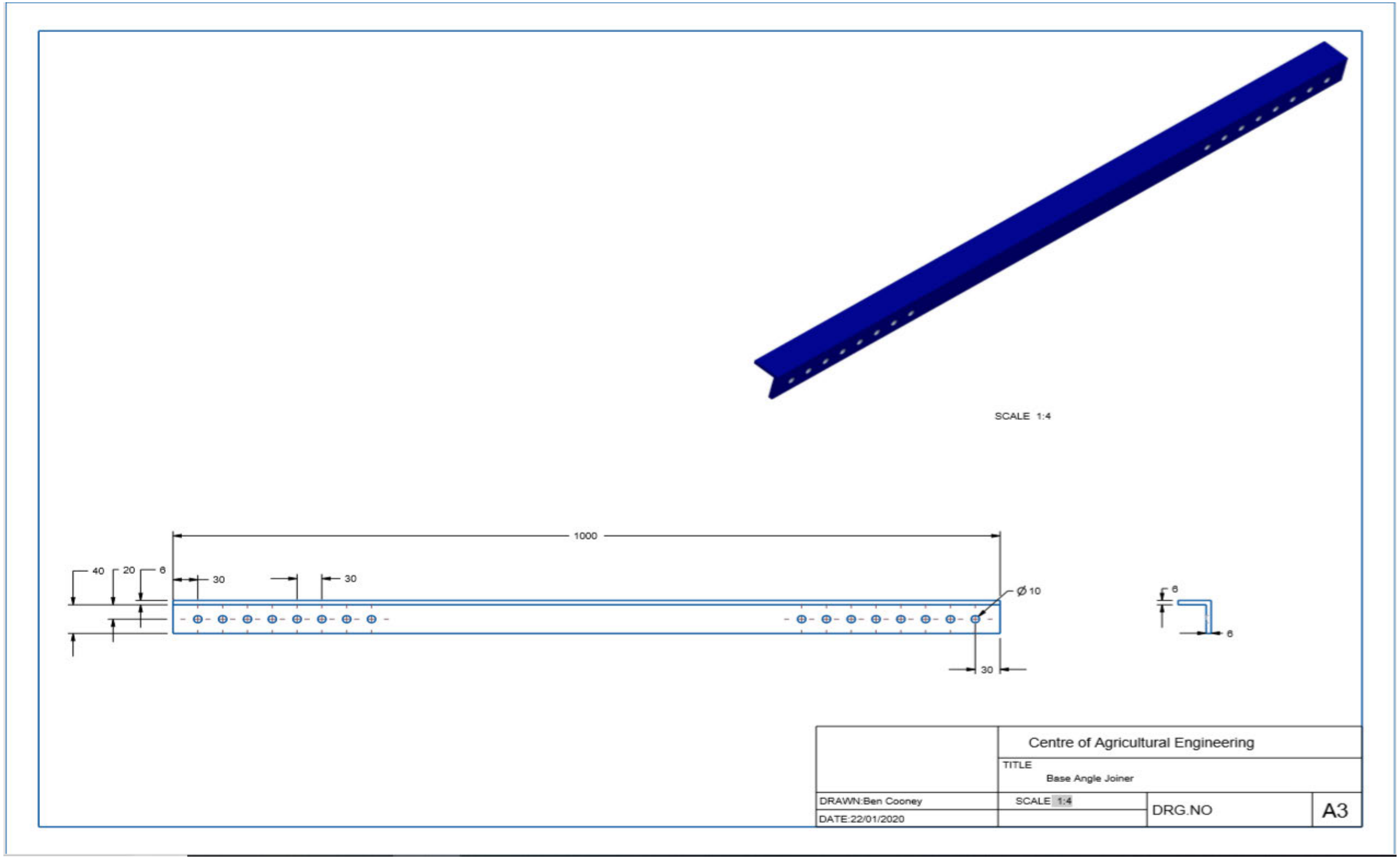
E.2.2.5 Base End Guide



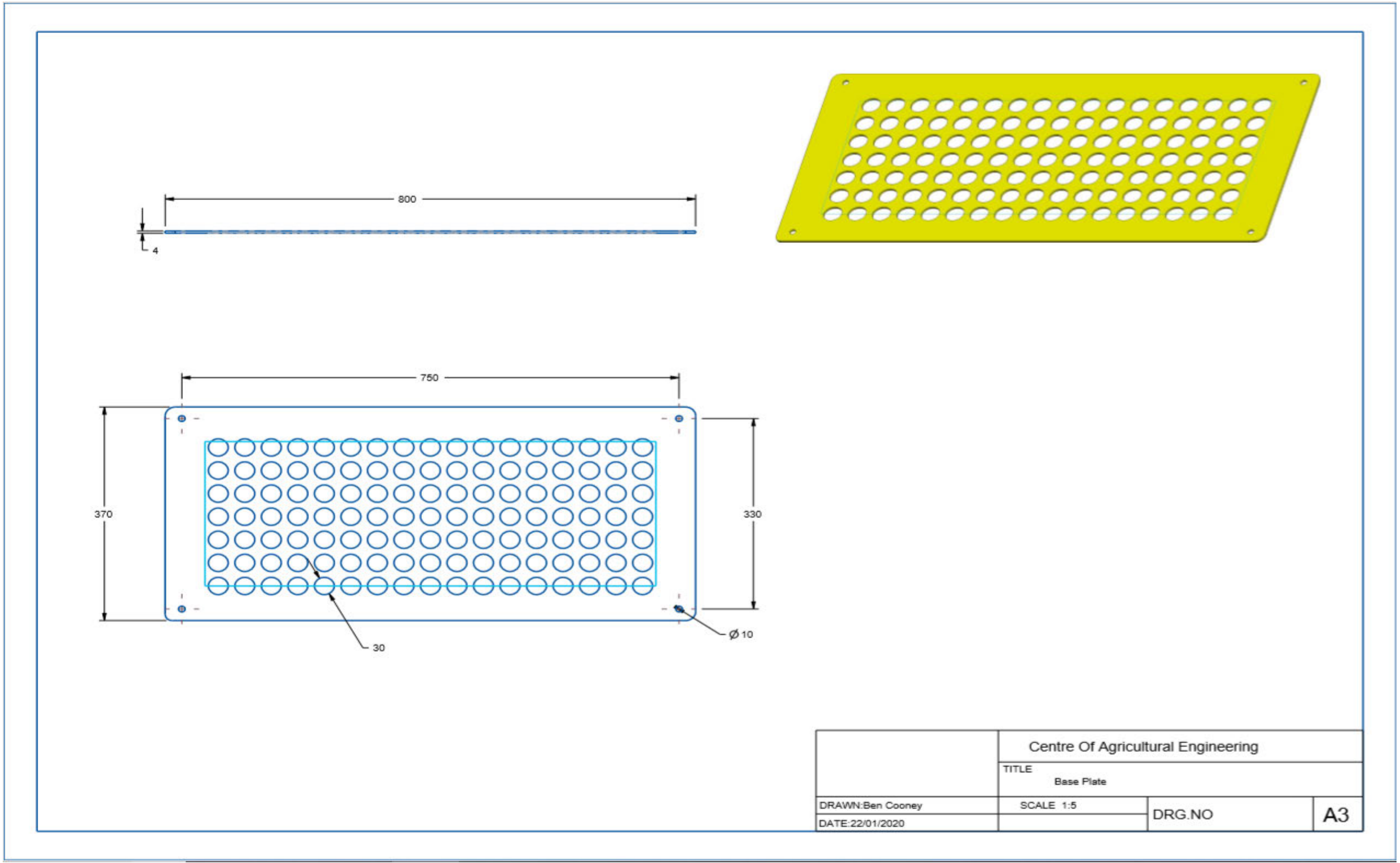
E.2.3 **Rig Mount**



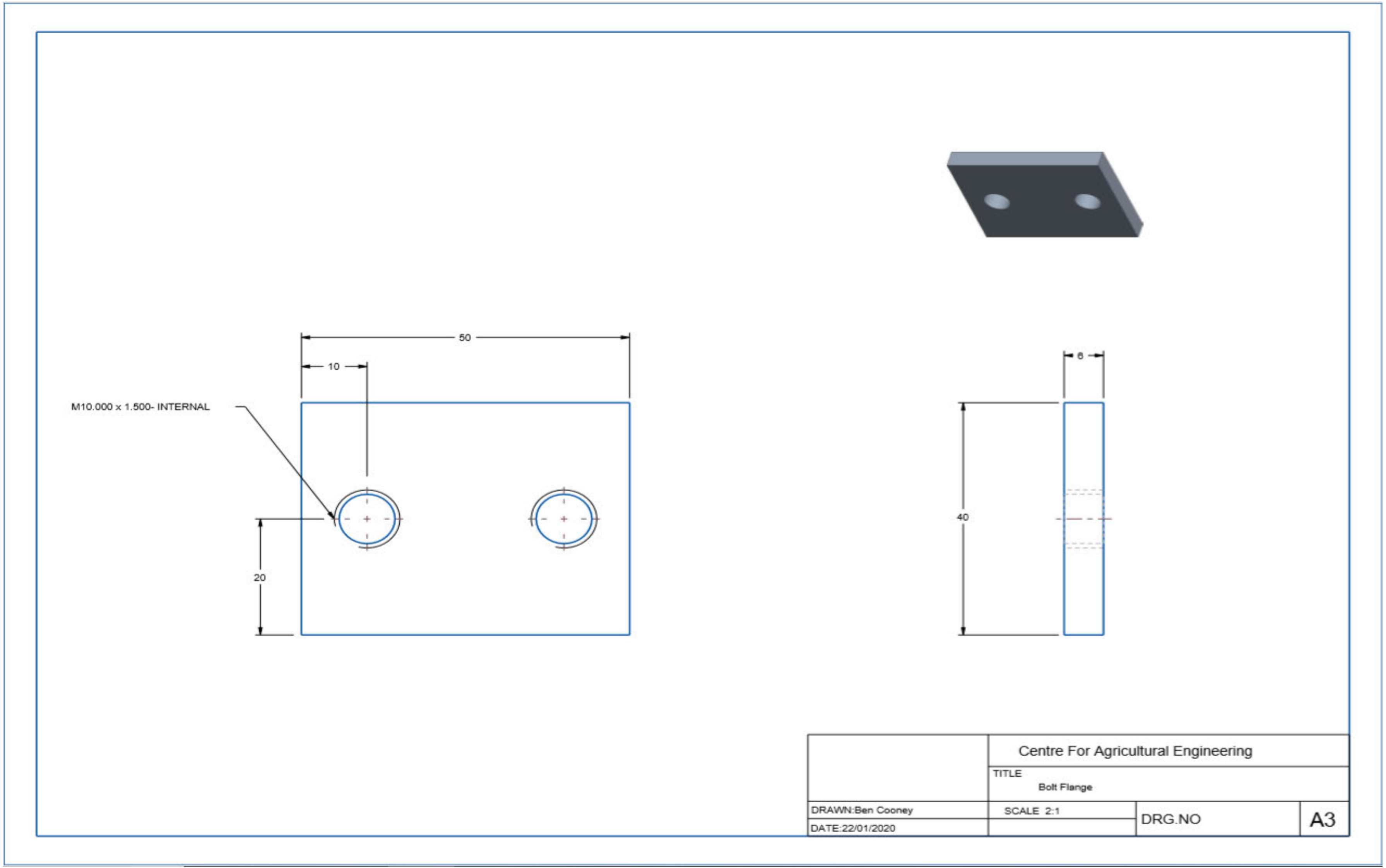
E.2.4 **Base Joiner**



E.3 **Platform**


800
4
750
370
330
30
Ø 10
Centre Of Agricultural Engineering
TITLE
Base Plate
DRAWN:Ben Cooney
DATE:22/01/2020
SCALE 1:5
DRG.NO
A3

E.4 **Bolt Flange**



Appendix F **Parts List**

Part	description	Use	Price $	Used price n$
20x40 vslot	2 x 1m	Platform attachment	12.95	15.32
40 x 40 vslot	2 x 1m	Platform attachment	77.70	77.70
40x40 vslot	2 x 1.5	x-axis rails	109.06	109.06
Aj20 aluminium angle conrer joint	10 pieces 4 pcs	Join v slot	6.17 9.22	15.39
Anti-backlash	1	Screw drive attachment	7.13	7.13
8mm lead screw	1	Lead screw for x axis	35.17	35.17
Bevel gears	4 gears	Transmit power from top to bottom y-axis	27.10	27.10
Controller kit	Controller pack	Controller pack	71.95	71.95
Electrical cable	Jumper cable pack	Cable for wiring up project	18.45	18.45
Cable drag chain	2	Cable tray for wiring	28.85	28.85
Eccentric nuts	10 4	Wheel space and alignment	10.65 14.00	24.65
endstops	6	Electrical switch endstops	16.88	16.88
fan	1	Cooling fan electrical	8.79	8.79

Nuts and bolts	30+	Bolts for assembly	19.50	7.00
Stepper motor	1	Stepper for y-axis	72.39	36.20
LED lighting	3	Uniform Lighting for platform	9.85	2.96
v-slot wheels	10	Wheels for x-axis	17.44	17.44
Power supply	1	1 of 2 power supply	25.49	25.49
solenoid	1	35mm long stroke solenoid	14.64	14.64
Gt3 timing pulley	2	X axis pully GT3	11.37	11.37
Mini shims	15	Spacers for wheels	6.12	6.12
Metric Aluminium spacers	10	Spacers for motors 40mm	6.12	6.12
Kflo8 pillow block flange bearing	2	Bearing for main shaft	19.20	6.20
M5 button head screws	2	wheels	10.83	10.83
Nylon hex locknut	10	wheels	7.24	7.24
M5 button head screws	4	wheels	11.73	11.73
Metric Aluminium spacers	10	Spacers for motors 6mm	6.37	6.37
GT3 timing belt	1	Belt for x axis	45	45
T nut	10	Vslot nuts	9.88	9.88
y axis screw drive	1	Rail assembly for y axis 1 of 2	94.19	94.19
Y axis screw drive	1	Rail assembly for y axis 2 of 2	86.61	86.61
Z axis screw drive	1	Rail assembly for z axis	53.46	53.46

NEMA 23 stepper	1	x-axis motor		50.00
NEMA 23 Motor driver	1	Motor driver for NEMA 23		50.00
24 volt PSU	1	PSU for NEMA 23		20
total				1035.29

Appendix G **Accuracy Results**

G.1 **Results from Full Run of Rig**

G.1.1 **2kg Weight**

									Results								average	Percentage error
0	0	0	0	0	0	0	0		0	0	0	0	0	0	0		0	0
40	0	0	0	0	0	0	0		40	40	40	40	40	40	40		40	0
80	0	0	0	0	0	0	0		80	80	80	80	80	80	80		80	0
120	0	0	0	0	0	0	0		120	120	120	120	120	120	120		120	0
160	0	0	0	0	0	0	0		160	160	160	160	160	160	160		160	0
200	0	0	0	0	0	0	0		200	200	200	200	200	200	200		200	0
240	0	1	1	1	1	0	1		240	241	241	241	241	240	241		240.714	0.00298
280	1	1	1	1	1	1	1		281	281	281	281	281	281	281		281	0.00357
320	1	1	1	1	1	1	1		321	321	321	321	321	321	321		321	0.00313
360	1	1	1	1	1	1	1		361	361	361	361	361	361	361		361	0.00278
400	1	1	1	1	1	1	1		401	401	401	401	401	401	401		401	0.0025
440	1	1	1	1	1	1	1		441	441	441	441	441	441	441		441	0.00227
480	2	2	1	1	1	1	1		482	482	481	481	481	481	481		481.286	0.00268
520	2	2	2	2	1	1	1		522	522	522	522	521	521	521		521.571	0.00302
560	2	2	2	2	2	1	1		562	562	562	562	562	561	561		561.714	0.00306
600	2	2	2	2	2	1	1		602	602	602	602	602	601	601		601.714	0.00286
640	2	2	2	2	2	1	1		642	642	642	642	642	641	641		641.714	0.00268

0	0	1	0		0	0	0		0	1	0	0	0	0	0		0.14286	0
40	0	1	0	0	0	0	0		40	41	40	40	40	40	40		40.1429	0.00357
80	0	0	0	0	0	0	0		80	80	80	80	80	80	80		80	0
120	0	0	0	0	0	0	0		120	120	120	120	120	120	120		120	0
160	0	0	0	0	0	0	0		160	160	160	160	160	160	160		160	0
200	0	0	0	0	0	0	0		200	200	200	200	200	200	200		200	0
240	0	0	0	0	0	0	0		240	240	240	240	240	240	240		240	0
280	0	0	0	0	0	0	0		280	280	280	280	280	280	280		280	0
320	0	0	0	0	0	0	0		320	320	320	320	320	320	320		320	0
360	0	0	0	0	0	0	0		360	360	360	360	360	360	360		360	0
400	0	0	0	0	0	0	0		400	400	400	400	400	400	400		400	0
440	0	0	0	0	0	0	0		440	440	440	440	440	440	440		440	0
480	0	0	0	0	0	0	0		480	480	480	480	480	480	480		480	0
520	0	0	0	0	0	0	0		520	520	520	520	520	520	520		520	0
560	0	1	1	1	1	1	1		560	561	561	561	561	561	561		560.857	0.00153
600	1	1	1	1	1	1	1		601	601	601	601	601	601	601		601	0.00167
640	1	1	1	1	1	1	1		641	641	641	641	641	641	641		641	0.00156

0	0	0	0	0	0	0	0		0	0	0	0	0	0	0		0	0
40	0	0	0	0	0	0	0		40	40	40	40	40	40	40		40	0
80	0	0	0	0	0	0	0		80	80	80	80	80	80	80		80	0
120	0	0	0	0	0	0	0		120	120	120	120	120	120	120		120	0
160	0	0	0	0	0	0	0		160	160	160	160	160	160	160		160	0
200	0	0	0	0	0	0	0		200	200	200	200	200	200	200		200	0
240	0	0	0	0	0	0	0		240	240	240	240	240	240	240		240	0
280	0	0	0	0	0	0	0		280	280	280	280	280	280	280		280	0
320	0	0	0	0	0	0	0		320	320	320	320	320	320	320		320	0
360	0	0	0	0	0	0	0		360	360	360	360	360	360	360		360	0
400	0	0	0	0	0	0	0		400	400	400	400	400	400	400		400	0
440	0	0	0	0	0	0	0		440	440	440	440	440	440	440		440	0
480	0	0	0	0	0	0	0		480	480	480	480	480	480	480		480	0
520	0	0	0	0	0	0	0		520	520	520	520	520	520	520		520	0
560	0	0	0	0	0	0	0		560	560	560	560	560	560	560		560	0
600	0	0	0	0	0	0	0		600	600	600	600	600	600	600		600	0
640	0	0	0	0	0	0	0		640	640	640	640	640	640	640		640	0

G.1.2 1kg Weight

Accuracy of run 1KG

postion	Run 1 x	Run 1 Y	run 2 x	run 2 y		
1,1	1	0	0	0	0	0
2,1	1	0	0	0	0	0
3,1	1	0	0	0	0	0
4,1	1	0	0	0	0	0
5,1	1	0	0	0	0	0
6,1	1	0	0	0	0	0
7,1	0	0	0	0	0	0
8,1	0	0	0	0	0	0
9,1	0	0	0	0	0	0
10,1	0	0	0	0	0	0

11,1	0	0	0	0	0	0
12,1	0	0	0	0	0	0
13,1	0	0	0	0	0	0
14,1	0	0	0	0	0	0
15,1	0	0	-1	0	0	0
16,1	-1	0	-1	0	0	0
17,1	-1	0	-1	0	0	0
1,2	1	0	0	0	0	0
2,2	1	0	0	0	0	0
3,2	1	0	0	0	0	0
4,2	1	0	0	0	0	0
5,2	1	0	0	0	0	0
6,2	1	0	0	0	0	0
7,2	0	0	0	0	0	0
8,2	0	0	0	0	0	0
9,2	0	0	0	0	0	0
10,2	0	0	0	0	0	0
11,2	0	0	0	0	0	0
12,2	-1	0	-1	0	0	0
13,2	-1	0	-1	0	0	0
14,2	-1	0	-1	0	0	0
15,2	-1	0	-1	0	0	0
16,2	-1	0	-1	0	0	0
17,2	-1	0	-1	0	0	0
1,3	1	0	2	0	0	0
2,3	1	0	2	0	0	0
3,3	1	0	2	0	0	0
4,3	0	0	2	0	0	0
5,3	0	0	1	0	0	0
6,3	0	0	1	0	0	0
7,3	0	0	1	0	0	0

8,3	0	0	1	0	0	0
9,3	0	0	1	0	0	0
10,3	0	0	1	0	0	0
11,3	-1	0	1	0	0	0
12,3	-1	0	1	0	0	0
13,3	-1	0	1	0	0	0
14,3	-1	0	1	0	0	0
15,3	-1	0	0	0	0	0
16,3	-1	0	0	0	0	0
17,3	-1	0	0	0	0	0
1,4	0	0	2	0	0	0
2,4	0	0	2	0	0	0
3,4	0	0	2	0	0	0
4,4	0	0	2	0	0	0
5,4	0	0	2	0	0	0
6,4	0	0	2	0	0	0
7,4	0	0	1	0	0	0
8,4	0	0	1	0	0	0
9,4	-1	0	1	0	0	0
10,4	-1	0	1	0	0	0
11,4	-1	0	1	0	0	0
12,4	-1	0	1	0	0	0
13,4	-1	0	0	0	0	0
14,4	-1	0	0	0	0	0
15,4	-1	0	0	0	0	0
16,4	-1	0	0	0	0	0
17,4	-1	0	0	0	0	0
1,5	0	0	1	0	0	-1
2,5	0	0	1	0	0	-1
3,5	0	0	1	0	0	-1
4,5	0	0	3	0	0	-1

5,5	-1	0	3	0	0	-1
6,5	-1	0	3	0	0	-1
7,5	-1	0	3	0	0	-1
8,5	-1	0	3	0	0	-1
9,5	-1	0	3	0	0	-1
10,5	-1	0	3	0	0	-1
11,5	-1	0	3	0	0	-1
12,5	-1	0	2	0	0	-1
13,5	-1	0	2	0	0	-1
14,5	-1	0	2	0	0	-1
15,5	-1	0	2	0	0	-1
16,5	-1	0	2	0	0	-1
17,5	-1	0	2	0	0	-1
1,6	1	0	2	1	0	-1
2,6	1	0	2	1	0	-1
3,6	1	0	2	1	0	-1
4,6	1	0	2	1	0	-1
5,6	1	0	2	1	0	-1
6,6	1	0	2	1	0	-1
7,6	1	0	2	1	0	-1
8,6	1	0	2	1	0	-1
9,6	0	0	2	1	0	-1
10,6	0	0	1	1	0	-1
11,6	0	0	1	1	0	-1
12,6	0	0	1	1	0	-1
13,6	0	0	1	1	0	-1
14,6	0	0	1	1	0	-1
15,6	0	0	1	1	0	-1
16,6	0	0	1	1	0	-1
17,6	0	0	2	1	0	-1
1,7	1	1	3	1	0	-1

Accuracy Results

2,7	1	1	3	1	0	-1
3,7	1	1	3	1	0	-1
4,7	0	1	3	1	0	-1
5,7	0	1	3	1	0	-1
6,7	0	1	3	1	0	-1
7,7	0	1	3	1	0	-1
8,7	0	1	3	1	0	-1
9,7	0	1	3	1	0	-1
10,7	0	1	3	1	0	-1
11,7	0	1	3	1	0	-1
12,7	0	1	2	1	0	-1
13,7	0	1	2	1	0	-1
14,7	0	1	2	1	0	-1
15,7	0	1	2	1	0	-1
16,7	0	1	2	1	0	-1
17,7	0	1	2	1	0	-1
start change	2	0	3	0	0	0

G.2 Test Results of Running to Position

postion test accuracy																		
x	y	x	y		x	y		x1	x2								error	
126.37	83.53							106.1	39.46			126.37		83.82			0	0
126.32	83.54							106.23	39.77			126.32		83.79667			-0.0004	-0.00028
126.68	83.43							106.59	40.01			126.68		83.79			0.002453	-0.00036
126.83	83.37							106.72	40.27			126.83		83.79			0.00364	-0.00036
126.86	83.44							107.04	40.46			126.86		83.76667			0.003878	-0.00064
127	83.47							107.38	40.68			127		83.83333			0.004985	0.000159
127.5	83.48							107.42	40.79			127.5		83.79			0.008942	-0.00036
127.59	83.51				127.63	83.99		107.94	40.94			127.61		83.78667			0.009812	-0.0004
127.81	83.74				127.87	84.05						127.84		83.74			0.011633	-0.00095
127.88	83.4				127.98	84.03						127.93		83.4			0.012345	-0.00501
128	83.57				128.09	84.09						128.045		83.57			0.013255	-0.00298
128.08	83.55				128.35	84.02						128.215		83.55			0.0146	-0.00322
128.26	83.48	128.47	83.94		128.36	84.08						128.3633		83.48			0.015774	-0.00406
128.4	83.6	128.45	83.8		128.45	83.97						128.4333		83.6			0.016328	-0.00262
128.53	83.54	128.5	83.91		128.71	84.03						128.58		83.54			0.017488	-0.00334
128.82	83.88	128.81	83.91									128.815		83.88			0.019348	0.000716
128.88	83.69	129	83.84									128.94		83.69			0.020337	-0.00155
129.87	83.69	128.97	83.95									129.42		83.69			0.024135	-0.00155
		129.2	83.92															
		129.45	83.82															

Appendix H **Technical Specifications formed from the project**

The technical specification that has been developed through the project have been tabulated and can be seen in Table 20. The specifications show the results of the engineering model analysis, test results and essential component specifications.

Table 20 Technical Specifications

Technical Specifications				
1	Consideration	Specification	Notes	Chapters discussed
2	Table stability	Centre of gravity 200mm below the top of the table. Stability fails at 25˚ roll	The table is stable and unlikely to roll under normal operating conditions. For safety, the table should be attached to a wall.	Chapter 3.5.1 Chapter 5.1 Chapter 8.2
3	Platform deflection	Ends restrained 0.427mm Mounting holes only 0.786mm Entire perimeter 0.005mm	The results show that by supporting the entire perimeter, the deflection has been dramatically reduced	Chapter 3.6.4 Chapter 5.2 Table 16.3 Chapter 8.2
4	1500mm v-slot beam	The moment caused by cutter 11.8Nm Ay force 145.8N Cy force 161.5N Total 307.3N Deflection of the beam 0.24mm	The shear forces and moments are minimal. The deflection is also minimal.	Chapter 3.6.5 Chapter 4.3.2 Chapter 5.3 Table 16.2
5	Force of machine	20N	Force applied by cutter or test sensors.	Chapter 1.6 Chapter 7 Appendix G
6	Main shaft 8mm	Torque under full load 0.182Nm Polar moment of inertia J $4.02x10^{\wedge}10$ The angle of twist 0.0526˚ Shear strain 0.00046 Shear stress 2.28Mpa	All values minimal and suitable to be used on the Rig	Chapter 4.4.3 Chapter 5.4 Table 16.10
7	X-axis stepper	Torque requirements 0.26Nm Torque capability is 2.4nM One revolution of travel 56.54mm	NEMA 23 will be sufficient	Chapter 3.7.1 Chapter 4.5 Chapter 4.6 Chapter 5.5 Chapter 6.3
8	y-axis stepper z-axis stepper	Torque requirements = 0 y-axis T=0.84Nm z-axis T=0.3	The motor has to only move the sensors into position	Chapter 3.7.1 Chapter 4.5 Chapter 4.6 Chapter 5.6 Chapter 5.7 Chapter 6.3

9	PSU	240V input 12V output 20Amp 9.6 amps required 24V output	Power was supplied from the mains and contained in a waterproof box. The 24v PSU ran the NEMA 23, and 12PSU supplied everything else.	Chapter4.8.5 Table 11 Chapter 6.3
10	Accuracy	FSD of 0.3% vertically 0.03mm horizontally	The accuracy vertically has been established through material analysis and part selection. The horizontal accuracy is provided by the resolution of stepper motors.	Chapter 1.6 Chapter 7 Chapter 8.2
11	Rig Size	1500mm x500mmx600mm	The external dimensions were dictated by table size of 1500mm long (X) x 700mm wide (Y) x 900mm high (Z) (LWH)	Chapter 1.2 Chapter 3.5 Chapter3.6.1 Chapter 6.1
12	Budget	$1100	The CAE set a budget of around $1000 and the price spent was w with in the limits	Chapter 1.6 Chapter 8.2 Appendix F
13	3d Models of the Rig	There were hundreds of models drawn and simulations done. Only ones that help to covey clarity to the project have been added.	Object Platform Concept Rig Moment Rail position Wheel position y-axis configuration sensor alignment Rig Models Platform simulation Rig analysis Shaft simulation	Chapter 1.6 Chapter 3.6.4 Chapter 4.1 Chapter 4.2.1 Chapter 4.2.2 Chapter 4.3.2 Chapter 4.4.4 Chapter 4.7 Chapter 4.9 Chapter 5.2 Chapter 5.3 Chapter 5.4 Appendix E

The Rig is a sturdy industrial tool that can be used for the study of striploin meat. It provides a high degree of accuracy and is able to work with a 20N force acting upon it. The sensors can be mounted on the Rig, and they are aligned and move synchronously. The Ultrasound can be placed on the meat.