University of Southern Queensland

Faculty of Health, Engineering and Sciences

# DIGITAL FABRICATION WITH COLLABORATIVE ROBOTICS

A dissertation submitted by

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## Abstract

Collaborative robots are typically used for digital fabrication processes in a machine tending implementation where the robot performs the tasks of placing and removing items to be machined. This creates a production line where the robot can outperform humans due to its ability to pick up objects of different weights, sizes, and temperatures faster and at a higher accuracy. It is possible however that the robot is more capable than the machine it is tending due to the high precision and orientation flexibility typical with collaborative robots. This paper investigates the idea that collaborative robots are being employed to tend machines that the robot itself can outperform. The hypothesis is assessed by performing computer numerical control (CNC) milling using a UR5 by Universal Robots (UR) and assessing the accuracy. Autodesk Fusion 360 was used to create models to be milled at different variations of intricacy to simulate in Polyscope, UR's native software. A prototype design was created for the UR5 to attach a spindle allowing the robot to perform CNC milling. A graph was created to plot ten popular three-axis CNC machines of varying accuracy against their cost in USD where the average accuracy of the UR5 can then be used to define its relevant cost as a three-axis CNC machine.

Machining was successfully simulated and later physically tested including five plane machining where the robot approaches the object to conduct three axis machining from five different planes to replicate multi-axis machining capabilities. The accuracy results provided an error up to 1.5mm with an average error of 0.89mm. All values however were positive errors which indicates a bias likely caused by a flawed design and/or cheap design parts. Assessing the imprecision of the errors gave a predicted accuracy of 0.275mm. The results indicate that the UR5 has no significant cost as a CNC machine when precise accuracy is desired however, the estimated accuracy is still an acceptable CNC performance where minute accuracy is not of importance. Though the results of the report can only provide an estimate of the accuracy, the overarching aim of the report has been satisfied. Collaborative robots can be used for digital fabrication.



## Keywords

Collaborative robotics. Digital Fabrication. CNC.

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## Limitations of Use

## Certificate of Dissertation

I certify that the ideas, designs and experimental work, results, analyses, and conclusions set out in this dissertation are entirely my own report, 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 specially stated.

JA Middenway

[redacted]

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# 1. Introduction

## 1.1. Background

The University of Southern Queensland (UNI-SQ) have started up a Formula Society of Automotive Engineers (FSAE) club. One of the projects required by the club is the production of carbon fibre panels. The panels are first designed in 3D software and a compiling process is used to create a 3D representation of the plug. The operator must now determine the size of plug material required and ensure the stock is larger than the final piece. The 3D design is then processed through software into three axis Gcode commands to be given to the CNC machine. The material is clamped or screwed onto a computer numerical control (CNC) machine ready for the cutting tool to be passed across at specific depths with multiple passes defined by the Gcode to create the plug. The cutting tool is spun in a spindle at speeds dependent on the operator's selection. An example of a CNC machined plug can be seen below in Figure 1 (DIYBlog 2020).

FIGURE 1 - CNC MACHINING OF A PLUG

Some of the panels that are required for the race car are much larger than the CNC machine located at the Toowoomba campus. A possible solution would be to use a collaborative robot to conduct the machining. Uni-SQ have access to multiple collaborative robots including two Universal robot UR5's at the Springfield campus. One of the most common jobs collaborative robots are being used for is machine tending where the robot's is implemented to insert and remove objects into machines designed to be used by humans. A collaborative robot is typically used to conduct processes such as placing and removing the material in the CNC machine, sanding edges, or flipping the piece for multi-plane machining. Some benefits of machine tending include time saved not having to wait for materials to cool while removing/replacing the material in the machine, the piece can be placed in specific orientations quickly and precisely, and the machine can run a consistent production line. There is a possibility that a collaborative machine is being used for CNC machine tending where the robot is capable of higher precision than the machine it is tending. Modifying the robot to include the tools necessary to conduct the job would likely save money in purchasing a CNC machine while possibly increasing the precision of the task. The feasibility of this is dependent on what specifically is being machined. This includes the material type, size, and application of the finished piece.

## 1.2. Collaborative Robotics

Collaborative robotics technology has had a healthy development over the last decade. Traditional industrial robotic machines almost always require a separation between humans and machines in order to keep people safe in the workplace. Collaborative robots however are designed specifically to be deployed in a shared space. Pairing this with low skill level developing software, these robots are being used all over the world for numerous tasks, improving efficiency and safety in the workplace. There are many collaborative robotic machines and software on the market. Both the robot and its interface software can be quite costly. As discussed earlier, UNI-SQ currently have two UR5 robots from Universal Robotics available to students and faculty. There are two programs that is used to run these robots. The first is Universal Robots software

Polyscope. Polyscope is designed for users with no coding experience with the ability to add complexity if the user has the skills. The second is called Robotic Operating System (ROS). ROS Is the backbone for many collaborative robot designs across numerous countries (Tellez 2019). The program gives developers complex functionalities with little coding complexity (Ademovic 2010). The major benefit of ROS is that it can be used with multiple robot manufacturers whereas Polyscope is designed specifically for UR robots.

Universal Robots are designed to improve the efficiency and safety of production tasks such as CNC machining (Universal robotics 2022). The implementation possibilities of collaborative robotics in industry are virtually endless. These robots can conduct repetitive tasks faster with increased accuracy over a longer period than human workers. For CNC applications, Universal Robotics claims that their robots maximise CNC machining efficiency as well as increase quality and performance (Universal robotics 2022). The typical application of machine tending for CNC machining is relatively easy to implement. The robot is developed to mimic a human operators processes. These tasks may improve productivity however it begs the question of whether these robots can be used to complete some of these processes such as CNC machining in its entirety to make use of the robot's impressive technology.

### 1.3. CNC Plug Machining

CNC machining is the process of using a computer-controlled machine to accurately apply a tool in various configurations to modify some material. The most common CNC machine application is cutting material such as wood, foam, and metal by moving a tooling bit attached to a spindle across the material. This process can be used to create extremely accurate designs based on 3D computer models. The application that is going to be discussed in this project is the fabrication of plugs. A plug is a piece of material that is shaped in a way that a material such as carbon or fibreglass can be layered on to it at a particular height to create the desired design. The material is layered onto the plug and removed once it hardens. The plug is developed as a 3D design that is essentially a negative of the object with tolerance for the thickness of the desired panel. A worker can then input the size of the material to cut from and the program will generate the Gcode required for the machine to mill the material into the plug. In order for CNC machines to work, a 3D file is loaded into a CNC program along with the size of the material to be milled. There is an abundance of programs capable of doing this however this project will use Autodesk Fusion 360 due to the availability of a student licence, experience with the program, an existing post processing tool for Universal Robots as well as the fact that the program is capable of both traditional three axis control and five axis control. Fusion 360 compiles into Gcode to be given to the CNC machine which is then processed by the post processor to ensure compatibility with a UR robot.

### 1.4. Aim and Objectives

The purpose of this report is to discover if digital fabrication can be conducted and/or further optimised by the use of collaborative robotics. There are a number of digital fabrication types that could be conducted to prove that this concept is a viable option. The UNI-SQ race car team have a requirement to fabricate carbon panels for their design. Directing the aim of this project to achieve this goal will give a clear end goal. Using a collaborative robot to machine the plug capable of being used to create a carbon door panel provides a purposeful goal with the ability to easily define the outcome's success. The objective of this project is to replicate the process of taking a 3D representation of a small panel with some level of complexity and create a plug capable of replicating that part. To understand the requirement and direct the design of the prototype that will achieve this, a literature review will need to be conducted in the relevant fields. Once this is complete, the methodology behind the project must be defined along with a discussion of the method of analysis. A design can then be created to integrate a collaborative robot to perform CNC machining. This design will need to be both a software and hardware design. The next objective of this project will be to analyse the data and provide a relative approximate scale of the collaborative robot's CNC capability. Finally, a conclusion on the findings in this report will be provided along with recommendations for future work.

The key aims of this project can be defined as:

- Demonstrate CNC machining with a collaborative robot
- Evaluate the performance of CNC machining using collaborative robots on industrial material

The project objectives are:

- Conduct initial background research on the UR5E including how it works, what software is used, and whether it has been used for CNC machining.
- Review current molding plug CNC technology including types of machines used, specific CNC requirements, typical materials, and the methods applied to evaluate CNC performance
- Select and purchase the milling material required ready for testing
- Design a prototype CNC Machine using a UR5
- Select or design software framework for translating CAD machine into programs usable by the UR5
- Simulate CNC machining with the UR5
- Identify suitable physical parameters and test cuts
- Perform physical test machining
- Evaluate the accuracy of these cuts using metrology equipment
- Analise and report on the results

## 1.5. Limitations

There are a number of limitations to this project with the first being time. As this is an honours project, there is only a specific amount of time allocated. The project is conducted over two university semesters consisting of approximately 28 weeks total. The project is also conducted concurrently with other subjects and practicals. The entire project must be completed in this time including topic selection, literature review, design, parts acquisition, building of the prototype, testing, analysis and finalising the report. The second limitation is money. Funding for honours projects varies with usually only a small allocation given. No specific limit was given for this project as there are some adjustable funds accessible if justified. The third limitation is access to the workshop and equipment. This is restricted by UNI-SQ campus opening times as well as the requirement for student supervision and access to the required machines and tools. The project's physical construction and testing must be conducted during normal business hours when staff supervision is available. Certain equipment such as the UR5 Robots may also be restricted when another student or staff member may be using the robot for other purposes. The final limitation of this project is the total size of the manufactured plug. The maximum payload of the UR5 is 5kg and the maximum reach is 850mm (Universal Robots 2016). The reach limits the maximum length that the robot can reach in order to mill the material if the material were to be fixed to a bed. The maximum weight of the material limits the maximum material volume if the it were to be attached as the payload. If a puzzle piece approach is taken, the ability to code the 3D software to split the object into manageable sized pieces would be beyond the scope of this project. A list of project-specific limitations and the associated limitation reason can be seen in Table 1 - Project Limitations.

TABLE 1 - PROJECT LIMITATIONS.

| Limitation | Reason for restrictions | | |
|---|---|---|---|
| | Time | Money | Supervision/Access |
| Test multiple types of collaborative robots | ✓ | ✓ | ✓ |
| Test multiple types of robotic software | ✓ | ✓ | |
| Test multiple types of materials | ✓ | ✓ | ✓ |
| Test the performance of the plug to make a carbon fiber panel | ✓ | | |
| Test other types of digital fabrication | ✓ | ✓ | |
| Create a program to split objects into manageable sized pieces | ✓ | | |

### 1.6. Scope

With acknowledgment of the limitations, the scope of the project must be determined in order to complete the aim and objectives. The first step will be to perform a critical literature review surrounding both collaborative robot integration and CNC machining to determine the design process and criteria. The literature review will provide important design possibilities as well as lessons learnt in similar designs. The method of determining the success of the design must then be identified and discussed. Once complete, the coding integration from a 3D design to a file the robot software can use will be documented. The physical design of the prototype can then be developed to provide the robot with a spindle and cutting tool. From this design, the parts list can be made and once ordered and obtained, the prototype can be built. The next step is to test and adjust to ensure the design is capable of simple CNC machining. Once the prototype is capable of basic CNC operation, a more complex CNC file can be created for advanced testing. The final object created from the advanced testing can then be measured and the results, conclusions and recommendations can be discussed.

## 2. Literature Review

### 2.1. Knowledge Gap

Collaborative robotic technology is an ever-improving technology with a specific focus on the difficulties of human safety and ease of programming (Villani et al. 2018). The safety provided by these during human and robot interaction is well developed however further safety mitigation processes must also be applied in workplace designs (Gualtieri, Rauch & Vidoni 2021). The main implementation that manufacturers are marketing for in industry applications is machine tending. Using collaborative robots for machine tending can significantly increase production (Robotics Online Marketing 2019). The practicality of purchasing a collaborative robot for machine tending is defined on a case-by-case basis. The cost of the robot and software as well as training workers to be able to use the robots can prove to cost more than the increase in production is worth. The gap in research that has been identified is the feasibility of implementing collaborative robotics to conduct digital fabrication rather than just tend the process of another machine. There are many practical applications that can be developed if collaborative robots are able to conduct the whole task from start to finish without significant cost and modification.

As the key objective of the project is to use a UR5 to conduct CNC machining on material capable of being a plug for a carbon fibre panel, the scope of this project guides the required research in a specific direction. The required research can be broken down into four sections. The first is to investigate collaborative robots including their implementation in industry. The second section of research involves an investigation of traditional CNC machining including both three-axis machining versus five-axis machining. The third section aims to investigate existing designs, prototypes and literature for collaborative robotics conducting CNC machining as well as investigating the UR5's technical information, instruction manual and relevant articles discussing the robot's implementations. The final section looks at plug machining and material selection to ascertain the information required to select an appropriate testing material.

### 2.2. Collaborative Robot Industry Implementations

Collaborative robotics engineering is specifically geared towards creating robots that can safely operate in collaboration with human workers. The initial implementations were to assist human workers in assembly line work which was considered an ergonomic risk (Cherubini et al. 2016). The intent was not to replace the worker but instead to work with them to reduce injury, increase accuracy and speed up the production process. Combining the repeatability, accuracy, and payload versatility of robots with the human intelligence of a worker provides a powerful tool for businesses small, medium, and large (Michalos et al. 2015). There are obvious limitations to the robot's capability such as payload and reach however applications are mostly limited only by the imagination and ability of the operator/developer. Developing software in the past was complicated and expensive, requiring highly skilled developers to program and prepare robots for specific tasks. (Peter & Greenspan 2020) discussed a comment by a third-party supplier who stated that the cost of the software that could replicate a process conducted by one hundred staff was more expensive than hiring one hundred staff to automate it. Due to this early perception of collaborative robots, a shift in focus was made by collaborative robot design engineers to create more intuitive user-friendly design software and controls. Modern collaborative robot designs boast the ability to be programmed and operated by individuals without extensive training. As the software interface becomes easier to use the training required for developers decreases and the implementation of robotics in more various applications become practical. Another impressive feature of collaborative robots is the versatility to be programmed to do multiple jobs. In larger companies, money can be saved by purchasing one type of collaborative robot across the production line which streamlines the company's machine maintenance and breakdown time by creating a single machine with the same parts across multiple production tasks. The more versatile the collaborative robot becomes, the more valuable it will be.

### 2.3. CNC Machining

Computer numerical control (CNC) involves the use of a computer to accurately control the movement of a robotic arm. CNC machining involves fixing a spindle with a cutting tool onto a controllable arm and moving it across a material in order to subtract material, leaving what is required to make up the desired part. The two most common design types of CNC machines are three-axis and five-axis machines (Lasemi, Xue & Gu 2010). Three-axis machines operate across the X, Y and Z axes as seen in Figure 2 (Shelton 2018).

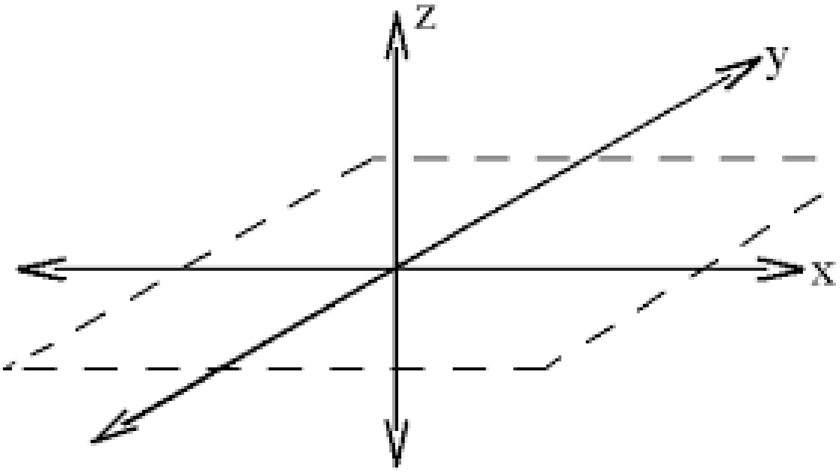


FIGURE 2 - X, Y AND Z AXES

Movement of the axes can be achieved by either moving the spindle or the machine bed. Five-axis machines add on another two dimensions of movement by tilting either the spindle or the bed over two perpendicular axes as seen in Figure 3 (GENSUN 2021).

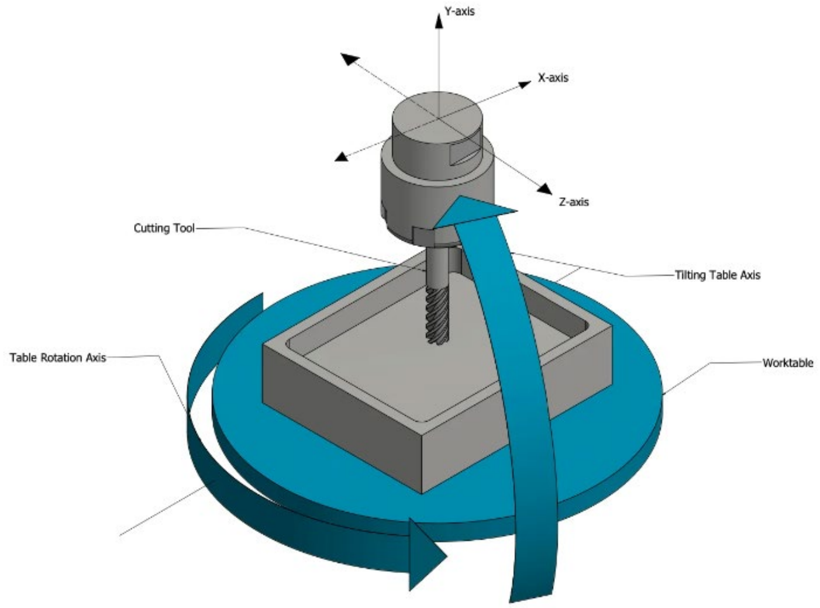


FIGURE 3 - 5 AXIS MACHINING EXAMPLE

Three-dimensional movement allows the machine to mill to depths on a single plane. For example, if a wooden dice were to be pictured with the number six facing upwards, the flat surface on the top is the plane is able to be milled. A three-axis machine could move left and right along this plane and mill depths limited only by the length of the tooling bit. If, however, it was desired to mill into the face of any other number, we would need to rotate the spindle to mill from the side or rotate the bed to change the work plane. A five-axis machine provides that capability through two methods. The fourth and fifth axis can either be moved across the five planes in between cuts or the piece is moved as the milling takes place. The first method can be replicated on normal three-axis machines by manually moving the piece in between cuts. This is one of the common implementations for collaborative robotic machine tending. The second method is the best performing method as, in theory, it moves across an infinite number of planes allowing incredibly smooth surface finishes (Lasemi, Xue & Gu 2010). Practically, however, this isn't the case due to the complexity of programming over infinite planes. (My & Bohez 2019) writes that the possible configurations of a five-axis machine are 2160 planes until we restrict the movement requirements to a rotational movement of the spindle or bed giving 108 plane configurations. The actual implementations of these configurations are not important for the purpose of this paper however an understanding of the difference in complexity between three and five axis machining as well as methods to improve must be understood. A collaborative robot can be used to "artificially" create the fourth and fifth axis on a three-axis machine however it does not imply that it is as effective as a five-axis machining.

Performance of CNC machines are not exclusively reliant on the number of axes used. A machines accuracy and speed can be affected by several factors including the quality of the tool and spindle, the distance of minimum movement across an axis and rigidity of the frame (My & Bohez 2019). Due to the limitations in this project and the interchangeability of spindles and tool bits, the focus of research for CNC machine performance is on the machine's accuracy specification. The standard measurement of accuracy is the minimum movement distance in millimetres. Measurement of the object's accuracy involves the comparison of the 3D representation of the object and the final product. This can be conducted using numerous tools and techniques. Variations in the accuracy of the material can be caused by other factors such as vibrations, impurities in the material and temperature (Marek et al. 2020). Mitigations can be put in place by ensuring similar temperatures across test comparisons, ensuring the machine is rigid with minimal vibration and ensuring sample material is free of impurities by purchasing high quality material. A further mitigation is to test the accuracy over multiple samples and use the averages.

### 2.4. CNC Machining and Collaborative Robots

Using collaborative robots to perform the CNC milling is a relatively unexplored field of research. A reasonable explanation for this is that collaborative robots are significantly more expensive than CNC machines. For this reason, the target market that this paper is investigating is consumers who have already purchased or are thinking of purchasing a collaborative robot for machine tending. The difference between collaborative robots and regular industry robots used for CNC is simply the robot's ability to work in close proximity with humans (Michalos et al. 2015). Therefor the question is not whether the robot is capable but whether it is a viable alternative. The number of axes that the collaborative robot has, defines the axes capability for the purpose of CNC machining. The UR5 has six degrees of freedom which will easily be capable of five-axis CNC machining (Universal Robots 2012). The maximum reach of 850mm limits the area of the material that can be milled if the robot is holding the spindle, and the five kilograms maximum payload limits the amount of material the robot can hold if the arm is to hold the material and move about the spindle.

Collaborative robot software would need to be integrated with existing CNC control code such as Gcode to conduct the movements. The complex movement of the robot arm can take a large amount of time to program. In situations where the robot is required to trace out an object such as layering liquid gaskets on an engine, Universal Robots has included a Gcode feature in their software to allow easy integration (PAN 2019). Gcode has been around for almost sixty years (Lynn et al. 2020) and is the industry standard for CNC control. The integration of multi-axis industry robot arms using Gcode has also been explored where researchers chose to use the existing industry standard due to its proven capability and the abundance of relevant software (Slavkovic et al, 2018).

## 2.5. Plugs and Materials

Carbon fibre panels are made by laying carbon fiber fabric over an object followed by the application of epoxy resin (Rock West 2020). These objects, called plugs, are modelled in computer-aided Manufacturing software to replicate the shape of the desired object (DIYBlog 2020). The material used for the plug depends on the temperature required in the curing process of the layer material as well as a balance of cost and speed versus accuracy (Rogers 2019). This can include materials such as MDF, Urethane, Epoxy, Aluminium and Carbon. These materials also vary in their density and composition. As the layer material is curing, temperature rises which can swell the plug and cause the layered piece to break. To ensure this doesn't occur, it would be desired that the material used as a plug needs to have a coefficient of thermal expansion (CTE) that is equal or less than the layer material which simply means that the plug will not expand more than the layering material. This is not always possible due to cost. To assess the amount of flex that would occur, the formula for the expansion can be calculated using the size of the desired panel as well as the relevant material and CTE. The thermal expansion for the typical plug materials can be seen in Figure 4 - Coefficient of thermal expansion for tooling materials (Rogers 2019).

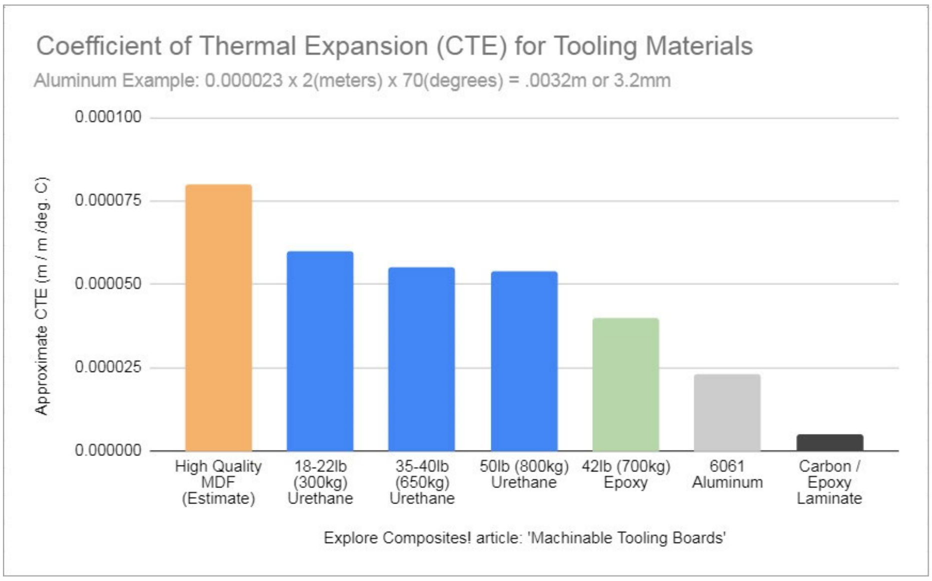


FIGURE 4 - COEFFICIENT OF THERMAL EXPANSION FOR TOOLING MATERIALS (ROGERS 2019)

It can be seen in Figure 4 that the expansion due to temperature significantly changes with material. The end goal that this paper is attempting to achieve is for a collaborative robot to be capable of any form of digital fabrication to an acceptable standard which means that the selection of material is somewhat arbitrary however some attention must be given to ensure that higher-end materials that are harder to machine can also be produced. There are numerous materials capable of withstanding the curing process of carbon fiber. One of the most popular choices for plug designs is tooling board. Tooling board is specifically designed to make plugs and moulds via CNC machining (Rogers 2019). There are various types of tooling board on the market that vary between manufacturers. Selection of the best material differs extensively across the available blogs and videos discussing carbon fibre plugs. The number of panels the plug is required to make plays an important role in the selection where plugs must be less susceptible to wear and tear for production use. It appears that low-end tooling board is preferred when the plug is not intended for constant production use. Tooling board comes in numerous compositions that change performance, weight and cost significantly. Due to the vast amounts of compositions and the majority of the literature coming from America, an exact selection for which tooling board is best cannot be determined. Information regarding the best composition for a particular application can be obtained from the local manufacturer. One of the local manufacturers in Toowoomba QLD, is a company called LSM Advanced Composites. The company specialise in plug machining amongst other things and have had experience using robotic arms for CNC milling. The material they use is a green epoxy called Necuron 702. This material is used for many different applications including plugs for carbon fibre. The coefficient of thermal expansion for this board is approximately $42\ X\ 10^{-6}K^{-1}$ (Necuron 2018), which corresponds to the green epoxy detailed in Figure 4. The low CTE allows multiple methods of carbon fibre layering and is therefore an appropriate selection.

# 3. Methodology

## 3.1. Approach

To assess the success of this project, a methodology must be clearly defined. The goal of this project is to investigate if a collaborative robot can be implemented in a digital fabrication application where the robot performs the computer-controlled process as well as the machine tending. As discussed earlier, the goal can be achieved using numerous digital fabrication techniques and robot models. For this project to be considered successful, only one implementation need be achieved. Therefore, gaining success in implementing a UR5 robot for the use of CNC machining will suffice to achieve the project goal. In order to confirm if this is a successful implementation, the performance of the CNC machining must be measured. This relates to the time taken from having a 3D drawing to final product, the time and cost taken to convert the robot to conduct the CNC machining, versatility of size and material type that can be machined, and the accuracy that the machining is capable of producing. To understand the level of accuracy required, research must be conducted into benchmark performance criteria and cost for CNC machines. Comparing multiple machines performance specifications with their cost will create a monetary scale of performance to get a visual representation of the robots machining capability compared to cost.

## 3.2. Assumptions

There are some assumptions in the methodology that must be clarified. To assess the viability of the UR5 as a CNC machine, it must be compared to other CNC machines with relation to costs and performance. The robot's implementation however also provides machine tending to the process. For the evaluation of performance, it is assumed that the final products market is a consumer who will either buy just the UR5 with the design module or a CNC machine as well as the UR5. This will mean that the project design option will nearly always be cheaper however, the consumer may need an accuracy level beyond the robot's capability.

Another assumption that will be made is that the multiple options for spindle and drill bit selection is relatively arbitrary. A machines performance can be affected by the tool and spindle specifications (Byrne, Dornfeld & Denkena 2003). The material used in the test should be capable of being used as a plug for carbon fiber in order to completely test the product and the tooling bit selected must be capable of cutting the material however, once a particular tooling bit and good level material have been successfully milled, it is assumed that the performance of the machine will vary linearly similar to other CNC machines with the same changes. It is also assumed that the variation in cost for spindle and tool bit selection is negligible and that the variation itself can be excluded from the cost analysis.

The final design will aim to be capable of doing smaller sized objects that can be pieced together to create the final plug. Parallel with this is the assumption that the performance of the prototype along with all the assessed CNC machines can be assessed without reference to the maximum object size. The machine tending capability of the UR5 will provide all models with the ability to reduce larger prints into smaller parts.

## 3.3. Design Approach

The prototype design consists of three components which include the material design, physical design, and software design. The material design involves choosing the size and material for each stage of testing. For the physical design, there are three possible configurations for conducting CNC milling. Configuration A is where the tooling bit is moved about the material, configuration B is where the material can be moved about the tooling bit and configuration C is a combination of both. All three of these configurations must be assessed to determine the appropriate design. A physical design prototype of the chosen configuration must then be created. The software component can be broken into three sections. The first is the 3D drawing design of the object that the robot must create through milling. These designs will be made in Fusion360 and must attempt to cover a range from simple to high complexity milling. The second section is the post processing of these designs into code that Polyscope, the universal robot software, can utilise. The final software stage is in the programming of the robot to perform the post-processed code and conduct the milling.

### 3.4. Methodology Justification

The methodology for the project requires justification. The performance criteria for CNC machines are well documented in each model's relevant technical specifications documents. Selection of a machine by consumers is mainly a balance between the machined maximum object size, the accuracy in millimetres and the cost of the machine. Considering that the maximum machinable size is fairly restricted in this project's implementation, justification must be made as to why it is being ignored. Traditionally, machining multiple parts to create plugs is seen as a time-consuming process and possibly inaccurate due to human error. There is a lot of time taken in compiling the material to be machined, fixing the material down and flipping the piece for multiple plane machining. With the machine tending capability of the UR5, this process can be streamlined into one click of a button where the robot can not only machine all pieces but also move them along and even piece them together. It should also be mentioned that the maximum size for the machined objects also defines the size of the machine. If piecing together separately machined objects to create the plug is employed, the overall workspace required for the CNC set-up will be small and is a desirable advantage. For these reasons, it is deemed justifiable that size is not discussed in the performance assessment criteria.

The analysis will be conducted using the selected tooling board and a generic cutting tool bit. To justify that this is sufficient, the limiting factors must be discussed. Material selection has a direct effect on the achievable accuracy. Lower-end material such as MDF will chip and swell at a particular point regardless of the machine used. As long as the material selected is capable of accurate milling above the accuracy values selected in the scale, the performance of the machine can be assessed using only that material. The final justification required is the simplification of the inherit variance in costs across machines based off different brands and machine bed sizes. Since the implementation of machine tending is assumed for all situations, when machines cost variation meets similar performance criteria, the lowest price machine will be selected. The final result of this cost analysis is simply to give an approximate relative cost for the UR5 as a CNC machine compared to traditional CNC machines in the current market.

### 3.5. Method of Analysis

The finished product will be analysed to assess the accuracy capability of the UR5 measured in mm. In order to measure this correctly, precision equipment must be used. UNI-SQ Springfield campus have a Romer Articulation Arm Multi-Gage. The Romer Multi-Gage can measure objects with a precision of plus or minus 0.005mm (Park Engineering 2015). To use the measuring device, the 3D representation of the file can be uploaded onto the Romer Multi-Gage software for direct comparison. The process involves manually moving the measuring arm to specific locations on the physical object defined by the measuring software. This matches the physical location of the object relevant to the probe in the software representation. The probe can then be sent automatically to specific locations along the physical object via software at which it will measure and display the variation. Using the average variance of this device over multiple test cuts will provide an accurate method of analysis.

To analyse the viability of implementing the UR5 to perform CNC machining, the UR5 must be compared to CNC machines on the market. The two main improvements that are being assessed when using the collaborative robot to conduct the machining versus solely machine tending is the accuracy capability and the savings in cost. To compare these factors, a list of machines along with their cost and accuracy must first be graphed. From here, the machines final accuracy measurement can define the location within that graph to provide an estimation of the UR5's relevant cost as a CNC machine.

### 3.6. Accuracy Measurement Approach

To estimate the average accuracy, measurements must be taken along each of the x, y and z axes. If for example, a square is cut into a cube of material 10mm deep on the top plane, the average accuracy of that depth represents the accuracy the z axis. The depth is measured with an expectation of 10 millimetres and any difference of value is taken as an error. Both widths of the square move along the x and y axis therefore the same process can be followed. The Romer multi-gage can be used to find the average of 5 of the same measurements to help average out measurement errors. If a cube is milled with a different shape on each plane to test accuracy across all mill movements, there will be a measurement available for each axis on each plane. For 5 planes of machining this will yield 3 measurements for each plane giving 5 measurements to be averaged per cube for each of the 3 axes. The average of all 3 axes will then provide a final accuracy estimate for the milling process. If time permits, the whole process should be conducted up to 5 times to create 5 milled boxes and allow for a more accurate estimate.

### 3.7. CNC Machine Cost and Performance

There is an abundance of CNC machines on the market with varying costs and performance criteria. These can range from cheaper hobby models to expensive highly accurate machines. Finding exact prices for machines is a difficult task. High end machines provide brochures with no prices and require requested quotes. As the final cost analysis is just an approximation, 'ballpark' figures will suffice. John, 2021 presents an article discussing CNC machine costs in American dollars as well as their performance. Using the machines discussed in this article, a list of six machines and their costs vs accuracy was compiled into Table 2 - CNC Machine Cost and Performance seen below, based on the variance in price and accuracy. The machine accuracy is not always mentioned specifically on data sheets and store listings; therefore, the minimum position movement is used where possible. Where this wasn't stipulated, an average of values discussed across multiple forums was used. These figures are not expected to be extremely accurate and should be valued lightly. The cost comparison was left in USD as majority of the available costs for CNC machines and collaborative machines are in USD. Once obtained, the final relative value can then be converted to AUD.

TABLE 2 - CNC MACHINE COST AND PERFORMANCE

| Machine | Accuracy (mm) | Cost (USD) | Reference - 25 May 2022 |
|---|---|---|---|
| CNC 3018 Pro Max 3 | 0.2 | 159 | (Amazon.com) |
| SainSmart Genmitsu 3018-PROVer Desktop CNC Router | 0.2 | 349 | (Amazon.com) |
| EVOLUTION 5 CNC ROUTER KIT | 0.0508 | 1479 | (BobsCNC.com) |
| X-Carve | 0.013 | 2757 | (Inventables.com) |
| Shapeoko HDM | 0.005 | 5400 | (shop.carbide3d.com) |
| Tormach PCNC 440 | 0.0025 | 7000 | (tormach.com) |

The data in Table 2 was placed in a graph with the minimum cutting accuracy in millimetres VS the cost in USD. The resulting graph showed an approximately logarithmic relationship between the cost and accuracy. The accuracy was then plotted along a logarithmic X axis with the cost in USD on the Y axis. A logarithmic trendline has been included to provide an estimate of a CNC machines cost based on its accuracy. The graph, seen in Figure 5 can be used in the results section of the report to approximate the equivalent cost based on the performance of the UR5 as a CNC machine.

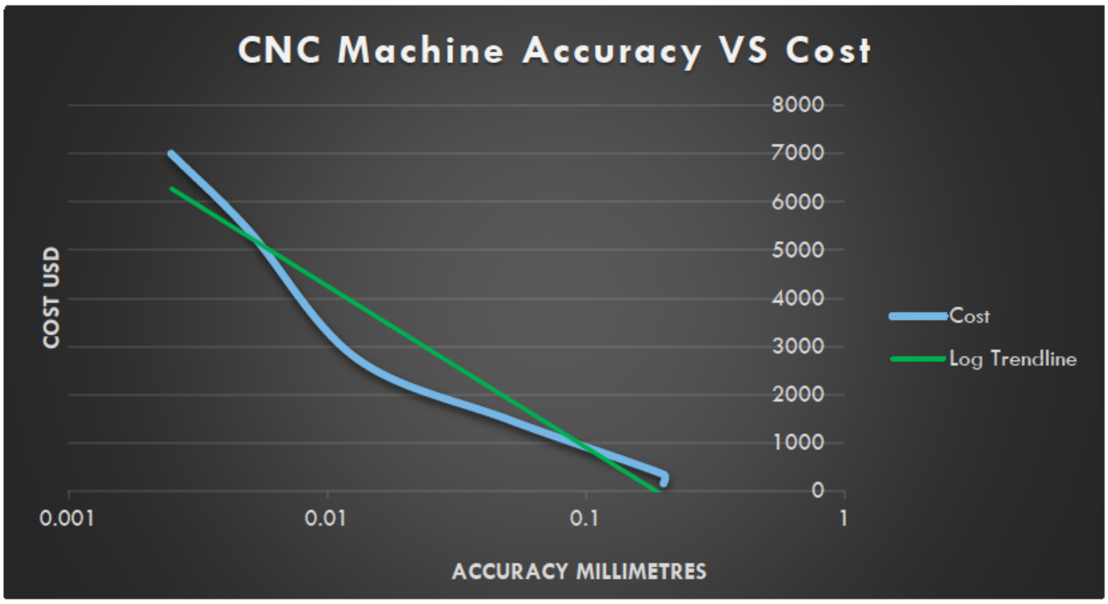


FIGURE 5 - CNC MACHINE ACCURACY VS COST

### 3.8. Consequences and Ethics

If this project were to be successful, it would prove that collaborative robots can be implemented in digital fabrication for more than just machine tending. This would open the door to countless options and ideas of integration for collaborative robotics. Consumers who may be on the fence on whether to invest in collaborative robotics may be swayed by the extra cost saving due to not having to buy other machines. If the software required to split a larger object into smaller joinable objects was developed, the implications of this project's success could greatly impact the desired use of collaborative robotics. Consumers would be able to produce plugs of almost any size accurately and relatively quickly in a machine that takes up a small amount of space. If the project were to be unsuccessful, this could negatively impact the collaborative robot market. Consumers may be reluctant to invest in the product, specifically the brand and model tested, if the accuracy was measure at a low standard. Care must be taken to demonstrate and document the limitations given to the performance of this robot as there is a high possibility of programming and build errors by the author in the design process that could cause poor performance.

The ethical implications of this study are minimal. The most evident ethical implication is the input and analysis of results. As discussed above, the project's success could provide a viable design and lead to a desired product which has potential to be profitable to the author resulting in financial incentives for the success of this project. Care must be taken to clearly record and discuss accurate data for analysis along with unbiased conclusions. The project could also impact the collaborative robot industry negatively. If the study concluded that the robotic performance of the UR5 was to a low standard, the integrity of all other factors including the software and hardware design must be addressed. An example of this is the fact that the prototype will use a low-end spindle with a cheap cutting tool. The final results and analysis of the UR5 must make clear mention of this limitation to ensure that no unwarranted objections to the UR5 and Universal Robotics as a whole is made. Another ethical dilemma to address is the material waste that comes with subtraction machining. This project is geared towards reducing the waste involved in subtraction machining in its endeavour to mill smaller objects to be connected. The smaller the pieces are, the less cut off required and therefore the less wastage created.

## 4. Project Planning

### 4.1. Resource Plan

There are a small number of resources required in this project. The most important resource is access to a collaborative robot and its software. UNI-SQ currently have two UR5 robots at the Springfield campus. There are currently no projects planned to utilise them other than this project. Only one of the robots is required therefor it is forecast that fairly flexible access is available throughout the year. The software used to operate these robots is called Polyscope. This software can be modified on the pendent attached to the robot or on a personal computer through simulation software which can later be used to operate the robot.

There are a number of directions that the prototype can be developed to complete the objective. It was identified early that there is a significant number of resources available through the project supervisor including materials, rails, sensors, and clamps. The design should take these resources in to account to lower the amount of parts acquisition required. Building of frames capable of holding the spindle can be easily outsourced to the UNI-SQ workshop using these resources. Brackets and clips can be 3D printed using one of UNI-SQ's many 3D printers.

The final resource required is the plug material. Initial prototype testing can be conducted on scrap material such as MDF until the final testing is due to be conducted. The final test piece to assess the accuracy of the prototype will need to be made of a material that can be cut and measured accurately. The material that is selected should also be capable of being used as a plug for the carbon door panels for complete conformation of objectives. Scrap Necuron 702 was sourced from a local manufacturer who confirmed this as an appropriate composition for carbon fiber panels.

## 4.2. Risk Assessment

There are several risks when conducting this project that must be discussed. To ensure that no unnecessary risks are being taken and that appropriate mitigations are in place, a risk assessment was conducted. Each identified risk with current mitigations were assessed to find the level of consequence as insignificant, minor, moderate, major or catastrophic. The possibility of this risk occurring is then assessed as rare, unlikely, possible, likely and almost certain. Each identified risk along with its consequence and possibility was assessed based on the UNI-SQ risk matrix in to give a level to the risk as well as the actions that are required to be taken. From here, further mitigations are proposed in order to re-assess the potential risk and lower its final level. With these new mitigations in place, a new assessment of consequence and possibility can be made, and the final risk level can be identified. The UNI-SQ risk matrix can be seen below in Figure 6.

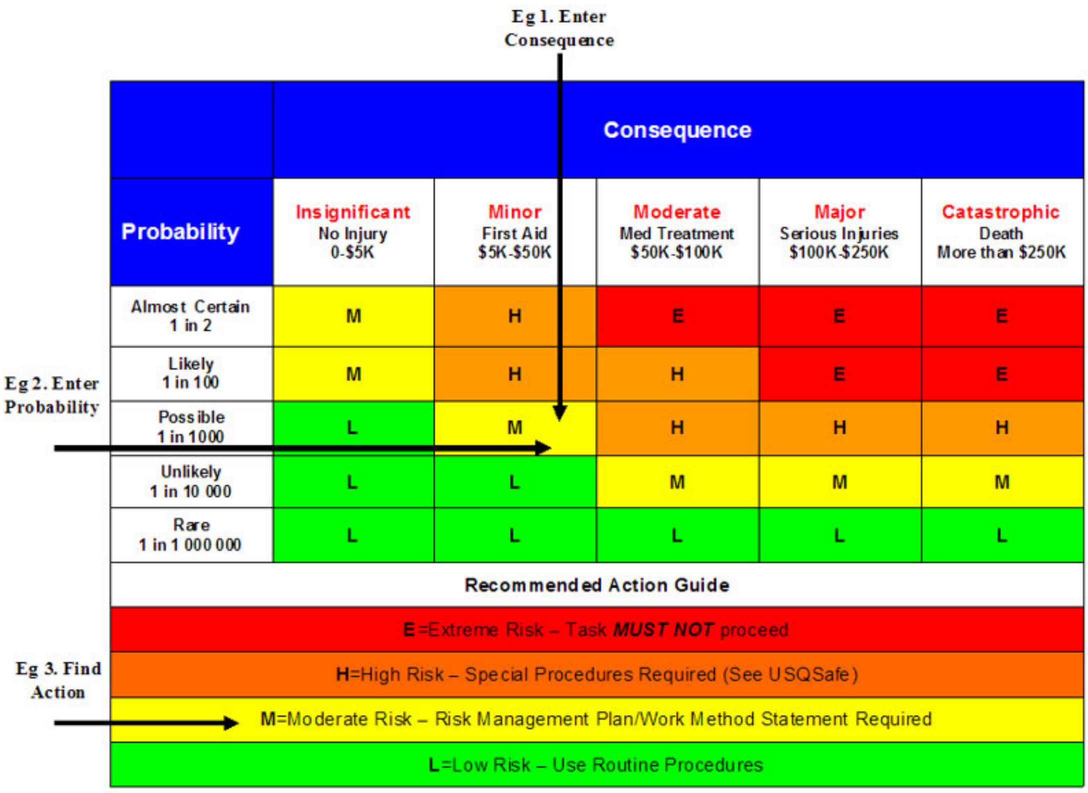


FIGURE 6 - UNI-SQ RISK MATRIX

Building the prototype design includes the use of numerous tools depending on the design. This tooling can include basic workshop items such as metal power saws, drills, grinders, and soldering irons. The risk when using this equipment includes injuries to personnel and equipment that can lead to serious injuries and complete destruction of equipment and was therefore defined as catastrophic. There are already measures in place for all personnel using the workshop including a required safety induction showing the emergency procedures and emergency response equipment as well as explaining the required safety apparel and clothing required when using particular workshop tools. There is also a requirement for all students to always have supervision in the workshop. The likelihood of injury occurring to general personnel without knowledge of their experience was assessed as possible giving a total risk level of high. To mitigate this risk, it is determined that personnel must be both qualified and competent on the equipment before use. Any tasks that are beyond the personnel capability will be outsourced. This brings the likelihood down to rare, giving a low risk rating which requires no further planning.

Another risk to be assessed is the possibility of injury or damaged equipment due to shrapnel from a tool bit breaking while spinning in the spindle. This could cause major damage to eyes and minor damage to limbs and equipment. The tooling bits are designed with this risk in mind, and it is an unlikely, almost rare event. Due to the severity of the consequence, this risk is rated as moderate. The first clear mitigation is the requirement for all personnel in vicinity of the prototype to be wearing eye protection when the spindle is on. This brings the risk down to a minor consequence. Further mitigation can be obtained by ensuring maximum distance is given during operation of the spindle as well as a barrier such as a window where possible. Limiting personnel who are in the room of operation will also decrease the likelihood. This risk is now identified as minor and rare giving it a low-risk rating which requires no further planning.

The third risk identified is the operation of a collaborative robot in the same space as people. The UR5 is specifically designed to work close with humans however there is a level of understanding that personnel must be aware of to understand these safety limitations. The consequence was assessed as minor with an unlikely possibility giving a risk level of low. The mitigation that can be made to lower the risk even further is ensuring all personnel operating the robot understand the safety functionality of the UR5 before working with it in close proximity. This lowers the possibility to rare which still maintains a low-risk rating requiring no further planning.

Operating the UR5 to move around a spinning tooling bit creates a risk of damage to the equipment. The UR5 costs a significant amount of money. If the device was required to be completely replaced, this was assessed as a moderate consequence. Considering that this is the first interaction with a UR5 for all personnel, it assessed that collision is possible creating a high-risk rating. To mitigate the possibility of this risk occurring it is concluded that all automated file executions are first run through without the spindle in place to ensure there is no chance of accidental damage from the spindle to the robot. This brings the possibility down to rare and lowers the risk to a low level which requires no further planning.

The final risk that was identified is the risk involved with the low voltage wires used for the spindle. Shorting of these wires can cause fires and/or damage to the spindle. Due to the low cost of the spindle, the requirement for machine supervision during operation and the sufficient firefighting equipment in the workshop, the consequence was identified as minor with a possibility of unlikely giving a low risk level. Further mitigation can be made by including a fuse in the spindle voltage line and ensuring the emergency stop button cuts power to all devices. This lowers the possibility to rare and maintains a low risk level requiring no further planning.

### 4.3. Timeline

The total time for this dissertation is two semesters spanning approximately twenty-eight weeks. Some tasks are obvious prerequisites of others while others can be conducted concurrently. In order to visualise and plan these tasks, a Gantry chart was created seen in Appendix D. The tasks were broken down into multiple steps with in six phases. Phase one is the preparation phase. Initially, this phase was projected to be complete in the middle of semester one however adjustments were necessary due to workload and time constraints. The adjustment leaves seven steps in this phase, and it, along with phase two, spans the first half of the year.

Phase one involves initial background research at the beginning of the project to define the project aims, objectives and limitations. This then helps provide guidance into the next step of conducting a literature review. The design, build and testing plans are then created, and a design can be finalised. The parts required can then be documented and ordered. The second phase is one step that can be conducted concurrently to phase one. It involves the documentation of the steps in phase one into the dissertation. This phase is very important and purposefully defined separate to phase one to ensure that the information gathered in phase one is double checked and well documented ready for phase three, the building and testing phase.

Phase three involves five repeatable steps that carry through the review of the design to order parts, building the prototype, testing the basic performance, conducting a full performance test if applicable and recording the results. This is followed by phase four which involves the compilation of the build and test results into the dissertation and reviews and concludes on these results. These two phases have been planned under the expectation that only one design will be built in this project. Phase five is conducted only if there is available time to do so and involves repeating phase three with design optimisation changes followed by adding this into the dissertation. The final phase, phase six, involves the full review and submission of the dissertation over the final two weeks of semester two.

# 5. Design

## 5.1. Material

The material to be used in testing will vary along the testing process. To begin with, cheap material such as MDF will be used until it is seen that the robot is correctly performing the milling. Once the procedure has been identified as suitable, a material capable of high precision must be used to allow for consistency when measuring the milling accuracy. As detailed in the literature review, the choice of material can vary greatly depending on the application. For the purpose of machining plugs capable of carbon fibre layering, the material chosen must be capable of withstanding the curing process of carbon fibre. The local manufacturer, LSM Advanced Composites, recommended Necuron 702. The company kindly provided some of their left-over material. The size of the tooling board required for testing is arbitrary. Simulation can be used to determine the maximum bed size where the robot will display an alert and pause when a movement is deemed impossible. Therefore, it is obviously advantages to keep this as small as possible for initial stages of testing. A ten-centimetre cube was selected for simplicity where all milling designs will be made to carve from this sized cube. The acquired tooling board can be cut down to 10mm cubes using a bandsaw.

## 5.2. Physical Design

The three configurations discussed in the design approach must be considered. Configuration C is used to be able to provide a fourth a fifth axis where the object can be rotated on the bed, allowing three-axis milling from multiple plains. This configuration is not an appropriate design approach for collaborative robots that can provide the five-axis movements through just one of the other two configurations. In the case of moving the material about the tooling bit, consideration must be made on the weight of the end effector as well as the material to ensure it is below the payload. Though it would be beneficial to have the robot be capable of picking up the material and therefore being able to repeat the process to create a production line effect, the payload for the UR5 is relatively small and would severely limit the maximum size of material that can be machined. Tooling board can range in weight from 100 to 1000 kilograms per cubic metre (Rogers 2019). Ignoring the weight of the end-effector and at the smallest of this range, the maximum volume of tooling board can be calculated. Setting the height to 0.1m and setting the length and width as an area in $m^2$ gives:

$$(height\ in\ m * area\ in\ m^2)\ weight\ in\ kg\ per\ m^3 = payload\ in\ kg$$

$$(0.1 * A)\ 100 = 5$$

$$A = 50\ m^2$$

In reference to this size limit at the lowest end of tooling board weight, the milling configuration where the robot holds the tooling bit is limited by the robots reach. If the material to be milled was to be a rectangle with a length of 0.75m which fits with in the robot's reach of 0.850m and allows for clearances, the maximum width would be:

$$(height\ in\ m * length\ in\ m * width\ in\ m)\ weight\ in\ kg\ per\ m^3 = payload\ in\ kg$$

$$(0.75 * \ 0.1\ * w)\ 100 = 5$$

$$\frac{15}{2} w = 5$$

$$w = \frac{5 * 2}{15} = \frac{2}{3} = 0.667m$$

Considering that this is the lowest tooling board density in the range and that the first configuration can maintain the same size up to the 1000kg/$m$^3, the optimal option for milling plugs will be to mount the spindle on to the robot itself. A point to note in this configuration is that the machine tending process can therefore not be conducted by the UR5 if the material is above the payload and additional machines such as conveyer belts may need to be used. If the consumer were to be milling objects below the payload of the robot, it would be practical to explore configuration B however, for the purpose of proving the capability of the UR5 to machine plugs, configuration A is the most appropriate fit for this design. To achieve configuration A, a spindle must be mounted to the robot and material must be fixed in front of it. For the prototype design, a vice will suffice as the material holding mechanism. For the spindle, a spindle from a Genmitsu CNC Router Machine 3018-PROVer seen in Figure 7 was used.


FIGURE 7 - GENMITSU CNC MOTOR

To mount this to the UR5 robot, a bracket needs to be created that aligns with the UR5 mounting points and the spindle. This can be achieved via 3D printing. The design for the mount will require a plate with holes that line up with the UR5 thread as well as a mechanism to clamp the spindle. A cylindrical metal clamp can be used for this along with a predesigned recess to limit the clamps movement. The spindle runs on 24V which can be powered and controlled through the tool outputs of the UR5. These outputs are set in the programming software. The bracket was printed using Onyx (Markforged, CF reinforced nylon), a high strength filament, on one of UNI-SQ's 3D printers. The final spindle mount design can be seen in Figure 8.

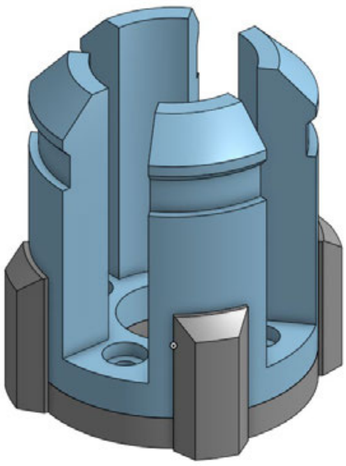

FIGURE 8 - MOUNTING BRACKET

The UR5 must be mounted to the same table as the vice to reduce the loss in accuracy due to the oscillation in the table as the robot moves. The vice should be located in the approximate centre of the robots reach. The vice must also be positioned to allow the robot to achieve maximum available surface area. For example, the vice will need to cover at least some of the two sides of the material it is clamping. If this is kept at the minimum and angled appropriately, the robot can mill the remainder of the available surface are on all sides except the bottom. Attention must also be made to the radius of the spindle and UR5 arm when mounting where the tooling bit mills could copied with the table or vice holding the material. If the object were raised off of the table by only 50mm and the radius of the arm was more than this, the table would limit the lowest point that milling can occur. For ease, the vice will be selected to have a height of more than the spindle and robot arm radius. All of the parts were collated into a table seen in The resulting parts list seen in Table 3.

TABLE 3 – PARTS LIST

| Part name | Method of Acquisition |
|---|---|
| Spindle (Genmitzu 24V) | Acquired from home CNC Machine |
| Tooling bit | Acquired from home CNC Machine |
| Cables (20A Minimum) | Toowoomba Stock |
| Fuse (20A) | Toowoomba Stock |
| Switch | Toowoomba Stock |
| Spindle Mount | 3D Printed by Supervisor Dr Craig Lobsey |
| Vice | Springfield Stock |

## 5.3. Test Object Design

The goal of the 3D object designs is to create varying levels of complexity for the robot. The first test should aim at traditional CNC machining of single plane, three axis machining. The next step would be to attempt multiple plane three axis machining. The final test is to attempt single plane 5 axis machining. Starting with the material size defined earlier of a 10cm cubed piece, three designs were created. The first design can be used for the first two tests. The other two designs vary in complexity for five axis testing. The spindle was set with a the relevant tooling bit with a length of 15mm from the tip to the spindle grip referred to as the tooling bit height.

The first test of single plane three axis machining can be achieved by cutting a shape out of the 10cm cubed block on the top surface. The way that Fusion 360 is constructed, each plane of approach develops its own machining process code. This means the other four planes of approach can be included on the same design where cuts can be machined separately. For the other four planes, different shapes were cut out of each side to define which cut was performed each plane during the measurement phase. The resulting design can be seen in Figure 9.

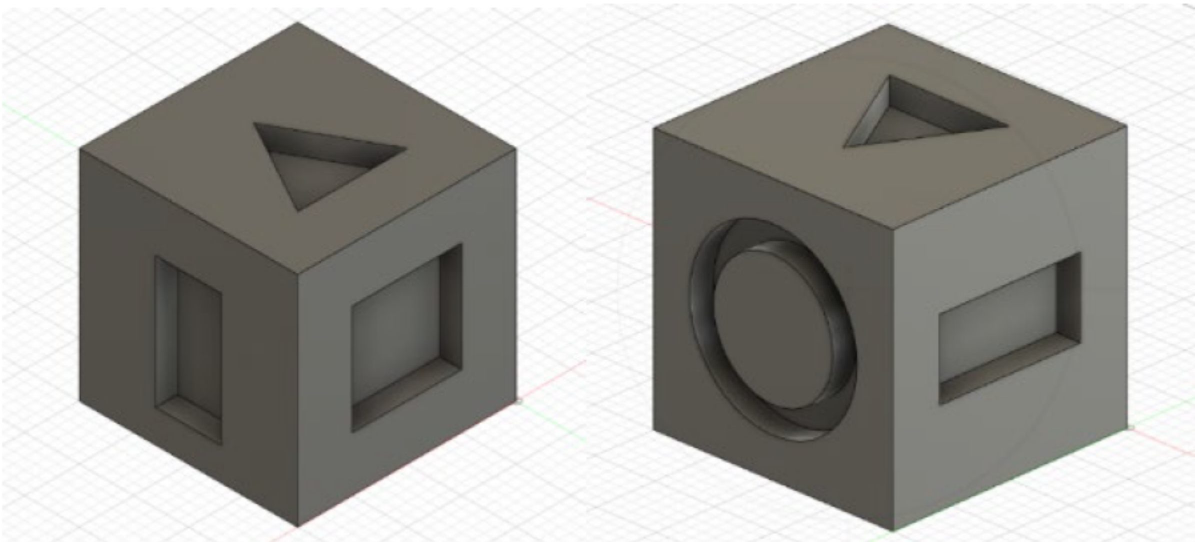

FIGURE 9 – FUSION 360 DESIGN 1

The second design needs to test the ability for single plane five axis machining at a lower complexity. The biggest benefit to five axis machining is that the tooling bit can be angled to avoid collision with the material allowing cuts deeper than the length of the distance between the tooling bit head and the spindle grip. With the length set to 15mm in the tooling bit configuration and setting auto collision avoidance on, the design seen in Figure 10 creates a curve that requires the robot to move about the fourth and fifth axis.

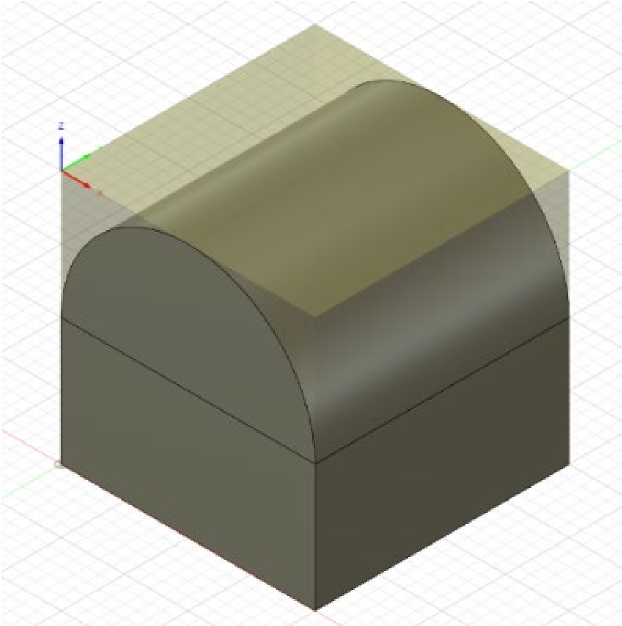

FIGURE 10 - FUSION 360 DESIGN 2

The third design is intended to put the robot to its limits. A shape that requires sharper movements about the fourth and fifth axis is required. To do this, a sphere was projected on top of a box. In order to cut the shape seen in Figure 11, the robot will require extensive movements across all five axes.

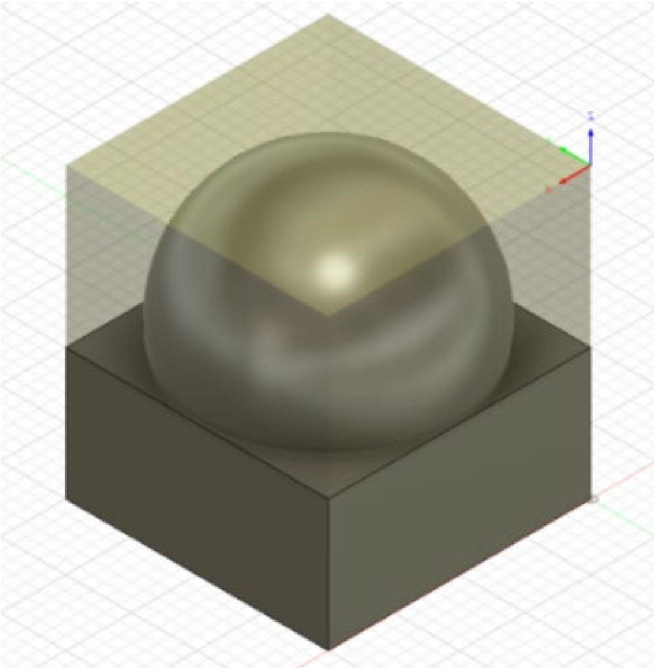

FIGURE 11 - FUSION 360 DESIGN 3

Universal robots and Fusion 360 have developed an add-on post processing software for use with Polyscope. The software converts the Gcode into a numerical code file that is compatible with Polyscope's numerical code input software. Settings such as speed, angle limits, and spindle on/off control can be set in the post processor. When the post-process is run, a file with the extension .nc is created which can be uploaded into Polyscope via USB. Only two settings were adjusted with all other settings configured in Polyscope. The robot head angle was set to 0 to indicate an approach from directly above for each plane of machining and the end-effector state was set to "+links on) which allows the code to turn the spindle on and off between cuts.

### 5.4. Polyscope Design

Universal robots have configured their operating software to run through multiple programming environments. The native software called Polyscope is designed to allow use from low experience programmers while still allowing complex adjustment. The final program code is called UR-Script which can be built in the Polyscope environment or in other typical coding platforms. The Polyscope environment provided users with building blocks that can be ordered and stacked to construct the flow of the program. Useful blocks allow movement based on directions or waypoints. Waypoints can be determined in relation to different planes and orientation and have the format in millimetres of (x,y,z) where -z indicated an upwards movement. There was also a block where raw script could be inserted which proved extremely useful. Universal Robots have produced software and instructions online to simulate their robots. To access this software, a computer with Linux or a virtual machine running LINUX is required.

The first step in building the program for CNC machining was to action a numerical code file. This is achieved through a block called URCaps where you can select a plane and tooling bit location to be relative to the zero point of the numerical code. The integration of this for single plane, 3-axis programs was straight forward. The next step is to set up the payload weight. This is conducted by telling the robot to use the payload called spindle. The spindle weight can be changed once the physical robot is built by actioning the automatic weight and setting this value to spindle. This weight will then be used in the program.

The robot then needs to move to a location to prepare for zeroing where the robot can be set to automatically zero itself to the material before performing the cut. This can be achieved by using the UR5's collision detection function. The robot's first location is relative to the vector (325,325,-200) which is set to be above the material. To zero the robot, the expectation is that the material is placed approximately 300mm from both the robots x and y axis in a positive direction. The only conditions involved with the placement of the material is that it overlaps the (325mm,325mm) vector from the robot zero and that one side of the material is parallel with the robot x axis and one side is parallel with the robot y axis. The robot then zeros at the start of the program by lowering through the z axis until collision is detected. This height is marked as the zero location. The robot then lifts slightly, moves in the x direction further than the material width, lowers slightly below the z height and sweeps back in until collision is detected. This is set as the y axis location. This is then repeated sweeping the y direction to set the x location. Each of the three locations are recorded as a variable in the system and these are used to set the tool zero point for the top cut. Since the cube width is known, these values are used to locate the zero point for the other four planes on each side mathematically. This also involves flipping the relevant robot axis to adjusts the robots tool approach.

For simulating purposes where the simulation does not have the ability to set material that can stop the robot at the right point, the robot is simply moved to the expected zero location where the calculations can be conducted. The five planes were given names based on looking at the object from the robot's base. Two sides can be seen from this vantage point which are called front left and front right. The top side is referred to as the top and the remaining two sides are called the rear left and rear right respectively. To perform the zero calculations, the robot moves to 100mm above the corner of the cube closest from the base known as the zero location. This location is then used to calculate the plane and axis based on that location. The plane and axis settings required for all five planes of approach can be seen below in Table 4 below where the X, Y and Z coordinates are in metres from the base and the RX, RY and RZ is in radians in relation to the default tool orientation that aligns with the X, Y and Z directions.

TABLE 4 - ROBOT AXIS SETTINGS- CUBE WITH FIVE PLANES

| Plane | X | Y | Z | RX | RY | RZ |
|---|---|---|---|---|---|---|
| Top | Xzero | Yzero | Zzero – 0.1 | 0 | 0 | 0 |
| Front Left | Xzero | Yzero + 0.1 | Zzero | 1.2089 | -1.2089 | -1.2089 |
| Rear Left | Xzero | Yzero + 0.1 | Zzero – 0.1 | 4.71238898 | 0 | 0 |
| Front Right | Xzero | Yzero | Zzero | 1.570796327 | 0 | 0 |
| Rear Right | Xzero + 0.1 | Yzero + 0.1 | Zzero | 0 | 1.570796327 | 0 |

Now that the robot knows the zero point and the angle of approach for each plane, each of the numerical code files can be actioned. Upon initial simulation, many errors occurred where the robot reached singularity faults. Ultimately this came down to the fact that the robot is trying to maintain a tool speed defined by the numerical code that it cannot perform in certain orientations. It became clear that moving to an optimal orientation before the robot conducted the cut was essential to the numerical code being completed without error. When approaching the top for three axis machining, the orientation of the robot's axes did not matter, however the two left sides and the two right sides required a specific orientation. Milling the left side required the robot shoulder to be on the right as you look from the robot base towards the material and the opposite was required for milling the right side. The wrists section of the material is required to be on the same side of that being machined with the spindle facing the machine perpendicular to the face of the side being machined. The process to achieve this was to have the robot have both a shoulder left and shoulder right home waypoints that was high above the material as well as giving each plane a high and low way point. The low point was for when the robot was in position ready to machine, and the high point was 200mm in the robots -z direction. The robot program started by moving to shoulder right high waypoint, top plane high and top plane low before conduction the numerical code followed by top low, to top plane high and back to shoulder right. The front left and rear left side was then conducted with relevant high and low plane waypoints. The robot then conducts a flip over movement to place itself into should left where it repeated the same relevant flow for the right-side front and rear. On completion the robot then flips itself to the shoulder right high location to finish the program.

# 6. Results and Discussion

## 6.1. Results Summery

The robot program was built and tested in simulation before being physically tested in the workshop. The latest version of the Universal Robots Graphical Programming Environment Picoscope for the CB series robots was 3.15. The program runs on Linux which was installed on a virtual machine on Windows. Once simulation had been successful, the program was then copied across to the physical robot for testing. First the program was run and assessed with no material and no payload to ensure the program could run without the robot colliding with itself or its surroundings. Next the payload was installed, and the program was checked again to ensure the extended tool length did not cause collisions. A third practice run was then conducted with the cables attached to ensure free range of movement. The final practice run was conducted with the spindle running, the vice in place and all cables attached. From here, scrap material (MDF) was inserted into the vice to check basic milling performance. On the success of this, the three testing cubes could then be milled using tooling board. These cubes can then be measured using the Romer Multi-Gage to document and assess the robot's milling accuracy.

## 6.2. Simulation Results

Simulation of the robot was conducted in the native robot's software. The building block type programming technique was used with inserted script for plane approach calculations. The method for simulation involved testing and adjusting each of the plane approaches to set the robots joints in a manner to ensure the highest likelihood of successfully running the milling script. The first section contains variables that will need to changed based on the physical set up. This includes the spindle distance which is the distance from the tooling bit to the original tool centre point and the spindle payload which will be the total weight the robot is holding. The next section sets up the new tool centre point (TCP) and payload based off the variables above. The timer is also configured in this part to provide a total milling time. The third section is only used for physical testing and is suppressed during simulations. It is expected that the robot is moved manually to the zero point of the material at the beginning at which the robot will move 100mm upwards in the Z direction for the calculations to take place. The fourth section simulates this by moving to the location that it is 100 above the simulated zero point. The fifth section performs the plane calculations. The current location of the TCP is used with the values from Table 3 to configure the location of the zero and direction of the tools coordinates system. The next five sections perform each of the five planes of milling. The top, front right and rear left begin with the robot's shoulder to the right and the front left and rear right begin with the robot shoulder to the left. Each of the sections then have two waypoints configured with the correct approach angle called a high and low where the high waypoint is positioned away from the material and the low waypoint sits close to the material. The program first moves into the high position from the shoulder right/left position to remain clear of the material before moving to the low position. Once the milling is complete, this is conducted in reverse order. The robot finishes off by moving back to a shoulder right safe position as well as calculating and displaying the program time in minutes. The resulting program structure can be seen on the left of Figure 12.

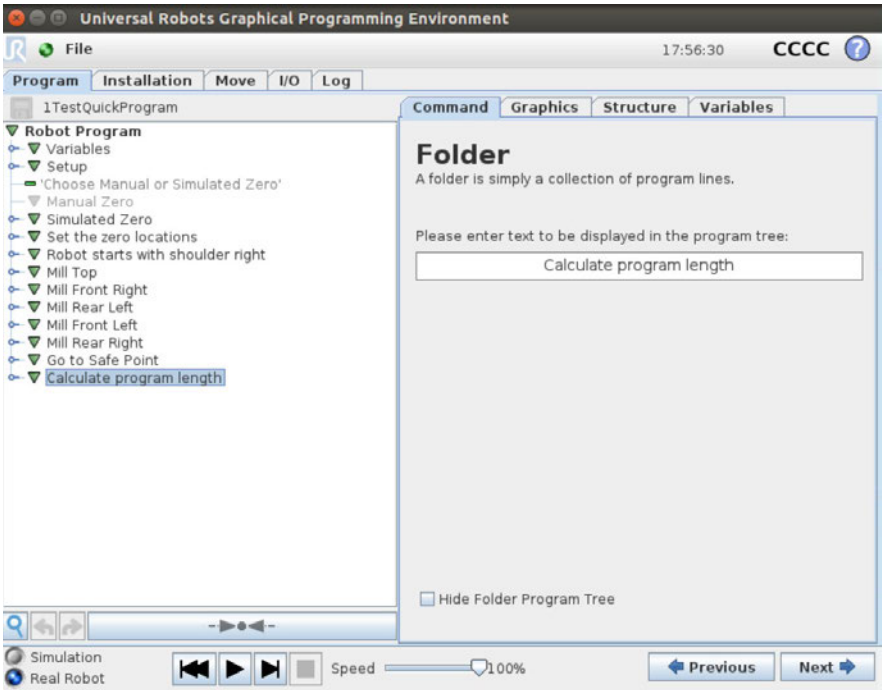


FIGURE 12 – SIMULATION PROGRAM STRUCTURE

When the robot approaches were not positioned appropriately, the milling script would run into singularity errors. The singularity error is triggered when the milling script is attempting to maintain a milling speed that cannot be produced by the robots' joints. The flexibility of the robot from a given position is depended on the space that is being milled as well as the complexity of the milling script itself. It is noted that there was difficulty in the beginning of simulation in understanding the motion of the robot enough to position it correctly for each plane of milling. There is not enough time in this project to test more than the five cuts built in Fusion 360 however each of these were tested for each plane with success. It is also noted that the simulation will be sufficient in checking that a program script can successfully be completed before risking the loss of material during physical milling.

### 6.3. Machine Construction Results

The machines construction went as planned except for the method of mounting and running the spindle. The final spindle holder was intended to be printed in Onyx (Markforged, CF reinforced nylon) for strength. The preliminary test mount was printed in PLA which was observed to be suitable for testing as the spindle did not produce any significant heat. Originally it was planned to use a relay to power the spindle which is controlled by one of the tool outputs programmed within the script. To use the actual function would have used up the limited time available. Considering that testing of the robot's ability to run a relay is not part of what is being tested, a simple switch was made for safety and the spindle was left on for the duration of the cut. A vice to hold the material was bolted to the same table as the robot to minimise vibration errors. The pretesting procedure was run as planned. The cable management involved testing and adjusting of the cables as the robot was moved across each of the planes. It was noted that great care must be taken to ensure each joint of the robot is given the required amount of cable slack to allow at least 180 degrees of movement. Once the final pre-test was run successfully with everything in place except for material, cardboard was placed in the vice as a basic milling test to ensure the robot moved the spindle around the material safely.

### 6.4. Five-axis Simulation Results

Five axis machining was briefly tested in simulation. The benefit of machining with more than three axes is not so much in the accuracy of the mill but rather the depth and angle of approach that becomes available. To simulate the performance of five axis machining, two objects were designed to increase in difficulty. The first is a box with a curved top box seen in the left of Figure 13 and the second is a box with topped with a sphere seen on the right.

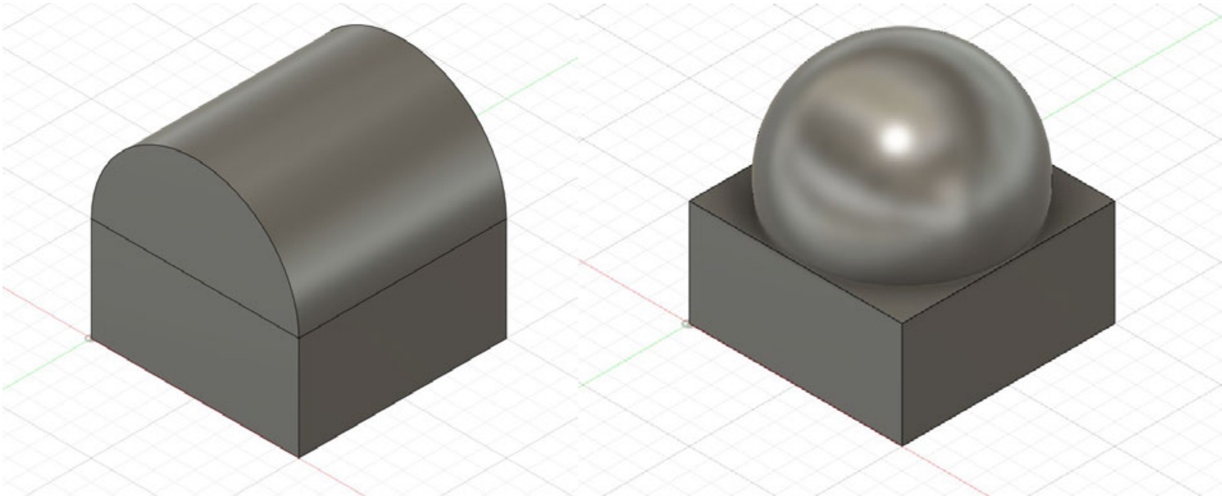

FIGURE 13 – CURVED AND SPHERE TOPPED BOX

The curved top box creates a milling process that requires machining at depths requiring the tooling bit to rotate to avoid collision between the spindle holder and the material. Testing of this file required that the robot approach angle and set up configuration was set up specifically in a way to allow flexibility in the joints in line with the boxes curve. As the tool centre point was required to be moved across the material, it created an exponential movement further up the robot's arm which would reach the robot joint speed limit and cause errors if the set up was not adequate. This type of machining is feasible as long as there is only one direction of angle that must be machined.

Machining of the sphere topped box was not successful. This was due to the same limitations of the curved box except in this case the tool centre point was moving too far around for the robot joints to keep up. Machining could be possible if extremely slowed down however, there is possibility that this shape could be machined using the 5 plane – 3 axis machining technique instead. This comes down to the skill and experience of the operator creating the milling processes on Fusion 360. Based on the simulations results, it was determined that physical testing of 5-axis machining was not necessary considering the difficulty in the robot having errors due to tool speeds and the fact that 5-plane, 3-axis machining is capable of achieving the same milling result.

### 6.5. Single Plane Three-axis Results

To begin machine testing, a scrap piece of epoxy was used to test the top plane milling procedure. The procedure involved first measuring the spindle height and payload. These variables were entered into the script. The scrap epoxy was placed into the vice and secured. Care was taken to ensure that the front right lined up with the robots base x axis and the front left lined up with the robots base y axis. The tool bit is then moved to the corner that intersects the two front planes and the top plane. This location is saved as waypoint ZERO. The script will then use this point as its reference zero for the milling script. A protective screen was placed around the robot and the procedure was initiated. The robot moved along the required movements and begun conducting the cut. The total time taken for the cut to be completed was 30 minutes. A photo of the final cut can be seen in Figure 14.

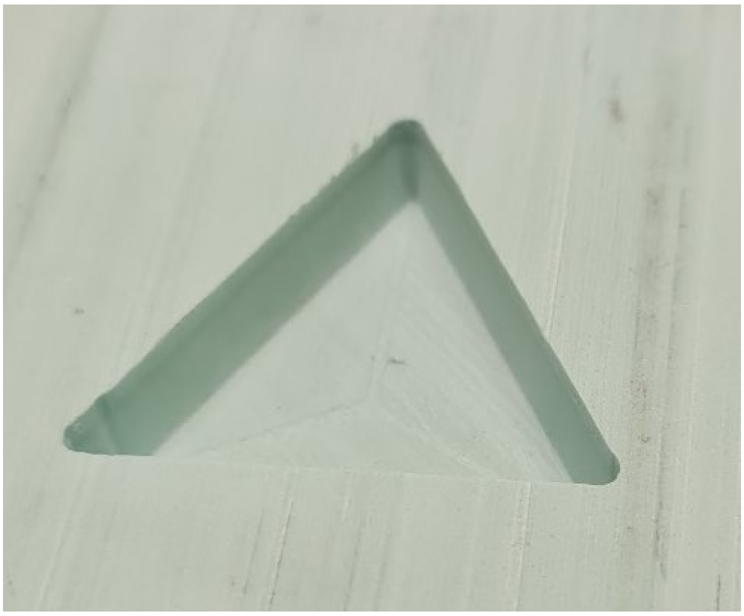

FIGURE 14 - PHOTO OF TOP PLANE TEST CUT

The first milling attempt was relatively successful. The goal was to ensure that the preparation script worked correctly as well as the milling script. The triangle that was milled appeared correct by eye and was smooth to touch with visible chips at a few points, attributed to the cheap cutting tool. Initial measurement of the triangle using the Romer proved difficult. It was recognised at this point the most appropriate shape to test accuracy would be a square for each side. The script for a square cut was then generated for each plane.

### 6.6. Multiple Plane Three-axis Results

Multiplane testing was conducted by first fixing the 10cm cube in place and running the preparatory plane movements with the spindle off to ensure the robot moved about the cube safely. As discussed in the single plane test, all scripts were adjusted to mill square shapes. Preparatory movements successfully moved without impedance by the surrounding cables and material. It was addressed in the process however that the milling of one side would cause a collision with the vice handle. The solution was to perform the cuts for three planes, leaving the vice handle and opposite side. The zeroing point was then raised which in effect caused the square to be cut at a higher point to avoid the collision. A photo of each plane of the first cube was taken and can be seen in Figure 15.

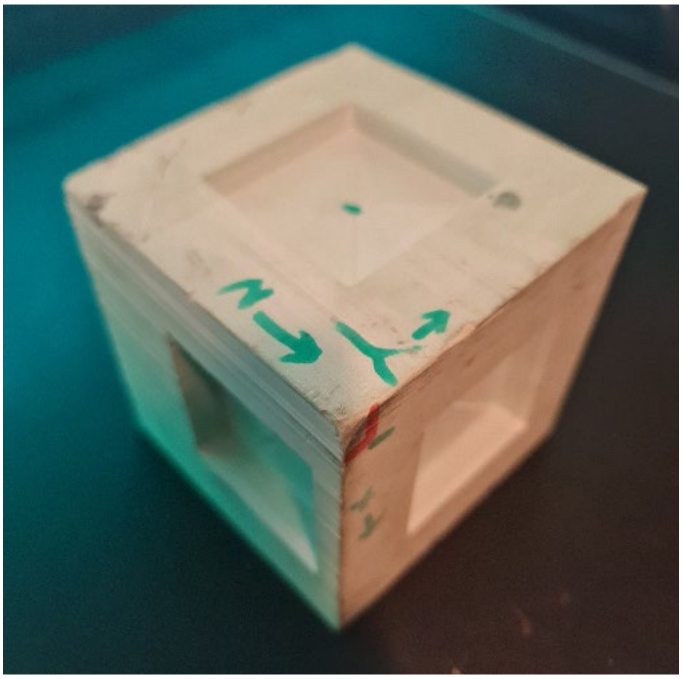

FIGURE 15– MULTI-PLANE INITIAL TEST

The resulting cut had smooth sides for the initial cuts with a breakdown of accuracy evident where the cheap tooling bit had clearly begun to wear down. The depth of two of the squares had a slow error along the cut which is attributed to the cuts made to the stock material before milling. The cube was then able to be fixed in place next to the Romer 3 for accuracy measurements. The measurements were taken between the width and length of the squares which would line up to a corresponding x, y or z of the robot's base plane. The material for the cube is very dense and difficult to cut exactly. To accurately measure the sizes of the square, it was determined that measuring the depth of a square would be conducted by measuring the distance between the bottom plane of a cut and the same bottom plane of the square on the opposite side. This measurement is then not reliant on the accuracy of the cube's dimensions. The measure of top to bottom on each of the side planes will be a measurement along the robots z axis and the side-to-side measurements will represent the accuracy of the robots x or y axis depending on the orientation of the square. The top squares width and length will also represent an x and y accuracy and the z measurement of the top plane will measure the z axis of the robot with error induced by the manual zeroing process.

## 6.7. Accuracy

Measurement of the shapes using the Romer Multi-Gage was conducted with the average of 5 measurements across each of the axes. This data can be seen in Appendix E – Results Data. The average of the 5 measurements were placed into a smaller table and the average per axis and total average was calculated, seen below in Table 5.

TABLE 5 - CUBE 1 - ACCURACY MEASUREMENTS

| Error From Expected Result (mm) | | | |
|---|---|---|---|
| Cube 1 | Axis | | |
| **Plane** | **x** | **y** | **z** |
| Top | 0.5448 | 0.9707 | 0.4372 (Not used) |
| Front Left | 0.980366667 | 1.197333333 | 0.959066667 |
| Front Right | 0.6705 | 1.495566667 | 0.6022 |
| Rear Left | 0.9877 | Same As FR | 0.596366667 |
| Rear Right | Same As FL | 0.856133333 | 0.845366667 |
| Average per axis | 0.795841667 | 1.129933333 | 0.75075 |
| Total Average | 0.892175 | | |

The first note to take on these results is that all of the errors are positive. This indicates that there is something in common for each axis which would cause more material to be milled than expected. The likely culprit is the low-quality spindle and tooling bit combination. If the spindle chuck were to be vibrating as it spins, this would cause removal of material bigger than the diameter of the tooling bit. There was visible vibration in the spindle when the rotating where the diameter of the spinning bit appeared to visibly increase. If a higher quality spindle and tooling bit were used and onyx was used to make the spindle mount, this vibration could be significantly reduced or removed. To assess the results with this vibration in mind, an assessment of the bias can be done. The standard deviation of the error estimates the imprecision of the machine which will give an indication of the likely average error if the bias were to be removed. The resulting figure can be assessed as a theoretical average error for analysis.

The bias in this case is the same as the total average because all values are positive. To work out the standard deviation for a small population size, the following equation is used:

$$s = \sqrt{\frac{\sum(x-\bar{x})^2}{N-1}}$$

Where:

s = Standard deviation

x = Each sample

$\bar{x}$ = The sample bias

N = The number of samples

Using the values from Table 6 gives:

$$s = \sqrt{\frac{\sum(x - 0.892175)^2}{12 - 1}} = 0.27463$$

The standard deviation from the bias is 0.27463mm. To assess the relevant cost of the machine based on its accuracy, the estimated accuracy without bias for the UR5 as a CNC machine was placed onto the CNC Machine – Accuracy VS Cost plot seen in Figure 16.

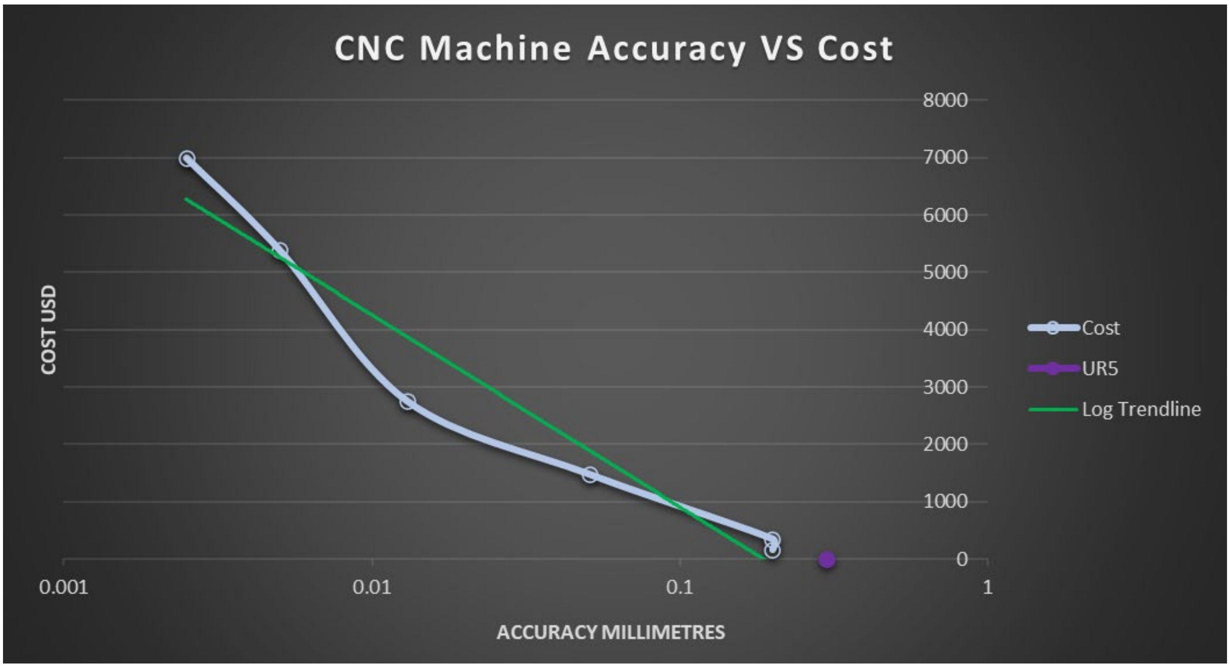


FIGURE 16 - UR5 ACCURACY VS COST ESTIMATE

The results indicate that the UR5 has no relevant cost as a CNC machine when precise accuracy is desired however, the estimated accuracy of plus or minus 0.3mm is still an acceptable CNC performance where minute accuracy is not of importance.

# 7. Conclusion

## 7.1. Design Summary

The overall design was a success. The clear possible improvements are in the spindle assembly where the mount could be made with a stronger material and a higher quality spindle and tooling bit could be used. Switching of the spindle to turn it off and on between cuts was programmed into the script however it was not physically wired to occur. The addition of this function would allow safer transitions between planes and shoulder positioning. The vice positioning was adequate for the particular position and shape that was being milled however the vice tightening handle inhibits milling the bottom 30mm of the cube on two sides. If milling in these areas were required, rotation of the material between cuts may be required or a new method of fixing the material will need to be implemented. The machines milling produced substantial dust which was mitigated by performing the milling under dust vents. A permanent design would require the use of a dust extraction system included in the design or use requirements. The milling produced significant noise which is expected due to the spindle assembly vibration as well as the roughing tooling bit. If the vibration issue were to be fixed, it is expected that the noise produced would become manageable for a typical workshop or production facility. Zeroing of the robot was conducted manually which induced error on the z axis depth measurement for the top plane. Further designs could make use of precision electric sensors which can be programmed to accurately set the tooling bit length as well as an automatic zeroing function. The design also relied on the material being square to the robots x and y axes. This was done by using squares and rulers during the vice installation. Further script could be written using pressure sensors to automatically locate the cube planes and adjust the plane generation accordingly.

### 7.2. Results Summary

Though the results of the report can only provide an estimate of the accuracy, the overarching aim of the report has been satisfied. Collaborative robots can be used for digital fabrication. This was proven at a minimum by performing CNC machining with a UR5 robot. Considering the multitude of applications that CNC machining has, the UR5 can be used practically with a worst-case accuracy of plus and minus 1.5mm. This accuracy can be significantly approved through redesign and a higher quality spindle assembly where it is estimated to have an accuracy of plus or minus 0.3mm. There are significant benefits in using a collaborative robot for CNC machining that were not assessed in this dissertation such as the multipurpose applications of the robot when not being used for CNC as well as the ability to conduct machine tending to itself. It is also advantageous in a production line to minimise the number of different machines and parts required across the board to reduce maintenance and repair costs. The assessment of the machines performance also placed it only against three-axis machines. It was proven that machining could be made on multiple planes of approach which three-axis machines are not capable of. This project used five perpendicular planes however any plane is possible as long as attention is given to the orientation of the robot joints upon approach to performing the cut. The unassessed benefits of using a collaborative robot for CNC machining may provide a significant advantage over other CNC machines. It also must be noted that collaborative robots are generally more expensive than three-axis CNC machines. It is suggested that if a consumer were investigating whether to invest in a collaborative robot for CNC machining the application would not rely on extremely precise machining and they would need to assess the extra cost compared to the regular CNC they would purchases and determine whether the extra benefits constitute the extra cost. To summarise the conclusion, results indicate that the UR5 has no significant cost as a CNC machine when precise accuracy is desired however, the estimated accuracy is still an acceptable CNC performance where minute accuracy is not of importance. Though the results of the report can only provide an estimate of the accuracy, the overarching aim of the report has been satisfied. Collaborative robots can be used for digital fabrication

### 7.3. Further Work

To provide an actual measurement of the accuracy of the UR5, the vibration of the spindle assembly would need to be addressed. It is expected however that though the accuracy will be significantly improved by reducing the vibration error, it will not improve the accuracy enough for the UR5 to rival dedicated CNC machines. The newer E series robots by UR5 provide the ability for two key improvements for CNC machining. The first is that the newer Polyscope software for the E series can perform machining from numerical code in real time rather than running prior generated scripts. This allows real time adjustments and enhancements of the robots processing of the required numerical code movements. The second is the ability for the software to conduct remote tool point machining where the machining code file can be processed to move material around a fixed spindle. This would allow the spindle assembly to be fixed in place lowering vibration issues where the robot can pick up material using a gripper that is then pushed onto the tooling bit to perform the milling. If the robot were to be mounted upside down to a ceiling gantry allowing movement across an entire room, the robot could be configured to pick up squares of material to mill which it can then place in puzzle piece configurations to create large plugs. As well as requiring a new physical design, this approach would require a post processing function in fusion 360 to split a plug into smaller cubes for the robot to then mill and construct. This particular design would save significant labour time in material acquisition, preparation and construction where large plugs are being produced.

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## 9. Appendix A – Project Specification

ENG4111/4112 Research Project

Project Specification

For: [redacted] Jayden Middenway

Title: Digital Fabrication with Collaborative Robotics

Major: Electrical and Electronic

Supervisors: Craig Lobsey

Enrollment: ENG4111 – EXT S1, 2022

ENG4112 – EXT S2, 2022

Project Aim: To investigate and develop the design of a multi-plane CNC router using UR5E collaborative robot arm for the purpose of milling molding plugs.

**Program: Version 3, 6 October 2022**

1. Conduct initial background research on the UR5E including how it works, what software is used, and whether it has been used for CNC before.
2. Review current molding plug CNC technology including machines used, specific CNC requirements, materials used, and methods used to evaluate methods of CNC performance (Accuracy and time)
3. Select and purchase the milling material required ready for testing
4. List the pros and cons of using a URE5 robot arm for CNC milling
5. Draft concept designs countering the cons and utilising the pros.
6. Choose one design
7. Divide the concept design into separate sequential designs with increasing features to allow for time and resource allocation
8. Conduct research parts required
9. Compile all information gathered so far into the dissertation
10. For the first sub design
    a. Review the design and order/collate the parts as required
    b. Build the prototype
    c. Test and adjust the design on scrap pieces
    d. Test the design on the selected milling material
    e. Review and record the performance of the CNC machine
    f. Record the test results for inclusion in the dissertation
11. Compile the test results into the dissertation
12. Conclude the dissertation and evaluate test results as well provide recommendations

*If time and resource permit:*

13. Follow through the sub-steps in step 7 for each sub-design
14. Add the additional design adjustments to the dissertation

## 10. Appendix B – Risk Assessment

# Risk Assessment [Ref Number: 1596]

Date Printed: Thursday, 15 September 2022

| | | | |
|---|---|---|---|
| **Name** | **Evaluation of UR5 Collaborative Robot for CNC Machining** | **Current Rating** | **Residual Rating** |
| **Location** | **Springfield** | Medium | Low |
| **Business Unit** | | **Last Review Date** | **Risk Owner** |
| Faculty of Health, Engineering and Sciences | | 15/09/2022 | Jayden Middenway |
| **Risk Assessment Team** | | **Risk Approver** | |
| Jayden Middenway<br>Craig Lobsey | | Craig Lobsey | |
| **Additional Notes** | | | |
| | | | |
| **Describe task / use** | | | |
| The UR5 Robot will be used to machine tooling board using a 24V low power spindle. Dimentional accuracy of the machine part will be evaluated. Completed as part of engineering honours project. | | | |

## Risk Factors

| Risk Factor | Mechanical and Fixed Plant |
|---|---|

**Description**

Injury to persons due to collision with moving robot.

- Is there the potential for:
- Crushing and pinch points? -- Yes
- Moving and rotating equipment? -- Yes
- Could hazards be caused by equipment or structural failure? -- No

| Medium | Very Low | | |
|---|---|---|---|
| **Existing Controls** | **Proposed Controls** | | |
| | Description | Responsibility | Target Date |
| • 4 - Engineering:<br>The UR5 robots are designed for collaborative space work with humans. | Robot is operated from a safe distance using the control pendant.<br>All personel are advised in safe operation of the UR5.<br>Emergency stop button is within reach at all times on the remote pendant.<br>Robot is always supervised during use.<br>Simulation of robot movements is performed prior to physical operation. | | 15/09/2022 |

| Risk Factor | Mechanical and Fixed Plant |
|---|---|

| Description | |
|---|---|
| Cuts due to rotating spindle. | • Is there the potential for:<br>• Cutting or severing? -- Yes<br>• Puncturing (including sharps) -- Yes<br>• Could hazards be caused by equipment or structural failure? -- No |

| Medium | Low | | |
|---|---|---|---|
| **Existing Controls** | **Proposed Controls** | | |
| • 6 - PPE: Eye protection to be worn at all times. | Description | Responsibility | Target Date |
| | Spindle is to be switched manually not by software control.<br>The spindle is not to be turned on unless protective shield is in place, preventing access to the robots operating area.<br>Active supervision by a UNISQ technical staff member during experiments is required. | | 15/09/2022 |
| | Protective sheild restricting access to the robot is to be used. | | 15/09/2022 |

| Risk Factor | Mechanical and Fixed Plant |
|---|---|

| Description | |
|---|---|
| Cuts and eye damage caused by shrapnel following robot collision. | • Is there the potential for:<br>• Cutting or severing? -- Yes<br>• Projectiles? -- Yes<br>• Could hazards be caused by equipment or structural failure? -- No |

<table>
<tr><th>Medium</th><th colspan="3">Low</th></tr>
<tr><th>Existing Controls</th><th colspan="3">Proposed Controls</th></tr>
<tr><td rowspan="3"><ul><li>6 - PPE:<br>Eye protection to be worn at all times.</li><li>5 - Administration:<br>Robot is operated from a maximum distance allowed allowed by the remote pendent. Access to the room is restricted to all other personel.</li></ul></td><td>Description</td><td>Responsibility</td><td>Target Date</td></tr>
<tr><td>Protective shield around robot operating area is in place.</td><td></td><td>15/09/2022</td></tr>
<tr><td>Simulation of robot movements is performed prior to physical operation.<br>A physical test is performed without the spindle operating to verify no collisions will take place.<br>The emergency stop button is with in reach on the remote pendant and pushed if a collision looks possible.</td><td></td><td>15/09/2022</td></tr>
</table>

| **Risk Factor** | Chemicals and Hazardous Substance |
|---|---|

**Description**

Exposure to airborne dust particles from machined material.

- Does the work involve Chemicals that are NOT classified as hazardous by SafeWork Australia? -- No
- Does the work involve:
- Does the work involve Nanomaterials? -- No
- Does the work involve or could there be exposure to:
- Does the work involve materials that can cause injury, illness or property damage:
- Gases, fumes & dust that may cause asphyxiation, respiratory conditions -- Yes
- During product storage and handling, is there a risk of spills or leaks? -- No
- Are there regulatory requirements for disposal of the chemical or hazardous substance (chemicals will likely require tracked disposal)? -- No
- Are there any other Chemical or Hazardous Substances hazards associated with the work? (please specify in the above text box) -- No

| Medium | Low | | |
|---|---|---|---|
| **Existing Controls** | **Proposed Controls** | | |
| • 2 - Substitution:<br>Material selection for physiologically harmless, material is intended for machining. | Description | Responsibility | Target Date |
| | Experiment is performed under ventilated hood in F112 heat treatment laboratory.<br>Roller door is open to maximise ventilation. | | 15/09/2022 |
| | A dust mask is worn during CNC milling experimentation. | | 15/09/2022 |
| | Clean up of work area using workshop vacuum cleaner. | | 15/09/2022 |

# Appendix

| Documents Referenced |
|---|
| NECURON® 702 BOARD MATERIAL - SDS<br>NECURON® 702 BOARD MATERIAL - Technical Specifications |

## Risk Matrix Level

| | |
|---|---|
| Very Low | Task can proceed upon approval of the risk assessment by the relevant supervisor, manager or higher delegate |
| Low | Task can proceed upon approval of the risk assessment by the relevant supervisor, manager or higher delegate |
| Medium | Task can proceed upon approval of the risk assessment by a Category 4 or higher delegate |
| High | Task can only proceed in extraordinary circumstances provided there is authorisation by the Vice Chancellor |
| Extreme | Task must not proceed. Appropriate and prompt action must be taken to reduce the risk to as low as reasonable practicable |

### ATTACHMENTS

## 11. Appendix C – Workshop induction

UNIVERSITY OF SOUTHERN QUEENSLAND AUSTRALIA

**FoHES Induction for Engineering Laboratories: F Block**
University of Southern Queensland
37, Sinnathamby Boulevard, Springfield TOBIAS LOW

**This Induction form outlines the process of entry into theMechanical Engineering Laboratory**

**Introduce relevant staff**
- Coordinating Technical Officer – Adrian Blokland, Toowoomba (Ext: 1719)............ ☑
- Technical Officer – T.B.A,.............. CHINTAN ............ ☑
- Admin Office: Mon-Fri: 08:00-17:00.............. Call 4100 (07 3470 4100) ☑
- Security.............. Call 4444 (07 3470 4444) ☑

➢ **Room Entry Requirements**
- Have you completed a general USQ health and safety induction? .............. NO / YES CHECK
- Risk Assessment Completed if required? .............. NO / YES IN PROCES
- PPE MUST be worn as outlined in the Risk Assessment Form or as requested.............. ☑
- Covered footwear MUST be worn at all times in these laboratories.............. ☑
- Safety shoes/boots may be compulsory in some areas or during some tasks .............. ☑
- NO food or drink to be consumed in these laboratories.............. ☑
- Competency assessed by Tech staff before using equipment or undertaking task.............. ☑

➢ **Explain Emergency Procedures**
- All Emergencies .............. **Call 2222** (07 4631 2222) ☑
- Life Threatening Events.............. **Call (0) 000** ☑
- Fire Exits.............. ☑
- Assembly point: USQ Car Park.............. ☑
- Alarm system (Automatic / Manual Evacuation in some cases).............. ☑
- Fire Extinguishers are located in the hallway on each floor .............. ☑
- Spill kit is located in the level 1 hallway .............. ☑

➢ **Show First Aid Details**
- The First Aid Kit is located in the hallway on each floor .............. ☑
- Safety shower/eyewash station is in the F114 Concrete Mixing & Durability Lab.............. ☑
- Sink is located in each lab .............. ☑

➢ **Room Details**
- Entrance via swipe card access or pre-arranged booking.............. ☑
- SWP and any relevant SDS are stored in folder in each area.............. ☑

➢ **House Keeping**
- Toilets are located on 1st floor.............. ☑
- Telephone is located in each lab (also street entrance hallway level 1 ).............. ☑
- All bags must be off the floor.............. ☑
- Make sure area is thoroughly tidied after each activity.............. ☑
- Close all doors (including storage areas) before leaving the lab.............. ☑

Name (Print): Jaydn Middenway Staff/Student No: [redacted]
Signature: [redacted] Date (dd/mm/yyyy): 16/03/22

Technical Staff: ADRIAN BLOKLAND Employee No: [redacted]
Signature: [redacted] Date (dd/mm/yyyy): 16/3/22

Supervisor: .............. Employee No: ..............
Signature: .............. Date (dd/mm/yyyy): ..............

CRICOS QLD 00244B NSW 02225M TEQSA PRV12081

## 12. Appendix D – Project Timeline

**Project Timeline**

| Task | | Description | Semester 1 ENG4111 | | | | | | | | | | | | | | | | | | Break | | Semester 2 ENG4112 | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Break | | | | | | | | | | | | | | | | | | | | | | | | | | Break | | | | | | |
| | | | 14/02/22 | 21/02/22 | 28/02/22 | 7/03/22 | 14/03/22 | 21/03/22 | 28/03/22 | 4/04/22 | 11/04/22 | 18/04/22 | 25/04/22 | 2/05/22 | 9/05/22 | 16/05/22 | 23/05/22 | 30/05/22 | 6/06/22 | 13/06/22 | 20/06/22 | 27/06/22 | 4/07/22 | 11/07/22 | 18/07/22 | 25/07/22 | 1/08/22 | 8/08/22 | 15/08/22 | 22/08/22 | 29/08/22 | 5/09/22 | 12/09/22 | 19/09/22 | 26/09/22 | 3/10/22 | 10/10/22 | 17/10/22 | 24/10/22 | 31/10/22 | 7/11/22 |
| Phase 1 | Step 1 | Conduct initial background research on the UR5E and review current CNC plug technology | | | | S | O | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Step 2 | Define the aim and objectives as well as the limitations | | | | | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Step 3 | Conduct a full literature review on collaborative robot use in CNC applications | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Step 4 | Define methodology and define measure for project success | | | | | | | | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Step 5 | Plan the project design, build and testing phases | | | | | | | | | S | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Step 6 | Finalise a prototype design. | | | | | | | | | | ■ | O | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Step 7 | Compile a list of the parts required and order. | | | | | | | | | | | | | S | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Phase 2 | Step 1 | Compile all information gathered so far into the dissertation for progress report submission. | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | S | | | | | | | | | | | | | | | | | | | | | | | | |
| Phase 3 | Step 1 | Review the design and order/collate the parts as required | | | | | | | | | | | | | | | | | | | | | SO | | | | | | | | | | | | | | | | | | |
| | Step 2 | Build the prototype | | | | | | | | | | | | | | | | | | | | | | O | SO | | | | | | | | | | | | | | | | |
| | Step 3 | Test and adjust the design on scrap pieces | | | | | | | | | | | | | | | | | | | | | | | | O | O | | | | | | | | | | | | | | |
| | Step 4 | Test the design on the selected milling material | | | | | | | | | | | | | | | | | | | | | | | | | | O | SO | | | | | | | | | | | | |
| | Step 5 | Record the test results for inclusion in the dissertation | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | | | | | | | | | | | | |
| Phase 4 | Step 1 | Compile the test results into the dissertation | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | | | | | | | |
| | Step 2 | Conclude the dissertation and provide recommendations | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | | | | | |
| Phase 5 | Step 1 | Follow through Phase 3 for each of the sub-design as time permits | | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | S | ■ | ■ | ■ | | | | |
| | Step 2 | Add the additional design adjustments to the dissertation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | |
| Phase 6 | Step 1 | Review and submit the dissertation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | S | ■ |

**Notes:** Cells marked with an **S** indicate supervisor meetings. Cells marked with an **O** indicated expected days on-campus for physical design work

## 13. Appendix E – Results Data

| Cube 1 * | Axis | | | | |
|---|---|---|---|---|---|
| Plane | x | | y | | z |
| Top 1 | 44.4722 | | 44.9092 | | 10.4274 |
| Top 2 | 44.5825 | | 45.094 | | 10.447 |
| Top 3 | 44.5797 | | 44.9089 | | 10.4372 |
| Top Total | 50.5448 | | 50.9707 | | 10.4372 |
| Top Z axis accurate to zeroing only | | | | | |
| Front Left 1 | 80.9711 | | 45.3164 | | 44.9261 |
| Front Left 2 | 80.9838 | | 45.1541 | | 45.0108 |
| Front Left 3 | 80.9862 | | 45.1215 | | 44.9403 |
| Front Left Total | 80.98037 | | 51.19733 | | 50.95907 |
| | | | | | |
| Front Right 1 | 44.6831 | | 81.5002 | | 44.1631 |
| Front Right 2 | 44.8294 | | 81.4942 | | 44.873 |
| Front Right 3 | 44.499 | | 81.4923 | | 44.7705 |
| Front Right Total | 50.6705 | | 81.49557 | | 50.6022 |
| | | | | | |
| Rear Left 1 | 45.0579 | | As FR | | 44.6036 |
| Rear Left 2 | 44.9473 | | As FR | | 44.5099 |
| Rear Left 3 | 44.9579 | | As FR | | 44.6756 |
| Rear Left Total | 50.9877 | | As FR | | 50.59637 |
| FR and RL was measured between cut depths and has only 1 measurement | | | | | |
| Rear Right 1 | As FL | | 44.7025 | | 44.7895 |
| Rear Right 2 | As FL | | 44.9129 | | 44.9659 |
| Rear Right 3 | As FL | | 44.953 | | 44.7807 |
| Rear Right Total | As FL | | 50.85613 | | 50.84537 |
| FL and RR was measured between cut depths and has only 1 measurement | | | | | |