UNIVERSITY OF CAPE TOWN

Department of Mechanical Engineering

RONDEBOSCH, CAPE TOWN
SOUTH AFRICA

FINAL REPORT 2020

PROJECT
No: 135

PROGRAMMABLE WEAVING LOOM

ANJANA GABRIELLE MARTIN YODAIKEN
YDKANJ001

Project Brief

The mechanical weaving loom was one of the first machines to be automated at the beginning of the industrial era. This project aims to build a mechanical loom capable of being programmed to weave simple patterns into cloth. In this project the weft yarns will be transported manually (unpowered), while the appropriate warp yarns will be raised or lowered via a mechanism designed by the student.

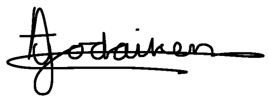
Supervisor: Ernesto Ismail

Word Count: 17641

Plagiarism Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.
2. I have used a numbered convention for citation and referencing. Each significant contribution to, and quotation in, this report / project from the work(s) of other people has been attributed and has been cited and referenced.
3. This report/project is my own work.
4. I have not allowed and will not allow anyone to copy my work with the intention of passing it off as his or her own work.

Signature:



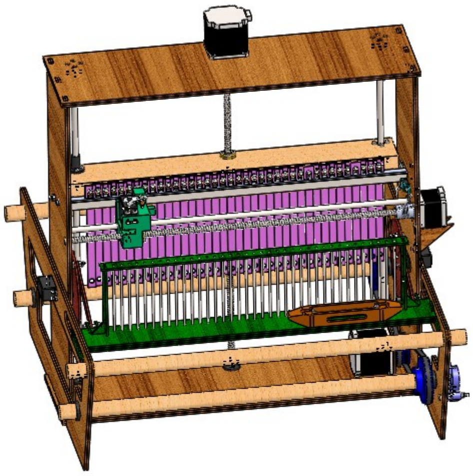
Abstract

The mechanical weaving loom was one of the first machines to be automated at the beginning of the industrial era. In this project a mechanical loom was designed, built and tested for its ability to weave programmed patterns of low and high complexity. In this project the weft yarns were to be transported manually, while the appropriate warp yarns were to be raised or lowered via a designed mechanism.

This project focused on a mechanism that would allow for individual selection (raising) of warp yarns. The value of a mechanism such as this is that it would allow for any pattern to be created. This project attempted to maximise the automation of the loom, ideally, making the user's only involvement in the weaving process being the insertion of the weft yarns.

Overview

The project entailed the design, build and testing of a programmable weaving loom. The final designed Solidworks model and final built model can be seen below. The weaving loom made use of individual heddle control which allowed for each warp yarn to be raised individually. This in theory would allow for any pattern to be created.



Minimizing the user's interaction with the weaving loom was desirable. The automation of the cloth roll and warp beam, the beater as well as the heddles limited the user's interaction to the insertion of the weft thread.

This design process started with a detailed literature review in order to gain a full understanding of the elements of a loom and how they had developed over time. This was followed by the conceptual designs of the three main sub-assemblies, namely; the heddle sub-assembly, the beater sub-assembly and the cloth roll warp beam sub-assembly. The final design for each sub-assembly was then generated. The materials, manufacturing, motors, drivers and other electronics methods were then decided upon. The electronic circuits were then designed and tested and the full code for the project was generated. Finally the loom was then assembled and tested.

For the testing phase, the weaving loom had different patterns programmed into it in order to display the level of complexity achievable in a fabric produced by the loom, as well as its ability to produce a standard fabric. The images below show the two patterns produced by the weaving loom; these being the 2/2 twill weave as well as a panda pattern.

The weaving loom produced a tightly woven fabric in the form of the 2/2 twill weave. However, the panda pattern although visible was not of a high quality in terms of the tightness of the weave.

There were some issues with some of the sub-assemblies. These issues will be addressed in later sections of the report. The issues that arose did not prevent the weaving loom from operating. However, the user's interaction with the loom had to be extended to aiding the loom during operation. Even with the issues that arose the loom was still able to produce the patterns programmed into it.

Acknowledgements

First and foremost I would like to thank my supervisor, Ernesto Ismail, for his contribution to this project. Ernesto's willingness to help compounded by his extensive knowledge and intelligence allowed for the project to be completed to the best of my ability. Ernesto also showed an incredible amount of compassion and emotional support for me throughout the especially stressful COVID year. For this I am immensely grateful.

I would like to thank Pilot Pens SA for sponsoring me with 50 of their Pilot G-2 07 pens. Without them the finished product would not have been what it was. The fact that their pens could facilitate one of the most complicated and critical operations of a weaving loom speaks volumes to the strength, quality and durability of their pens.

I would like to thank Netram Technologies, specifically Brendon Maartens, Matthew Preswich and Nisrine Jirari, for all of their help in terms of organizing parts for me during the pandemic as well as assistance in the control sections of my project.

I would like to thank Julian Tomkins for assisting me in the re-manufacturing of a part that broke. Without his emergency assistance the project would have been delayed further.

I would like to thank my parents and twin sister for their support and positivity not only during this year but throughout my four years of studying. I struggle to see myself having gotten through this degree without them by my side.

Contents

List of Figures

List of Tables

Abbreviations

GPIO General Purpose Input Output
HDF High-Density Fibreboard
MDF Medium-Density Fibreboard
LCD Liquid-Crystal Display
PRS Product Requirement Specification
PLA Polylactic acid
UCT University of Cape Town
3D Three-Dimensional
LED Light-Emitting Diode
VCC Voltage Common Collector
PWM Pulse Width Modulation
CNC Computerized Numerical Control

1 Introduction

1.1 Subject of report

This report deals with the detailed design phase of Project 135, the programmable weaving loom. The report builds on the interim report for this project by presenting the final designs from the conceptual designs of each sub-assembly as well as a complete mechanical design for the loom. The control aspects of the loom are presented to the reader. This is all followed by the commissioning and testing that took place in the building of the loom, with a discussion and recommendations for the loom to follow.

1.2 Problem definition and background

The premise behind the project is the recreation of a historical device in a novel and contemporary manner.

This project is a revision of a previous final year project. This project was rerun because there were areas for improvement. These areas being the level of automation of the loom, the quality of the control aspects and the degree of complexity of the completed fabric pattern. There were restrictions and constraints on the previous project and these also applied to this project. The main constraint being time and budget. A section on the budget and budget variance of this project can be seen in Appendix F. As a result, it would have been difficult to fully automate the loom. However, critical features for automation were focused on in order to increase the complexity of the completed fabric.

The problem can be described as follows; design, build and test a programmable weaving loom that will allow for any pattern to be created through the individual control of the heddles and thus warp yarns.

1.3 Project scope and constraints

There are various levels of automation that are possible for a weaving loom. The most desirable being a fully automated weaving loom where the user has no involvement during operation. However, based on the allocated budget, the allocated time and the affects of the pandemic, this was not possible. Only the critical parts of the loom were automated. These being the heddles, the cloth roll and warp beam and the beater. The heddles are the part of the loom that control the raising of the warp threads. The cloth roll is responsible for taking up and holding the completed fabric. The warp beam holds the unwoven warp threads and is responsible for letting off unwoven warp threads into the weaving area. The beater is the part of the loom that is responsible for compacting the weft thread after the picking operations as well as creating a compact fabric. These processes and parts will be discussed in Section 2.2 and Section 2.3 respectively.

In order of priority of automation:

1. Heddles
2. Cloth roll and warp beam
3. Beater

The goal of this automation was to produce a fabric of a high complexity and not necessarily one that was usable. This meant that only a number of heddles, enough to demonstrate this complexity, were required. The number of heddles was selected as 38.

1.4 Plan of development

The final design of the weaving loom can be seen in the preliminary section titled 'Overview'. The report begins with a detailed literature review. A Product Requirements Specifications (PRS) is then presented. This is followed by the design process that led to the final design. The report then outlines the three sub-assemblies (heddle, cloth roll and warp beam and beater) and their conceptual designs and final designs that form part of the full final design of the weaving loom. The final overall loom design is then presented with a description of its operation and the primary materials selected. The report then deals in the control aspects of the project that allow for the operation of the loom in the desired way. A section that describes the commissioning and testing of the loom is then presented. This leads into a section that broadly discusses the success of the testing and the conformance of the final product with the PRS. A recommendations section follows drawing on previous sections. This section will be used for further iterations of this project. The report is then tied together with a conclusion.

2 Literature review

2.1 What is weaving and what is a weaving loom?

Weaving can be described as an art in which fabrics are made through the interlacing of threads [1]. A tool that allows and assists in the weaving process is known as the weaving loom. There are allusions to the loom and weaving in the Old Testament [1]. These are the earliest records of the existence of the loom [1]. The history of the loom can be seen in Appendix A. The loom has evolved continuously from ancient times to the present day. However, the basic premise behind the weaving loom remains the same.

The basic weaving process can be described with threads known as weft threads and warp threads, as seen in Figure 1. The weft threads are those that run perpendicular to the loom and the warp threads are those that run parallel to the loom. According to the desired pattern, certain warp threads must be lifted and certain warp threads lowered. This action creates a gap between the lifted and lowered warp threads, known as a shed, as seen in Figure 1. A weft thread then passes through the shed in a process known as picking. The entire process is then repeated, with different warp threads being lifted and lowered, until the fabric is completed.

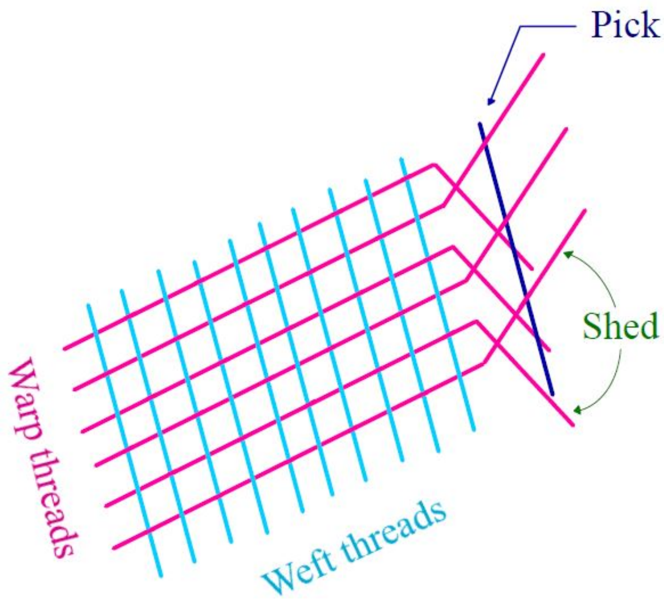


Figure 1: Key features of the basic weaving process

2.2 More detailed weaving process

It should be noted that this section purely focusses on the processes involved in weaving. For more information on the parts mentioned here refer to Section 2.3. Figure 2 shows the steps involved in the set-up of the weaving loom, the basic primary and secondary actions and the finishing processes. These being the basic processes any loom would need to complete in order to create a successful fabric.

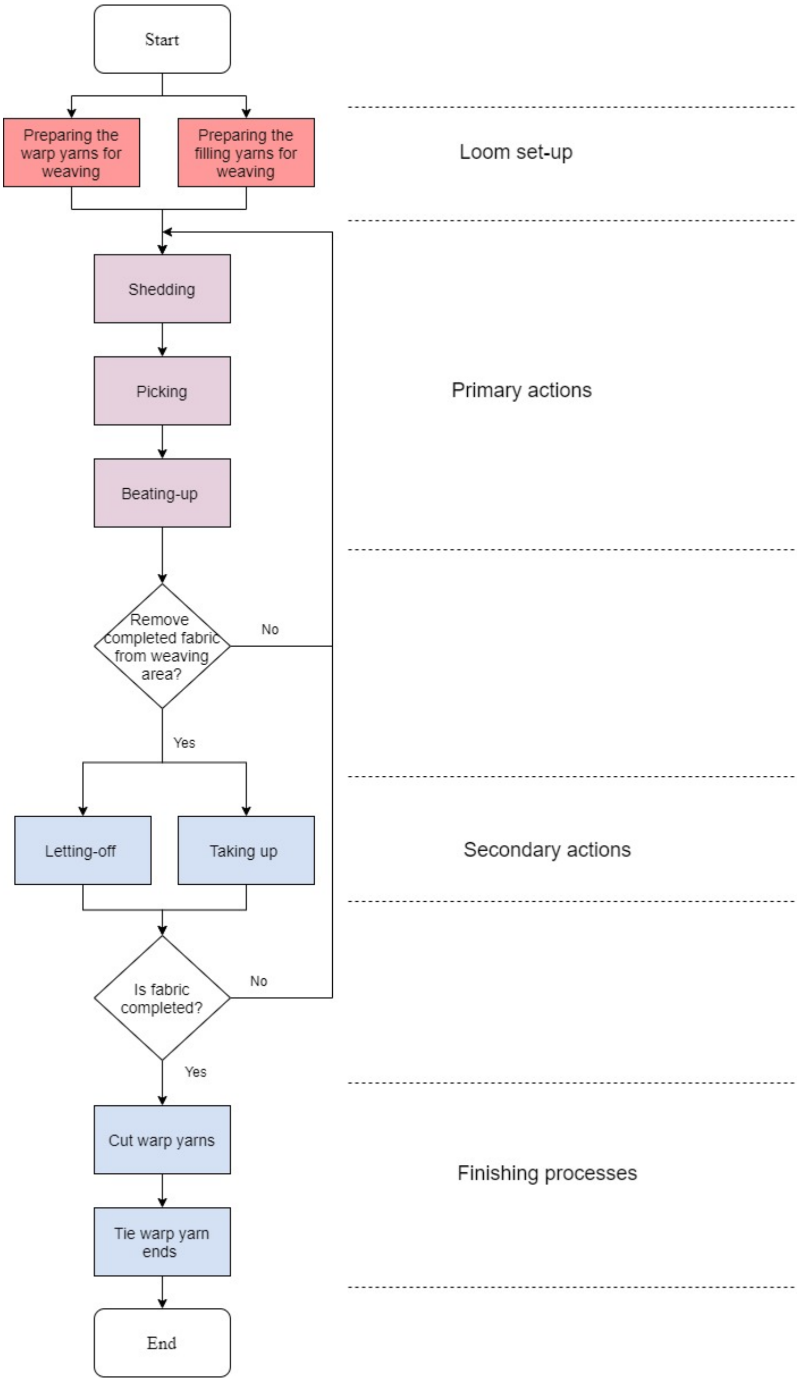


Figure 2: The more detailed weaving process

Loom set-up

The set-up of the weaving loom is extremely time consuming but correct set-up is vital in creating a successful fabric. The process involves the following:

- Preparing the warp yarns for weaving:
  This process can either take the form of drawing-in or tying-in. Drawing-in involves the threading of each warp yarn through each heddle eye and reed dent [2]. Tying-in is performed if the same end count and pattern are required and the warp yarn has depleted [3]. This process involves tying the ends of a new warp supply to the ends of the depleted warp yarn. This avoids repeating the drawing-in process [3].

- Preparing the filling (weft) yarns for weaving:
  The yarn that is used in picking must be packaged in such a way that it can be transported across the width of the loom and release thread as it moves across. This usually takes the form of a shuttle and bobbin [2].

Primary actions

The three primary actions must be performed in strict rotation.

1. Shedding:
   For each pick insertion, particular warp threads must be raised or lowered as determined by the weave plan. This action of raising or lowering warp threads is known as 'shedding'. While the passage created by the splayed warp threads is known as the shed [4].

2. Picking:
   The passing of the shuttle through the shed and the insertion of the filling thread (weft thread) is known as 'picking' [4].

3. Beating-up:
   After insertion of the pick of the weft, this thread must be pushed into position in order for a compact fabric to be made. This action is made possible with the beater, which moves forwards and pushes the thread into position. This action is known as 'beating-up' [4].

Secondary actions

The two secondary actions should be performed in connection with one another in order to maintain the tension necessary for weaving and to prevent the potential breaking of warp threads through over-tensioning [4]. These two actions do not necessarily need to occur after every line of weaving but rather whenever the weaving area becomes full.

- Taking up:
  The completed fabric which has not yet been wound around the cloth roll is known as the fell. The action of winding this complete fabric around the cloth roll is known as 'taking up' [4].

- Letting-off:
  The action of releasing more warp thread into the weaving area is known as 'letting-off'. The warp threads are released by the rotation of the warp beam [4].

Finishing processes

These processes include the preparation of the completed fabric for further operations or distribution:

1 Cut warp yarns:
The warp yarns are cut in order to separate the complete fabric from the length of warp yarns that have not interacted with the weft threads [5].

2 Tie warp yarn ends:
The warp yarn ends are tied. The way in which the ends are tied is dependent on what the fabric will be used for. This process is important in preventing the fabric from losing its shape or unthreading [5].

2.3 The basic parts of the loom and their function

The list of parts in this section will facilitate the aforementioned actions. Figure 3 depicts a floor loom with labelled parts. The loom that will be designed in this project will not need all the parts labelled and as such only the parts critical in the current looms design will be elaborated on. Figure 4 shows a cross section of the loom with its basic parts. The arrows in the diagram show the movements of the heddles to control the warp threads as well as the movement of the beater required to compact the threads.

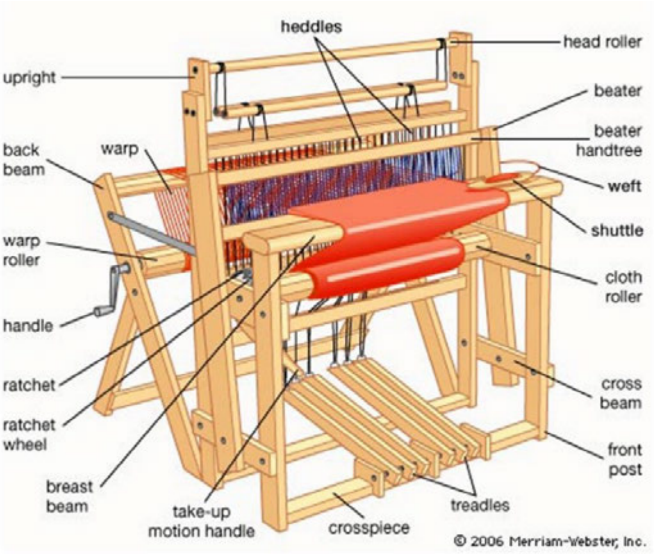


Figure 3: Labelled weaving loom [6]

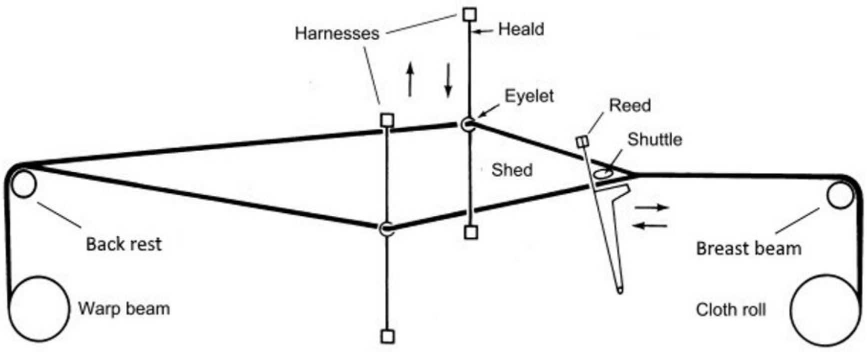


Figure 4: Simplified loom schematic (this image has been edited) [7]

Harness/Shaft

A harness or shaft is a frame onto which the heddles are attached. The number of harnesses and number of warp yarns attached to each will determine the level of fabric complexity achievable [8].

Heddles/Healds

Heddles or healds are made of wire or string and have a single hole along their length, called an eye. The warp threads are threaded through the eye [8]. Thus, there are as many heddles as there are warp threads [8]. Heddles play an important role in shed formation, as it is through their control that certain warp threads are lowered or raised. The number of heddles that can be controlled at one time will determine the degree of complexity of pattern the loom can create. If each warp yarn can be controlled individually (each heddle can be raised or lowered individually) there would be infinitely many patterns possible, the only restriction being the number of warp threads. However, if a simpler pattern is desired this level of control would not be necessary.

Mechanisms that allow for the creation of sheds and the degree of complexity allowed:

Cam or tappet shedding: this mechanism makes use of profiled cams in order to move harnesses up and down. Cam looms usually have 6 to 8 harnesses and are used for more simple weaves such as plain weaves, satin weaves and basic twills. These patterns can be seen in Section 2.4. To change the pattern, one needs to change the harness cams [9].

Dobby shedding: this mechanism makes use of an electronic or mechanical device to select and move individual harnesses. Up to 28 harnesses can be accommodated. This type of loom can be used to weave complex twills, satins and small geometric figures and pattern stripes. These patterns can be seen in Section 2.4 [9].

Jacquard shedding: this type of shedding does not make use of harnesses and is thus the most complex shedding system. There is control of each individual warp yarn. This loom allows for control of up to 1200 warp yarns, each being controlled by its own harness chord coming from the Jacquard head. This chord is attached to a heddle which in the more modern design is pulled down by a spring. Mechanical or electronic devices may be used to move the warp ends. The design complexity is virtually unlimited. Due to this increased complexity and an increased time of production a more expensive product is created [9].

Bobbin and Shuttle

The filling thread, or weft thread, is wound around a bobbin which is held by a shuttle or bobbin container. The shuttle is passed through the warp shed. As it does this the bobbin releases thread which forms the filling cloth [8].

Modern methods of automation:
Using a shuttle and bobbin is tedious and inefficient as it requires someone to physically pass the bobbin and shuttle through the warp shed. Modern industrial looms are shuttleless. There are various ways of passing the filling thread through the shed. These methods are highlighted below:

Projectile loom: This loom makes use of small shuttle-like projectiles to perform picking [4]. Figure 5 shows the projectile being used during picking.

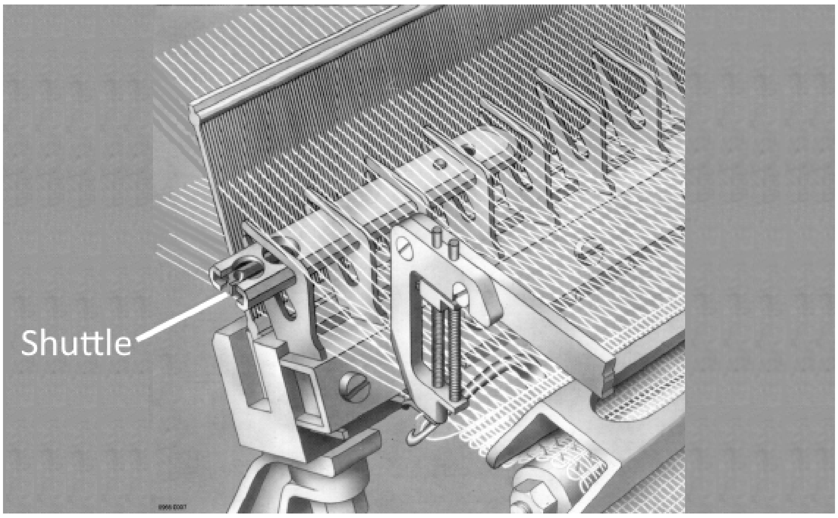


Figure 5: Shuttle-like projectile (this image has been edited) [10]

Rapier loom: Two slim shafts known as rapiers facilitate this type of automation. This loom type branches into rigid and flexible rapier looms. However, both allow for weft insertion from a stationary supply package [4]. Figure 6 shows the end fixtures of the two shafts that pass the thread.

Figure 6: The end fixtures of the shafts in a rapier loom [11]

Jet loom: This loom is either an air or water-jet loom. Weft insertion is performed through the use of pressurized water or air [4]. Figure 7 shows the parts required for picking operations in a jet loom.

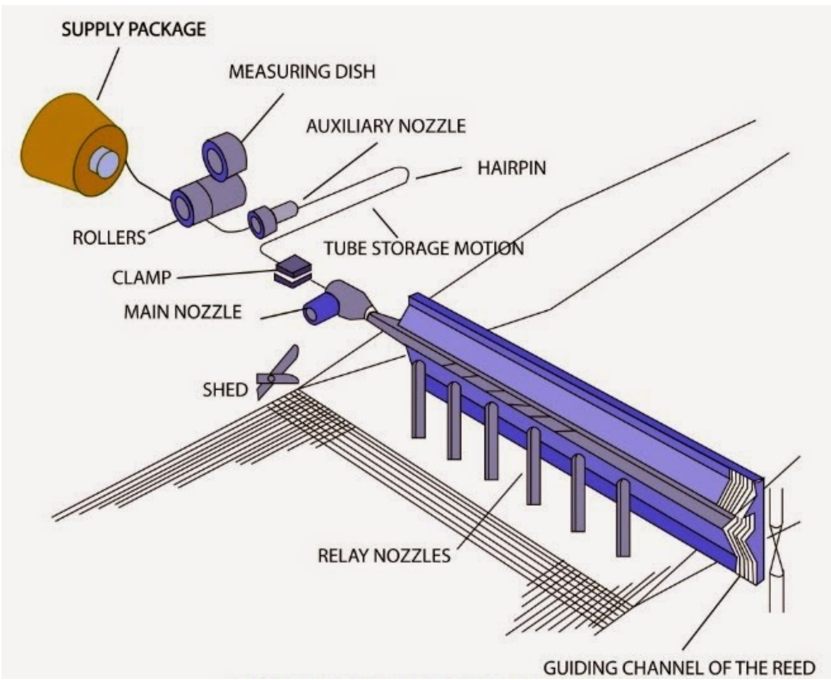


Figure 7: The parts of a jet loom needed for picking operations [12]

Cloth roll

Takes the form of a circular beam. Located at the front of the loom. It stores the completed fabric to be taken off the loom [8].

Warp beam

Takes the form of a circular beam. Located at the back of the loom. It stores the warp threads. It plays a roll in the tensioning of the warp threads. It releases threads to the weaving area as needed [8].

Back rest and breast beam

The back rest and breast beam are usually flat metal, in the past wooden, plates. The back rest is used to create tension and feed the warp threads to the weaving area. The breast beam aids in the compacting of the fabric with the beater, as well as stopping the beater from making contact with the frame. The breast beam also maintains weaving tension and guides the fabric to the cloth roll [13].

Beater bar

A beater bar is made up of a batten with a reed comb. The gaps between each tooth in the reed comb is known as the reed dent. Typically a bar is mounted across the loom. The beating is performed by metal teeth known as reeds, while the slots are known as dents. The warp threads are fed through these dents. The beater moves backwards and forwards parallel to the warp threads after picking. It is used to ensure the weft yarn is pushed into place and that the fabric is compacted [13].

2.4 Basic types of weaves

Plain weave and basket weave

A plain weave can be seen in Figure 8. This pattern is produced by the interlacing of warp and weft threads in a criss-cross pattern. This creates a checker-board of threads. This is the most basic type of textile weave and it forms a strong and durable fabric, such as poplin [14]. A basket weave is created when a plain weave has two or more threads grouped in the pattern [14]. Oxford cloth uses this weave [14]. The weave is depicted in Figure 9.

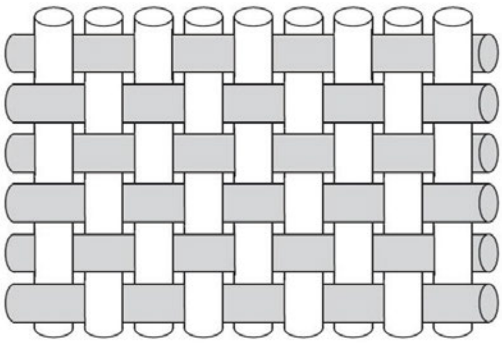


Figure 8: Plain weave [14]

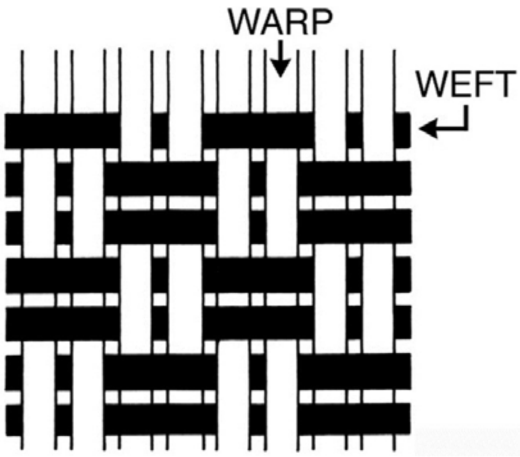


Figure 9: 2x2 basket weave [14]

Twill

This type of weave is used extensively and can be identified by its characteristic diagonal lines as seen in Figure 10. This type of weave creates strong fabrics such as denim and tweed [14].

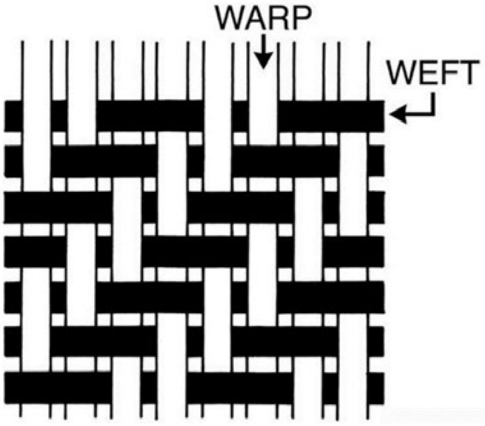


Figure 10: Twill weave [14]

Figure 10 shows a 2/2 twill weave. The fraction associated with the name indicates that the filling yarn will pass over two warp yarns and under the next two warp yarns. There are many variations of this type of weave indicated by the number in its name. The first number in the fraction indicates the number of warp threads the filling yarn will pass over and the second number indicates the number of warp threads the filling yarn will subsequently pass under.

Satin weave

This type of weave creates a smooth fabric that drapes well [14]. This characteristic can be attributed to the distance between the interlocking threads. This is created by the warp and weft arrangement depicted in Figure 11.

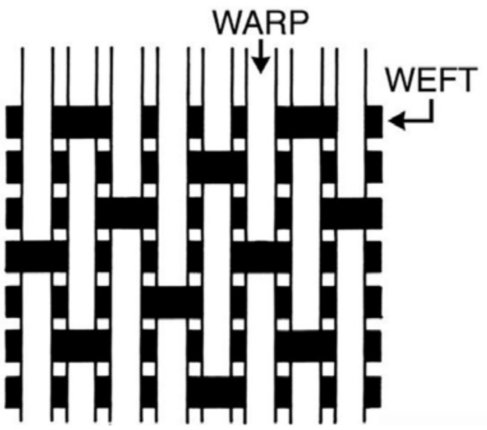


Figure 11: Satin weave [14]

Figure 11 shows what is known as a 5 harness satin weave. This number indicates that the filling yarn will pass over four warp yarns and under the fifth. Other common satin weaves include the 4 harness and 8 harness satin weaves.

Dobby and Jacquard

These types of weaving allow for the most complexity and diversity of fabric patterns possible. The Jacquard weave is a weaving process in which a custom image or pattern is created. This type of weaving is made possible with a Jacquard Loom. Dobby weaving is a simplified version of Jacquard weaving. Dobby weaves contain small geometric patterns and is created on a Dobby Loom [14].

2.5 Motors

In order for the loom to be automated in the desired way two types of motors were to be used in the various automated sub-assemblies. These were the servo motor and stepper motor. An explanation of the operation of these two types of motors will be presented in this section. With the pros and cons of each being highlighted. This will be used as the basis for the selection of the type of motor for each application in the sub-assemblies.

2.5.1 Servo motor

Description of operation and parts

A servo motor's motion and final position are controlled with a closed loop system with positional feedback. A servo motor is made up of a DC motor, a gearbox, a potentiometer and a control circuit. This can be seen in Figure 12. The DC motor is attached to the output shaft through a set of gears this is to reduce the output speed and increase the output torque. The potentiometer is connected to the final gear or the output shaft. Thus, the motors output shaft rotation causes the potentiometer to rotate. This produces a voltage that corresponds to the shaft position. This voltage can then be compared to the desired voltage (corresponding to a position) from the signal line. If there is a difference between the two voltages an integrated H-bridge is activated that rotates the motor shaft until the difference between the voltages is zero. This allows for the movement of the motor shaft to be precisely controlled [15].

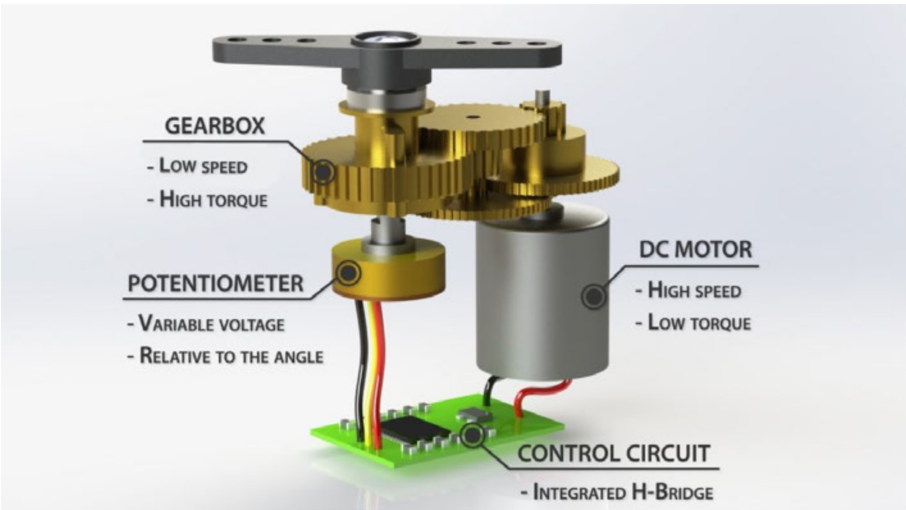


Figure 12: Internal layout of components in a servo motor (this image has been edited) [15]

Servo motors are controlled using pulse width modulation (PWM). This is a series of pulses sent along the signal line. A servo motor has a minimum and maximum PWM. The width of the pulse sent to the servo motor will determine the position to which the motor shaft will rotate. Typically servo motors can rotate 180° [15].

Advantages and disadvantages

In order to understand which application would suit a servo motor it is necessary to understand their strengths and shortcomings. This is by no means an exhaustive list. Only the advantages and disadvantages relevant to this project's application have been highlighted. It should be noted that these advantages and disadvantages apply to small hobby servo motors as these are the servo motors that will be used in this project.

A servo motor, generally, can only turn through 180°. This may be seen as an advantage or disadvantage depending on the application.

In terms of advantages, servo motors make use of positional feedback. This means that the system can sense an error in the position of the motor and make the necessary adjustments. In servo motors, as speed increases, the torque remains constant, i.e. it does not decrease as seen in the behaviour of stepper motors [16].

Disadvantages include that the motor can be damaged if overloaded. A servo motor will behave unpredictably if any of the internal components or circuitry break [16].

Servo motors are suited to applications in which accurate positional control is needed and where continuous rotation or rotation through 360° is not needed.

2.5.2 Stepper motor

Description of operation and parts

There are 2-phase and 5-phase stepper motors. The operation for both remain essentially the same. The explanation to follow is for the operation of a 5-phase stepper motor. A 2-phase motor has eight magnetic poles with only two phases, whereas, a 5-phase motor is made up of ten magnetic poles and five phases [17]. This physical difference between the two types of stepper motors can be seen in Figure 13.

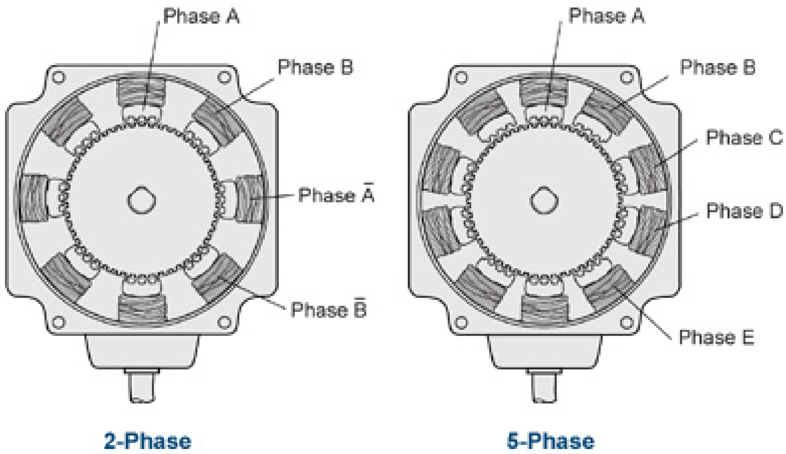


Figure 13: Phases in a 2 phase and 5 phase stepper motor [17]

Stepper motors consist of two main parts; the stator and the rotor [18]. The rotor is made up of rotor 1, rotor 2 and a permanent magnet [18]. These can be seen in Figure 14. Also labelled in the figure are the motors output shaft and ball bearing. The rotor is magnetised axially, this means that rotor 1 and rotor 2 will have opposing polarities. It will be assumed that rotor 1 is polarised north and rotor 2 is polarised south for the explanation.

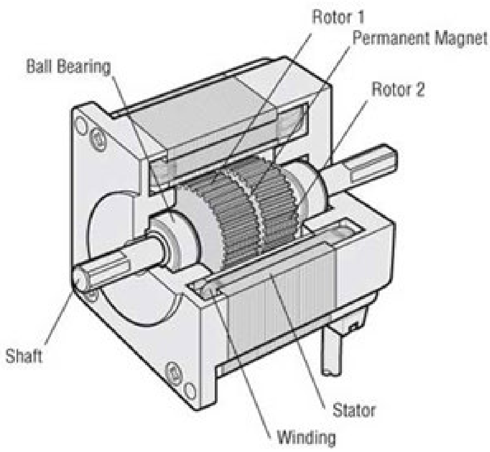


Figure 14: Internal layout of components in a stepper motor [18]

In a 5-phase motor there are ten magnetic poles that have small teeth [18]. This can be seen in Figure 13. Each pole has a winding. Windings on opposing poles are connected so that when a current flows through those windings they are given the same polarity. Poles energised together are known as phases. These are labelled A through to E in a 5-phase motor, as seen in Figure 13. Each rotor has 50 teeth. The rotors are offset from one another by half a tooth pitch [18].

If a current is sent through the windings on phase A, in other words if phase A is 'excited', then its poles are polarised south. This repels the teeth on rotor 2 which are polarised south and attracts the teeth on rotor 1 which are polarised north. The teeth on rotor 1 will be offset from the teeth on phase B by 0.72°. This can be seen in Figure 15. If phase B is then excited i.e. its poles are polarised south, it will repel the teeth on rotor 2 and attract the teeth on rotor 1. This makes the shaft of the stepper motor rotate. Exciting the phases in order A, B, C, D, E and back to A will make the shaft turn one step at a time. Reversing the order of phase excitation will make the shaft rotate in the opposite direction. Stepper motors make use of open loop control systems this means that there is no positional feedback [18].

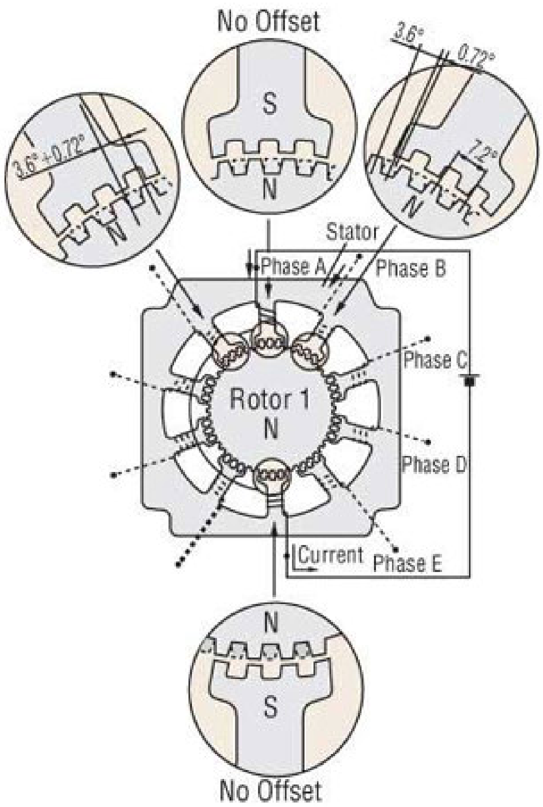


Figure 15: The excitation of phase A [18]

Different stepper motors have different step angle ratings, i.e. the angle the motor shaft turns through for every step varies. This angle can be made smaller through micro stepping.

Advantages and disadvantages

In order to understand which application would suit a stepper motor it is necessary to understand their strengths and shortcomings. This is by no means an exhaustive list. Only the advantages and disadvantages relevant to this project's application have been highlighted.

A stepper motor can rotate through 360°. This can be seen as an advantage or a disadvantage depending on the application.

Advantages include its higher torque rating when compared to servo motors of similar sizes. This torque is provided by the motor even at standstill. Stepper motors will cease operation if anything breaks internally. They can also sustain overloading without damage. Stepper motors have high torque outputs at low speeds. This type of motor has a high level of repeatability, meaning it can return to the same position accurately [19].

Disadvantages include that stepper motors can have a low accuracy, which means that they can miss steps. Because there is no positional feedback, if steps are missed then there will be nothing to indicate this and no corrective action will be taken by the motor. However, this can be combated by micro stepping or by using a motor with more teeth. A further disadvantage is that the torque of a stepper motor decreases rapidly with increasing speed [19].

Stepper motors are suited to a low speed and high torque applications where rotation through 360° is necessary.

2.6 Motor drivers

The basic purpose of a stepper motor driver is to sequence the phases and control the phase current of the stepper motor [20]. Generally drivers are not needed for hobby servo motors as PWM can be given to the motors directly off a micro controller's general purpose input output (GPIO) pins.

2.7 Micro limit switches

Micro limit switches were to be used in the heddle automation in two places. The finer details of which have been explained in Section 5.5.

A limit switch is a component used to detect the presence of an object or to determine whether the desired limits of an objects motion have been reached [21]. Limit switches are contact sensors. Some non-contact sensors that can achieve similar functionality include inductive, capacitive proximity and photoelectric sensors [21]. A micro limit switch operates in the same way as the more common limit switch. However, it is much smaller allowing for its placement in confined spaces, and it usually has a lever that only needs to move a small distance in order to allow for this detection [21].

Figure 16 shows the physical layout of a micro limit switch as well as an equivalent schematic of a micro limit switch. The terminals as seen in Figure 16 are labelled 'Com', 'NO' and 'NC'. 'Com' stands for common. This indicates a common terminal. 'NC' stands for normally closed. 'NO' stands for normally open. This means that when the lever is not actuated the electrical connection will exist between the 'Com' and 'NC' terminals and not between the 'Com' and 'NO' terminals. When the lever is actuated the electrical connection will exist between the 'Com' and 'NO' terminals and not the 'Com' and 'NC' terminals.

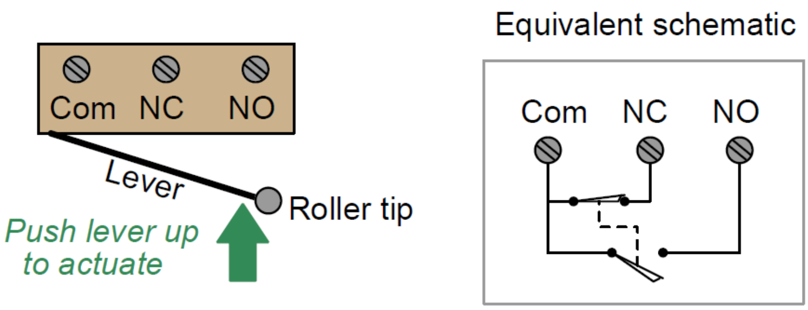


Figure 16: Physical image and schematic of a limit switch [22]

In practice the presence of an object will depress the lever (as indicated by the green arrow in Figure 16). This will cause the electrical connections to switch. This connection switching is indicated by the dotted line in Figure 16. Thus, the mechanical movement of the lever changes the switches electrical state. This change in electrical connection can be detected and fed back to a control system that can then be programmed to respond in the appropriate way.

3 Product requirements specification

The product requirement specifications (PRS) is a tool used in product development. It is used to outline and highlight the critical features and goals of the finished product. The PRS should be referred to throughout the project in order to ensure the product is meeting or moving towards these intended goals. This list can be used on completion of the project to assess the success of the product. The comparison between this list and the finished product can be used in future iterations to consider the shortcomings and how the future projects can be improved. For these reasons the PRS is a vital document to the project. A more detailed PRS can be found in Appendix B.

A summary of the PRS can be seen below in order of importance:

1. Each heddle should be individually and automatically controlled.
2. The automation should allow for changes in the weaving pattern.
3. There should be enough heddles and thus enough warp threads for a relatively complex pattern to emerge.
4. The cloth roll should automatically roll finished material for storage and in relation to this winding the warp beam at the same time should automatically roll to release more of the warp threads for weaving.
5. The loom should be able to produce a tightly woven pattern.
6. There should be a high enough accuracy that the pattern appears consistent to the naked eye.
7. The loom should be small enough to fit on a work desk, within a volume of roughly $60\ cm \times 50\ cm \times 50\ cm$.
8. The beater's back and forth motion should be automated.
9. The design should be relatively light and easy to transport.
10. As an upper limit, the loom should be able to complete a line of weaving in a minute.
11. The loom should be easy to store.

4 Design process

In this section a brief explanation of how the sub-assemblies fit together is given with a description of the steps taken to arrive at the final loom.

The programmable weaving loom that has been designed focused on the method of automation of the heddles. It was of the utmost importance to this project that the heddles were to be controlled individually. There were to be sufficient heddles, and thus warp threads, to allow for a material with a complex pattern to be created by the loom.

The final design was based on Concept Cv1 which made use of pen click mechanisms in order to complete the selection process. This will be discussed in Section 5. The pen click mechanisms size as well as the desired width of the loom as specified in the PRS constrained the number of pen click mechanisms. The number of heddles selected in order to display this level of complexity, while keeping the loom at a reasonable width in conformance with the PRS was 38.

This heddle subsystem was to be supported by a frame. The frame supported four bars. Two of these bars were to act as a guide for the warp threads as well as assisting in the creation of the tension necessary for weaving to take place. These two bars were stationary and thus require no automation. The third bar was to be the cloth roll and the fourth bar was to be the warp beam. The cloth roll and warp beam were to be able to release and take up completed fabric or warp threads automatically during operation. This forms the cloth roll and warp beam sub-assembly. The minimum diameter calculation for the four bars can be found in Appendix D.1.1. A calculation for the maximum deflection of the four bars can be found in Appendix D.1.2.

The fabric had to be compacted after each pick insertion. This was facilitated by a beater bar through an automated back and forth motion. The beater also acts as a support or a guide for the picking operations to take place. The picking operation were to be manual. This forms the beater sub-assembly.

With their connection being the warp threads, each of these systems interacted with the other and were mindful of the needs of the others in their design.

Conceptual designs were generated for each sub-assembly. Subsequently a final design was selected for each sub-assembly. At the same time the control aspects of the loom were being investigated. The electrical circuits were designed, tested and the code for the control systems was written.

In this detailed design report the sub-assemblies have been broken down into sections. The conceptual designs for each sub-assembly will be presented followed by a final design as well as a section on material selection, and actuator and driver selection.

The control aspects of the assembly will then be discussed these include the selection of micro controller, connection diagrams, the method of converting an image into an array for the loom to weave as well as a discussion on the code.

5 Heddle automation

The heddles and their automation were critical to the design of the loom. In this project emphasis was placed on the level of the heddle automation and its importance. The heddles control the warp yarn and their level of control determines the complexity of the designs possible. This was to be similar to a Jacquard mechanism in its individual heddle control. Several conceptual designs were generated in order to solve this problem. They will be outlined in this section of the report and a concept scoring matrix will be used to select the design most appropriate for this project. The final design for this sub-assembly will then be presented.

5.1 Conceptual designs

5.1.1 Concept A

Although the basic operation remains the same Concept A can be executed in two different ways. One version makes use of micro servo motors and the other makes use of solenoids. Both will be referred to as the 'actuator' to simplify the explanation.

Each heddle has its own actuator that controls its motion. The actuators sit in a frame. The frame moves up and down with the motion of a motor and lead screw. Each actuator controls a pin that slides through a plate and engages or disengages the heddles. Engagement of the heddle (and consequently warp thread) would mean that it moves with the frame and disengagement would mean that it remains where it is. This creates the shed for picking to be performed.

Concept Av1 - In this concept each heddle has a micro servo motor that controls the motion of the pin. This can be seen in Figure 17 and Figure 19. A zoomed in top view of the sub-assembly can be seen in Figure 18.

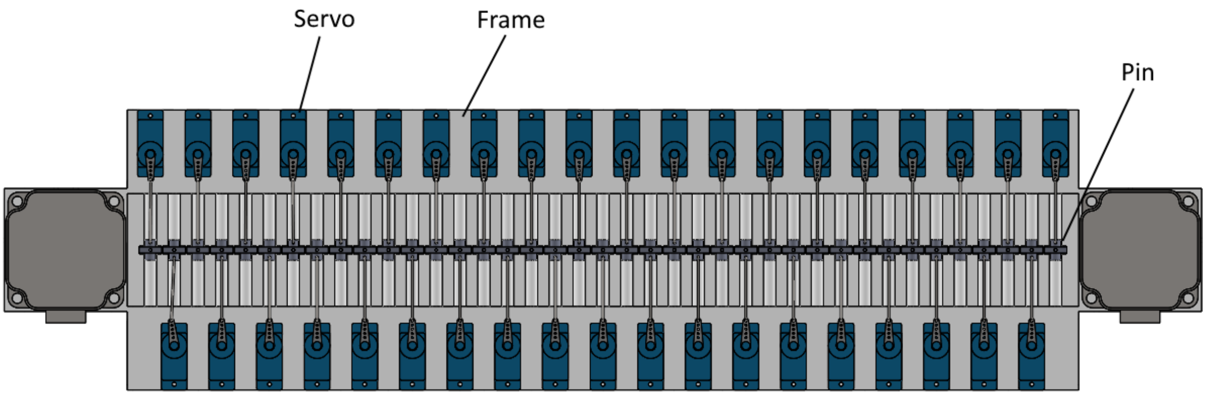


Figure 17: Top view of concept Av1

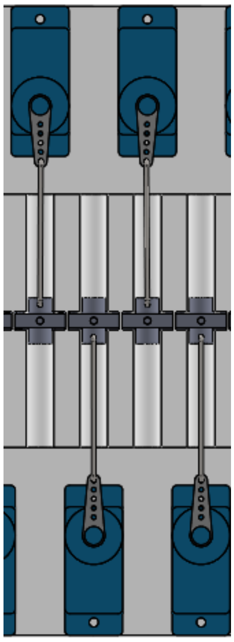


Figure 18: Zoomed in top view of concept Av1

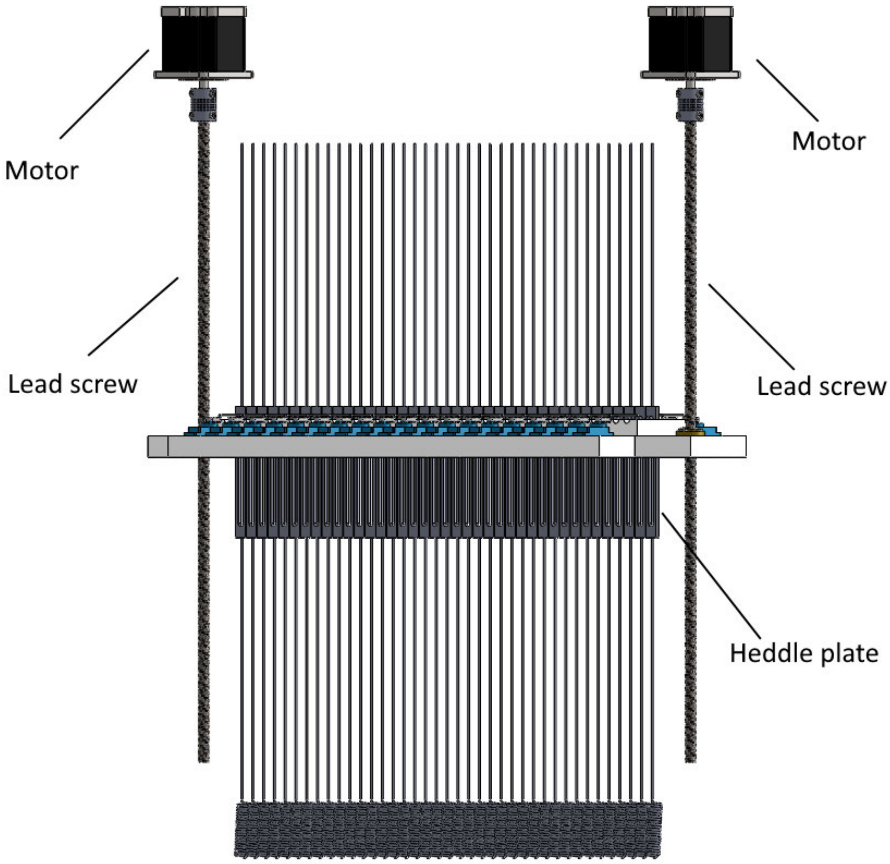


Figure 19: Isometric view of concept Av1

Concept Av2 - In this concept each heddle has a solenoid that controls its engagement or disengagement with the frame. In this design the plunger of the solenoid acts as the pin. This can be seen in Figure 20 and Figure 22. A zoomed in top view of the sub-assembly can be seen in Figure 21.

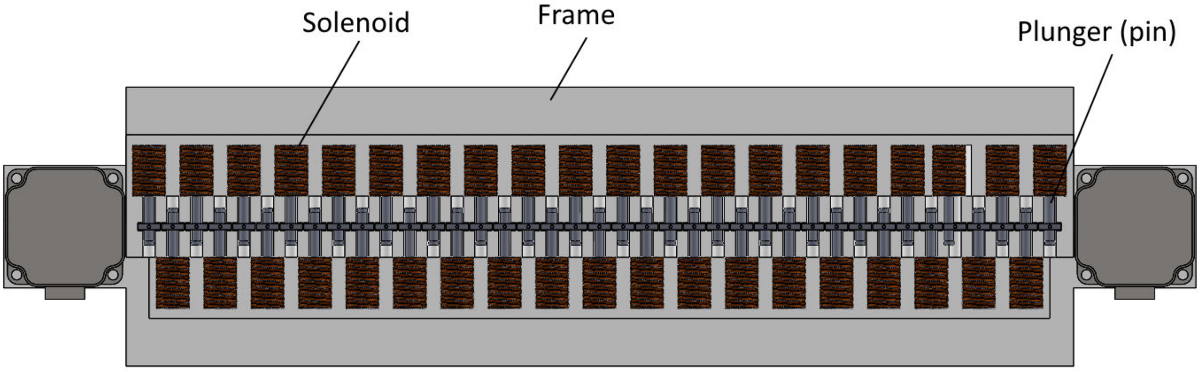


Figure 20: Top view of concept Av2

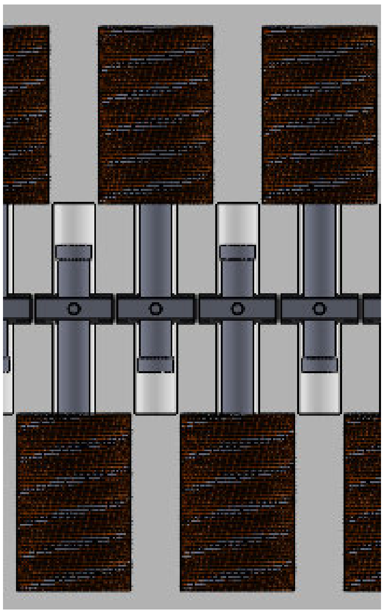


Figure 21: Zoomed in top view of concept Av2

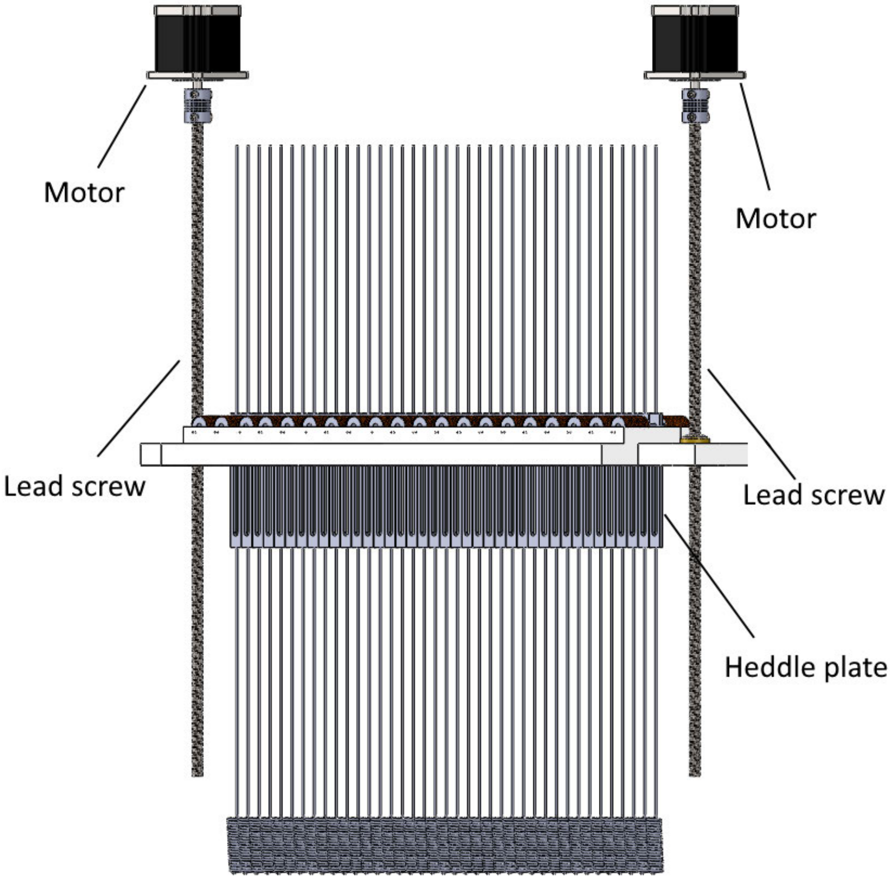


Figure 22: Isometric view of concept Av2

5.1.2 Concept B

Concept B makes use of a single motor. The motor rotates a shaft that has electromagnetic clutches mounted onto it. Each heddle wire is connected to the rotor of its own electromagnetic clutch i.e. one electromagnetic clutch per heddle wire. If the clutch remains off there will be no transfer of rotational motion and the heddle wire and consequently warp thread will remain in their original positions. When the clutch is on, it transfers the rotational motion from the shaft to the part of the electromagnetic clutch that is attached to the heddle wire (the rotor). In this way the clutch allows for the heddle wires to be wound up for shedding to take place. The design can be seen in Figure 23 and Figure 24.

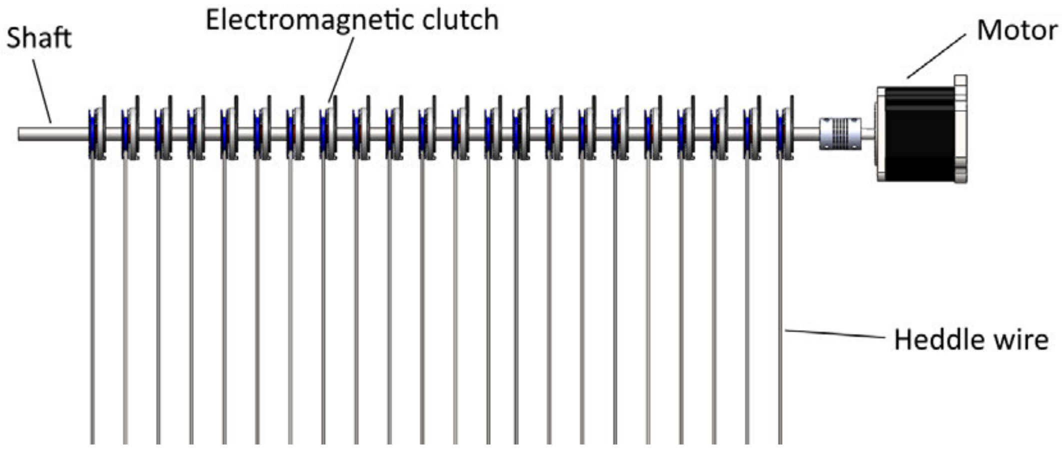


Figure 23: Close-up front view of concept B

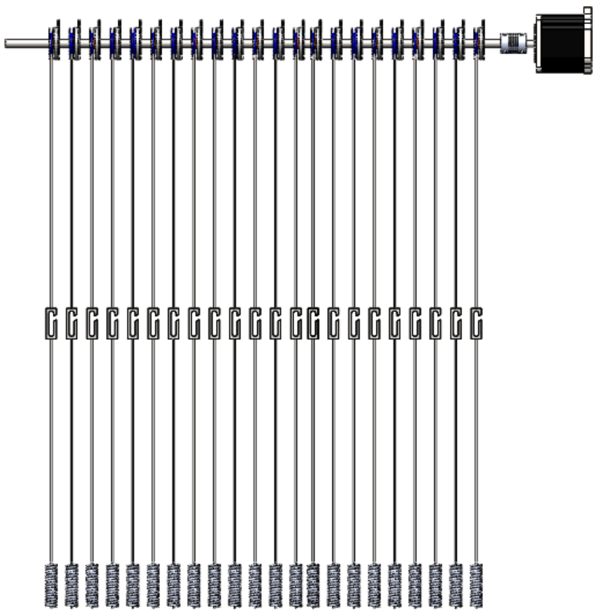


Figure 24: Front view of concept B

5.1.3 Concept C

Concept C has two variations. Both designs make use of a linear actuator to move either a servo motor or an electromagnet perpendicular to the warp thread's length. The designs have a frame that moves vertically using a motor and a lead screw. In both designs the frame holds pins that interact with the heddles in order to select warp threads for shedding. The pin's motion is controlled by the servo motor or electromagnet.

Concept Cv1

In this concept a servo motor is mounted on the linear actuator. The servo motor makes a stop at each heddle wire. A pen click mechanism, Figure 25, is mounted in the frame, Figure 26, at each heddle wire. An explanation of how the pen click mechanism works can be found in Section 5.6. This pen click mechanism interacts with a plate that forms part of the heddle. The servo motor uses a pin to push the push button or does not push the push button depending on the desired state of that particular warp thread. The push button in its extended state will constrain the motion of the plate to the motion of the frame and the push button in the retracted state will not constrain the plates motion. When the frame moves up those plates constrained to the frames motion will move up and consequently pull warp threads up, creating the shed. Figure 27 and Figure 28 show different views of the conceptual design.

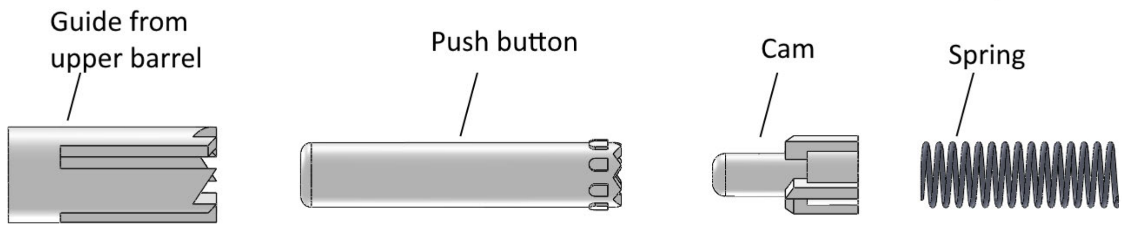


Figure 25: Pen click mechanism

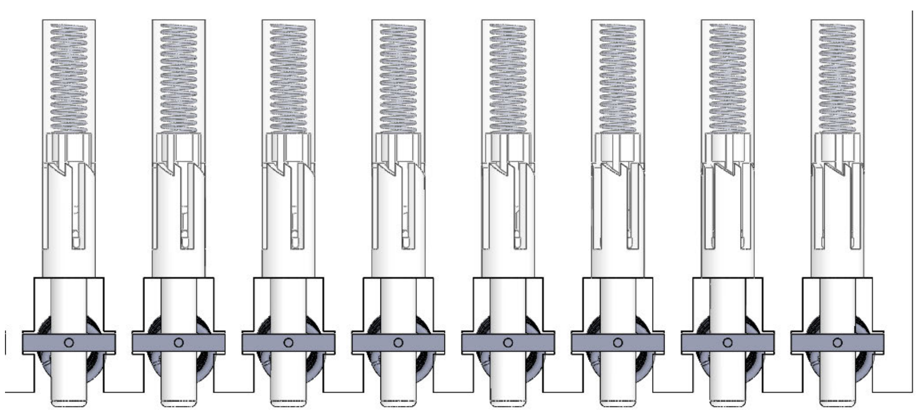


Figure 26: Pen click mechanism mounted in frame

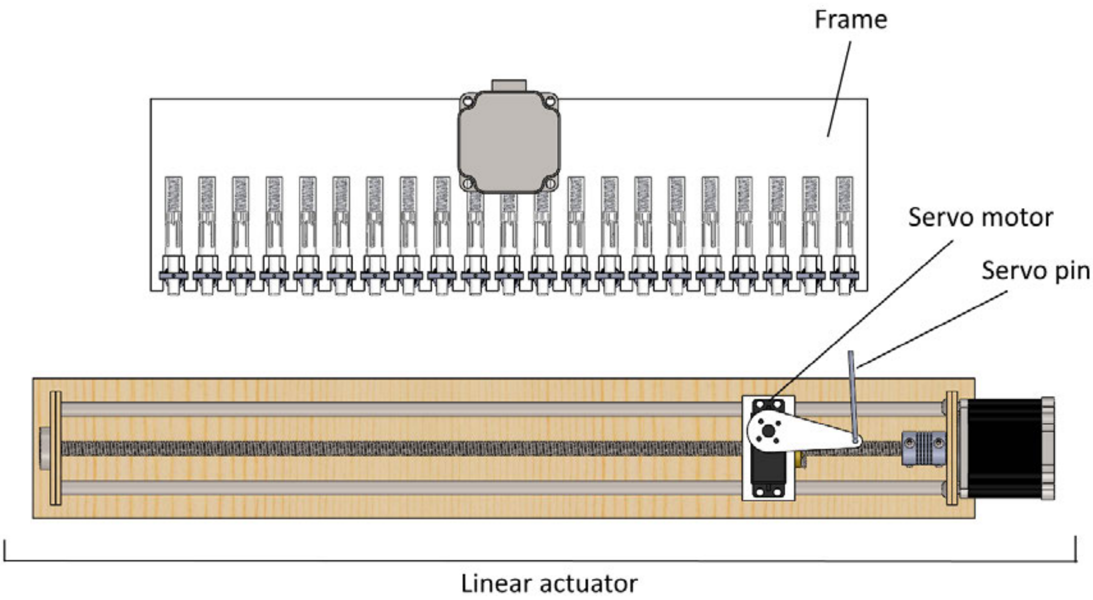


Figure 27: Top view of concept Cv1

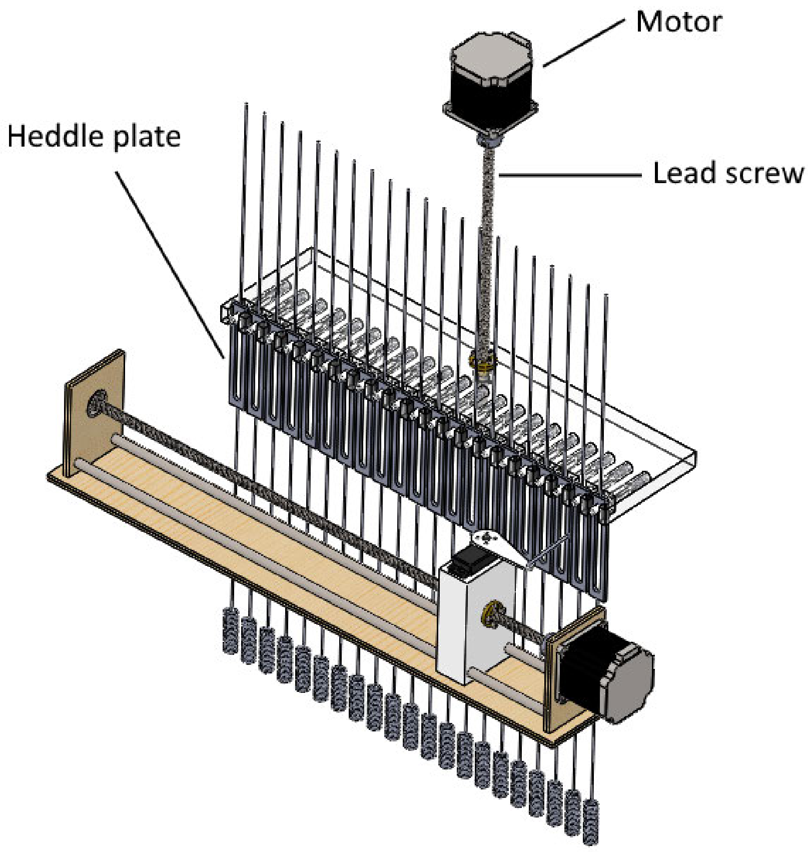


Figure 28: Isometric view of concept Cv1

Concept Cv2

In this concept a single electromagnet is mounted on the linear actuator. Each heddle has a plate that interacts with a pin. The pins have permanent magnets mounted onto them. The pins are held in a rigid frame. The pins make use of stoppers to prevent them from being removed from the frame by the electromagnet's actions. The electromagnet makes a stop at each pin and either repels the magnet, which would engage the pin, or attracts the magnet, which would disengage the pin. Engagement of the pin would mean that the pin slides through the plate of the heddle and constrains the heddle plate to the frame. Disengagement of the pin would mean the pin is pulled away from the heddle plate and the heddle would not move with the frame. After the electromagnet has made a stop at each pin, the frame will move upwards through the motion of a motor and lead screw. This motion will move the heddles (and warp threads) that were engaged upwards and leave the heddles (and warp threads) that were disengaged where they were. This will create a shed for picking. Figures 29 and 30 show different views of the conceptual design.

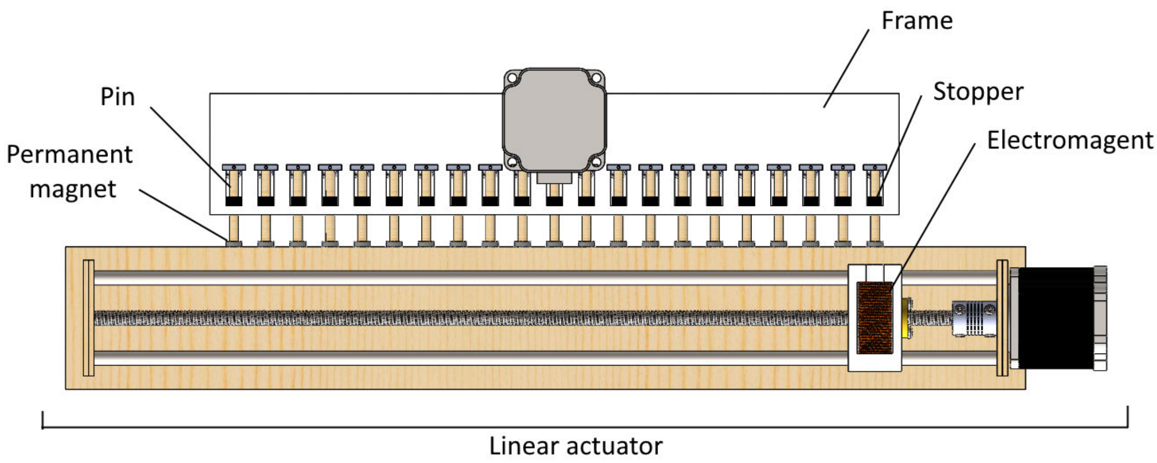


Figure 29: Top view of concept Cv2

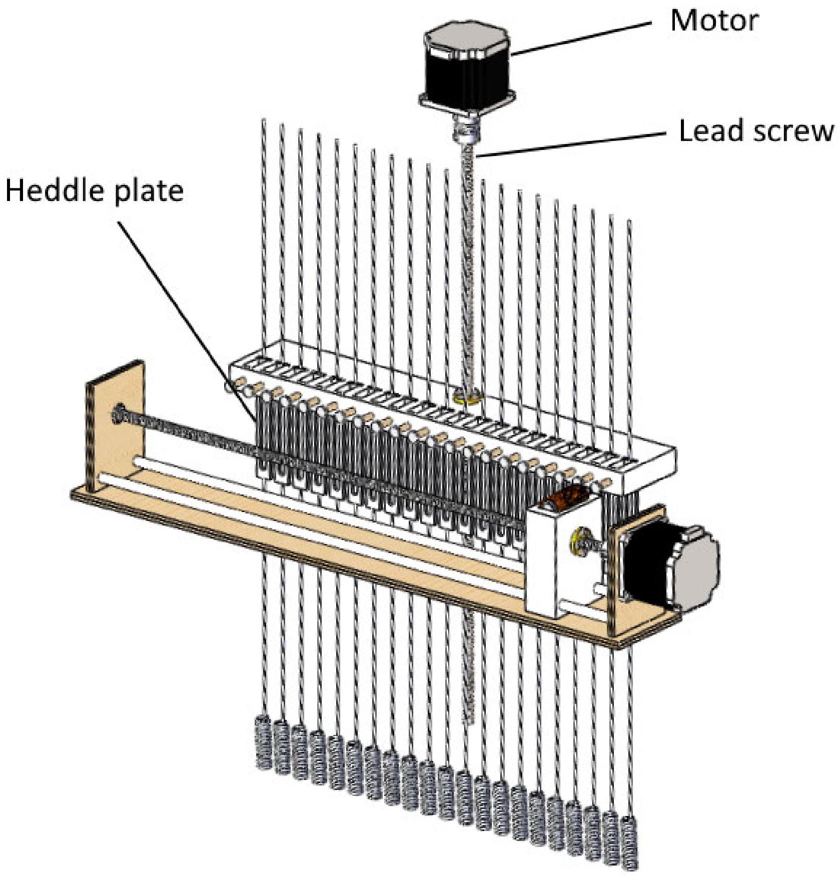


Figure 30: Isometric view of concept Cv2

5.1.4 Decision matrix

Table 1: Concept scoring matrix for heddle automation

		Concepts									
		Concept Av1		Concept Av2		Concept B		Concept Cv1		Concept Cv2	
Selection criteria	Weight	Score (1-5)	Weighted score	Score (1-5)	Weighted score	Score (1-5)	Weighted score	Score (1-5)	Weighted score	Score (1-5)	Weighted score
Estimate time for heddle selection for shedding to take place	10%	4	0.4	4	0.4	4	0.4	1	0.1	1	0.1
Availability of components	20%	5	1	5	1	1	0.2	5	1	5	1
Distance between heddles	10%	3	0.3	3	0.3	3	0.3	2	0.2	2	0.2
Time to build components and full assembly	15%	2	0.3	1	0.15	4	0.6	3	0.45	2	0.3
Complexity	10%	3	0.3	3	0.3	3	0.3	4	0.4	2	0.2
Repeatability (including consistency in built components)	15%	4	0.6	2	0.3	3	0.45	3	0.45	1	0.15
Estimated cost	20%	1	0.2	3	0.6	4	0.8	5	1	5	1
	Total score		3.1		3.05		3.05		3.6		2.95

Table 1 indicates that concept Cv1 would be the most appropriate design for this project. This can be attributed to the design's low cost, with the pen click mechanism coming from recycled pens. For the same reason the concept scores very high for the criterion of component availability. The design requires only one servo motor and for this reason has a relatively low complexity. The major design complexity comes from the alignment of the servo motor pin and pen click mechanism as the servo motor moves from heddle to heddle. A rough and conservative calculation of the servo motor torque requirement can be seen in Appendix D.3.1.

5.2 Final design

Prior to the completion of the final design of the mechanism chosen for the automation of the heddles a prototype was made and tested in its ability to function as a selector and its ability to carry a load. This can be seen in Appendix E.

After confirming that the functionality of the pen click mechanism was appropriate, the final design for the automation of the heddles was derived from concept Cv1 as described in Section 5.1.3. The concept is very similar to that of the conceptual design. The main difference being the removal of the springs. The springs were to be used to keep the heddle plates vertical, however, this was deemed unnecessary as the heddle plates would be kept vertical through the tensioned warp threads. There was the addition of a heddle plate guide (see Figure 34) to locate the heddle plates. The heddle plates were also staggered and the pen click mechanisms brought closer together in order to try to compact the design and bring the warp threads closer.

The final design has specified the complete means of lifting the frame that holds the pen click mechanisms, this being a stepper motor with two vertical support rods. Labelled 'vertical stepper motor' and 'vertical support rods' in Figure 31. A stepper motor was selected due to its effectiveness in this low speed and high torque application as well as its ability to rotate through 360°. The stepper motor could also be instructed to move the number of steps corresponding to the size of the shed which is an accurate and effective method of performing this operation. The stepper motor drove a lead screw that ran through the center of the frame that holds the pen click mechanisms. This action was supported by two vertical support rods.

In terms of the other actuators; a servo motor and stepper motor would perform the selection process. A servo motor was selected to push in and out the pen click mechanisms. The selection of a servo motor was made as it was necessary to accurately position the servo motor shaft in order to perform this function and it was not necessary to rotate through an angle greater than 180°. A stepper motor was selected to move the servo motor from push button to push button as it could be instructed to turn the number of steps corresponding to the distance between two pen click mechanisms and it was necessary for the motor to be able to turn through 360°.

A means of homing the stepper motors was selected. This being through the use of micro limit switches. Micro limit switches, as discussed in Section 2.7, change their electrical connection when their lever is depressed. This change can be detected by a control system. This was an easy, yet effective way of determining the presence of an object. Thus, micro limit switches were selected for the homing of the horizontal and vertical stepper motors. The mounting of the limit switches can be seen in Figure 35.

The operation of the final design as a whole can be described as follows; the horizontal and vertical stepper motors will begin by homing using the vertical and horizontal limit switches. The vertical stepper motor then moves the frame holding the pen click mechanisms to its starting position, i.e. the pen click mechanisms aligned with the slots in the heddle plates. The horizontal stepper motor then moves the servo motor to its starting position i.e. its selector pin aligned with the first pen click mechanism. The horizontal stepper will then move the selector servo motor on the selector servo mount. The selector servo motor will make a stop at each heddle plate - pen click mechanism unit. The selector servo will either engage or disengage the pen click mechanism depending on the pattern design. This process works in the same way as described in the conceptual design. Once the selector servo has made a stop at each pen click mechanism the vertical stepper motor will move up the frame holding the pen click mechanisms as well as the engaged heddle plates and consequently the warp threads attached to the engaged plates. This action will create a shed for the picking operations. The vertical stepper motor will then move the frame holding the pen click mechanisms down and the process will repeat until the pattern is formed.

For the reasons mentioned previously, such as the width constraint of the loom and the need for sufficient warp threads for a complex pattern to emerge, the final design made use of 38 pen click mechanisms and consequently 38 warp threads.

A front view of the sub-assembly can be seen in Figure 31. An isometric view of the sub-assembly can be seen in Figure 32 with a zoomed in isometric view of the servo motor seen in Figure 33. A top view of the critical features can be seen in Figure 34.

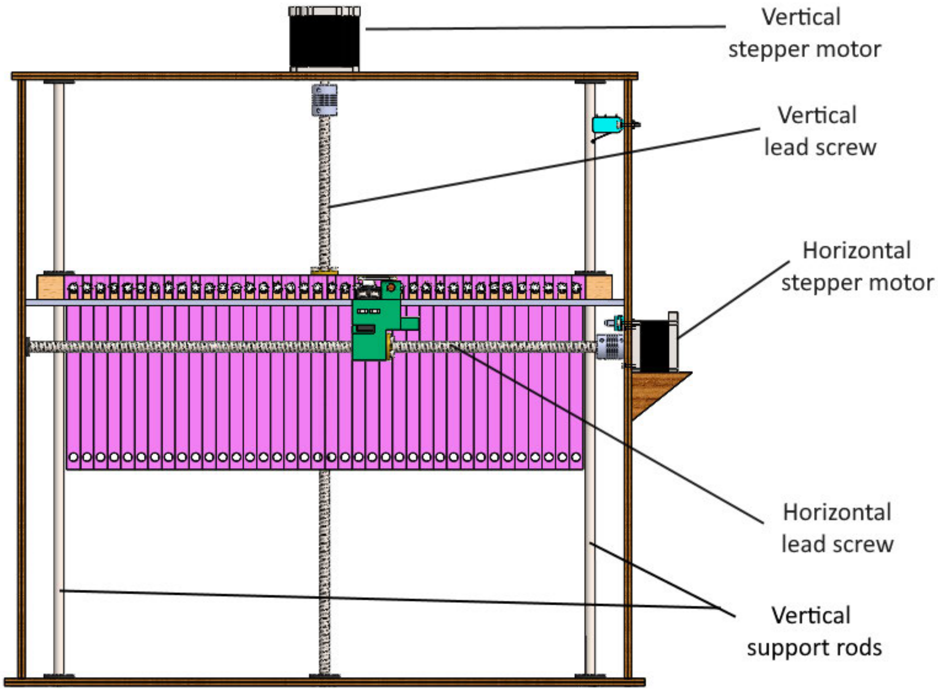


Figure 31: Front view of heddle automation sub-assembly

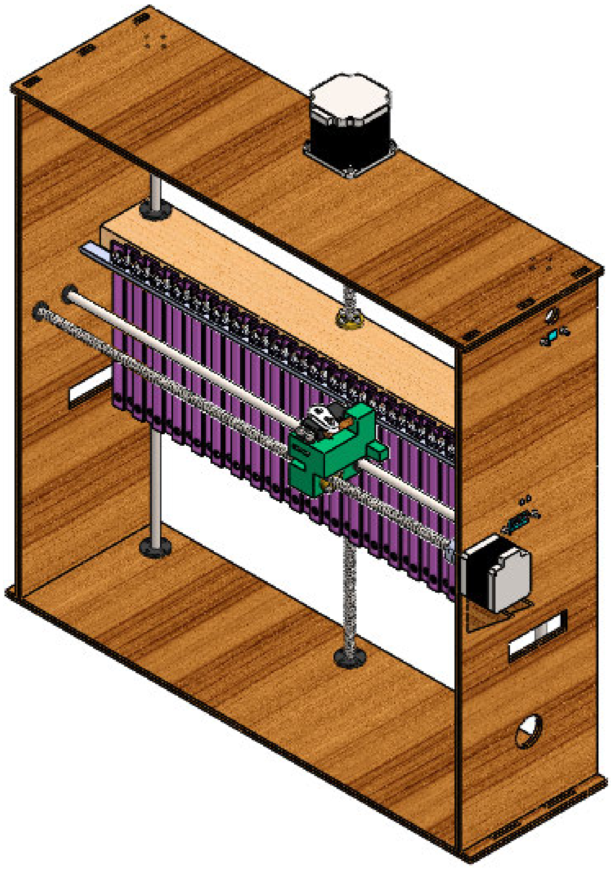


Figure 32: Isometric view of heddle automation sub-assembly

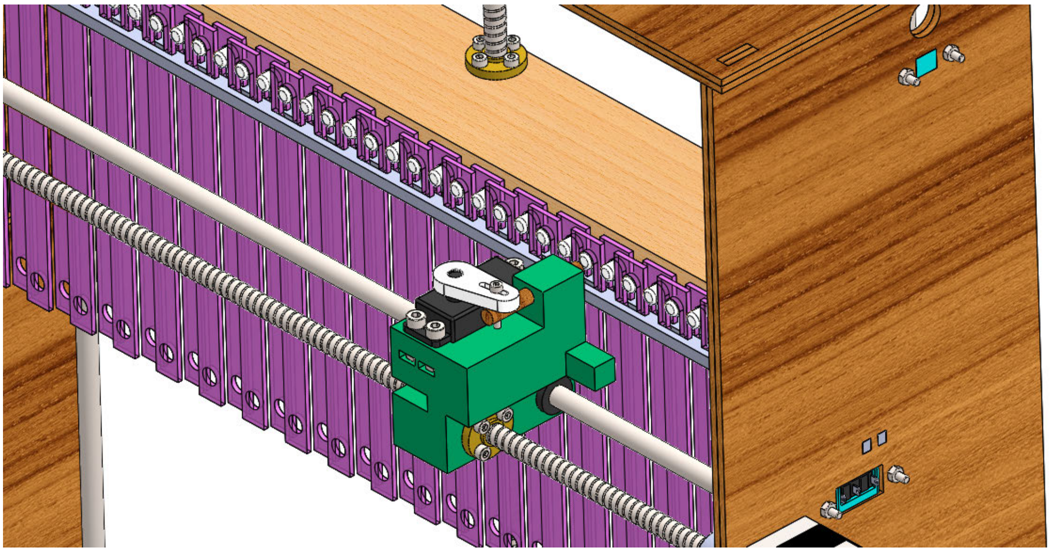


Figure 33: Zoomed in isometric view of heddle automation sub-assembly

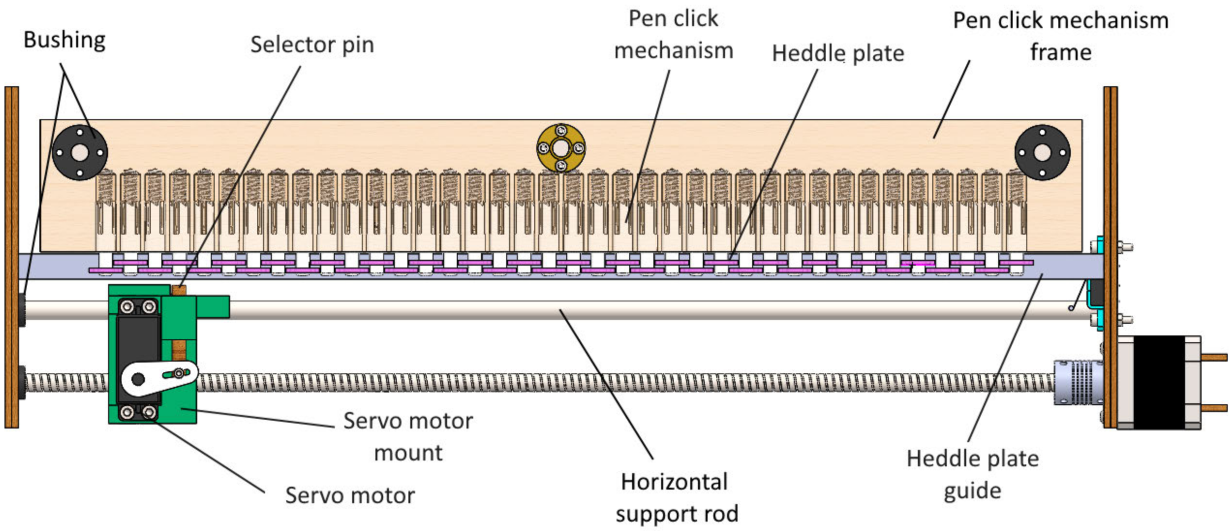


Figure 34: Top view of heddle automation sub-assembly with a transparent pen click mechanism frame

5.3 Material selection

The primary material selected was polylactic acid (PLA) for the 3D printed parts such as the selector servo mount and the limit switch mounts. Clearer images of the 3D printed parts can be seen in Appendix C. Meranti was used for the frame that holds the pen click mechanisms because of its strength. The lead screws were made from steel. The lead screw nuts were made from brass. The vertical and horizontal support rods were also made from steel. The mounting for the stepper motors was the hardboard frame. The limit switch mounts were also mounted to the hardboard frame. The bushings were made from nylon. The heddle plates were made from 2 mm Perspex. The heddle plate guide was made from 5 mm Perspex. The pen click mechanisms were made from plastic Pilot G-2 07 pens. The size of the pen click mechanisms as well as the arrangement of the final design meant that a thick wool needed to be selected for weaving. The approximate diameter needed was 7.2 mm.

5.4 Actuator and driver selection

The motor chosen to perform the pen click mechanism selection was the 180° Towerpro MG995 servo motor, with a rated torque of 13 kg.cm. This motor did not require a driver. A brief torque requirement calculation for this motor can be seen in Appendix D.3.1.

A NEMA17 stepper motor, with a rated holding torque of 0.4 N.m and 1.8 deg/step, was selected for the movement of the horizontal linear actuator. The driver selected was the DRV8825. A brief torque requirement calculation for this motor can be found in Appendix D.3.2.

A NEMA23 stepper motor, with a rated holding torque of 1.26 N.m and 1.8 deg/step, was selected for the movement of the vertical linear actuator. The driver selected was the TB6600 driver. A brief torque requirement calculation for this motor can be found in Appendix D.4.2.

5.5 Limit switch position and mounting

Figure 35 shows the mounting positions for the horizontal and vertical limit switches in their respective mounts.

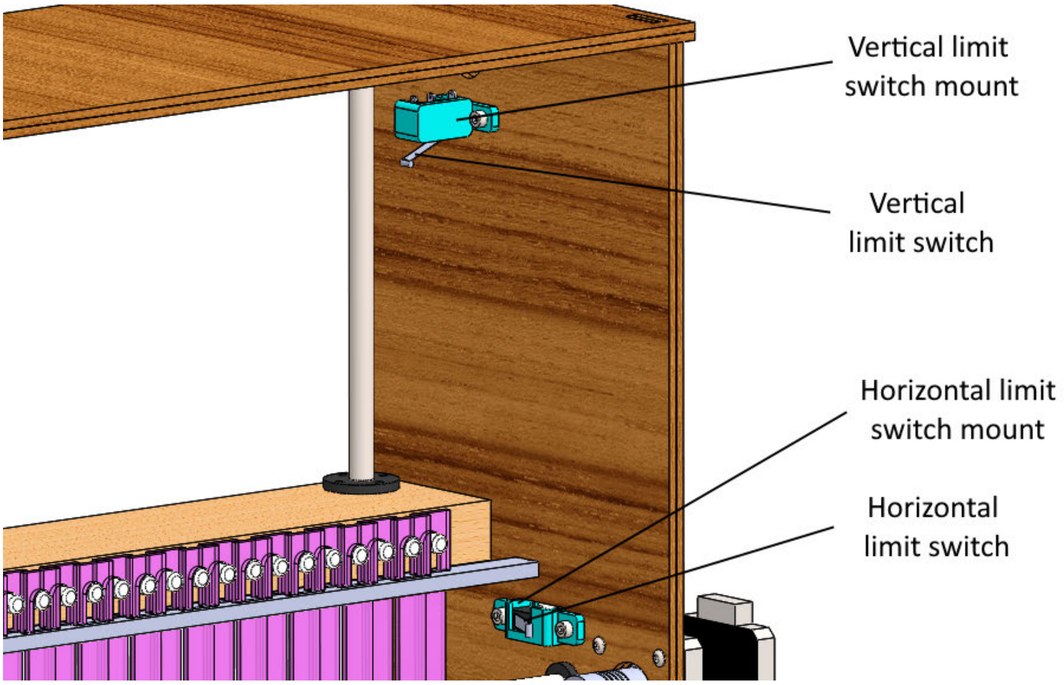


Figure 35: Front view of beater automation sub-assembly

The position of the vertical limit switch was important as it needed to allow for sufficient room for the necessary shed to be created. A calculation for this minimum height can be seen in Appendix D.4.1.

5.6 Operation of the pen click mechanism

This explanation is done in reference to Figure 36.

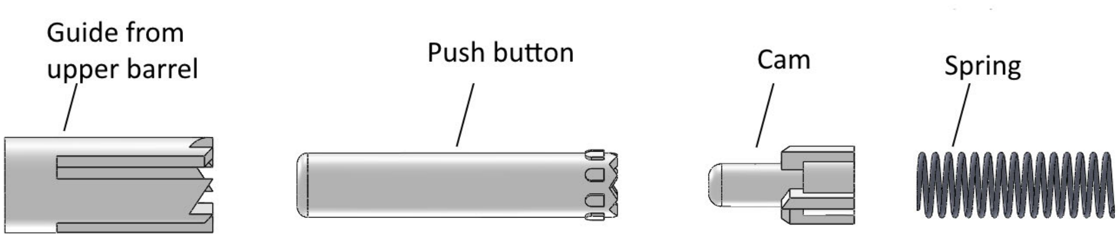


Figure 36: Pen click mechanism (this is repeated image of Figure 25)

A push button generally has eight notches on its sides. These notches guide it as it slides in and out of the guide. The push button has jagged edges or teeth.

The guide has these same teeth. The guide is generally moulded into the upper barrel of a click pen. Every second tooth of the guide has a gap as can be seen in Figure 36.

The cam generally has four teeth. These teeth point in the opposite direction to the teeth on the push button and the guide. The teeth slide up and down the edges of the push button and guide teeth. The cam converts translational motion into rotational motion.

The spring provides resistance against a push button press.

This explanation will start with the cam in a position where its teeth are engaged half way along the teeth of the push button. It stays in this state because the guide prevents the cam from sliding fully into the push button teeth. When the button is pressed the cam loses contact with the guide. It can now rotate and slide all the way into the push button teeth. When the pushing force is removed the spring pushes the cam and push button towards the guide. The cam teeth then make contact with a tooth on the guide and it slides along this tooth, rotating to a point where it is engaged half way along the push button tooth. The guide tooth is either a full tooth or a half tooth. Assuming the tooth on the guide is a full tooth, the cam will remain in its position and prevent the spring force from being transferred to the push button which would force the push button out. Instead the push button remains in its retracted state.

When the button is pressed again the cam loses contact with the guide tooth and rotates along the next tooth of the push button. The pushing force is released and the cam and push button slide towards the guide. The cam teeth then make contact with a tooth on the guide and it slides along this tooth, rotating to a point where it is engaged half way along the push button tooth. Since the last guide tooth was a full guide tooth the next one will be a half guide tooth. The cam tooth encounters the gap in the half guide tooth and transfers the spring force to the push button. The cam and push button slide along the guide until the notch on the push button hits the end of the guide preventing it from sliding further out. The push button is now in its extended state [23].

6 Beater automation

The movement of the beater during weaving is a simple back and forth motion. This motion completes one of the primary actions, 'beating-up'. The automation of the cloth roll and warp beam will ensure that the beater has a set distance in which it needs to move back and forth every time.

6.1 Conceptual design

There were various methods considered for this automation. Some of these include belt-driven and screw-driven linear actuators, a cam and follower, rack and pinion as well as a slider-crank mechanism. The belt-driven and screw-driven linear actuators were excluded as they provided a level of precision unnecessary for this task. The cam and follower mechanism was excluded due to its high mechanical complexity. The rack and pinion was excluded due to the cost that would be associated with either buying or 3D printing the rack and pinion. The slider-crank mechanism was selected based on its simplicity as well as its ability to perform the required movement in a fast and precise manner. The conceptual design for this system can be seen in Figure 37.

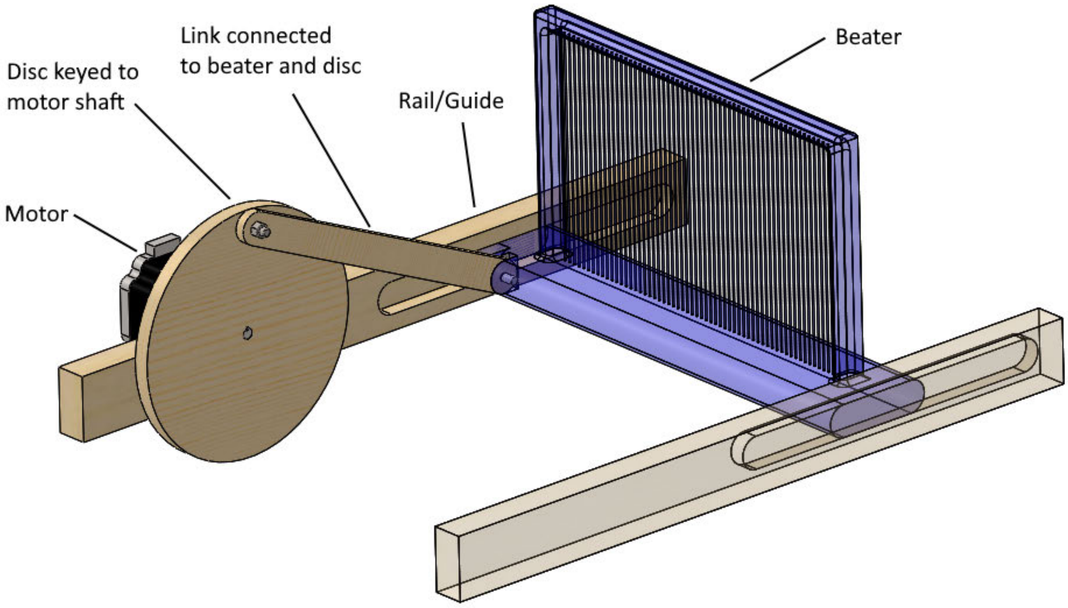


Figure 37: The assembly for the beater automation

6.2 Final design

The final design of the beater has been modified slightly from the conceptual design. The motors selected for the automation of the beaters final design are servo motors. Servo motors were selected as in this application it was necessary for accurate positional control and it was not necessary for rotation beyond 180°. This modification includes the use of two servo motors and two slider-crank mechanisms, on either side of the beater, to actuate the motion of the beater as opposed to one motor and one slider-crank mechanism.

The servo motors rotate in a synchronised manner. The slider-crank mechanism the motors were mounted to drive the beater forwards and backwards when they were moved. Driving the beater from both sides lessened the risk of the beater getting jammed in its grooves due to it rotating.

An isometric view of the final beater design can be seen in Figure 38. A front view of the final beater design can be seen in Figure 39. A zoomed in isometric view of the slider-crank mechanisms can be seen in Figure 40.

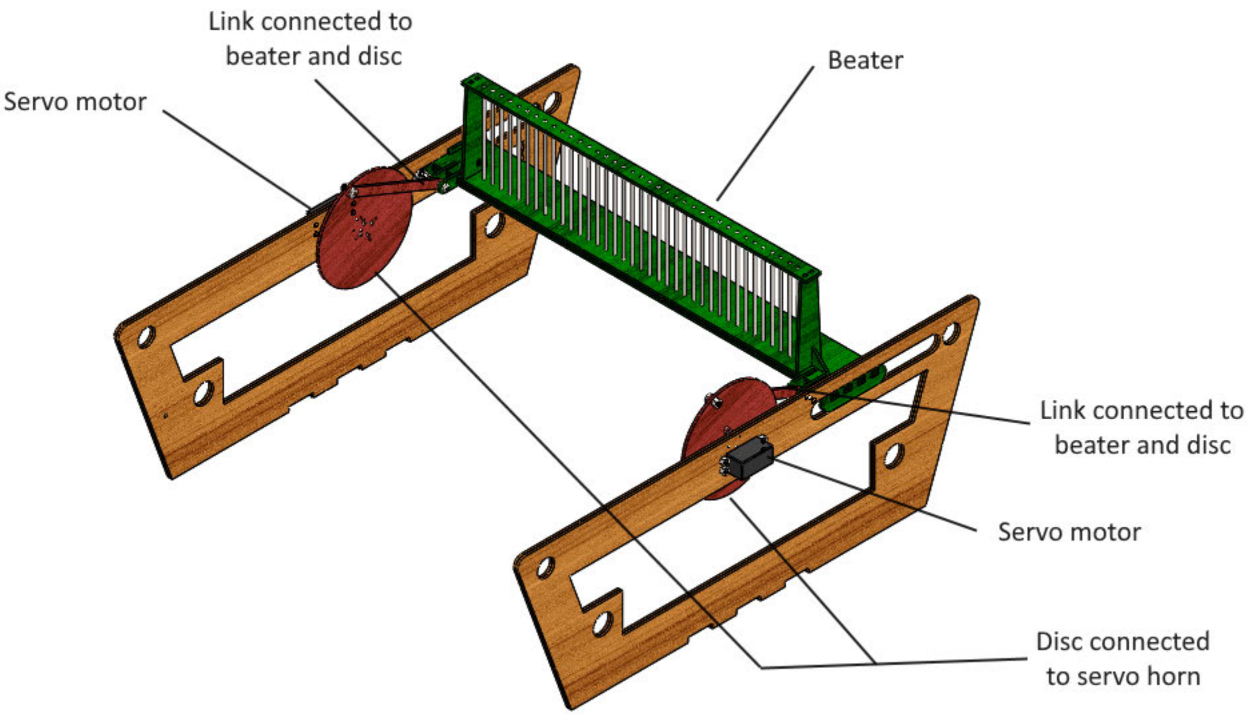


Figure 38: Front view of beater automation sub-assembly

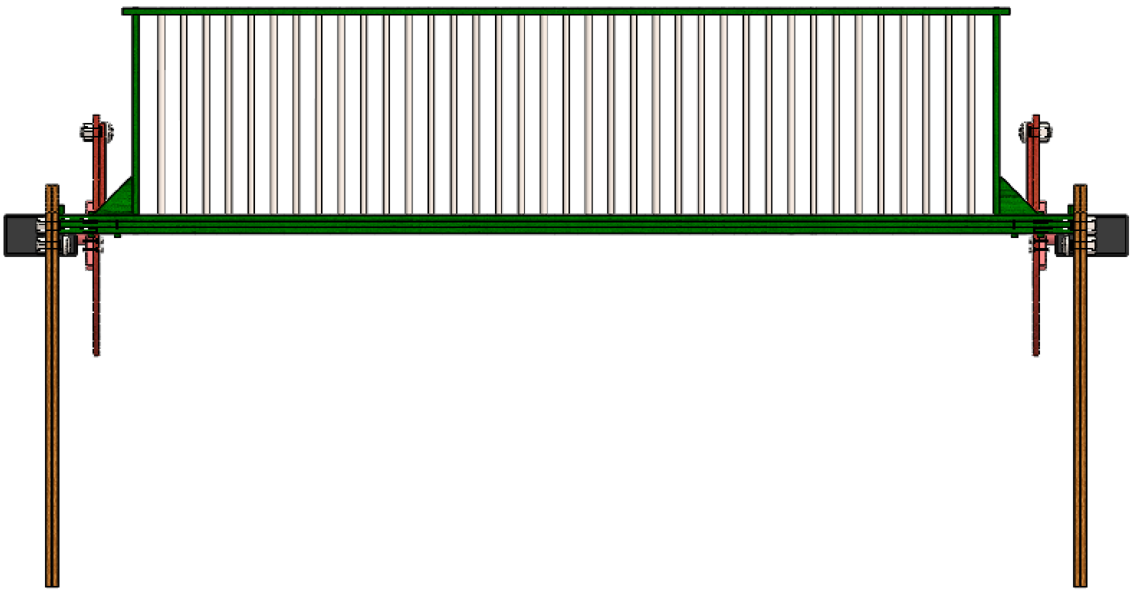
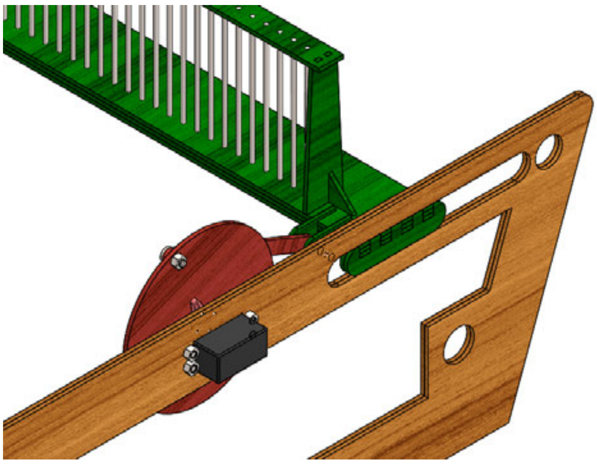
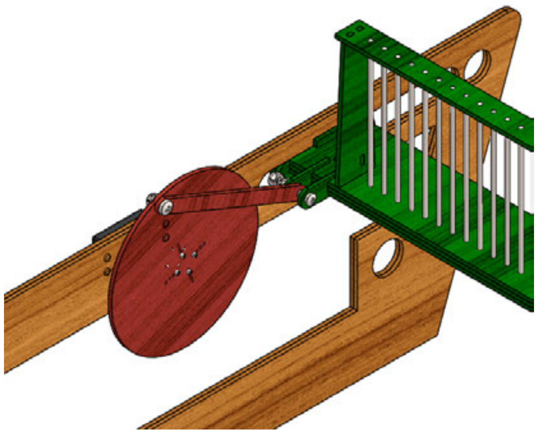


Figure 39: Front view of beater automation sub-assembly



(a) Zoomed in isometric view of beater automation sub-assembly side 1



(b) Zoomed in isometric view of beater automation sub-assembly side 2

Figure 40: Zoomed in isometric view of beater automation sub-assembly

6.3 Material selection

The main material used in this sub-assembly was hardboard. The only parts in the sub-assembly not made from hardboard are the servo motors, the servo motor horns, wires (the wires form the teeth or reeds of the beater) and the fasteners.

6.4 Actuator and driver selection

The actuator selected for the automation of this sub-assembly was two servo motors. They were to be driven directly off the micro controller. The servo motors needed to be synchronised in their motion and for this reason the servo motors were connected to one PWM pin on the micro controller. This connection can be seen in Figure 49 and is discussed in Section 9.2. A brief calculation of the torque requirements of the servo motors was performed in Appendix D.2.1. The final calculated torque required was extremely low. Possible reasons for this include an oversimplification of the system. Instead servo motors of a higher torque rating were used for the beater automation, these being two 180° Towerpro MG995 servo motors. These servo motors had a rated torque of 13 kg.cm.

7 Cloth roll and warp beam automation

The automation of the cloth roll and the warp beam would allow for the taking up of completed fabric and letting off of unwoven thread to happen autonomously. This was done to save the weaver the time and effort of having to do these tasks by hand.

7.1 Conceptual design

The conceptual design makes use of three 3D printed timing pulleys with a GT2 tooth profile as well as two separate timing pulley belts and a stepper motor. There are two pulleys mounted on the cloth roll and warp beam respectively and a twin pulley is mounted on the motor. Images of the pulleys can be seen in Figure 41.

(a) Cloth roll and warp beam timing pulley

(b) Motor twin timing pulley

Figure 41: Pulleys to be 3D printed

The idea is that with the rotation of the stepper motor the cloth roll and warp beam will rotate the same amount and thus maintain the necessary weaving tension in the warp threads. The conceptual design can be seen in Figure 42.

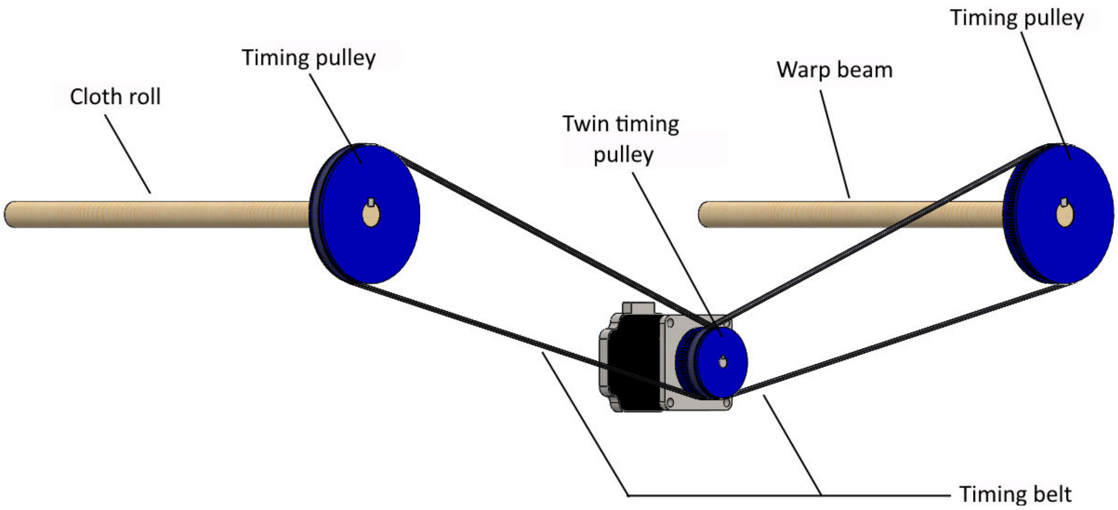
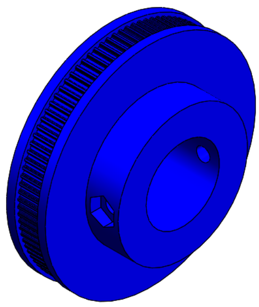


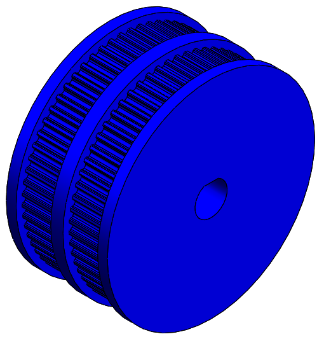
Figure 42: Sub-assembly for the cloth roll and warp beam automation

7.2 Final design

The final design was altered very slightly from the conceptual design. The main difference being the method of attachment of the pulleys to the beams as well as to the stepper motor. A stepper motor was selected as it was necessary to rotate through 360°. The operation is also low speed and high torque which is ideal for stepper motors. The operation of a stepper motor meant that the stepper motor could be instructed to move a certain number of steps at a time which is ideal for this application. The design originally made use of keys and key ways, however, the stepper motor purchased had a D-shaft and the beams being wood meant that cutting key ways would have proven difficult. In the final design the pulleys that attach to the beams made use of a bolt and captive nut. The dual pulley that attaches to the stepper motor made use of a D shape bore for tangential constraint to the motor shaft. These pulleys can be seen in Figure 43.



(a) Cloth roll and warp beam timing pulley revision



(b) Motor twin timing pulley revision

Figure 43: Pulleys to be 3D printed

The full sub-assembly can be seen in Figure 44. This image shows the attachment of the beams to the side frames of the loom. A sectioned view of the sub-assembly can be seen in Figure 45 and Figure 46. The system operates much like the conceptual design. A stepper motor rotates a twin timing pulley that is attached to its shaft. The twin timing pulley is attached via two timing belts to timing pulleys located on the cloth roll and warp beam. This allows for the rotation of the beams in relation to each other. This takes up the completed fabric while releasing unwoven warp threads into the weaving area.

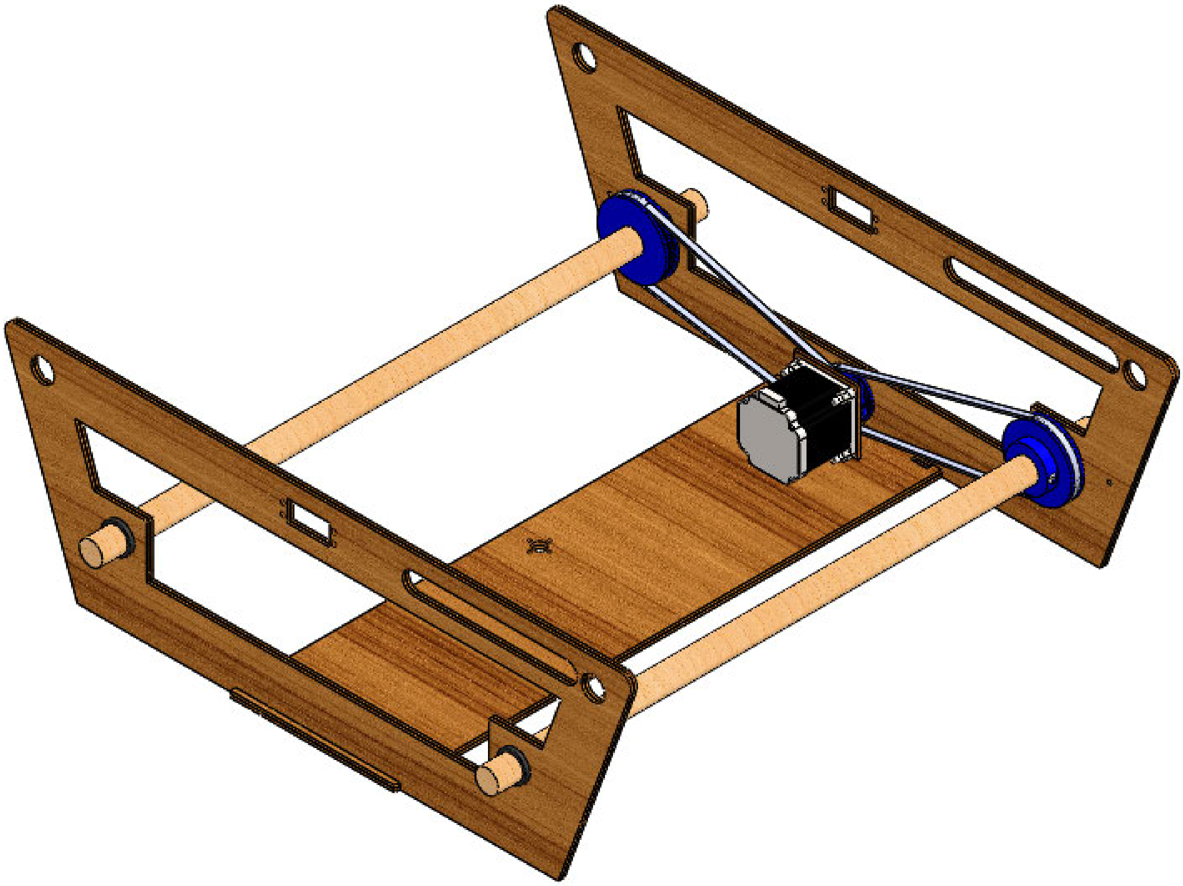


Figure 44: Isometric view of full cloth roll, warp beam automation sub-assembly

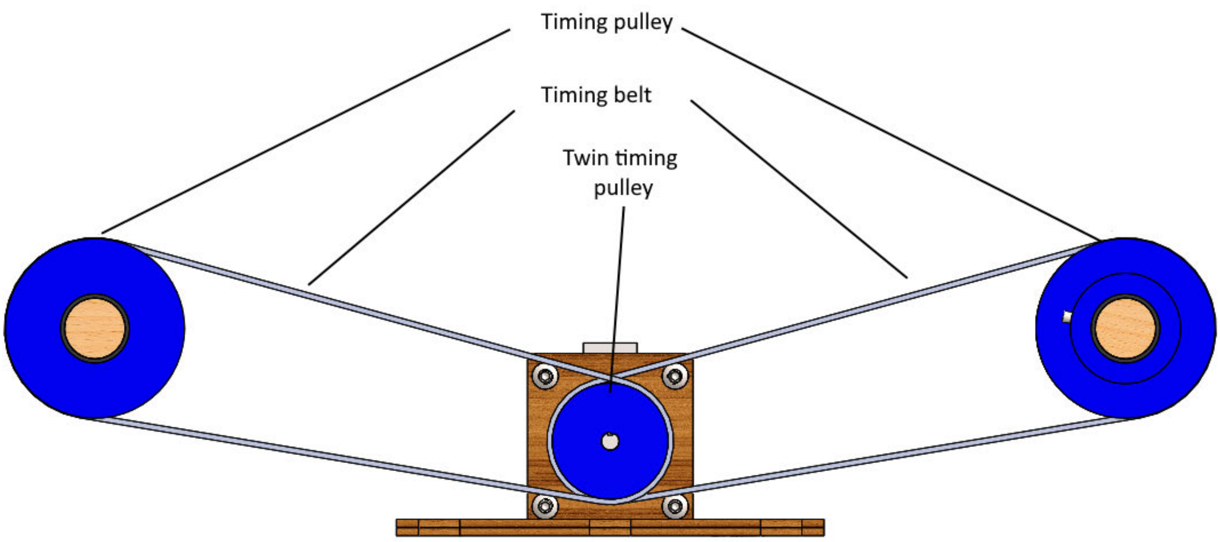


Figure 45: Front view of cloth roll, warp beam automation sub-assembly

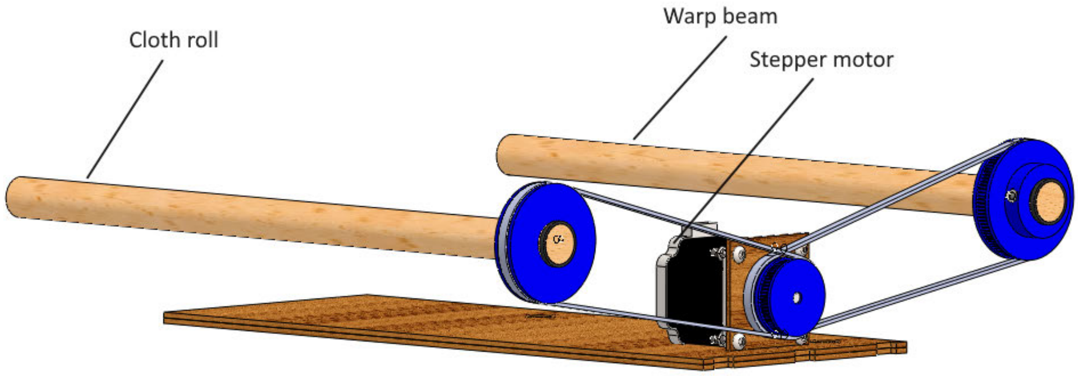


Figure 46: Isometric view of cloth roll, warp beam automation sub-assembly

7.3 Material selection

The main material used in this sub-assembly was PLA. The PLA was used in 3D printing the GT2 timing pulleys. The GT2 timing belt was purchased. The timing belt was made from neoprene rubber and was fiberglass reinforced. The cloth roll and warp beams were to be made from Malaysian hardwood. The bushings that the cloth roll and warp beams sit in and that support the beams were made from nylon. The stepper motor mount was made from hardboard.

7.4 Actuator and driver selection

A calculation for the torque requirement of the motor can be found in Appendix D.1.3. The calculated torque requirement of this motor was extremely high. The cost of such a motor would be extensive. The high torque requirement could be due to the calculation being overly conservative. A NEMA23 with a lower torque output would be used initially and if it did not provide sufficient torque would be upgraded to a motor with a higher torque output. The stepper motor selected was a NEMA23 stepper motor, with a rated holding torque of 1.26 N.m and 1.8 deg/step. The driver used was the TB6600 stepper motor driver.

8 Final design

The sub-assemblies discussed fit together to form the final weaving loom design. This final full weaving loom assembly can be seen in Figure 47. Figure 48 shows the final design with the critical sub-assemblies labelled.

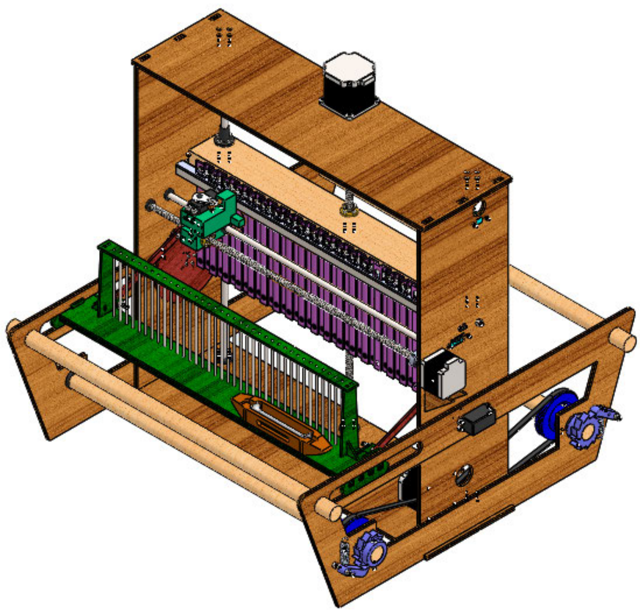


Figure 47: Final full weaving loom assembly

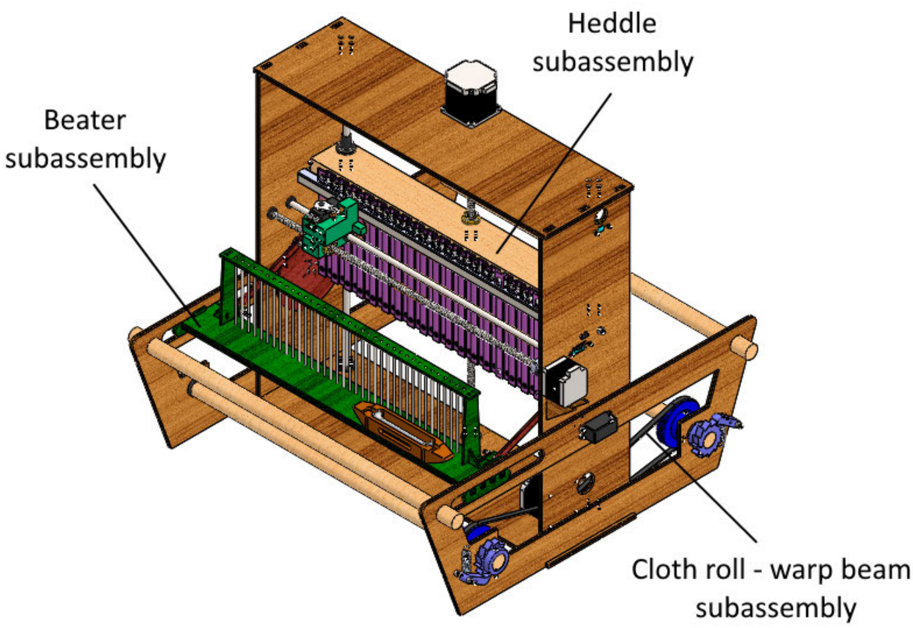


Figure 48: Final full weaving loom assembly with labelled subassemblies

8.1 Description of operation

A basic description of the operation and sequence of operations for the weaving loom will be outlined in this section.

The operation of the weaving loom is derived from the basic requirements of any weaving loom highlighted in the literature review as well as the unique objectives of this project. The most critical of these unique objectives being the control of individual heddles.

The operation begins with the homing of the stepper motors that control the horizontal and vertical linear actuators. This is initiated by the push of a button. This homing process is made possible with limit switches mounted on the side frame of the loom. After the homing of the vertical stepper motor is complete, the vertical stepper motor moves the frame that holds the pen click mechanisms to its starting position, the pen click mechanisms aligned with the heddle plate slots. After the homing of the horizontal stepper motor is complete, the horizontal stepper motor moves the selector servo motor to the starting position, the selector servo pin aligned with the first pen click mechanism. The beater begins in the retracted state i.e. at its furthest distance from the breast beam. This is made possible with two synchronised servo motors that control the beater. The weaving process then begins with the push of a button. The selector servo motor is moved across the width of the loom by the action of the horizontal stepper motor, making a stop at each of the pen click mechanisms, ensuring they are in the correct state. Once the selector servo has made its stop at the last pen click mechanism the vertical stepper motor moves the frame up. This moves up the heddle plates that were engaged and consequently their warp threads. This creates a shed for the picking operations. The weft thread is then inserted manually by the user. A button to indicate that the weft has been inserted is then pushed. The beater extends, by the action of the two servo motors, towards the breast beam compacting the fabric. The vertical stepper motor moves the frame that holds the pen click mechanisms down to its starting position, the pen click mechanisms aligned with the heddle plate slots. The selection process then repeats, except this time the selector servo motor is moved across the width of the loom in the opposite direction. This is to speed up the operation and mitigate the need for returning the selector servo motor to its starting position.

After every five lines of weaving the stepper motors repeat their homing process. The selector servo is returned to the side it had been on after this process is completed. Every five lines of weaving the cloth roll and warp beam stepper motor rotates. This releases unwoven warp threads held on the warp beam into the weaving area and takes up completed fabric held on the cloth roll. This process is repeated until the fabric is completed.

As is illustrated in the above description the automation of the loom is made possible through the extensive use of different types of motors and limit switches. A description of the motors, drivers and limit switches and how they operate can be seen above in Sections 2.5, 2.6 and 2.7 respectively.

8.2 Primary material selection

The primary material selection for the frame and beater of the weaving loom was 3 mm hardboard. This selection was made based on the affordability of the material, ability to laser cut this type of material as well as ease of modification of the material. For example, if an extra hole needed to be made or an area needed to be sanded this could be done with the use of common power tools and with minimal effort. Although the material does not exhibit the greatest stiffness in comparison to materials such as aluminium, the overall stiffness was increases by using double layers of the hardboard sheets. The resulting stiffness of the board was thought to be sufficient in this low force application. The laser cutter drawings used can be seen in Appendix H.

The complexity and uniqueness of certain parts meant that they needed to be 3D printed. A detailed look at these parts can be seen in Appendix C.

The heddle plates were made from laser cut 2 mm Perspex. This selection was made based on the affordability of the material and the ability to laser cut the material.

The heddle plate guide was made from 5 mm Perspex. The heddle plate guide was originally going to be 3D printed but the part would have had to be split into three pieces. This would have compromised the structural integrity of a part that would need to span across the whole weaving loom and that would only be supported on two sides. Another option was to make the part from 3 mm aluminium. However, this would have made the part costly. It was decided to use 5 mm Perspex and in the event that this did not work to use 3 mm aluminium with a 2 mm Perspex shim that would allow for the part to fit into the laser cut side frame slots, preventing the need to re-cut the sides of the weaving loom frame.

In terms of the components made by the workshop, the bushings were made from nylon, the beams were made from Malaysian hardwood and the frame that held the pen click mechanisms was made from meranti. The machine drawings for the parts made by the workshop can be seen in Appendix G.

9 Control

The control aspects of the project were vital to the coordination of the loom as a whole. This section details the micro controller used, an explanation for the connection diagram for the entire control system, the explanation of how the patterns will be created from arrays as well as the code flow diagrams.

9.1 Micro controller

The micro controller selected was the Arduino Mega 2560 R3. The availability of resources and information for Arduino micro controllers is unmatched. This allows for the coding, assembly and debugging to take place at a much faster rate. With the delays caused by the pandemic in terms of parts and access to the necessary electronic equipment these benefits were seen as vital to the completion of this project. The Arduino Mega was selected over the Arduino Uno due to increased number of pins. The number of components that needed to be controlled in this project meant that the Uno would not have enough GPIO pins for this to be possible.

9.2 Connection diagram

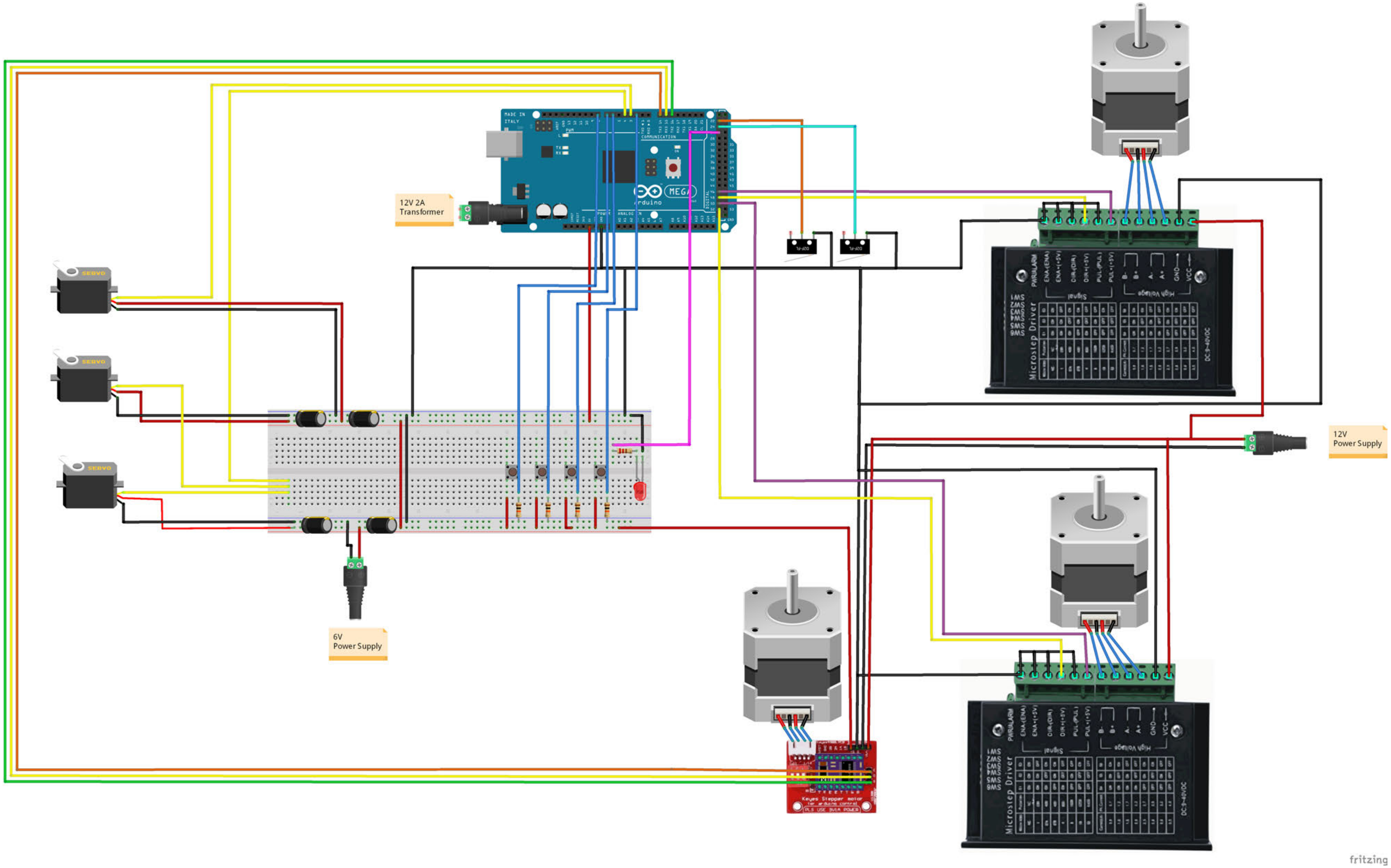


Figure 49: Connection diagram for the automation of the weaving loom

A connection diagram was created to show the components that were used and how these interfaced with one another. This diagram can be seen in Figure 49. The diagram was created with the intention of simplifying the coding and assembly of the control elements of the loom as well as providing for a more in depth understanding of the project by the reader.

The connection diagram shows the two limit switches that were used to home the stepper motor that controlled the horizontal linear actuator (the NEMA17) and the stepper motor that controlled the vertical linear actuator (one of the NEMA23s). The two NEMA23s are shown with their wiring to the TB6600 driver and the drivers wiring to the Arduino Mega. The one NEMA17 is shown with its connection the breakout board that is connected to the DRV8825 driver and the Arduino Mega. All the stepper motors were connected to the same external 12 V power supply. The wiring for this can be seen in the connection diagram. The diagram shows the wiring of the three servo motors to two of the Arduino Mega's PWM pins as well as their connection to an external 6 V power supply. During testing it was found that the servos behaved erratically. Thus, decoupling capacitors were added to the connection between the servo motors and their power supplies. Two of the servo motors were connected to the same control pin. These two servo motors were responsible for extending and retracting the beater during operation. The last servo motor, connected to its own control pin, was responsible for selecting the pen click mechanisms. Lastly four push buttons are shown with their connection to the Arduino Mega. There was one push button used to start the homing process, one to start the weaving process, one to indicate that the weft insertion was completed and one used as an emergency stop. All power supplies are indicated by a barrel jack and can be seen in Figure 49. The three stepper motor drivers used a 12 V supply. The servo motor used a 6 V supply. The Arduino was powered with a 12 V and 2 A transformer.

The software used to create the connection diagram was 'Fritzing'. The TB6600 as well as the breakout board for the DRV8825 were not components available on Fritzing nor could they be sourced online. Thus, these parts were created using stock images of the parts. The images were taken into Inkscape, which is a vector graphics editor. In short, the images were converted to a bitmap, scaled to their actual size and rectangles layered on top of the ports. The images were then saved as .svg file and opened in Fritzing where the rectangles were converted to connection ports that could be interacted with on Fritzing. The files were then saved as .fzpz files and opened in the connection diagram.

9.3 Conversion of image to array

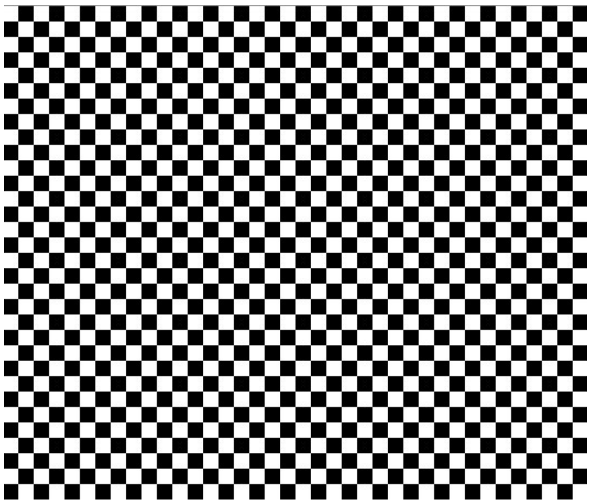
In order to test the functionality of the weaving loom, the ability of the loom to create different patterns had to be tested. The weaving patterns varied in complexity from a plain weave to a Jaquard weave. The patterns generated were a plain weave, 2/2 twill weave, 4 harness satin weave and a Jaquard weave which was an image of a panda head.

It should be noted that the number of heddles was 38. This meant that the array created needed to have 38 columns. The number of rows could vary.

The repetitive nature of the plain weave, 2/2 twill weave and 4 harness satin weave meant that the patterns could be created on Visual Studio Code. The arrays were created on Visual Studio Code. The arrays were then put through an online converter which converted the binary in the array into an image [24]. This image was then compared to a standard form of the weaving patterns and confirmed to be correct. The plain weave, 2/2 twill weave and 4 harness satin weave arrays can be seen in Figure 50a, Figure 51a and Figure 52a respectively. The plain weave, 2/2 twill weave and 4 harness satin weave output images can be seen in Figure 50b, Figure 51b and Figure 52b respectively.

```
{{0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0}};
```

(a) Array

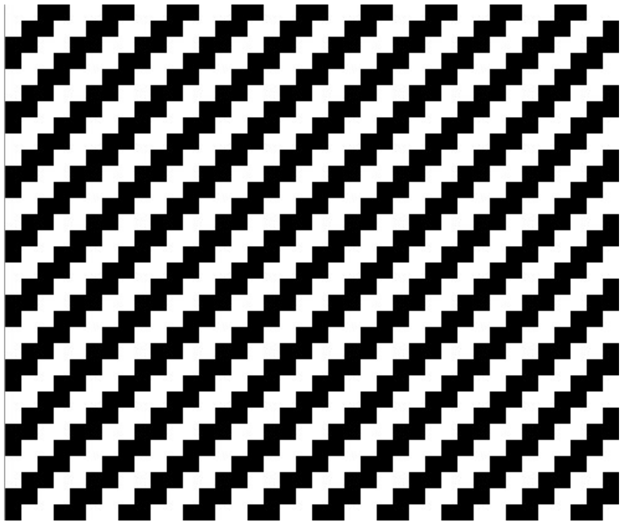


(b) Image generated by online converter

Figure 50: Plain weave pattern array and online converter image

```
{{0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0},
 {0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1},
 {1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1},
 {1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0},
 {0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0},
 {0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1},
 {1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1},
 {1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0},
 {0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0},
 {0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1},
 {1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1},
 {1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0},
 {0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0},
 {0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1},
 {1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1},
 {1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0},
 {0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0},
 {0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1},
 {1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1},
 {1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0},
 {0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0},
 {0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1},
 {1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1},
 {1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0},
 {0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0},
 {0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1},
 {1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1},
 {1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0},
 {0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0},
 {0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1},
 {1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1},
 {1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1,0}};
```

(a) Array

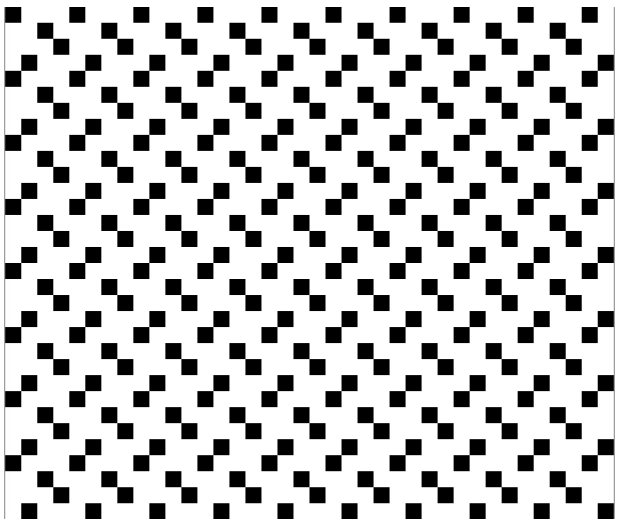


(b) Image generated by online converter

Figure 51: Twill weave pattern array and online converter image

```
{{1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0},
 {0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0},
 {0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0},
 {0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1},
 {1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0},
 {0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0},
 {0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0},
 {0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1},
 {1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0},
 {0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0},
 {0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0},
 {0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1},
 {1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0},
 {0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0},
 {0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0},
 {0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1},
 {1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0},
 {0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0},
 {0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0},
 {0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1},
 {1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0},
 {0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0},
 {0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0},
 {0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1},
 {1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0},
 {0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0},
 {0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0},
 {0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1},
 {1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0},
 {0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0},
 {0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0},
 {0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1},
```

(a) Array



(b) Image generated by online converter

Figure 52: Satin weave pattern array and online converter image

In terms of the Jacquard weave it would have been extremely time consuming to try to create an array from looking at the pattern of a panda. Instead the online converter was used to convert the desired image into binary [24]. The converter allowed for the number of pixels in the width to be selected. The output from the converter was then opened in Visual Studio Code where it was edited. It was edited into a form of a nested array that could be understood in C. A plain weave border was created around the image in order to provide stability and structure to the fabric. The use of only two colours, one for the warp yarn and one for the weft yarn, meant that there would be long sections of unwoven thread. The border mitigated some the issues that could be caused by this, the main one being the fabric not holding its shape. The image used was of a panda. This allows for the complexity of design possible with the use of individual heddle control. Figure 53a shows the image that was fed into the online converter. Figure 53b shows the final array that will be used in code to generate the pattern.

(a) Image of panda [25]

```
{{0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,1,1,0,0,0,1,1,1,0,0,0,0,1,1,1,0,0,0,1,1,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,1,0,0,0,1,1,1,1,0,0,1,1,1,1,0,0,0,1,0,0,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,1,0,0,1,1,1,1,1,1,0,0,1,1,1,1,1,1,0,0,1,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,1,0,0,1,1,1,0,1,1,0,0,1,1,0,1,1,1,0,0,1,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,1,0,0,1,1,1,1,1,1,0,0,1,1,1,1,1,1,0,0,1,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,1,0,0,1,1,1,1,1,1,0,0,0,1,1,1,1,1,0,0,1,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,1,0,0,1,1,1,1,0,0,0,0,0,0,1,1,1,1,0,0,1,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,1,0,0,0,0,0,0,1,1,1,1,1,1,0,0,0,0,0,0,1,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,1,1,1,1,0,0,0,0,0,0,1,1,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,1,0,0,0,0,1,0,0,0,0,0,1,0,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,0,0,1,0,0,0,0,1,1,1,1,1,1,0,0,0,0,1,0,0,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,0,0,0,1,1,1,0,0,0,0,0,0,0,0,1,1,1,0,0,0,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0},
 {0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0},
 {0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1},
 {1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0}};
```

(b) Array of panda pattern

Figure 53: Panda image to array

9.4 Code flow diagrams and explanation of code

Figure 54 shows the main program and the external interrupt. This figure has been displayed over two pages for ease of reading. The main code flow diagram shows the main control loop of the loom. It contains functions that will be displayed in their own flow diagram separate to this main flow diagram. This will allow for the code to be followed and explained in a more detailed and systematic way.

The main code flow diagram will be presented. Followed by a brief explanation of how the main code flow diagram works. This will be followed by the display of the function flow diagrams and their more detailed code explanations.

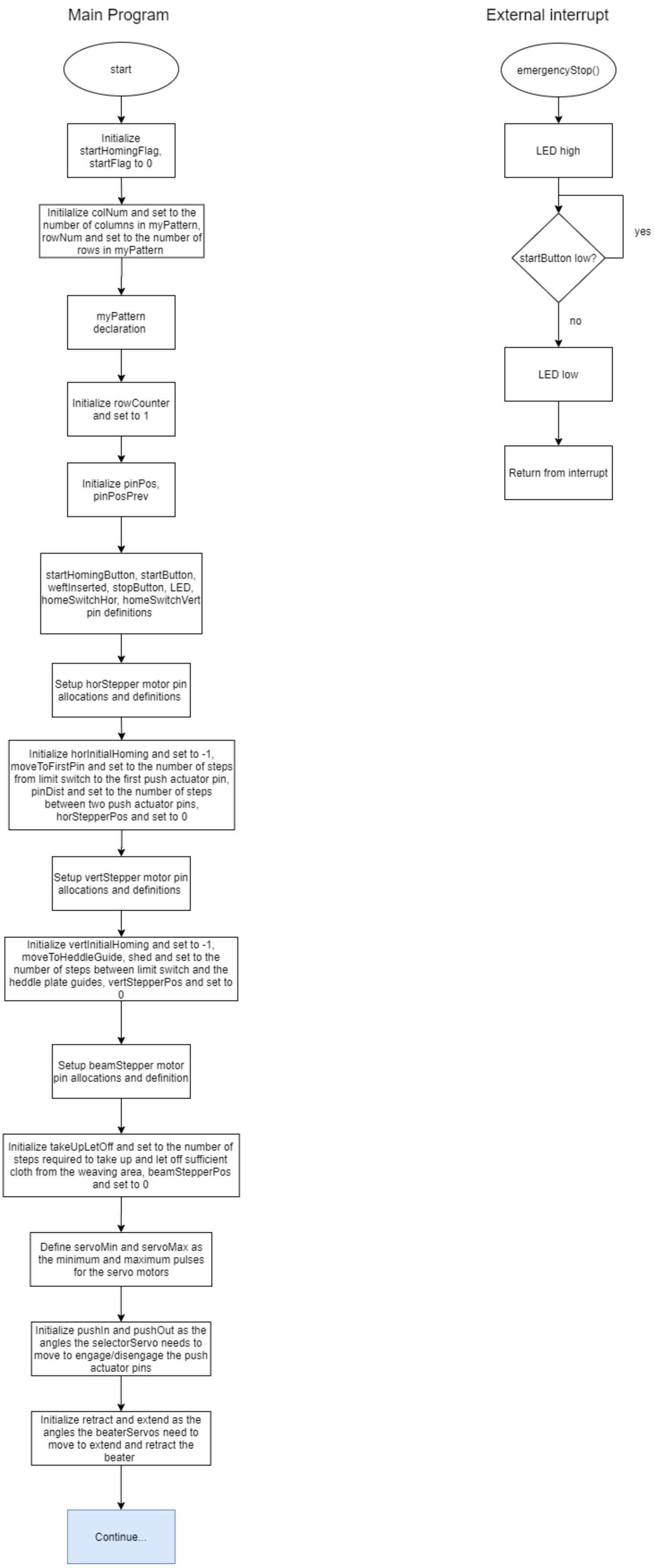
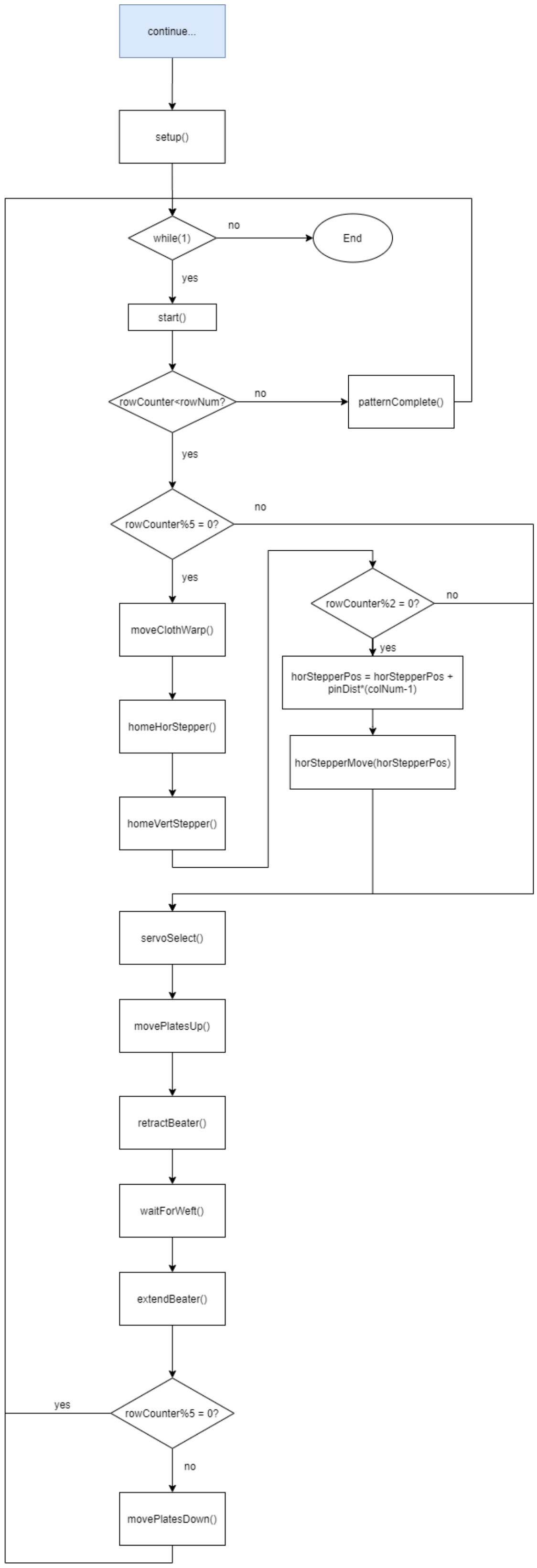


Figure 54: Main and external interrupt code flow diagram


continue...
setup()
while(1)
no
End
yes
start()
rowCounter<rowNum?
no
patternComplete()
yes
rowCounter%5 = 0?
no
yes
rowCounter%2 = 0?
no
yes
moveClothWarp()
horStepperPos = horStepperPos + pinDist*(colNum-1)
homeHorStepper()
horStepperMove(horStepperPos)
homeVertStepper()
servoSelect()
movePlatesUp()
retractBeater()
waitForWeft()
extendBeater()
yes
rowCounter%5 = 0?
no
movePlatesDown()

Explanation of main code flow diagram

The code, as seen in Figure 54, begins with pin definitions, initialization of variables and the set-up of the stepper and servo motors. The code then calls the setup() function before entering the main loop. The main loop calls the function start() if the startFlag is 0 it waits for the start button to be pressed before proceeding.

The code then assesses whether or not the global rowCounter variable (which holds the current row number of the pattern the loom is about to weave) is less than the global rowNum variable (holds the total number of rows in the pattern). If it is not, i.e. row-Counter equals rowNum the patternComplete() function is called and the program enters an infinite loop in which no other code is executed. If it is, i.e. rowCounter is less than rowNum, then the program checks if rowCounter is a multiple of 5 or not. If it is, the moveClothWarp() function is called which will take up and let off cloth from the relevant beams by moving the stepper motor (beamStepper). The vertical and horizontal stepper motors then home by calling the homeHorStepper() and homeVertStepper() functions. If rowCounter is a multiple of 5 and is a multiple of 2 then the selector servo motor is moved to the other side of the loom (where it had been) in order to avoid disruption to the rest of the code. If rowCounter is not a multiple of 5 then the moveClothWarp(), homeHorStepper() and homeVertStepper() functions are skipped.

Next the selection process takes place using the servoSelect() function in which the selector servo and horizontal stepper motor work together to change the states of the pen click mechanisms as necessary to create the desired pattern.

Next the frame that holds the pen click mechanisms moves up through the movement of the vertical stepper motor using the movePlatesUp() function. This means that the relevant warp threads move up creating a shed for the picking operations.

Next the beater is retracted using the retractBeater() function which moves the relevant servo motors to the required position.

The waitForWeft() function is then called which waits until the user has inserted the weft and for a button to be pressed before continuing with the code.

When the button has been pressed the beater is extended by calling the extendBeater() function which moves the relevant servo motors to the required position.

The next part of the code is simply added to save time. The limit switch position for the vertical stepper motor homing, as shown in Section 5.5, is at the top of the weaving loom. The condition checks if the horizontal and vertical stepper motors are going to home in the next loop. If homing will not be done next then the frame holding the pen click mechanisms will be moved down by calling the movePlatesDown() function. If homing will be done next then this step will be skipped.

The main loop then repeats.

Explanation of external interrupt - emergencyStop()

The external interrupt is triggered by the push of a push button (the stopButton button). The external interrupt makes a red light-emitting diode (LED) turn on to alert the user to the fact that this button has been pushed and that the operation has ceased. The program will stay in the external interrupt until another button is pressed (the startButton button) at which point the red LED will turn off and the code will return from the interrupt.

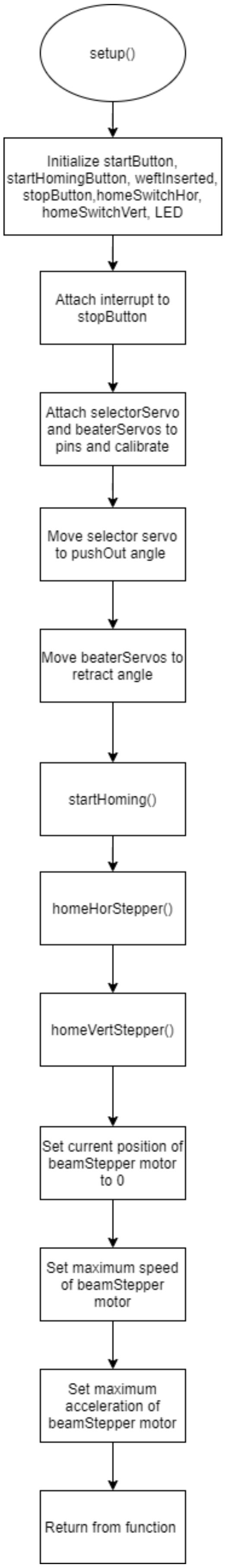
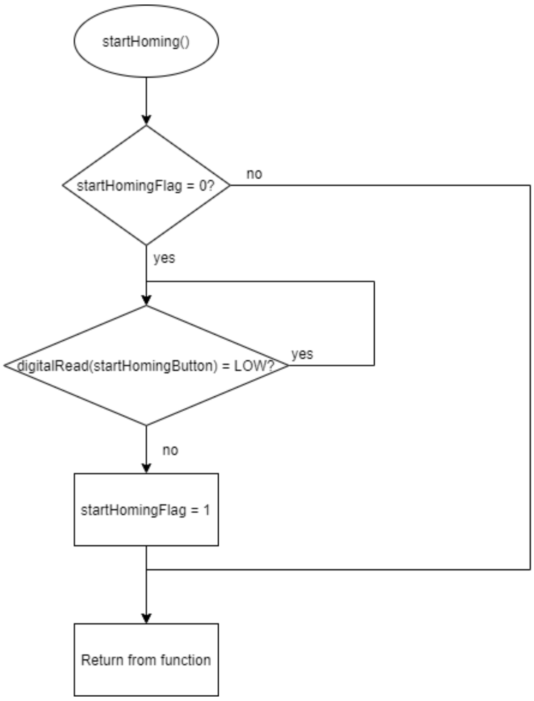


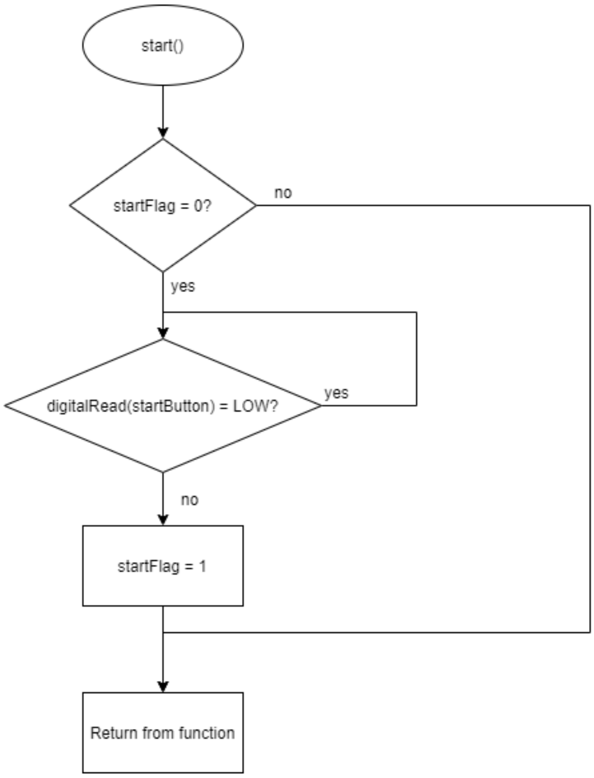
Figure 55: setup() code flow diagram

Explanation of setup()

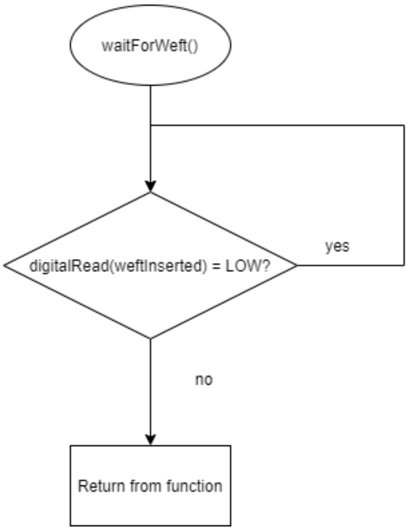
In this function, as seen in Figure 55, the buttons and limit switches are initialized. The servo motors are attached to their relevant pins and their maximum and minimum PWM signals are set. The servo motors are then moved to their start-up positions. The vertical and horizontal stepper motors begin their homing operations at the press of a button (the startHoming button). The stepper motor that controls the cloth roll and warp beam does not need to be homed, instead its starting position is set to zero and its maximum speed and acceleration are set.



(a) startHoming() code flow diagram



(b) start() code flow diagram



(c) waitForWeft() code flow diagram

Figure 56: Button press code flow diagrams

Explanation of startHoming()

This function, as seen in Figure 56a, is only called once and is not called in the main loop but rather in the setup() function. There is a startHomingFlag that is initialized to a value of 0. The function checks to see if this value is 0. If it is, it waits until a button (the startHomingButton button) is pressed. When the button is pressed it sets the startHomingFlag to 1 and returns from the function. If the function is called again the startHomingFlag being set to 1 does not meet the initial condition of being equal to 0 consequently the button press will not be waited for, and the main code will be returned to.

Explanation of start()

This function, as seen in Figure 56b, is called in the main loop. It works in a similar way to the startHoming() function except in this case the button is the startButton button and the flag is the startFlag. This function will be called more than once as it exists in the main loop. However, the startFlag being set to a value of 1 means that the button press will only be waited for at the very start of the program when it is 0. Every time after this first calling of the function the initial condition of being equal to 0 not being met will immediately return from the function to the main loop.

Explanation of waitForWeft()

This function, as seen in Figure 56c, waits for a button (the weftInserted button) to be pressed. This function is called in the main loop and every time it is called it will wait for the button to be pressed before returning to the main loop.

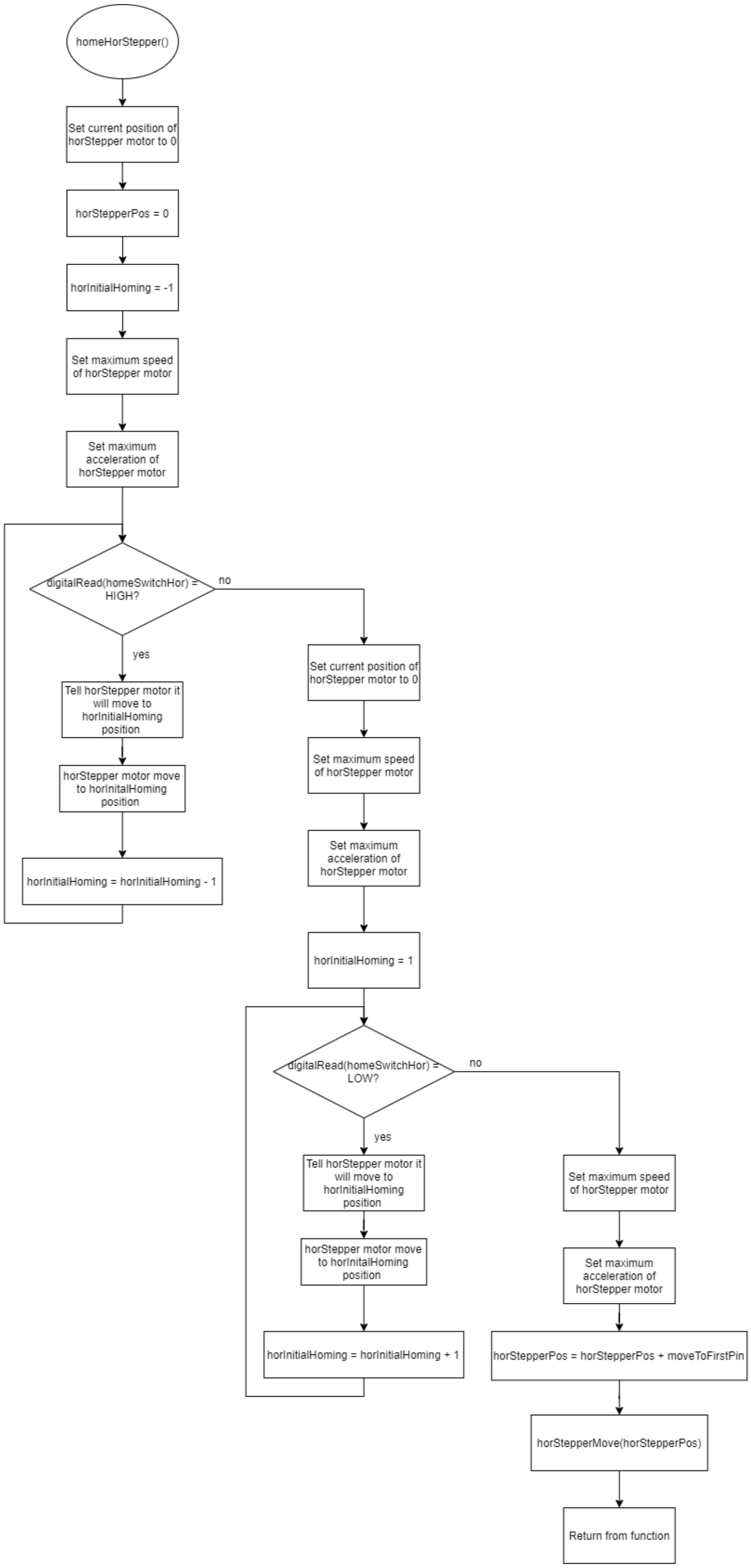


Figure 57: homeHorStepper() code flow diagrams

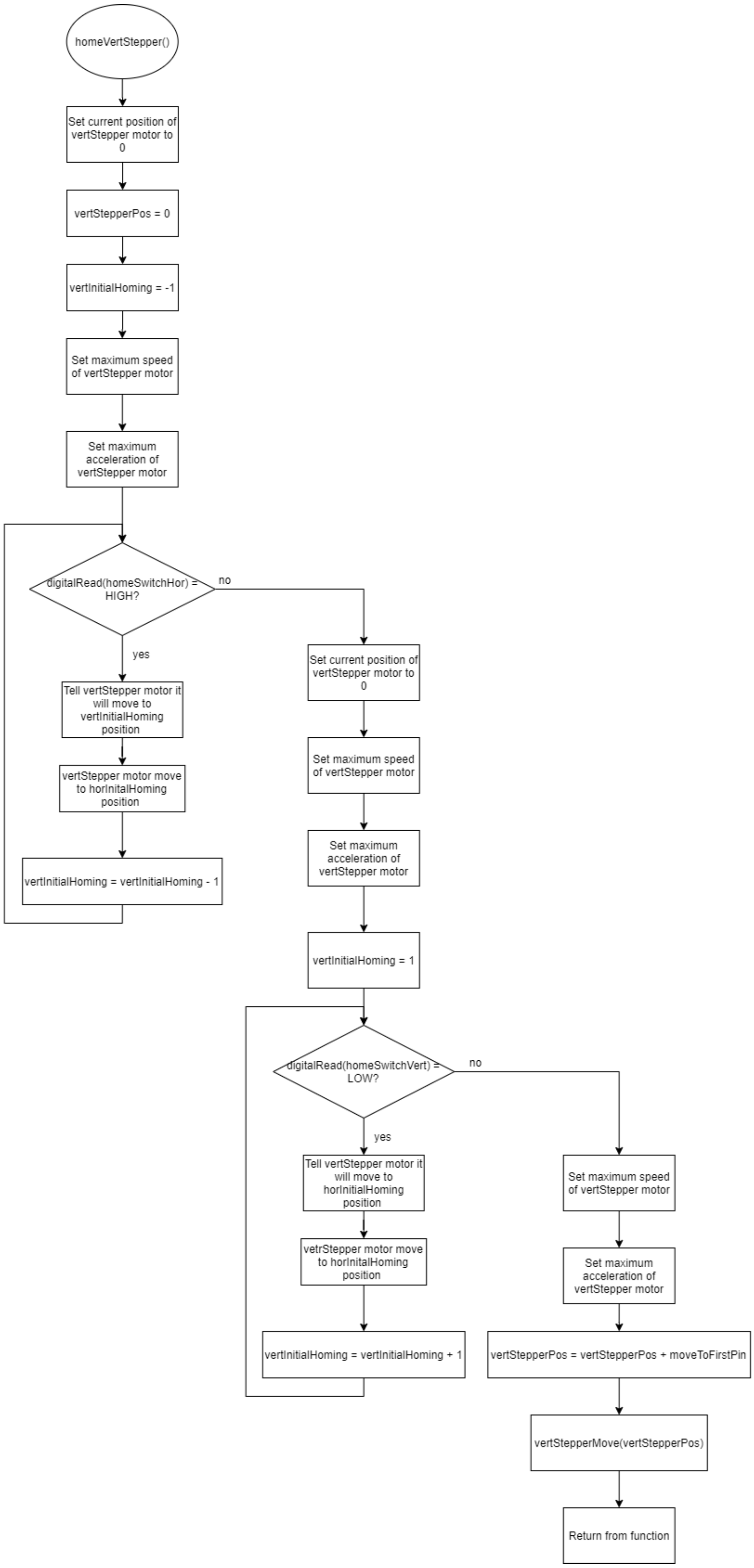
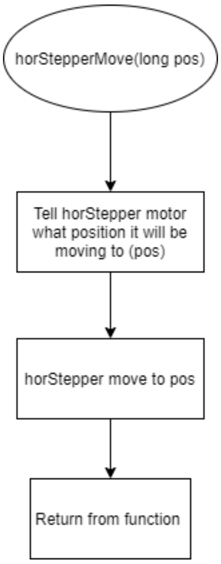


Figure 58: homeVertStepper() code flow diagrams

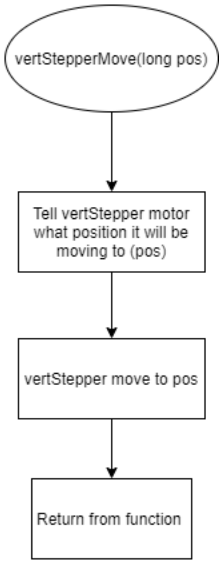
Explanation of homeHorStepper() and homeVertStepper()

The homing of the horizontal and vertical stepper motors in the homeHorStepper(), as seen in Figure 57, and homeVertStepper(), as seen in Figure 58, functions are very similar. Their only difference being the movement of the stepper motors to their starting positions at the very end of the function. The vertStepper and horStepper will be referred to as the 'stepper' and the code explanation will be done once for both functions.

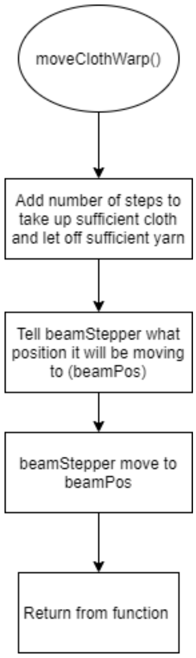
The initial position of the stepper motor will be set to 0 and the global variable that holds the stepper motors positions will be set to 0. A variable called initialHoming will be set to -1. The maximum speed and acceleration for the stepper motor will be set. The stepper motor will move one step at a time until the limit switch is depressed. When the limit switch is depressed the current position of the stepper motor will be set to zero and the maximum speed and acceleration will be set once again. The initialHoming variable will now be set to 1. The stepper motor will move in the opposite direction until the limit switch is no longer being depressed. The maximum speed and acceleration for operation are set. The stepper motors are then moved to their starting positions. This action is facilitated by the horStepperMove(long pos) and vertStepperMove(long pos) functions.



(a) horStepperMove() code flow diagram



(b) vertStepperMove() code flow diagram



(c) moveClothWarp() code flow diagram

Figure 59: Move stepper motors code flow diagrams

Explanation of horStepperMove(long pos) and vertStepperMove(long pos)

The horStepperMove(long pos), as seen in Figure 59a, and the vertStepperMove(long pos), as seen in Figure 59b, functions operate in a very similar manner. The functions both take in a long, 'pos', and move the stepper motors to that position.

Explanation of moveClothWarp()

This function, as seen in Figure 59c, adds the number of steps to take up sufficient cloth and let off sufficient yarn to a global variable that holds the current position of the stepper motor and then moves the stepper motor that number of steps.

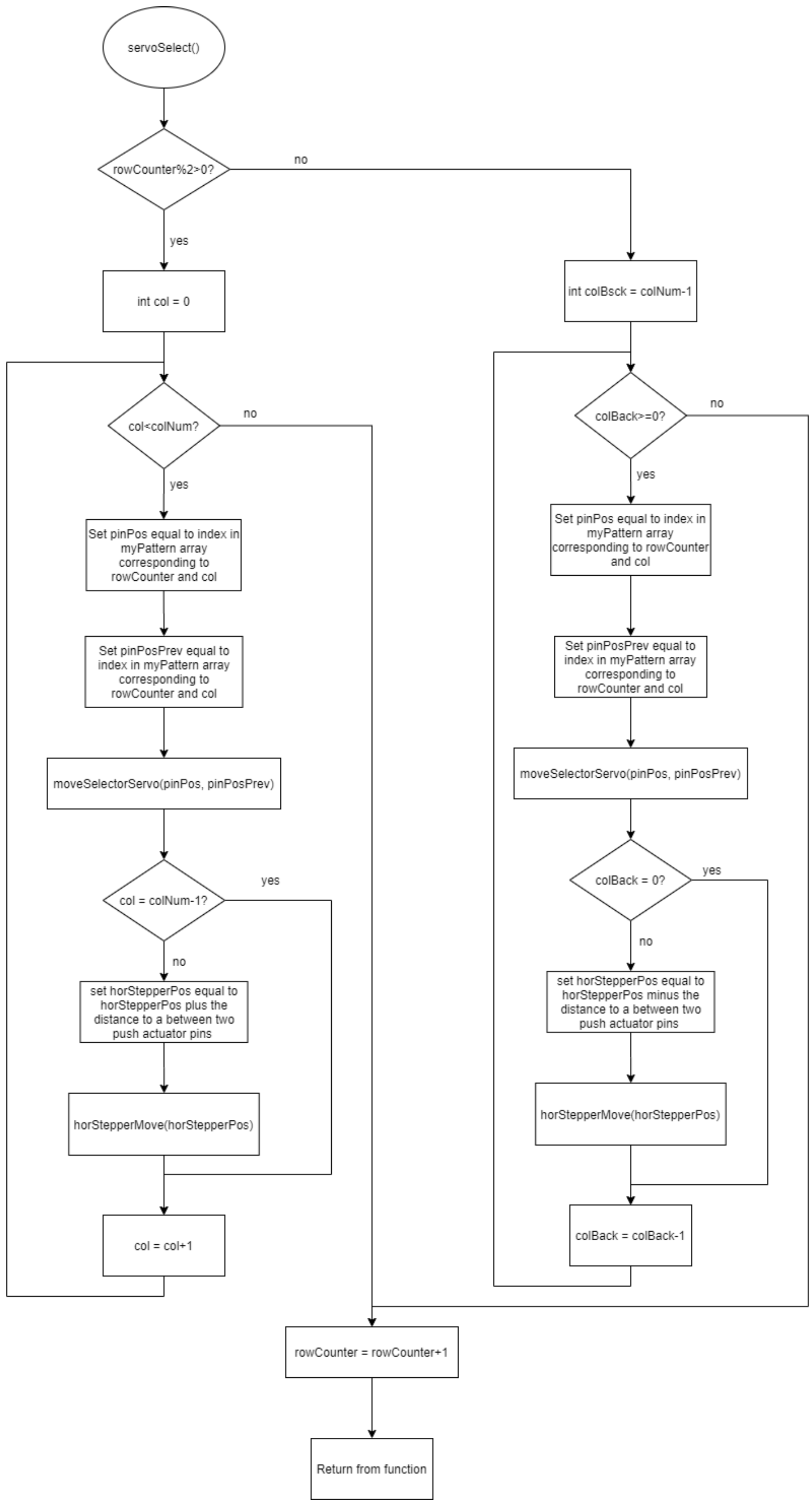


Figure 60: servoSelect() code flow diagrams

Explanation of servoSelect()

This function, as seen in Figure 60, is responsible for moving through the array that holds the pattern and passing the desired state of the pen click mechanism as well as the current state of the pen click mechanism to the moveSelectorServo(int pinPos, int pinPosPrev) function as well as moving the horizontal stepper motor. Movement of the horizontal stepper motor will consequently move the selector servo which is mounted on the lead screw to which the horizontal stepper motor is attached.

The function first determines if the global variable, rowCounter, is an even or odd number. If it is odd the pattern array, myPattern is read from left to right. If it is even the pattern array, myPattern, is read from right to left. In this way the selector servo can be moved across the width of the loom back and forth and not from one specific side. This will save the user time during the weaving process. The code then determines what state the pen click mechanism that the selector servo is at should be and what it was previously. It then passes this information to the moveSelectorServo(int pinPos, int pinPosPrev) function. Upon returning from this function the code then determines if the selector servo is at the last pen click mechanism in that column of pattern. If it is not, the global variable that holds the horizontal stepper motors position, horStepperPos, is either increased or decreased by the distance between two pen click mechanisms (depending on whether or not the selector is being moved from left to right or from right to left). The horStepperMove(int pos) function is then called, passing the in the horStepperPos variable. This is then repeated until the selector servo is at the last pen click mechanism. When the selector servo is at the last pen click mechanism the rowCounter variable is incremented and the code returns from the function (the horStepperPos variable is not changed).

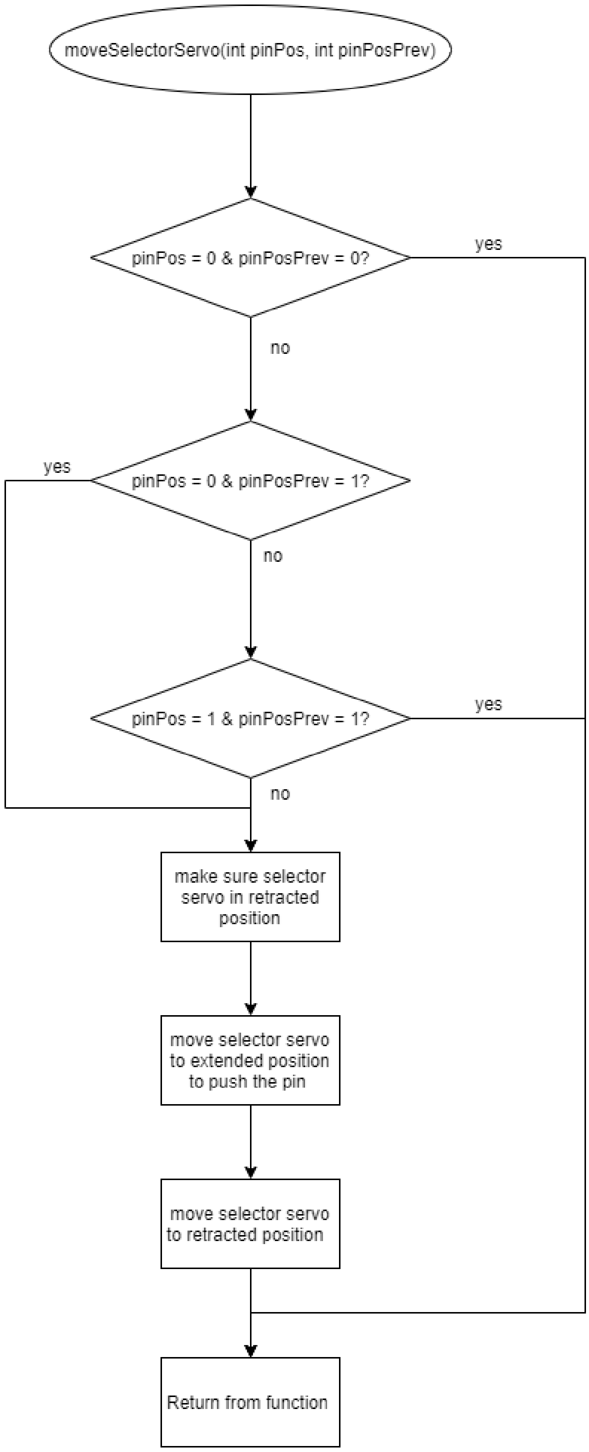
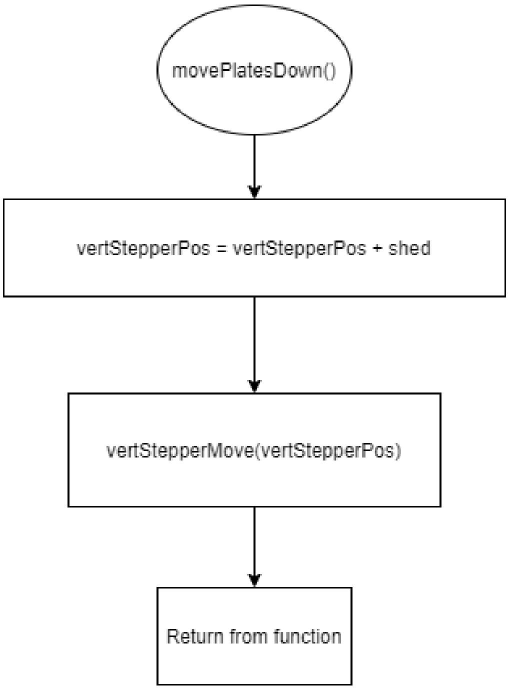


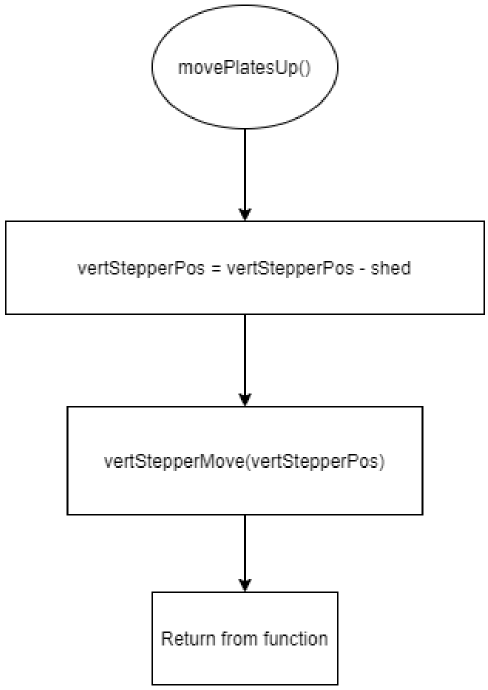
Figure 61: moveSelectorServo() code flow diagrams

Explanation of moveSelectorServo(int pinPos, int pinPosPrev)

This function, as seen in Figure 61, takes in two integers that represent the desired state of the pen click mechanism (pinPos) and the previous position of the pen click mechanism (pinPosPrev). A 1 representing the extended position and a 0 representing the retracted position of the pen click mechanism. The function then goes through a series of 'if', 'if else' and 'else' statements. If the pinPos and pinPosPrev are the same then the function is returned from. However, if the pinPos and pinPosPrev are not the same the selector servo is moved in such a way to change the state of the pen click mechanism, after this the function is returned from.



(a) movePlatesDown() code flow diagram

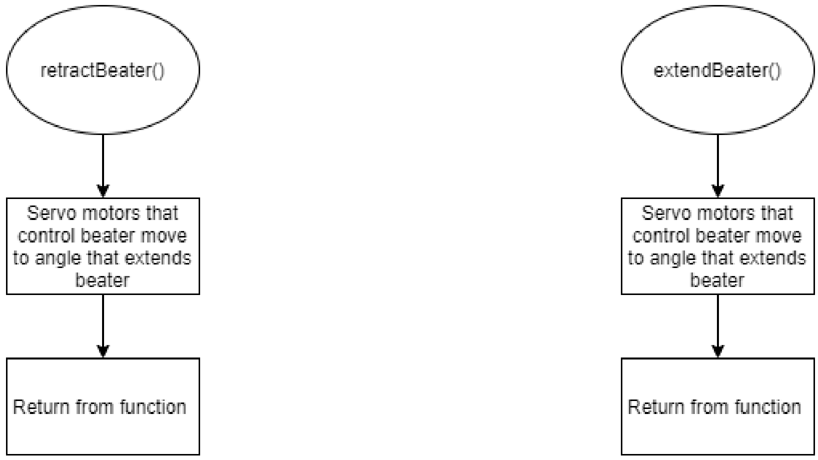


(b) movePlatesUp() code flow diagram

Figure 62: Move frame that holds pen click mechanisms code flow diagrams

Explanation of movePlatesDown() and movePlatesUp()

These functions, as seen in Figure 62a and Figure 62b, pass an integer to the vertStepperMove(long pos) function. The integer corresponds to the position that would put the frame that holds the pen click mechanisms in a position that would allow the selector servo to interact with them (movePlatesDown()), or in a position where the frame has been lifted to create a shed and allow for picking operations to take place (movePlatesUp()).



(a) retractBeater() code flow diagram (b) extendBeater() code flow diagram

Figure 63: Move beater servos code flow diagrams

Explanation of retractBeater() and extendBeater()

These functions, as seen in Figure 63a and Figure 63b, move the two servo motors that control the beater. The retractBeater() function moves the servo motors to a position in which the beater is retracted. The extendBeater() function moves the servo motors to a position in which the beater is extended.

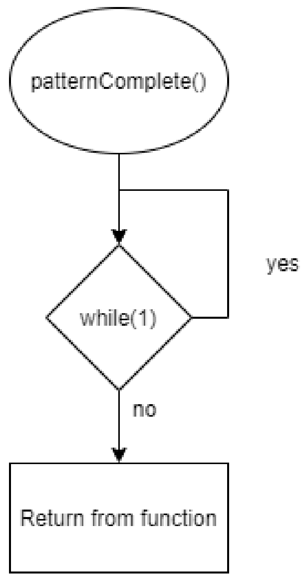


Figure 64: patternComplete() code flow diagrams

Explanation of patternComplete()

This function, as seen in Figure 64, is simply an infinite loop that ensures that no other code executes when the pattern is completed.

10 Commissioning and testing

In this section a detailed description of the commissioning and testing process is presented. This section includes the description of problems that arose as well as the steps that were taken to rectify these issues. This section describes the commissioning and testing of the control aspects, 3D printing, frame, sub-assemblies with a final subsection on the testing of the loom as a whole.

10.1 Circuit design on breadboard and veroboard

The electrical circuits were initially tested on a breadboard. The circuit design and testing for the stepper motors, push buttons, LED and limit switches went smoothly. These electronic components presented no problems and the reliability and repeatability of results were very good. However, the three servo motors displayed unreliability. During testing on the breadboard one or more servo motor would malfunction by spinning uncontrollably. The power supply would then be turned on and off and they would start to function as expected again. Decoupling capacitors were added, as can be seen in Section 9.2 in Figure 49, and this solved the problems.

In the transfer to veroboard, Ethernet cabling was used as the primary wiring with higher gauge wires being used for connection to the power supply voltage and ground lines. Transferring the circuits for the stepper motors, push buttons, LED and limit switches to veroboard went smoothly. However, again the servo motors presented problems. The servo motor making use of the longest wires would sometimes not move when instructed to do so. This servo motor was one of the servo motors that controlled the beater. The servo motor veroboard was redesigned. This time the beater servo motors were given PWM signals from two different pins on the Arduino. Higher gauge Ethernet cabling was also used for the servo motor veroboard. During the testing of this circuit the servo motors displayed greater reliability at a higher voltage. This being a voltage of 6.5 V as opposed to the 6 V that the circuit was originally being powered by.

The veroboard used for the push buttons, LED, limit switches and stepper motors common ground connection can be seen in Figure 65. The veroboard used for the servo motors can be seen in Figure 66. The entire electronics set-up can be seen in Figure 67.

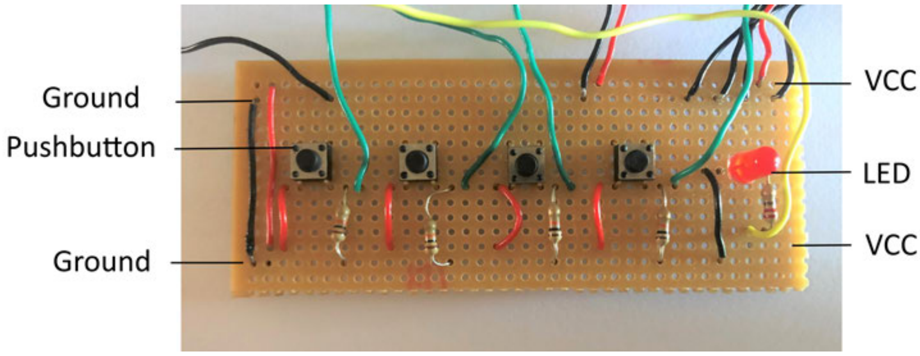


Figure 65: Veroboard used for the push buttons, LED, limit switches and stepper motor common ground connection

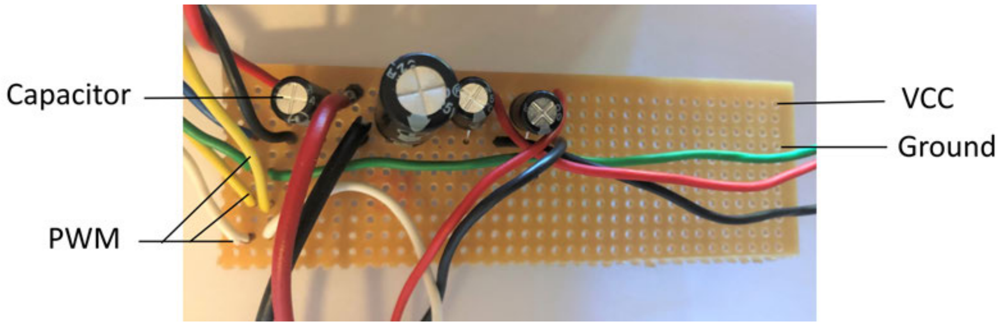


Figure 66: Veroboard used for the servo motors

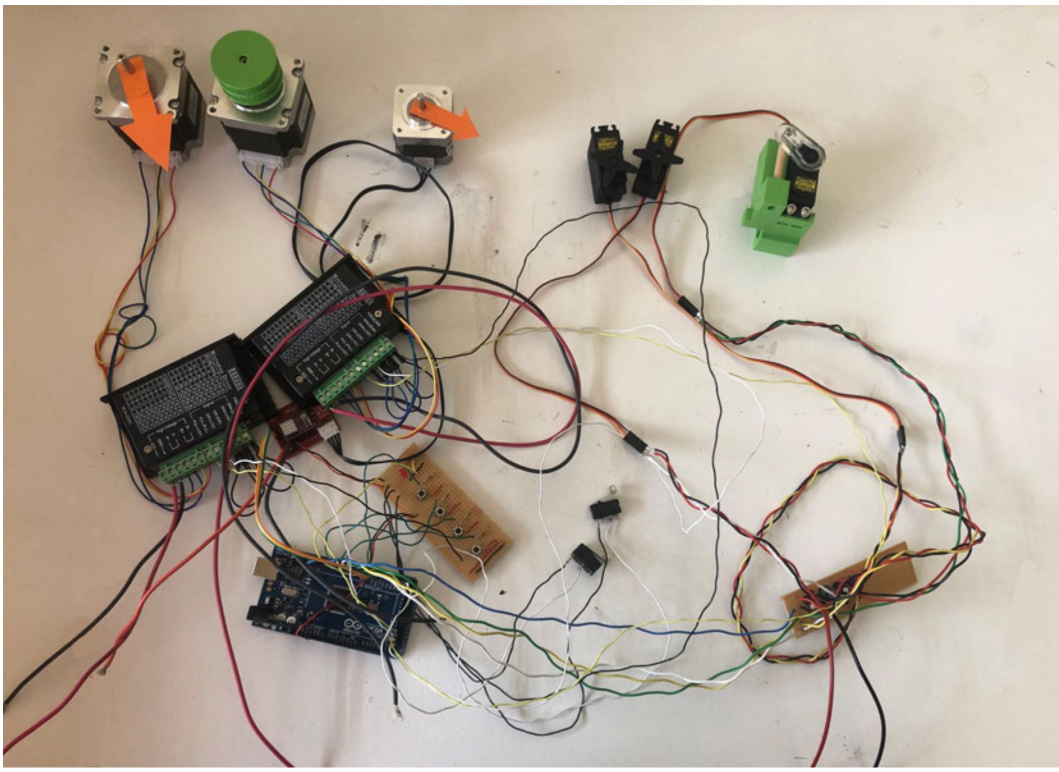


Figure 67: Full electrical setup

10.2 3D printing

All parts to be 3D printed can be seen in Appendix C. Most of the 3D printed parts turned out as expected and just needed to be sanded in some areas. However, the bobbin for the bobbin and shuttle had to be redesigned. A render of the original part can be seen in Figure 68. The shape of the part proved problematic in relation to 3D printing. Instead of 3D printing the entire bobbin as had been originally intended, the two conical shaped ends were 3D printed and a wooden dowel was press fitted through the center. This can be seen in Figure 69. The final bobbin and shuttle can be seen in Figure 70.

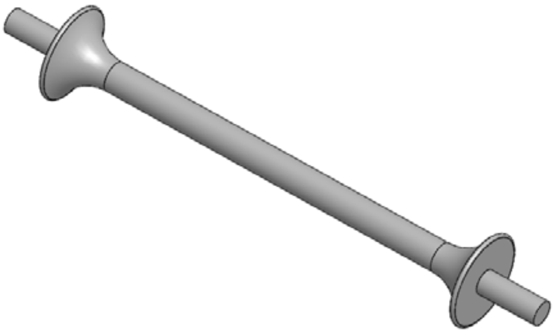


Figure 68: 3D printed bobbin

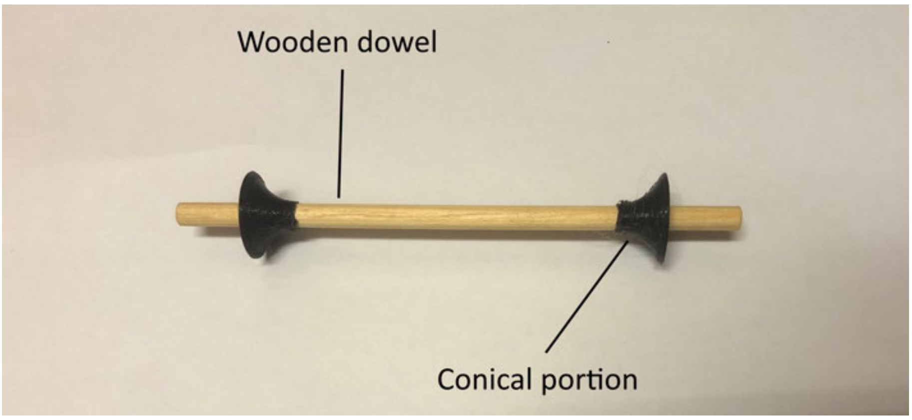


Figure 69: Final bobbin

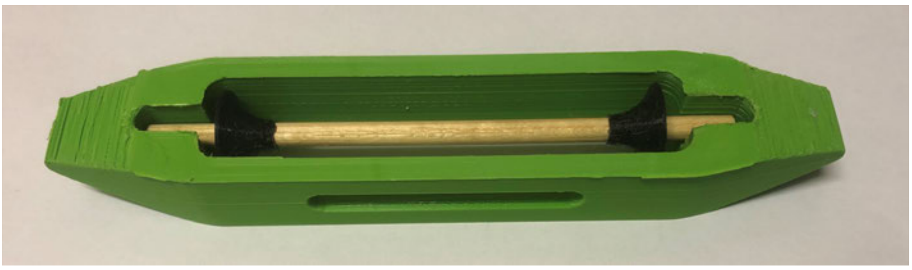


Figure 70: Final bobbin and boat shuttle

10.3 Frame

The frame was initially laser cut from medium-density fibreboard (MDF). There was concern for the strength of the top of the frame that needed to support the weight of the NEMA23, veroboards and some of the motor drivers. It was decided to re-laser cut the frame out of high-density fibreboard (HDF) in order to improve the structural integrity of the loom. Using the HDF prevented the bending of the top of the frame.

During the early stages of building it was noted that the frame could deviate from its intended shape with a light force applied. To combat this, L-shaped joints were added. These L-shaped joints can be seen in Figure 71.

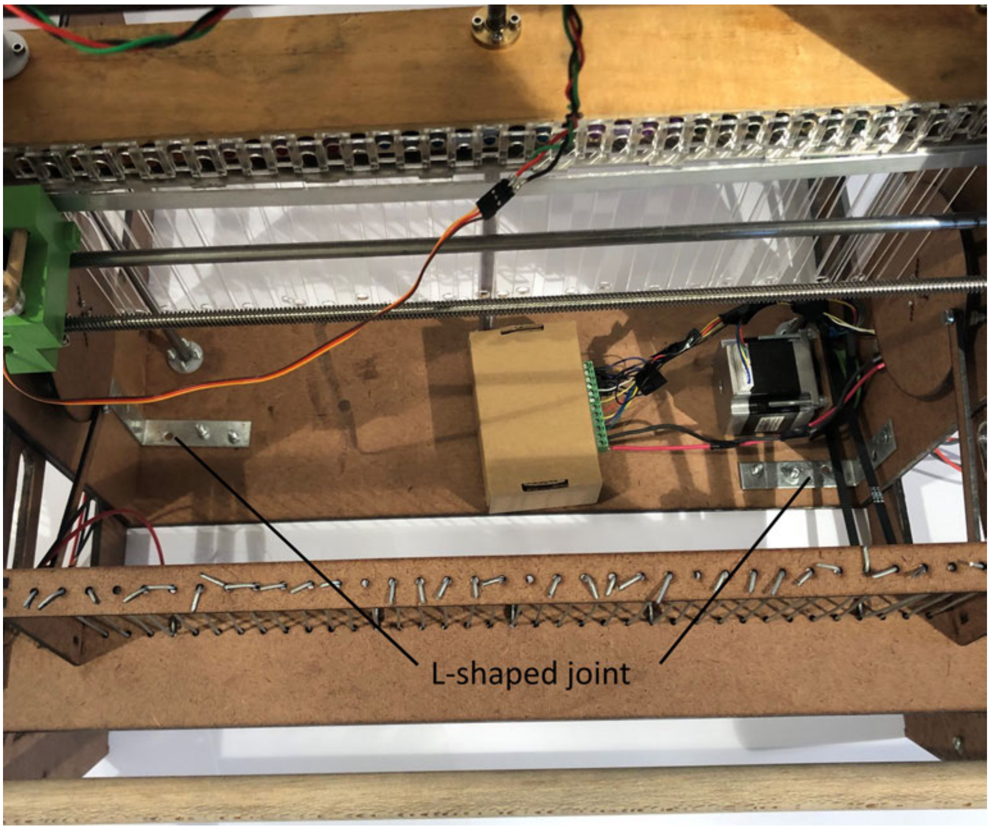


Figure 71: L-shaped joint

10.4 Sub-assemblies

10.4.1 Heddle automation

The automation of the heddles was critical to this design and can be deemed the most important sub-assembly of the loom, as without this part being operational the loom could not function as was intended. There were many challenges faced during the testing of this sub-assembly and corrective measures had to be taken in order to get this sub-assembly to work.

As mentioned previously the part that was to guide the heddle plates (referred to previously as the heddle plate guide) was to be made from 5 mm perspex. There was concern for the bending of this component prior to assembly. However, perspex was the low-cost option and it was decided to wait and see the performance of the part during the early stages of the build, should issues arise then it would be replaced. During the early stages of testing and when all of the heddle plates were added and the part was mounted onto the frame, an unacceptable amount of bending occurred. It was then decided to have this part made out of 3 mm aluminium. The part was manufactured by Vulcan Steel. Tabs had to be added to the part and cut off at a later stage as there was concern for the warping of the component due to expected excessive heat input to the plate during cutting. The engineering drawing for this part without the tabs can be seen in Appendix I. The aluminium part exhibited no bending when the heddle plates were added and the part was mounted onto the frame. However, a light push down on the part showed a degree of bending that was unacceptable. The light push down simulated the warp threads in tension as they had not been added yet. In order to prevent this bending, a part was made by bending and cutting another piece of aluminium. This part was then mounted below the heddle plate guide. A cut out had to be made in the part in order to avoid interference with the limit switch. This support part can be seen in Figure 72 and can be seen mounted below the heddle plate guide in Figure 73.

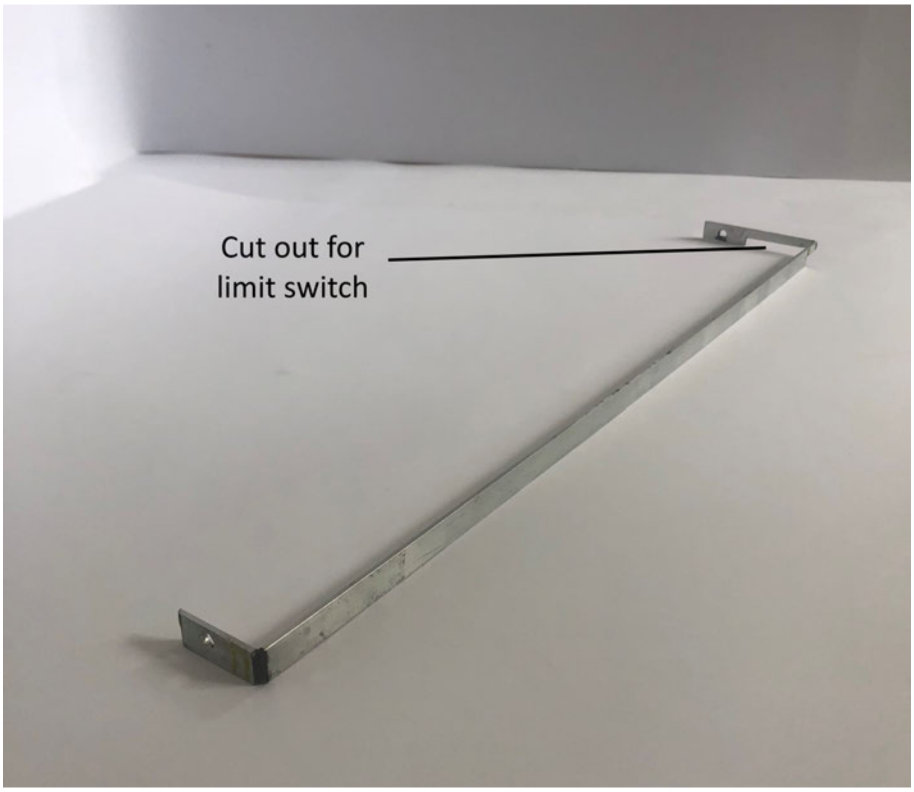


Figure 72: Support for heddle plate guide

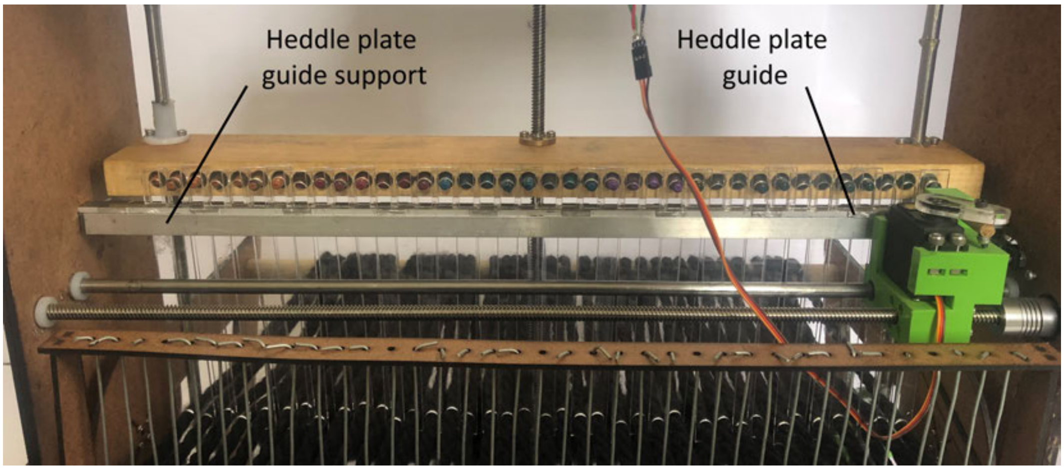


Figure 73: Support for heddle plate guide mounted on loom

The next challenge faced was the movement of the vertical linear actuator which was used to raise and lower the frame that holds the pen click mechanisms. This system comprised of a central lead screw driven by a stepper motor and two support or guide rods on either side. The upward motion of this system was successful from the outset, however, during its downward motion the frame would become stuck on one side. The error potentially being caused by the thread pitch angle, misalignments between the bushings and the rods, inconsistent fits of the bushings and rod diameter inconsistencies. Many attempts were made to correct this error. Eventually it was decided to use longer bushings with one bushing mounted on the underside of the frame and the other mounted on the top of the frame as well as to slow down the rotation of the stepper motor controlling the lead screw. The thought behind this was that the longer bushings would aid in keeping the correct alignment and mounting the one bushing on the underside and top of the frame would lessen the effect of the thread pitch angle on the raising and lowering of the frame. Slowing down the stepper motor that controlled the lead screw allowed the system to self-correct any misalignments. A lubricant was also added to the vertical support rods in order to prevent the system from becoming stuck. The final vertical linear actuator can be seen in Figure 74 and Figure 75.

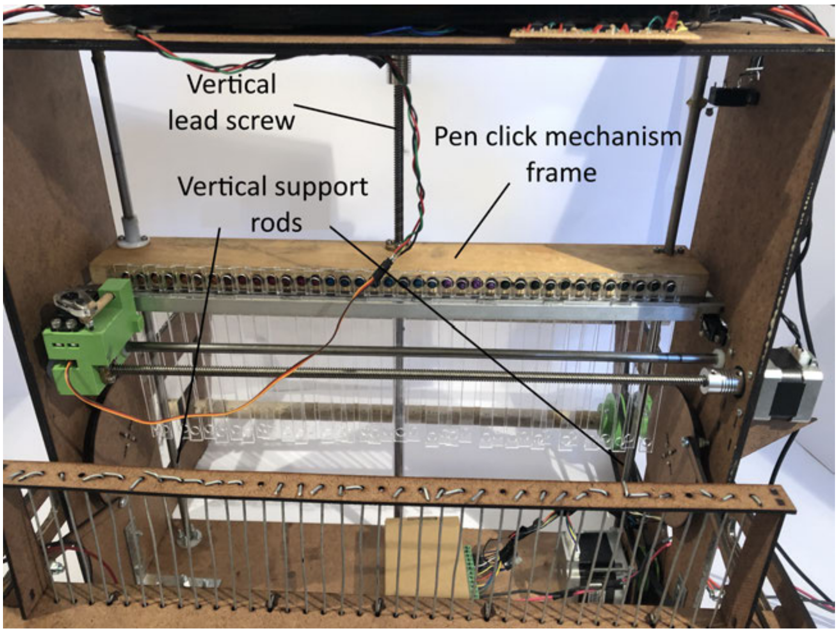


Figure 74: Vertical linear actuator view from front

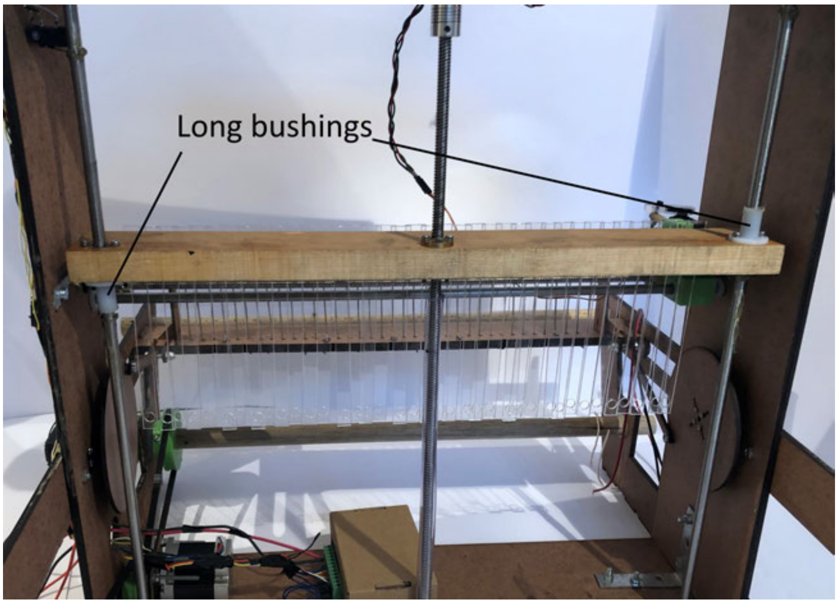


Figure 75: Vertical linear actuator view from back

The lead screw of the vertical linear actuator would interfere with the warp threads. As it rotated the warp threads would deteriorate as the thread turned and tried to wrap them around with it. To combat this a piece of plastic tubing was used to cover the bottom half of the lead screw. To stop the plastic tubing from rotating with the lead screw and causing further interference with the threads the plastic tubing was stuck to the bottom of the loom with a piece of Prestick. The plastic tubing surrounding the lead screw can be seen in Figure 76.

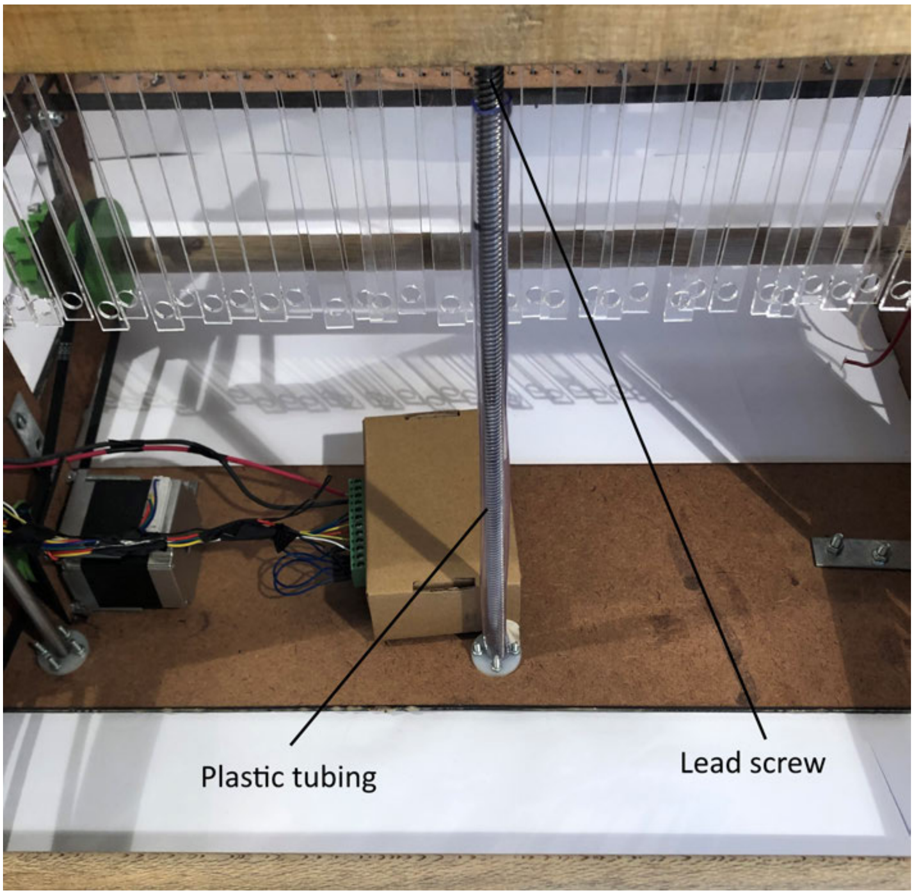


Figure 76: Plastic tubing surrounding lead screw

The next issue was in the alignment of the pen click mechanisms housed in the frame and the slots in the heddle plates. The servo motor pin needed to be able to slide through the slot in the heddle plates and make sufficient contact with the pen click mechanism. Then the pen click mechanism had to be able to slide through the slot in the heddle plates. The heddle plates being made from 2 mm Perspex and the high torque rating of the servo motor meant that if excess contact was made between the pin of the servo motor and heddle plates that the heddle plates would shatter. Thus, the correct alignment was essential. Figure 77 shows the parts that needed to be in the correct alignment. Compensations had to be made in the code to cater for the misalignments.

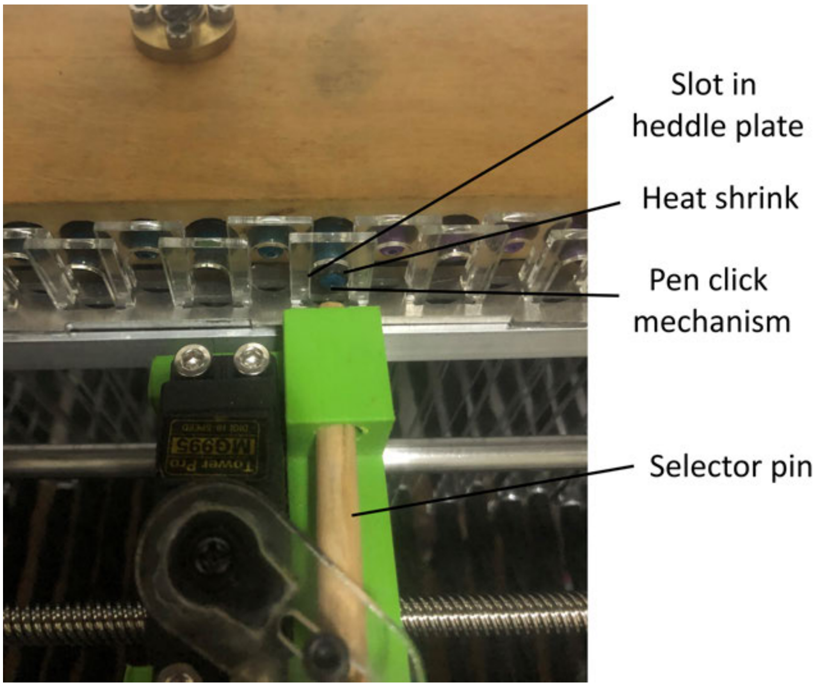
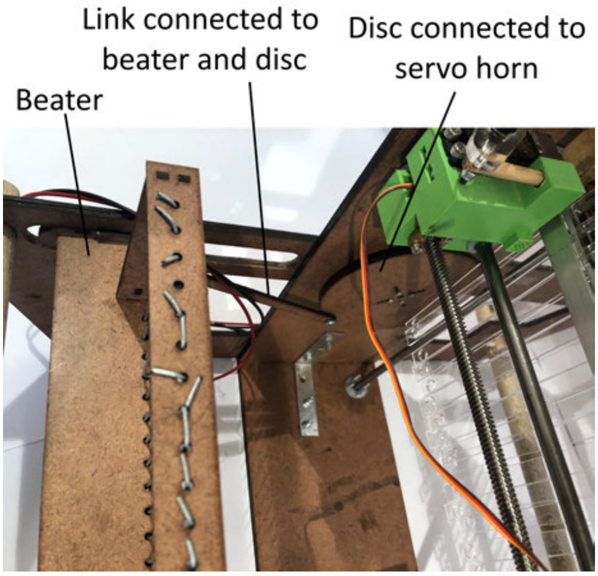


Figure 77: Parts that had to be in correct alignment and heat shrink on pen click mechanisms

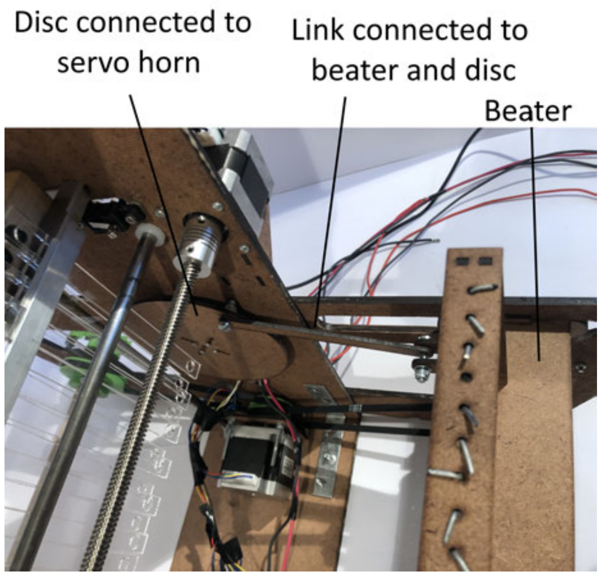
The pen click mechanisms presented three issues. The first was in relation to the heddle plates sliding off the pen click mechanisms during raising and lowering. It was decided to attach a piece of heat shrink onto the front of the pen click mechanisms that interacted with the heddle plates in the further out position. This solved this problem. The heat shrink can be seen in Figure 77. The second issue was that the push button when in the retracted state was not held fixed in the guide from the upper barrel i.e. it could slide out. The push buttons would slide out if the vertical linear actuator moved the frame up at too slow a speed. This would create issues when the frame was moved down as the push buttons would hit the tops of the heddle plates. However, the vertical linear actuator could not move too fast as this would cause the frame to become stuck as it was not given sufficient time to self-correct for misalignments, as mentioned previously. The vertical linear actuator speed was increased slightly and this solved the problem. The last issue was that sometimes the pen click mechanisms when in the retracted state, could still make contact with the heddle plates and lift them. This issue had to be solved by the user.

10.4.2 Beater automation

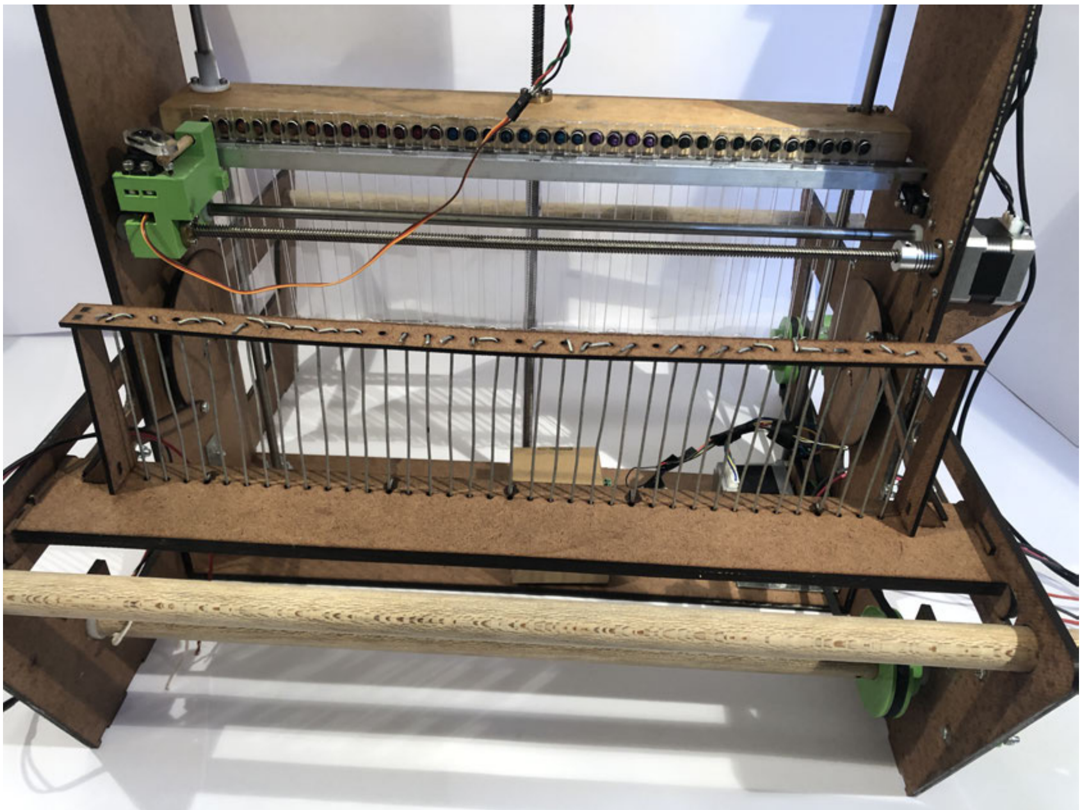
The building and testing of this sub-assembly went smoothly. The only thing to note would be that the top of the beater exhibited slight bending. This was corrected by bending some wires in such a way that they supported the top of the beater. The sub-assembly can be seen in Figure 78.



(a) Slider-crank left hand side



(b) Slider-crank right hand side

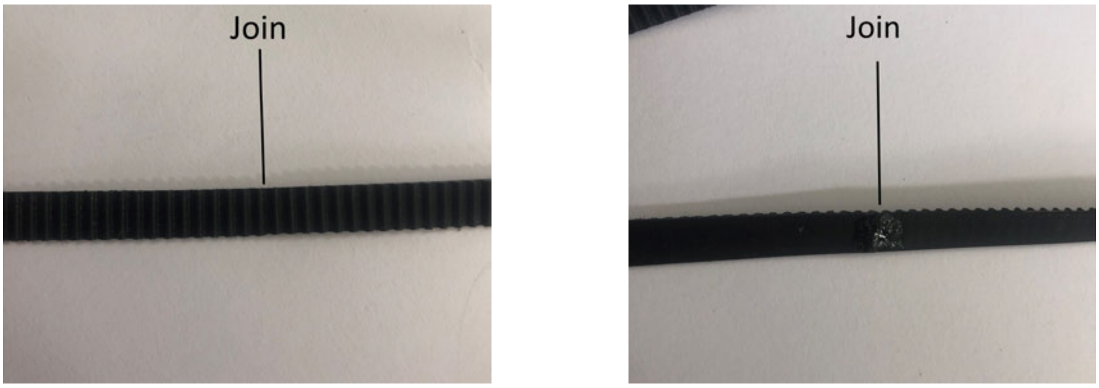


(c) Full sub-assembly

Figure 78: Beater automation sub-assembly

10.4.3 Cloth roll and warp beam automation

The building and testing of this sub-assembly went smoothly. There was a slight issue in the joining the ends of the open-ended timing belt in order to create a continuous loop. An adhesive that exhibited great strength was Q-bond. This was used to join the ends of the belt. The join can be seen in Figure 79. The final closed loop timing belt can be seen in Figure 80.



(a) Join of the timing belt tooth side (barely visible) (b) Join of the timing belt outer side

Figure 79: Join of the timing belt

Figure 80: Closed loop timing belt

Two of these timing belts, the 3D printed pulleys and the NEMA23 were used to form the sub-assembly for the cloth roll and warp beam automation. The sub-assembly can be seen in Figure 81.

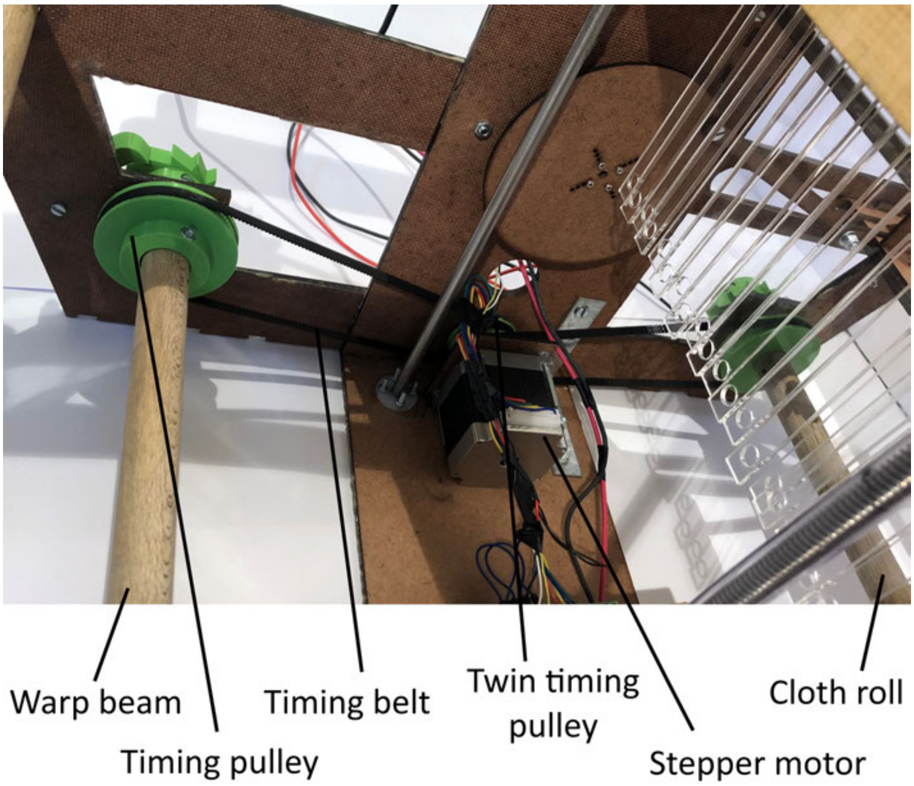
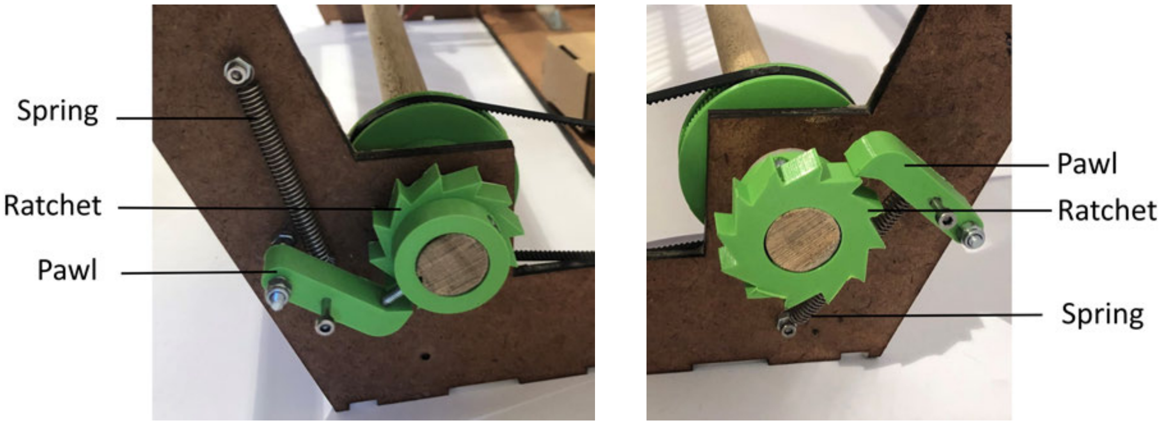


Figure 81: Cloth roll and warp beam automation sub-assembly

The ratchet and pawl on the cloth roll and warp beam prevented the unwinding of the warp threads when the NEMA23 was not energized (i.e. the motors holding torque did not prevent this unwinding). The ratchets and pawls on the cloth roll and warp beam can be seen in Figure 82.



(a) Ratchet and pawl on the cloth roll (b) Ratchet and pawl on the warp beam

Figure 82: Ratchets and pawls on the cloth roll and warp beam

10.5 Functioning during pattern creation

The sub-assemblies fit together to form the final weaving loom. The complete weaving loom, coordinated through the control system, allowed for the sub-assemblies to work together to create patterns. An image of the final loom can be seen in Figure 83.

Figure 83: Full weaving loom assembly

The loom performed well during testing and could successfully create patterns with minimal assistance. However, some unexpected issues arose as the pattern was being created. The first issue relates to maintaining the correct weaving tension in the warp threads. This issue arose from unequal amounts of threads being taken up as compared to those being let off. The diameter of the cloth roll and warp beam to start off with would be different in that the most fabric would be on the warp beam. This combined with the very thick wool that needed to be used meant that this difference was magnified. The use of the same pulley size on the cloth roll as on the warp beam meant that with each turn of the motor the rotation of each beam would be the same but due to the diameter differences there would be more thread released into the weaving area than what was taken up. To combat this the timing belts had to be removed and the threads had to be re-tensioned every now and then by turning the warp beam back (removing thread from the weaving area).

The next issue related to the vertical linear actuator becoming stuck. The frame holding the pen click mechanisms would become stuck intermittently. The side of the frame that became stuck had to be assisted down by hand. This could have been due to the lubricant needing to be replenished as well as the bushing's fit becoming looser as testing progressed.

10.6 Pattern

The operation of the loom was extremely slow and as a result of this it was decided to only test two patterns. The one pattern would demonstrate the ability of the weaving loom to create a fabric and the second one would be to display the complexity of pattern achievable with the loom. The pattern that would demonstrate the ability of the weaving loom to create a fabric was the 2/2 twill weave. The generation of the arrays used to make these patterns has been discussed in Section 9.3. The weave produced by the loom can be seen in Figure 84. The pattern that would demonstrate the complexity achievable with the loom was the panda pattern. The weave produced by the loom can be seen in Figure 85.

Figure 84: 2/2 twill weave produced by the weaving loom

Figure 85: Panda pattern produced by the weaving loom

11 Discussion

In this section a general comment will be made on the success of the various sub-assemblies, the loom as a whole and the control aspects of the loom. The conformance of the final loom with the PRS will also be discussed.

11.1 Sub-assemblies

11.1.1 Heddle sub-assembly

There was difficulty in attempting to get the heddle sub-assembly to operate in the way it needed to. Alterations to the sub-assembly were made in order to try to solve for the problems that arose. The alterations made showed success for the most part. However, in the end the issues with the frame becoming stuck on the vertical linear actuator persisted and this system within the sub-assembly had to be assisted by hand at some points.

11.1.2 Beater sub-assembly

The beater operated as expected without difficulty or need for alteration. The beater moved backwards and forwards, compacting threads in its forwards motion and providing a surface for picking operations when in its retracted position.

11.1.3 Cloth roll and warp beam sub-assembly

The cloth roll and warp beam automation operated as expected and without difficulty or need for alteration. The sub-assembly successfully took up woven cloth and let off unwoven warp threads into the weaving area. However, due to the issues highlighted in Section 10.4.3 the warp beam had to be turned back intermittently in order to re-tension the warp yarn.

11.2 Control

The three stepper motors used, the push buttons and the LED all worked as expected and were reliable. The servo motors took some time and troubleshooting in the early stages of circuit design and circuit testing to obtain reliable results. This reliability continued through the testing of the loom and its sub-assemblies.

11.3 Overall comments

The loom performed its intended function. The individual selection of warp threads can be considered successful. This allowed for a complex pattern to be created. Each sub-assembly operated for the most part in the way they were expected to and were coordinated through code in order to achieve the creation of this pattern.

11.4 Conformance with PRS

In this section the PRS will be presented (in order of importance) with each point being discussed and commented on below. At the end of this section an overall comment will be given on the conformance of the loom with its PRS.

1. **Each heddle should be individually and automatically controlled.**
   Each heddle was successfully controlled individually and automatically.

2. **The automation should allow for changes in the weaving pattern.**
   Entering a new array in the code will allow for the pattern to be changed. This operation would not be complicated, even to a user who is not experienced in coding.

3. **There should be enough heddles and thus enough warp threads for a relatively complex pattern to emerge.**
   The use of 38 heddles was sufficient in the creation of a relatively complex pattern and to demonstrate the level of automation of the loom.

4. **The cloth roll should automatically roll finished material for storage and in relation to this winding the warp beam at the same time should automatically roll to release more of the warp threads for weaving.**
   The cloth roll and warp beam were automated in such a way that unwoven warp threads would be released into the weaving area from the warp beam while completed fabric was taken up by the cloth roll. There were issues with this sub-assembly that could not be rectified in the time allocated to this project. The issues resulted in the warp threads having to be manually re-tensioned at certain points.

5. **The loom should be able to produce a tightly woven pattern.**
   Due to the long lengths of unwoven wool in the panda pattern the panda pattern was not tightly woven, however, the panda pattern was used to demonstrate complexity and not necessarily to demonstrate this requirement. This requirement would be demonstrated by a more common fabric weave, such as the 2/2 twill weave. The 2/2 twill weave can be considered tightly woven.

6. **There should be a high enough accuracy that the pattern appears consistent to the naked eye.**
   The 2/2 twill pattern and panda pattern produced were both relatively consistent and could visually be identified by the naked eye.

7. **The loom should be small enough to fit on a work desk, within a volume of roughly 60 cm $\times$ 50 cm $\times$ 50 cm.**
   The loom was small enough to fit on a work desk. In the end it fit within a volume of $60\ cm \times 60\ cm \times 60\ cm$. The volume specified in the initial requirement was a rough estimation and was reasonably complied with.

8. **The beater's back and forth motion should be automated.**
   The beater's back and forth motion was successfully automated.

9. **The design should be relatively light and easy to transport.**
   In the end the loom weighed approximately 8 kg. Something of this weight is transportable, however, one would not want to carry the loom for a prolonged period of time. Carrying the loom for a prolonged period of time would unlikely be necessary. Thus, it can be said that this requirement was met.

10. **As an upper limit, the loom should be able to complete a line of weaving in a minute.**
    Due to the speed of the selection process as well as the need to slow down the vertical motion of the frame that holds the pen click mechanisms this requirement was not met. The amount of time taken to weave a single line was approximately 4 minutes.

11. **The loom should be easy to store.**
    Due to the looms size and its inability to fold up it would not be the easiest to store. However, it is not excessively large and so could be stored in a large cupboard.

Although some of the requirements in the PRS were not met the final loom adhered to the product requirements specification to an acceptable degree.

12 Recommendations

In this section recommendations will be given for the different sub-assemblies, the materials used for the loom as well as for the control aspects of the project. This will aid design in future iterations of this project.

12.1 Sub-assembly recommendations

12.1.1 Heddle sub-assembly recommendations

There were many problems that needed to be overcome during the testing phase of the loom in specific reference to the heddle sub-assembly. The recommendations that will follow will mitigate or lessen the amount of time needed to solve for these issues in future iterations of this project.

The first recommendation comes from the issues experienced in relation to the vertical motion of the frame that held the pen click mechanisms. During testing the vertical linear actuator would become stuck on one side on one support rod. In order to avoid this issue in the future one could use two synchronised stepper motors and two lead screws and nuts in order to raise and lower the system from both sides. In the event that this option becomes too expensive one could replace one motor with a belt and pulley. Essentially one stepper motor would drive a lead screw and nut on one side and this lead screw and nut would be connected to another lead screw and nut on the other side using a belt and pulley. This way the same principle holds, however, it avoids the cost of an extra stepper motor and driver.

The misalignments between the pen click mechanisms in the frame and the slots in the heddle plates were due to the inconsistent spacing of the pen click mechanisms in the wooden frame. This could be corrected by manufacturing the frame in a different material such as aluminium and using precision equipment to manufacture the part such as a computerized numerical control (CNC) machine. Another way to lessen misalignment would be to add a guide that allows for the frame to lock into the correct position in relation to the heddle plate guide for selection to take place. The heddle plates should be made out of a different material, such as aluminium, so that if a misalignment does occur for whatever reason there is no shattering of the heddle plates.

In terms of the heddle plates sliding off the pen click mechanisms and the push buttons sliding out of the guide from the upper barrel, it would be ideal to redesign and manufacture the pen click mechanism. The push button could be designed with an end stop that would prevent the heddle plates from sliding off. The guide from the upper barrel could be redesigned to prevent the push button from sliding out when in the retracted position.

There were issues caused by the thickness of the wool that needed to be used due to the size of the pen click mechanisms. In order to reduce the thickness of the yarn that needed to be used as well as increase the number of warp threads, two horizontal linear actuators could be used, each having its own selector. One could be positioned above the other.

12.1.2 Beater sub-assembly

The beater functioned as was expected. A minor recommendation would be to add more locating features to the beater. The synchronisation of the servo motors meant that the issue of the beater moving outside of the tracks was never encountered. However, adding features that locate the beater in its track could increase the structural integrity of the loom as a whole and would reduce concerns over the loom breaking during transportation. The beater could be made out of a stronger material or the layers of hardboard used for the top of the beater could be doubled in order to prevent bending.

12.1.3 Cloth roll and warp beam sub-assembly

The cloth roll and warp beam automations functioned as expected. However, joining the ends of an open-ended timing belt is not ideal. Although the adhesive used allowed for testing to take place with the belts it is unknown whether the adhesive and consequently the belts will survive the test of time. Thus, ordering a custom continuous timing belt of the correct length would be preferable. If this is not possible an alternative would be to use a continuous timing belt of a longer length and use an idler pulley to take up the slack. The issues in relation to the weaving tension in the warp threads could be solved by using thinner warp threads. This way the starting diameter of the cloth roll and warp beam would be almost identical.

12.2 Material recommendations

All of the 3D printed parts performed their functions well and so it is not necessary to use anything other than PLA as the 3D printer filament. The frame of the loom was made out of HDF. Overall the frame was relatively stable. However, supporting structures had to be added to bring the structure to a level of stability that was deemed acceptable. For these reasons consideration may be given to using a more rigid material such as bent and cut aluminium. The heddle plate guide material is thin and long. As a result of this the part exhibited bending. Consideration should be given to the thickness of the part. As mentioned previously the heddle plates should be made out of a stronger material such as aluminium in order to prevent shattering.

12.3 Control recommendations

A recommendation for the control aspects would be to include the cable management and housing of electronics in the design phase of the project. There were holes added to the frame in order to assist in the management of cables. However, housings for the electronics mounted on the top of the loom were not designed. Adding these features would improve the final appearance of the loom and make it more appealing to its viewer. The wiring for the selector servo was attached at the top of the loom and made long enough to allow for the selector servo motor to reach either side of the loom. The cable management of the selector servo could be improved by adding a track below the servo motor that holds the cables and neatly allows for slack to be given or taken.

A liquid crystal display (LCD) could be added to the loom that informs the user of what action the loom is performing and what steps need to be taken i.e. insert weft.

Advancement in the code could make the loom more user friendly. A program could be written that takes in any image entered by the user and makes the necessary updates to the code. In this case all the user would need to do is the button presses and insertion of the weft thread.

13 Conclusion

Overall, the weaving loom performed its intended function. The weaving loom successfully created patterns through individual heddle control. This allowed for a complex pattern as well as a standard fabric to emerge. The weaving loom was automated to the extent that the user's only interaction with the loom was to insert the weft yarn. Issues highlighted in previous sections meant that this was not always the case and the user had to aid the weaving loom at some points. Recommendations for these issues have been presented and can be corrected in future iterations of the project.

References

[1] A. Barlow, *The History and Principles of Weaving: By Hand and by Power.* Low, Marston, Searle, & Rivington, 1878.

[2] Textile School. Basics of Weaving and Woven Fabrics. [Online]. Available: https://www.textileschool.com/246/basics-weaving-woven-fabrics/ [Accessed 2020-04-22]

[3] Textile Knowledge. Weaving Mechanism : Drawing-in & Tying-in. [Online]. Available: http://textileknowledges.blogspot.com/2014/09/weaving-mechanism-drawing-in-tying-in.html [Accessed 2020-04-22]

[4] International Labour Office and United Nations Industrial Development Organization, *Small-scale Weaving*, ser. AT microfiche reference library. International Labour Office, 1983. [Online]. Available: https://books.google.co.za/books?id=kBMpPwAACAAJ [Accessed 2020-03-26]

[5] S. Rude. Weaving: The Complete ProcessFrom Thread to Cloth. [Online]. Available: http://patricklepetit.jalbum.net/NAKHONRATCHASIMA/LIBRARY/WeavingtheCompleteProcess.pdf [Accessed 2020-04-22]

[6] Principal parts of a traditional hand loom. [Online]. Available: https://kids.britannica.com/students/assembly/view/163144 [Accessed 2020-03-26]

[7] E. Wood. Weaving Technologies and Structures. [Online]. Available: https://www.woolwise.com/wp-content/uploads/2017/07/Wool-482-582-08-T-18.pdf [Accessed 2020-03-18]

[8] A. Sayed. Different Parts Of A Loom. [Online]. Available: https://textileapex.blogspot.com/2015/01/different-loom-parts.html [Accessed 2020-03-20]

[9] D. Baugh. How the Loom Works. [Online]. Available: https://www.youtube.com/watch?v=UPuAdWYlr_8 [Accessed 2020-03-18]

[10] M. I. Kiron. Projectile Loom | Projectile Weaving Machines | Working Procedure of Projectile Loom. [Online]. Available: https://textilelearner.blogspot.com/2012/01/projectile-loop-projectile-weaving.html [Accessed 2020-09-24]

[11] Sino Textile. Rapier Gripper. [Online]. Available: http://www.sinotextilemachinery.com/textile-machinery-parts/rapier-loom-spare-parts/rapier-gripper.html [Accessed 2020-09-24]

[12] M. A. Sayed. Operation Principle Of Air Jet Loom. [Online]. Available: https://textileapex.blogspot.com/2014/08/operation-principle-air-jet.html [Accessed 2020-09-24]

[13] K. Skyler. Weaving Loom Parts. [Online]. Available: https://www.slideserve.com/kanoa/weaving-loom-parts [Accessed 2020-03-20]

[14] J. Smith. 7 Weave Patterns to Know – Twill, Basketweave, Satin, and More. [Online]. Available: https://www.heddels.com/2017/12/7-weave-patterns-to-know-twill-basketweave-satin-and-more/ [Accessed 2020-03-22]

[15] Dejan. How Servo Motor Works & How To Control Servos using Arduino. [Online]. Available: https://howtomechatronics.com/how-it-works/how-servo-motors-work-how-to-control-servos-using-arduino/ [Accessed 2020-09-24]

[16] RealPars. SERVO MOTORS ADVANTAGES AND DISADVANTAGES. [Online]. Available: https://realpars.com/servo-motors-advantages/ [Accessed 2020-12-01]

[17] Oriental motor. 2-phase and 5-phase Stepper Motor Comparison. [Online]. Available: https://www.orientalmotor.com/stepper-motors/technology/2-phase-vs-5-phase-stepper-motors.html [Accessed 2020-09-24]

[18] Oriental motor. Stepper Motor Overview. [Online]. Available: https://www.orientalmotor.com/stepper-motors/technology/stepper-motor-overview.html [Accessed 2020-09-24]

[19] RealPars. STEPPER MOTORS ADVANTAGES AND DISADVANTAGES. [Online]. Available: https://realpars.com/stepper-motors-advantages/#:~:text=StepperMotorsprovideruggedness,high,willworkinmanyenvironments.&text= SomeofthetopStepperMotordisadvantagesarein,motorsprovidealowefficiency. [Accessed 2020-12-01]

[20] B. Porter. What's a Stepper Motor Driver & Why Do I Need It? [Online]. Available: https://all3dp.com/2/what-s-a-stepper-motor-driver-why-do-i-need-it/#:~:text=It'sthejobofthe,ordertocloselycontrolit.&text=Itisthejobof, arrivingatthedesiredlocation. [Accessed 2020-09-24]

[21] E. Edwards. Limit Switch Characteristics. [Online]. Available: https://www.thomasnet.com/articles/instruments-controls/limit-switches/#register [Accessed 2020-09-24]

[22] Inst Tools. Basics of limit switches. [Online]. Available: https://instrumentationtools.com/basics-limit-switches/ [Accessed 2020-09-24]

[23] J. Owen. How does a clicky pen work? [Online]. Available: https://www.youtube.com/watch?v=Zv5Qa2kGL04 [Accessed 2020-04-22]

[24] Image in Binary 0 1. [Online]. Available: https://www.dcode.fr/binary-image [Accessed 2020-09-23]

[25] IMGBIN. Minecraft Giant Panda Pixel Art Drawing PNG. [Online]. Available: https://imgbin.com/png/Hr7PVmiV/minecraft-giant-panda-pixel-art-drawing-png [Accessed 2020-09-25]

[26] Britannica. Development of textiles and the textile industry. [Online]. Available: https://www.britannica.com/topic/textile/The-Jacquard-attachment [Accessed 2020-05-16]

[27] R. Woods. Jacquard Loom. [Online]. Available: https://ethw.org/Jacquard_Loom [Accessed 2020-03-18]

[28] G. Bruno and A. Fouillée, *Le tour de la France par deux enfants: devoir et patrie, livre de lecture courante...* Belin, 1877.

[29] Computer Hope. Jacquard Loom. [Online]. Available: https://www.computerhope.com/jargon/j/jacquard-loom.htm [Accessed 2020-03-18]

[30] M. Mahfuz. Different Types of Shedding Mechanism in Weaving Process. [Online]. Available: https://textilelearner.blogspot.com/2013/09/different-types-of-shedding-mechanism_4.html [Accessed 2020-04-23]

[31] Victoria and Albert Museum. How was it Made? Jacquard weaving. [Online]. Available: https://www.youtube.com/watch?v=K6NgMNvK52A&t=142s [Accessed 2020-04-23]

[32] R. C. Junivall and K. M. Marshek, *Fundamentals of Machine Component Design.* John Wiley and Sons, New York, pp. 270 & 276, 1991.

[33] I. Burgert and D. Eckstein, "The tensile strength of isolated wood rays of beech (fagus sylvatica l.) and its significance for the biomechanics of living trees," *Trees*, vol. 15, no. 3, pp. 168–170, 2001.

[34] AmesWeb. YOUNG'S MODULUS (MODULUS OF ELASTICITY) OF WOOD. [Online]. Available: https://amesweb.info/Materials/Youngs-Modulus-of-Wood.aspx [Accessed 2020-08-06]

[35] L. O'Rourke. The Mathematics of Simple Beam Deflection. [Online]. Available: https://www.raeng.org.uk/publications/other/15-beam-deflection#:~:text=Beamdesigniscarriedout,as20mmwithoutadverseeffect.[Accessed 2020-08-06]

[36] Yueshan. What Is The Difference Between MDF And HDF. [Online]. Available: https://www.yspanel.com/info/what-is-the-difference-between-mdf-and-hdf-37355300.html [Accessed 2020-08-05]

[37] The Engineering Toolbox. Friction Coefficients for some Common Materials and Materials Combinations. [Online]. Available: https://www.engineeringtoolbox.com/friction-coefficients-d_778.html [Accessed 2020-08-06]

[38] S. Emiliano. All About the Density of PLA. [Online]. Available: https://all3dp.com/2/pla-density-what-s-the-density-of-pla-filament-plastic/ [Accessed 2020-12-01]

[39] AmesWeb. SCREW NUT COLLAR FRICTION TABLE. [Online]. Available: https://amesweb.info/Screws/screw-nut-collar-friction-table.aspx [Accessed 2020-08-11]

Appendices

Appendix A History of the weaving loom and punched card mechanism

A.1 A brief history of the modern industrial loom

The first power-driven machine for weaving was patented in 1785 by Edmund Cartwright [26]. The initial design was simplistic as it only considered shedding picking and winding of the woven cloth onto the cloth beam [26]. Many refinements and adaptations of the machine followed. Modern looms still function similarly in their repetition of the sequence of primary actions. These being the sequence of primary actions as seen in Figure 2.

There are many models of looms available in today's market with varying size and level of automation. However, the modern large-scale industrial looms that display the highest level of complexity and automation are based on the Jacquard Loom. The Jacquard Loom was invented by Joseph Marie Jacquard in 1801. The Jacquard Loom can be thought of as the culmination of the best aspects of the predecessor looms. At the heart of the Jacquard Loom design is the use of perforated cards or paper as a means of instructing the loom to weave a particular pattern, a simple illustration of this can be seen in Figure 86. M. Bonchon invented the use of a perforated band of paper for working the draw loom in 1725. This invention was then adapted by M. Falcon in 1728 in the use of a chain of cards and a square prism instead of the band of paper. Finally, in 1745 Jacque de Vaucanson, made use of a large pierced cylinder to mount the pierced paper on. The cylinder would travel backwards and forwards at each stroke and could revolve through a small angle using ratchet work. This made the loom completely self-acting. Vaucanson also "invented the rising and falling griffe" [1] (which is a comb that the upper end of what is now known as a heddle wire was attached [27]). The inventions made by Vaucanson and their effect on the loom operation bear great similarity with the Jacquard loom. Figure 87 is an illustration of the Jacquard Loom mounted on a textile loom [1].

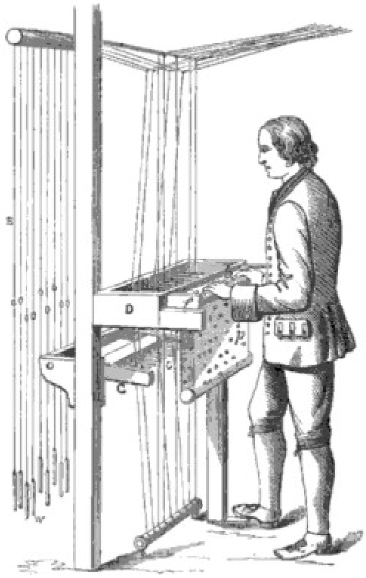


Figure 86: Simplified illustration of the use of perforated cards or paper [1]

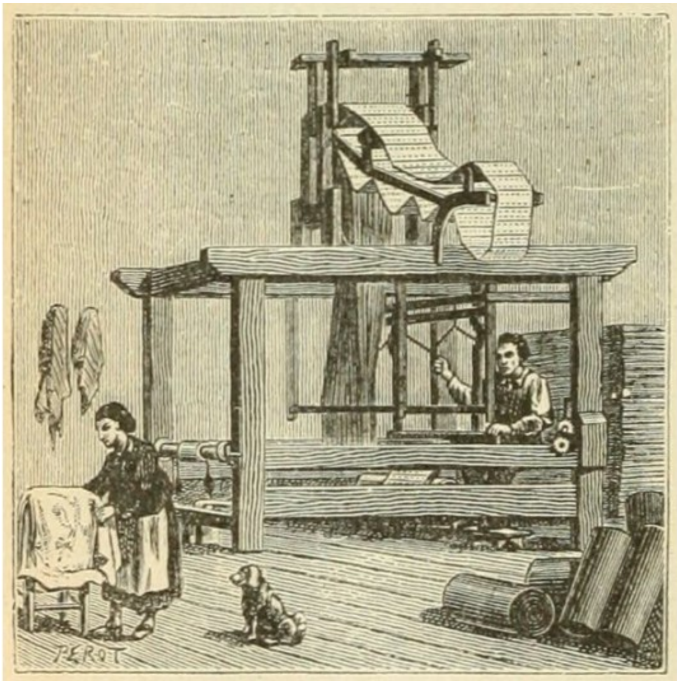


Figure 87: Jacquard Loom mounted on a textile loom [28]

The Jacquard Loom would be the first apparatus to instruct a machine to perform an automated task with the use of punched cards. These cards would be important in the development of computers and programming. Punched cards are no longer used in modern day textile looms. Instead the modern loom makes use of digital scanners to create a pixelated digital image of the desired pattern. This digital image is then used to instruct the loom [29].

A.2 How the punched card mechanism works

The control of heddles through punched cards was revolutionary to the textile industry. A simplified image of the critical components of the mechanism can be seen in Figure 88.

For the mechanism to be understood the interactions between the components must be understood. In reference to Figure 88, hooks are engaged with blades. The blades are able to move up and then down. The hooks are threaded through a hole in the needles. The needles are attached to a spring and a board. The needles interact with a cylinder with perforated cards mounted onto it. The hooks are attached to griffe hooks which sit on a platform known as the griffe. The griffe hooks are attached to harness cords which are then fed through a comber board. These harness cords then form the heddles with eyes which are then attached to weights.

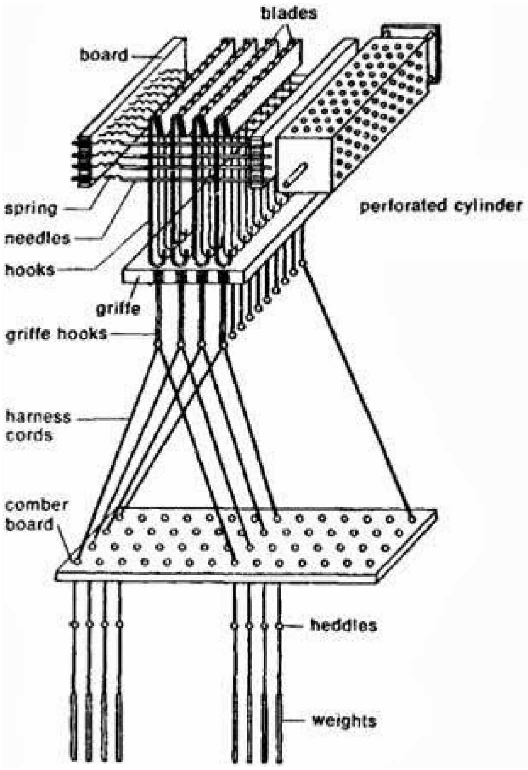


Figure 88: Critical components of the Jacquard Loom [30]

The mechanism works in the following way; first a fabric design is transferred onto square paper. A skilled worker then translates the design into the form of the punched cards. These cards are then stitched together and fed into the loom [31]. The punched cards are mounted on a cylinder as seen in Figure 88. The cylinder moves towards the needles. If a needle meets a hole in the punched card the needle will enter the cylinder and the hook will remain engaged with the blade. If the needle does not meet a hole the needle will be pushed against the board, this will move the hook that is threaded through it, disengaging it from the blade. The blade moves up, pulling up with it the hooks that have not been displaced. This in turn pulls up the heddle and warp threads. The hooks that have been displaced are prevented from moving from their initial vertical position through the griffe hooks and its attachment to the stationary griffe. This creates the shed needed for picking. The blade moves down after picking. The cylinder moves away from the needles. The needles return to their original position through spring action, returning the hooks to their original position of engagement with the blade. The cylinder then rotates to utilize a new punched card and the entire process repeats itself [30].

Appendix B Detailed Product Requirement Specifications (PRS)

Introduction

This project involves the design, building and testing of a programmable manual weaving loom. This project is the first revision of a previous student's project. The purpose of this project is to revise the previous project in an attempt to reach an improved outcome.

Description of the product

Product Description and rationale

The product will be used for the weaving of small pieces of fabric. The product will be used as a way of re-imagining something first invented in the 1800s on a smaller scale and in a more modern manner. It would be used for demonstration purposes.

User Characteristics

The product would require a relatively unskilled user. The aim is to have the product as automated as possible. In this project the user would be required to perform set up and finishing operations as well as perform the picking operations.

General Constraints

The budget being only R1500 is a major constraint. This will affect the materials selected as well as the components purchased and could lead to a greater time needing to be spent on building parts rather than buying them.

Assumptions and Dependencies

1. Arduino Mega.
2. It will be assumed that a bench top power supply will be used in order to increase the safety during operation and during the testing of the loom.

Functional Requirements

These requirements focus on the level of automation and control of the loom as these are the areas that were suggested for improvement in the previous running of the project.

1. The product should be modular in that it should able to weave a piece of material with any pattern the user requires.
2. There should be enough heddles and thus enough warp threads for a relatively complex pattern to emerge.
3. Each heddle should be individually controlled.

4. The product should be almost completely automated in its operation. However, the user would still need to perform the picking primary action, loom set-up and the finishing processes as seen in Figure 2.
    4.1. The cloth roll should automatically roll finished material for storage and in relation to this winding the warp beam at the same time should automatically roll to release more of the warp threads for weaving.
    4.2. The beater should move back and forth as required.
    4.3. The movement of the heddles should be automatic.

Performance requirements
These requirements are derived from the basic needs that should be fulfilled by any weaving loom.

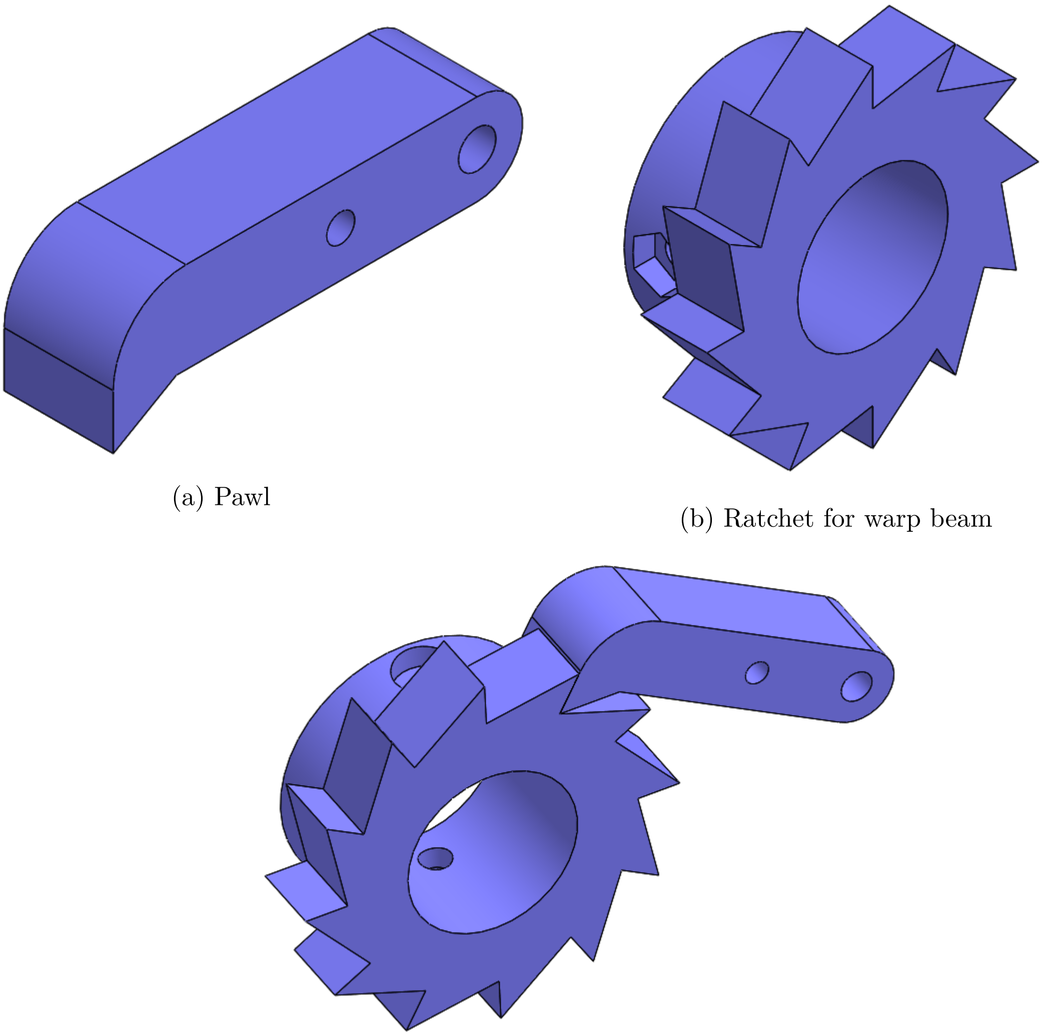
1. The loom should be able to produce a tightly woven pattern.
2. The loom should have a high enough accuracy that the pattern appears consistent to the naked eye.
3. As an upper limit, the loom should be able to complete a line of weaving in a minute.

Design constraints
These constraints are imposed on the project in order for the aims of the project to be achieved in the most compact and ergonomic way.

1. The loom should be relatively light and easy to transport.
2. The loom should be small enough to fit on a small work desk. The loom should fit within a volume of roughly 60 $cm \times 50\ cm \times 50\ cm$.
3. The loom should be easy to store, i.e. can be folded up in some way.

Appendix C 3D printed parts

The 3D printed parts included the ratchets for the cloth roll and warp beam as well as the pawls. The pawl can be seen in Figure 89a and 90a. The ratchets for the cloth roll and warp beam are identical except for their teeth which are a reflection of each other. The ratchets for the warp beam and cloth roll can be seen in Figure 89b and Figure 90b respectively. The subassmblies can be seen in Figure 89c and Figure 90c.

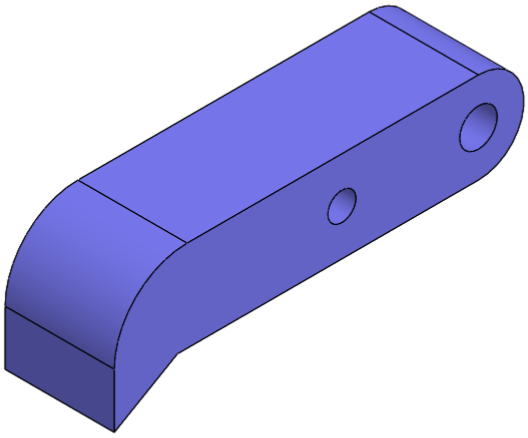


(a) Pawl

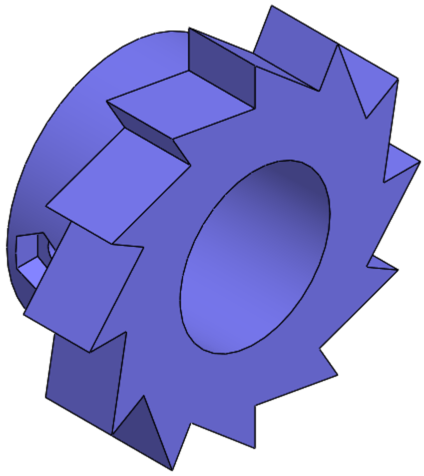
(b) Ratchet for warp beam

(c) Ratchet and pawl sub-assembly for warp beam

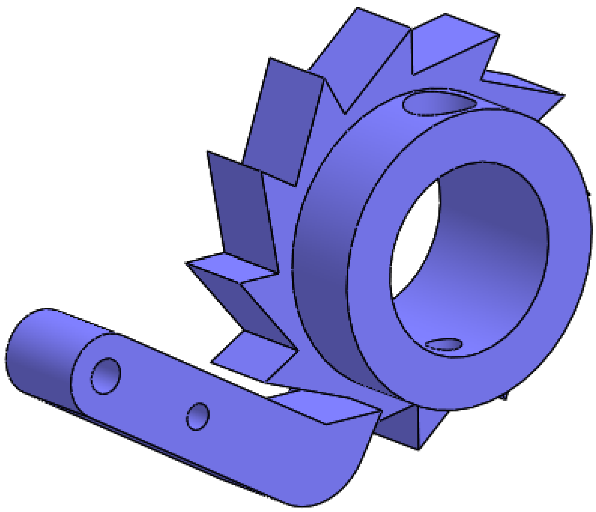
Figure 89: Ratchet and pawl for warp beam to be 3D printed



(a) Pawl



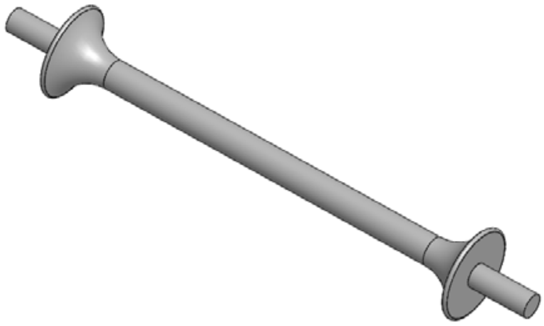
(b) Ratchet for cloth roll



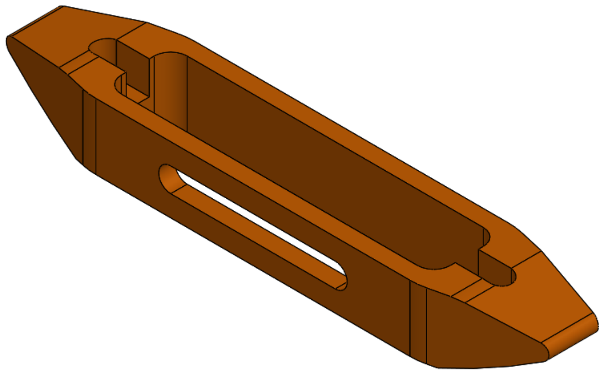
(c) Ratchet and pawl sub-assembly for cloth roll

Figure 90: Ratchet and pawl for cloth roll to be 3D printed

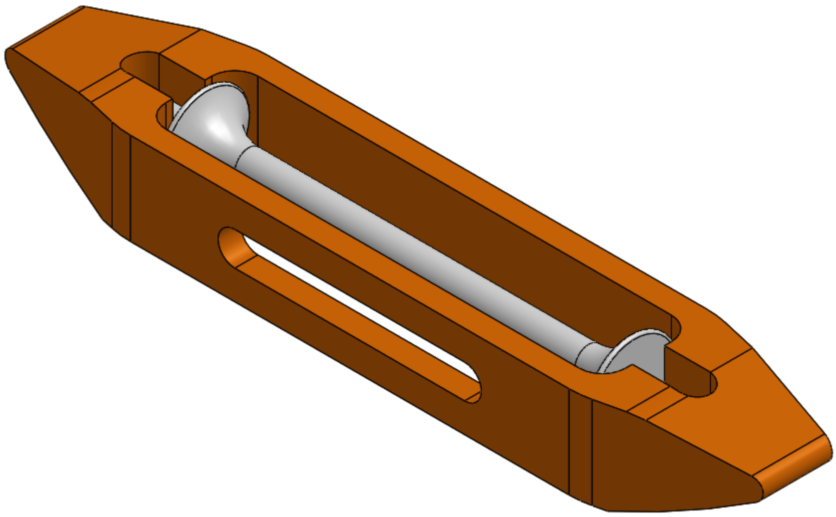
A bobbin and boat shuttle were to be 3D printed. The bobbin can be seen in Figure 91a. The boat shuttle can be seen in Figure 91b. The full sub-assembly of the bobbin and shuttle can be seen in Figure 91c.



(a) Bobbin (this is a repeated image of Figure 68)



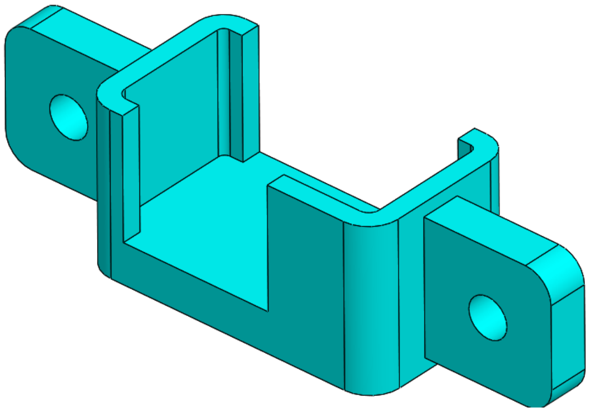
(b) Boat shuttle



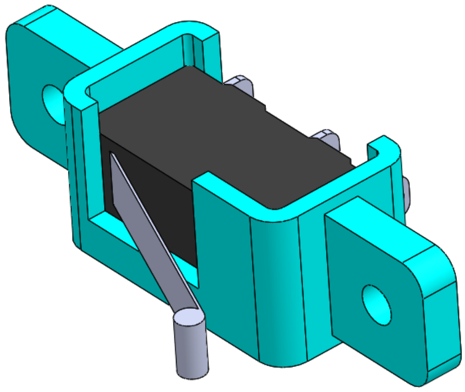
(c) Bobbin and shuttle sub-assembly

Figure 91: Bobbin and shuttle to be 3D printed

The mounts for the limit switches were 3D printed. The two limit switches were the horizontal and vertical limit switches. They were to attach to the vertical side frame of the weaving loom. The horizontal and vertical limit switch mounts can be seen in Figure 92a and Figure 93a respectively. An image of the horizontal and vertical limit switches mounted in their mounts can be seen in Figure 92b and Figure 93b respectively.

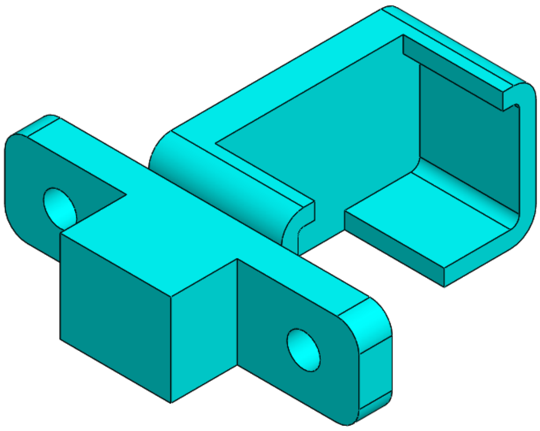


(a) Horizontal limit switch mount

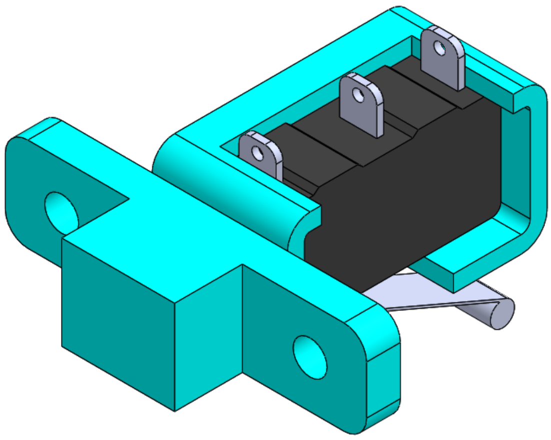


(b) Horizontal limit switch mount with limit switch

Figure 92: Horizontal limit switch mount to be 3D printed



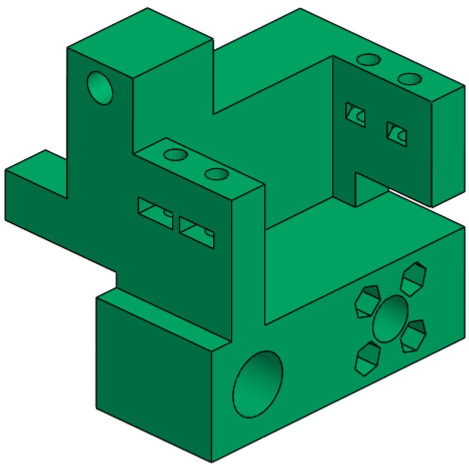
(a) Vertical limit switch mount



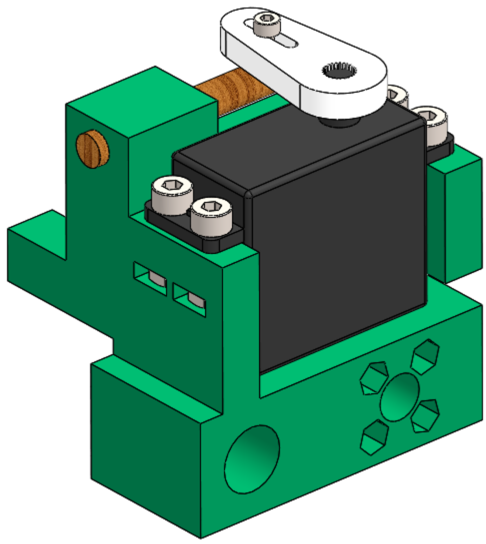
(b) Vertical limit switch mount with limit switch

Figure 93: Vertical limit switch mount to be 3D printed

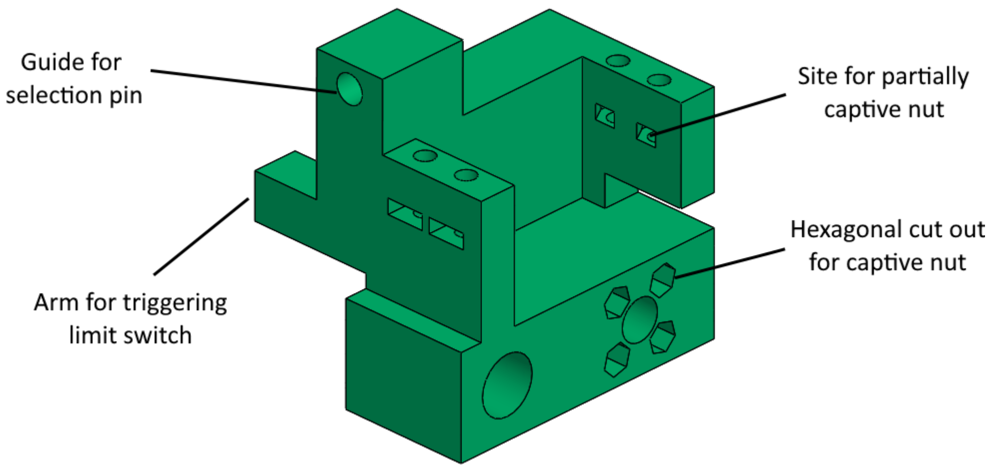
The selector servo motor mount was an extremely complex and customized part. As a result it needed to be 3D printed. It included an arm for triggering the limit switch. It also included a guide for the pin used in the selecting action. There were hexagonal holes cut for captive nuts. Partial captive nuts were used in the mounting of the servo motor in order to reduce the chance of the nut turning and damaging the motor during operation as well as for ease of assembly. The selector servo motor mount can be seen in Figure 94a. The labelled selector servo motor mount can be seen in Figure 94c. The servo motor mounted in the servo motor mount can be seen in Figure 94b.



(a) Selector servo motor mount



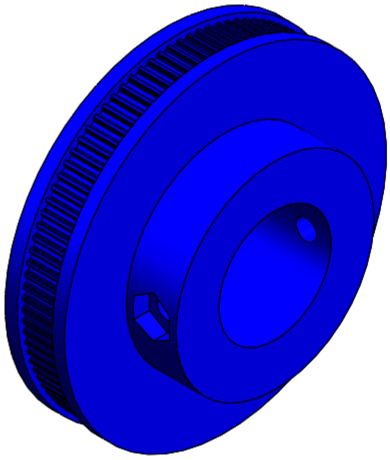
(b) Selector servo motor mount shown with servo



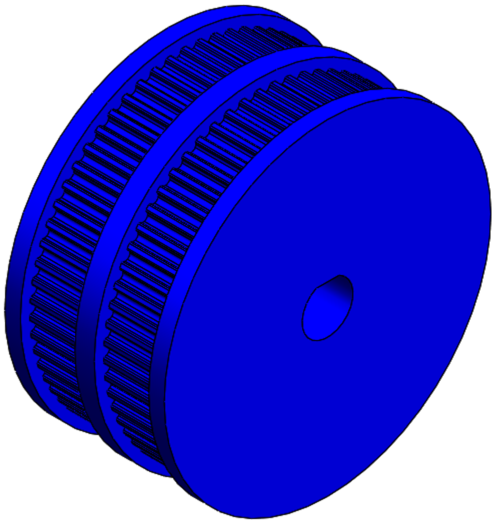
(c) Selector servo motor mount with labels

Figure 94: Selector servo mount to be 3D printed

The timing pulleys were 3D printed. The timing pulleys made use of a GT2 tooth profile. The twin pulley had a D shaped bore hole for attachment to the NEMA23 stepper motor. The pulley for mounting onto the cloth roll and warp beam made use of a hole for a pan head screw and a hexagonal hole for a captive nut. The captive nut reduces the chance of the nut loosening during operation. The timing pulley can be seen in Figure 95a and Figure 95b.



(a) Cloth roll and warp beam timing pulley revision



(b) Motor twin timing pulley revision

Figure 95: Pulleys to be 3D printed (these are repeated images of Figure 43)

Appendix D Calculations

The calculations performed in the subsections to follow were necessary in order to either specify the motors that needed to be used or to aid in design decisions that would prevent the failure of the weaving loom. A shortened nomenclature with only the terms relevant to that section will be presented at the start of each subsection for ease of reading. It should be noted that the calculations make assumptions and oversimplify the real world application. The results of the calculation as well as intuition will be used in making final selections of components.

D.1 Warp beam, cloth roll, back rest and breast beam

D.1.1 Determination of the warp beam, cloth roll, back rest and breast beam minimum shaft diameters

Table 2: Nomenclature for warp beam, cloth roll, back rest and breast beam diameter calculations

Symbol	Description
F_{total}	Total force exerted on one beam by the warp threads in tension
T_{warp}	Tension in a single warp thread
m_{mug}	Mass of the mug
g	Gravitational acceleration
N	Total number of warp threads
L	Span over which uniformly distributed load acts
R	Distance from fixed point to distributed force
F_{y1}, F_{y2}	Reaction forces at fixed points of beams
M_{max}	Maximum moment on beams
σ_b	The bending stress caused by the maximum moment
σ_1, σ_2	Principal stresses
d_{min}	Minimum shaft diameter
S_{ut}	Ultimate tensile strength
τ	Uniformly distributed load
η_1	Safety factor used in minimum shaft diameter calculation

The minimum diameter of the warp beam, cloth roll, back rest and breast beam needed to be determined in order to ensure failure would not occur during operation.

The force on the beams was created by the warp threads in tension. The force on the warp beam and cloth roll would be less due to the geometry of the weaving loom and this geometry resulting in the the back rest and breast beam supporting the majority of the force. However, in order to create a conservative design and in order to simplify the calculations it will be assumed that the force acting on all four beams will be the same.

A diagram showing the forces acting on the beams and the distances used can be seen in Figure 96.

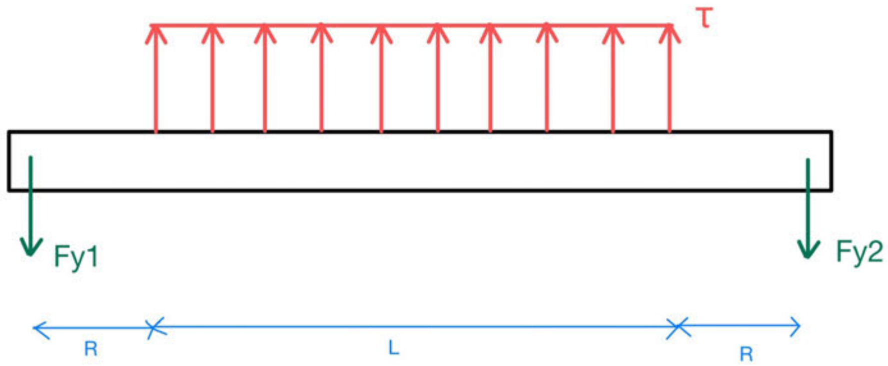


Figure 96: Free body diagram of beams

The warp threads exist in two states one being the lifted state and the other being the neutral state (not lifted). The state that creates the highest tension is the lifted state. The high tension state will be assumed of all of the warp threads in order to create a conservative design. The tension in the threads in their neutral state (not lifted) would be a fraction of this tension.

The COVID pandemic meant that there was no access to laboratories and hence the necessary equipment in order to correctly measure the force exerted on these beams by the warp threads in tension. Instead an estimate for this force was made. This estimate was made by hanging different objects from a piece of wool. This created tension in the wool. The object that created a tension that was estimated to be the tension the warp threads would create when lifted was a mug. The mug hanging from the piece of wool can be seen in Figure 97. The mass of the mug was then determined using a kitchen scale, the reading on the scale can be seen in Figure 98.

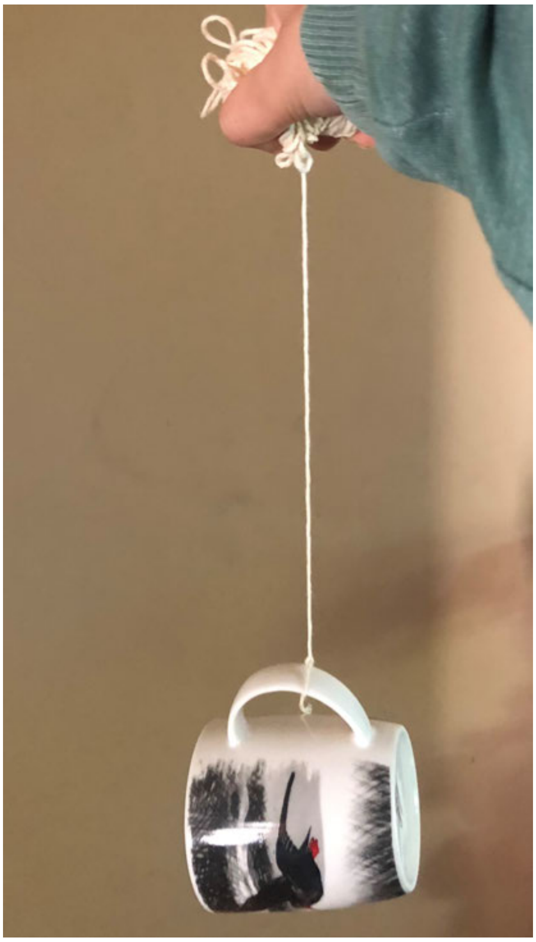


Figure 97: Mug hanging from a piece of wool

Figure 98: Mug on a kitchen scale

The mass determined by the kitchen scale was then converted into a force. This can be seen below.

$$T_{warp} = m_{mug}g = 0.280 \times 9.81 = 2.747 \ N$$

There were 38 warp threads. It was assumed that all the threads would be lifted at once. This is unlikely to occur in a pattern but this was done in order to simplify the calculation and design for the worst case scenario. Therefore each warp thread exerts a force of 2.747 N. According the the Solidworks model the force is distributed over 422 mm. The calculation for the total force can be seen below:

$$F_{total} = T_{warp} \times N = 2.747 \times 38 = 104.378 \ N$$

The total force created by the tension in the threads would result in a reaction force at the fixed points of attachment between the beams and the frame of the weaving loom. These are denoted by $Fy1$ and $Fy2$. The calculation of these reaction forces can be seen below:

$$F_{y1} = F_{y2} = \frac{F_{total}}{2} = \frac{104.378}{2} = 52.189 \ N$$

The distributed force can be calculated as:

$$\tau = \frac{F_{total}}{L} = \frac{104.378}{422} = 0.247 \ N/mm$$

The material that will be used for these beams will be wooden dowels. This is a brittle material and because of this the modified Mohr theory of failure and a safety factor of 2 will be used, as recommended by R. Juvinall and K. Marshek in the *Fundamentals of Machine Component Design* (2011) [32]. This safety factor was selected for a better known material used in uncertain environments or subjected to uncertain stresses. The stresses are uncertain as the tension in the warp threads was not determined accurately. The radial tensile strength of a common material used to make wooden dowels (dry beech wood) is 23.4 MPa [33].

The maximum moment in the beams will be determined graphically. The shear force and bending moment diagrams can be seen in Figure 99.

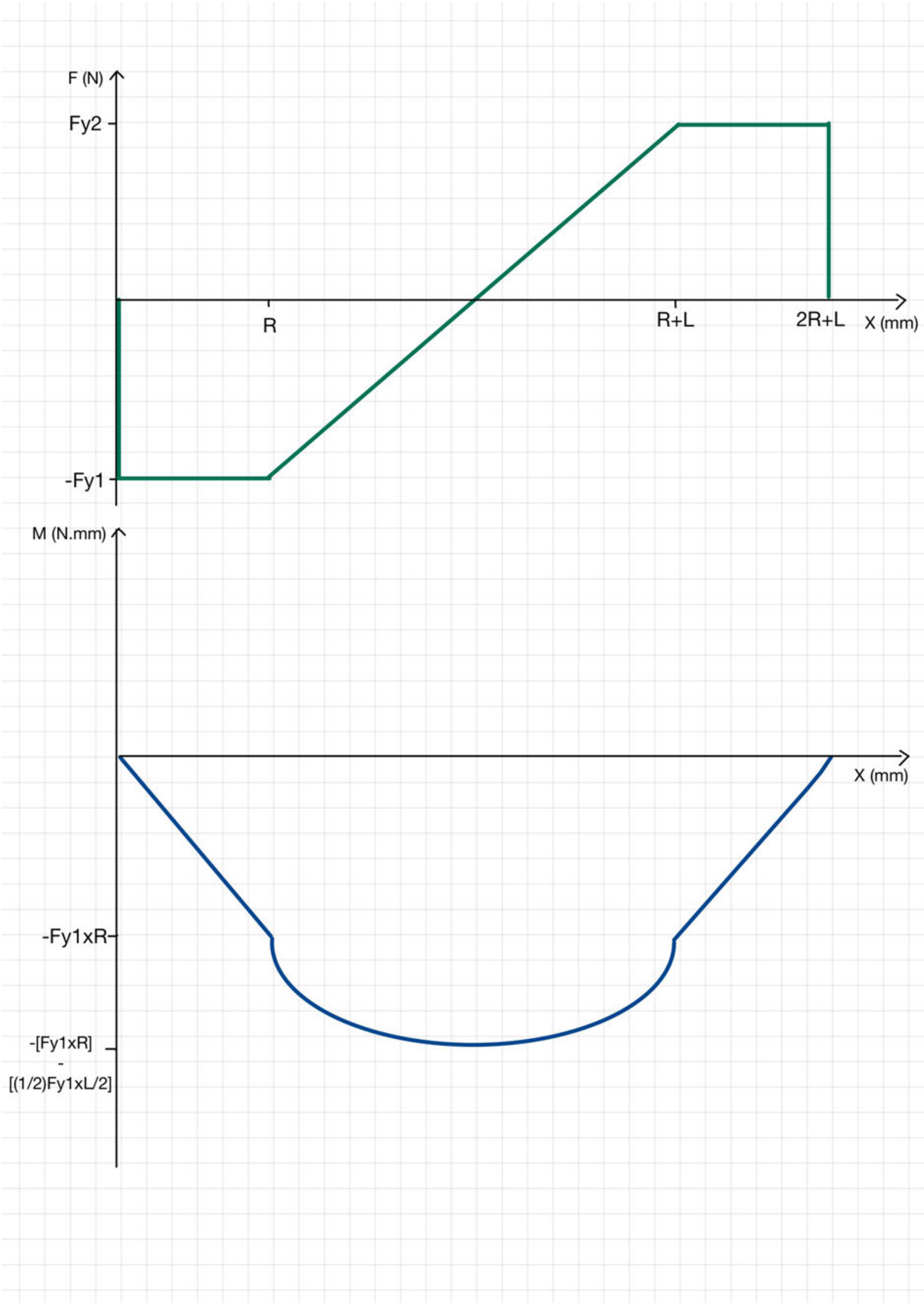


Figure 99: Shear force and bending moment diagrams

A value for the distance between the fixed point and the distributed force, R, was found using the Solidworks model to be 49.4 mm. Determination of maximum moment:

$$M_{max} = -F_{y1} \times R - \frac{1}{2} \times F_{y1} \times \frac{L}{2} = -52.189 \times 0.0494 - \frac{1}{2} \times 52.189 \times \frac{0.422}{2} = -8.084\ N.m$$

Let:

$$\sigma_b = \frac{32\,|M_{max}|}{\pi {d_{min}}^3}$$

Calculating principle stresses (it is assumed that there is a shear stress of zero):

$$\sigma_1, \sigma_2 = \frac{\sigma_b}{2} \pm \sqrt{\frac{{\sigma_b}^2}{2}}$$

$$\sigma_1 = \sigma_b \ and\ \sigma_2 = 0\ MPa$$

Calculating the minimum shaft diameter using the modified Mohr theory of failure in the appropriate quadrant:

$$\sigma_1 = \frac{S_{ut}}{\eta_1}$$

$$d_{min} = \sqrt[3]{\frac{\eta_1 \times 32 \times |M_{max}|}{\pi \times S_{ut}}} = \sqrt[3]{\frac{2 \times 32 \times 8.084}{\pi \times 23.4 \times 10^6}} = 19.164\ mm$$

Therefore selecting a diameter of 22 mm would be appropriate for each beam.

D.1.2 Checking the maximum deflection of the warp beam, cloth roll, back rest and breast beam

Table 3: Nomenclature for maximum deflection of the warp beam, cloth roll, back rest and breast beam

Symbol	Description
F_{y1}, F_{y2}	Reaction forces at fixed points of beam
τ	Uniformly distributed load
L	Span over which uniformly distributed load acts
R	Distance from fixed point to distributed force
P	Fictitious load
M_{ab}, M_{bc}	Internal bending moment in beam sections
V_{ab}, V_{bc}	Internal shear in beam sections
x	Distance from origin in x direction
E	Young's modulus of beam material
I	Area moment of inertia of beam
D	Distance from fixed end of beam to the center of the beam
δ_P^v	Deflection

Assuming deflections are small and elastic the maximum deflection of the beam can be determined using Castigliano's Theorem. The deflection of the beam will be at a maximum at the centre of the beam. This point is indicated by the point C, labelled in Figure 100. As a result this is where the force P is added to the beam.

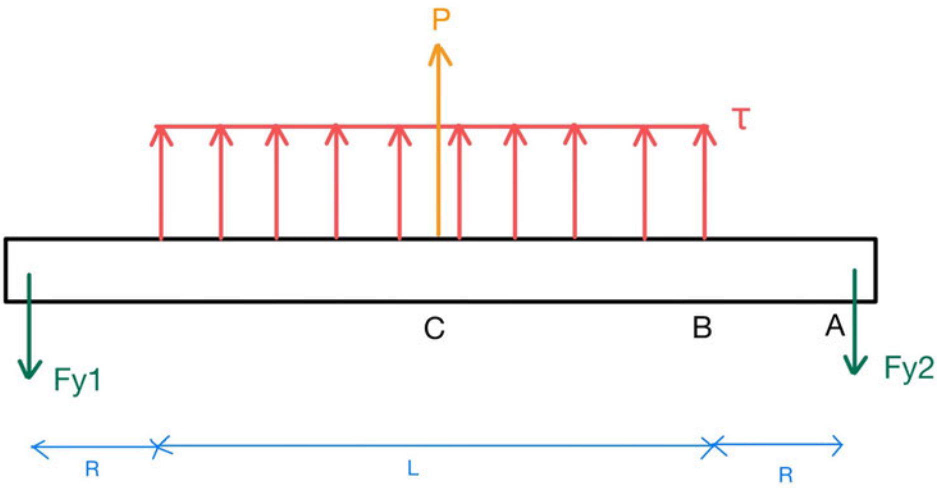
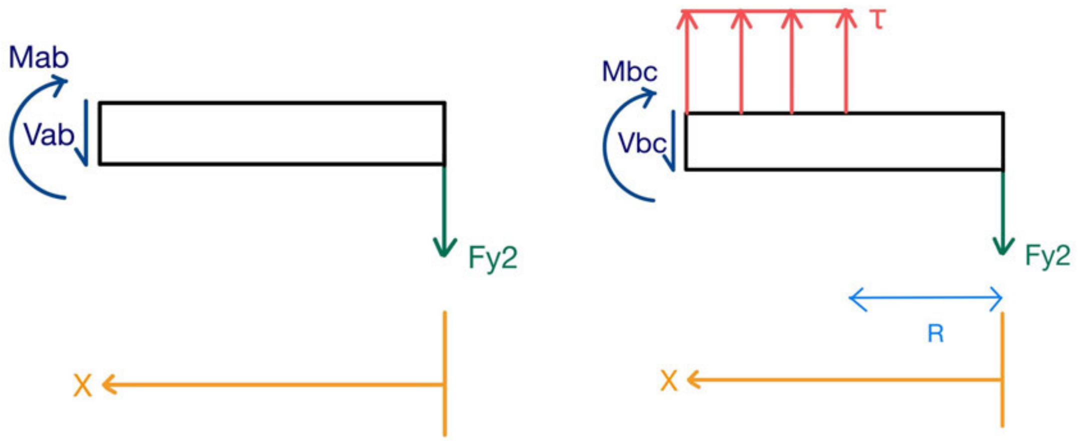


Figure 100: Beam with points labelled and the force, P

Determining reaction forces:

$$F_{y2} = F_{y1} = \frac{P}{2} + \frac{\tau L}{2}$$

The symmetry of the beam means that two sections of the beam can be evaluated and the deflection doubled. The sections of the beam AB and BC can be seen in Figure 101.



(a) Section AB of the beam

(b) Section BC of the beam

Figure 101: Sectioned beams

Looking at Figure 101a, the equation for the moment M_{ab} is determined to be:

$$M_{ab} = -F_{y2}x = -\frac{P}{2}x - \frac{\tau L}{2}x$$

Taking the partial derivative with respect to P:

$$\frac{\partial M_{ab}}{\partial P} = -\frac{x}{2}$$

Looking at Figure 101b, the equation for the moment M_{bc} is determined to be:

$$M_{bc} = -F_{y2}x + \tau(x-R)\frac{(x-R)}{2} = -\frac{P}{2}x - \frac{\tau L}{2}x + \frac{\tau(x-R)^2}{2}$$

Taking the partial derivative with respect to P:

$$\frac{\partial M_{bc}}{\partial P} = -\frac{x}{2}$$

Finding the deflection at the center of the beam:

$$EI \times \delta_P^v = 2\left[\int_0^R M_{ab}\frac{\partial M_{ab}}{\partial P}dx \ + \ \int_R^{\frac{L}{2}+R} M_{bc}\frac{\partial M_{bc}}{\partial P}dx\right]$$

$$EI \times \delta_P^v = 2\left[\int_0^R \left(-\frac{P}{2}x - \frac{\tau L}{2}x\right)\left(-\frac{x}{2}\right)dx \ + \ \int_R^{\frac{L}{2}+R} \left(-\frac{P}{2}x - \frac{\tau L}{2}x + \frac{\tau\left(x-R\right)^2}{2}\right)\left(-\frac{x}{2}\right)dx\right]$$

$$EI \times \delta_P^v = \left. \frac{P}{6}x^3 + \frac{\tau L}{6}x^3 \right|_0^R + \left. \frac{P}{6}x^3 + \frac{\tau L}{6}x^3 - \frac{\tau}{8}x^4 + \frac{\tau R}{3}x^3 - \frac{\tau R^2}{4}x^2 \right|_R^{\frac{L}{2}+R}$$

Let $\frac{L}{2} + R = D$ and set the additional force P to zero:

$$EI \times \delta_P^v = \left. \frac{\tau L}{6}x^3 \right|_0^R + \left. \frac{\tau L}{6}x^3 - \frac{\tau}{8}x^4 + \frac{\tau R}{3}x^3 - \frac{\tau R^2}{4}x^2 \right|_R^D$$

$$EI \times \delta_P^v = \frac{\tau L}{6}R^3 + \frac{\tau L}{6}D^3 - \frac{\tau}{8}D^4 + \frac{\tau R}{3}D^3 - \frac{\tau R^2}{4}D^2 - \frac{\tau L}{6}R^3 + \frac{\tau}{8}R^4 - \frac{\tau R}{3}R^3 + \frac{\tau R^2}{4}R^2$$

$$EI \times \delta_P^v = \frac{\tau L}{6}D^3 - \frac{\tau}{8}D^4 + \frac{\tau R}{3}D^3 - \frac{\tau R^2}{4}D^2 + \frac{\tau}{24}R^4$$

$$\delta_P^v = \frac{\frac{\tau L}{6}D^3 - \frac{\tau}{8}D^4 + \frac{\tau R}{3}D^3 - \frac{\tau R^2}{4}D^2 + \frac{\tau}{24}R^4}{EI}$$

$$\delta_P^v = \frac{\frac{\tau L}{6}D^3 - \frac{\tau}{8}D^4 + \frac{\tau R}{3}D^3 - \frac{\tau R^2}{4}D^2 + \frac{\tau}{24}R^4}{E \times \frac{\pi d^4}{64}}$$

Using the value of E determined from research (9500 MPa) [34], the distances measured from the Solidworks model and the diameter selected based on the strength calculation (22 mm) the maximum deflection of the beam can be determined:

$$\delta_P^v = \frac{\frac{247.342 \times 0.422}{6}0.260^3 - \frac{247.342}{8}0.260^4 + \frac{247.342 \times 0.0494}{3}0.260^3 - \frac{247.342 \times 0.0494^2}{4}0.260^2 + \frac{247.342}{24}0.0494^4}{9500 \times 10^6 \times \frac{\pi \times 0.022^4}{64}}$$
$$= 2.076\ mm$$

In practice it can be assumed that the maximum allowable deflection of a beam is limited by its span. The span divided by 250 will allow for the calculation of the deflection that can occur in the beam without having adverse effects [35]. This calculation is shown below:

$$maximum\ allowable\ deflection = \frac{L + 2R}{250} = \frac{422 + 2 \times 49.4}{250} = \frac{520.8}{250} = 2.0832\ mm$$

The beams calculated maximum deflection is less than the maximum allowable deflection, $\delta_P^v < maximum\ allowable\ deflection$. It can be assumed that beams of 22 mm diameter will be appropriate for the weaving loom.

D.1.3 Specifying the stepper motor used to automate cloth roll and warp beam motion

Table 4: Nomenclature for specifying the stepper motor used in the automation of the cloth roll and warp beam

Symbol	Description
X	Horizontal distance between the cloth roll and breast beam (also the horizontal distance between the warp beam and the back rest)
Y	Vertical distance between the cloth roll and breast beam (also the vertical distance between the warp beam and the back rest)
H	The hypotenuse of the triangle created by X and Y
β	Angle between the line through the center of the cloth roll and breast beam and the vertical (also the angle between the line through the center of the warp beam and the back rest)
T_{cw}	Required motor torque for motor controlling cloth roll and warp beam automation
T_{warp}	Tension in a single warp thread
N	Number of warp threads
d_{pull}	Diameter of pulley connected to motor shaft
η_2	Safety factor used in specifying stepper motor for the cloth roll and warp beam automation

There are various stages of operation that could be looked at in specifying the motor for this application. However, in the stages of operation that do not involve the taking up or letting off of cloth from the cloth roll and warp beam most of the forces are taken up by the ratchet and pawl. The motors holding torque will assist in the prevention of undesired motion of the cloth roll and warp beams. However, the torque requirement of the motor during these stages will be less than the torque required to take up and let off cloth. As a result this stage of operation will be assessed and used to generate a minimum torque requirement for the motor.

The motor needs to overcome the torques created by the warp threads on both the warp beam and the cloth roll as well as the friction that exists in the bushings. Not enough is known about the deflections of the beam at the supports and the frictional coefficients that exist between the beams and the bushings. Instead friction will be ignored and a safety factor will be applied to the final minimum torque requirement for the motor.

Figure 102 shows the arrangement of the cloth roll pulley, warp beam pulley and the dual pulley that sits on the motor. It also shows the directions that the pulleys will turn during the operation and the forces from the warp threads that resist this motion.

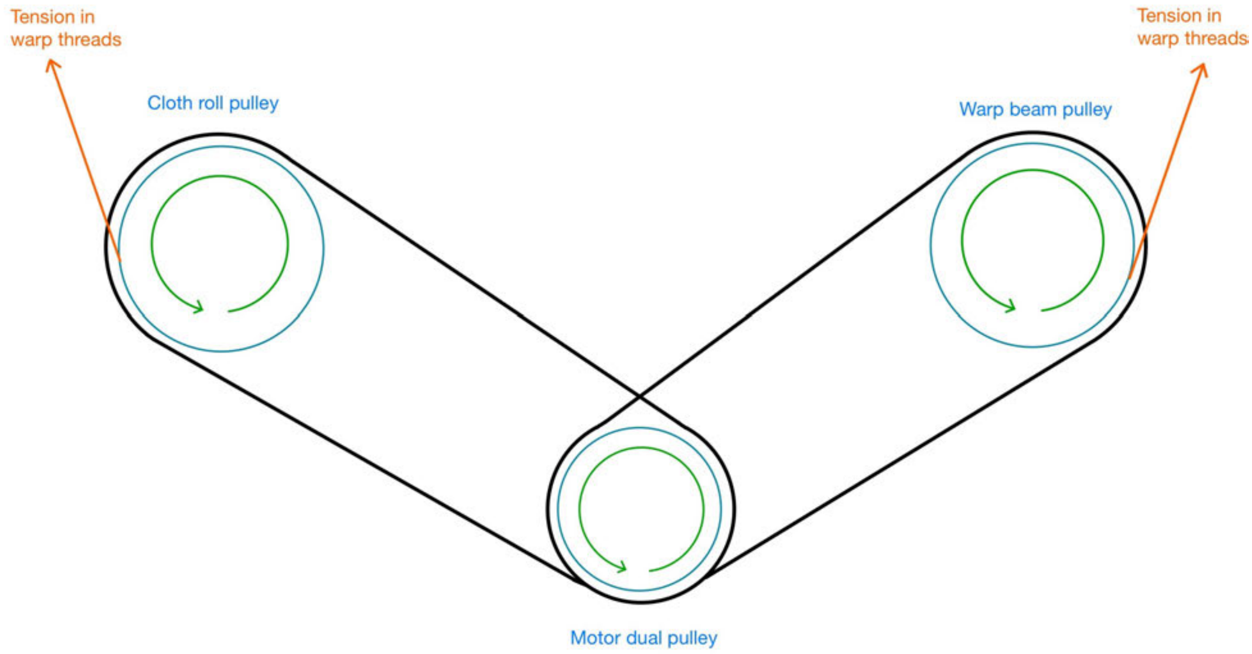


Figure 102: Cloth roll and warp beam automation

The tension from the warp threads act at a constant angle to the cloth roll and warp beam. This angle is defined by the positions of the back rest and breast beam in relation to the cloth roll and warp beam. These distances and the angle have been labelled in Figure 103.

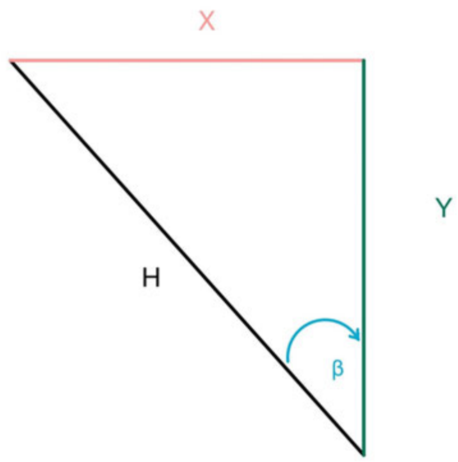


Figure 103: Distances between the back rest and warp beam and the distances between the breast beam and cloth roll

Table 5: The distances according to the Solidworks model

Symbol	Description
X	73.2 mm
Y	99 mm
H	123.12 mm

Calculating the angle the tensions from the warp threads act to the cloth roll and warp beam, β:

$$\beta = arctan\left(\frac{73.2}{99}\right) = 36.48deg$$

As determined in Section D.1.1, the maximum tension in each warp thread is approximately 2.747 N. The approximate diameter of the dual pulley according to the Solidworks model is 40 mm. A safety factor is added to this calculation to account for the unknown frictional forces. Determining the minimum torque requirement of the motor:

$$T_{cw} = 2 \times N \times T_{warp} \cos(\beta) \times \frac{d_{pull}}{2} \times \eta_2 = 2 \times 38 \times 2.747 \cos(36.48) \times \frac{0.040}{2} \times 1.5 = 5.036\ N.m$$

The minimum torque requirement for the motor is 5.036 N.m. This is a very high torque requirement and the cost of such a motor would be quite high. The high torque requirement could be due to the calculation being overly conservative. A NEMA23 with a lower torque output will be used initially and if it does not provide sufficient torque will be upgraded to a motor with a higher torque output.

D.2 Beater

D.2.1 Specifying the servo motors used to automate beater motion

Table 6: Nomenclature for torque requirement of servo motor used to automate beater motion

Symbol	Description
m_{beat}	Mass of beater
ρ	Density of hardboard
V	Volume of beater
g	Gravitational acceleration
F_f	Frictional force acting on beater
F_{beat}	Force exerted by crank on slider in the beater sub-assembly
d	Distances between the center of the disc and the point of attachment of the link
F_N	Normal force on beater
α	The angle the disc makes with the horizontal
θ	Angular motion of beater disc
μ_s	Coefficient of static friction between beater and its guide
T_{beat}	Required torque for motors controlling the beater

The density of HDF wooden boards is between 750 kg/m^3 and 930 kg/m^3 [36]. The middle of this range, 840 kg/m^3, will be used as the density, ρ, of HDF in calculation.

According to the Solidworks model the volume of material used for the beater equates to 345036.93 mm^3.

Calculating the mass of the beater:

$$m_{beat} = V \times \rho = \frac{345036.93}{1000^3} \times 840 = 0.28983\ kg$$

The beater's motion will be automated with two slider-crank mechanisms. These will be controlled by two servo motors on either side of the beater. A simplified calculation will be used in order to determine what the required torque of the servo motor will likely be. Figure 104 shows the components that make up the slider-crank mechanism, namely the disc, link and beater. The servo motor will be attached and drive the system from the center of the disc. Figure 105 shows the force diagrams for the components that make up the beater.

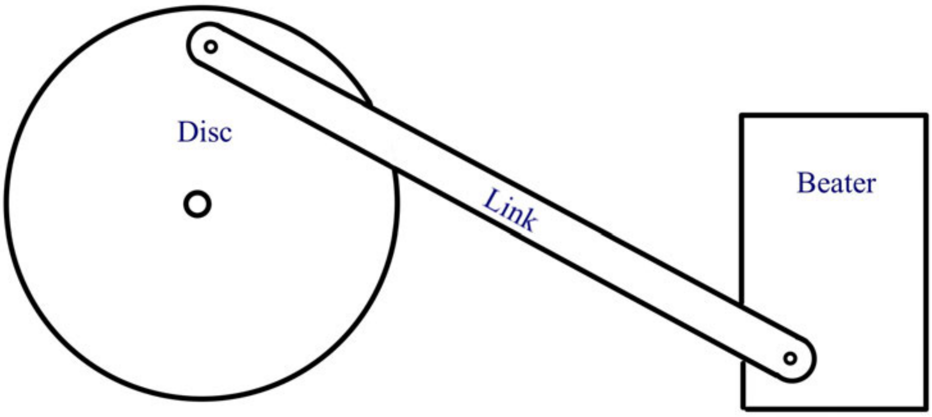


Figure 104: The components that make up the beater crank-slider mechanisms

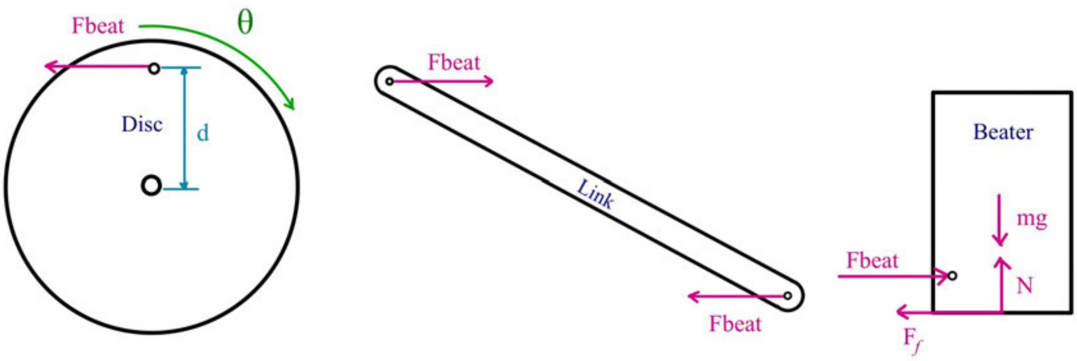


Figure 105: The force diagrams for the components of the beater crank-slider mechanism

In order to simplify the calculation and prevent the need for a full dynamic analysis of the system, a static analysis of the system will be performed. As the disc rotates the angle that the force, F_{beat}, makes with a line that connects the center of the disc to the point at which the force acts changes. This angle, α, can be seen in Figure 106. This means that the torque varies throughout the slider-crank's motion. The force, F_{beat}, will be made equal to the frictional force, F_f. This means that the maximum torque calculated is the minimum torque that will be required to overcome the static frictional force.

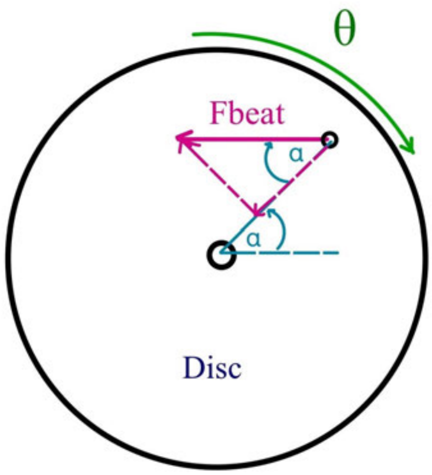


Figure 106: The angle the force, F, acts as the disc rotates

The coefficient of static friction between two pieces of wood ranges between 0.25 and 0.5 [37]. A safety factor will be added to the coefficient of static friction in order to account for misalignments in the parts as well as the fact that the surfaces will be running perpendicular to the grain. Selecting the upper value in the range and applying a safety factor of 6 the coefficient of friction becomes 3.

Noting that the beater is supported on two sides (at either end of the weaving loom) and that there will be two motors the normal force and frictional force is determined as follows:

$$F_N = \frac{m_{beat}g}{2} = \frac{0.28983 \times 9.81}{2} = 1.422\ N$$

$$F_f = \mu_s \times F_N = 3 \times 1.422 = 4.265\ N$$

The distance, d, according to the Solidworks model is 55 mm. By stepping through the angles of alpha from 0 to 180 degrees, the graph shown in Figure 107 of torque versus alpha is produced. The equation used to produce the graph is shown below:

$$T_{beat} = F_f \sin(\alpha) \times d$$

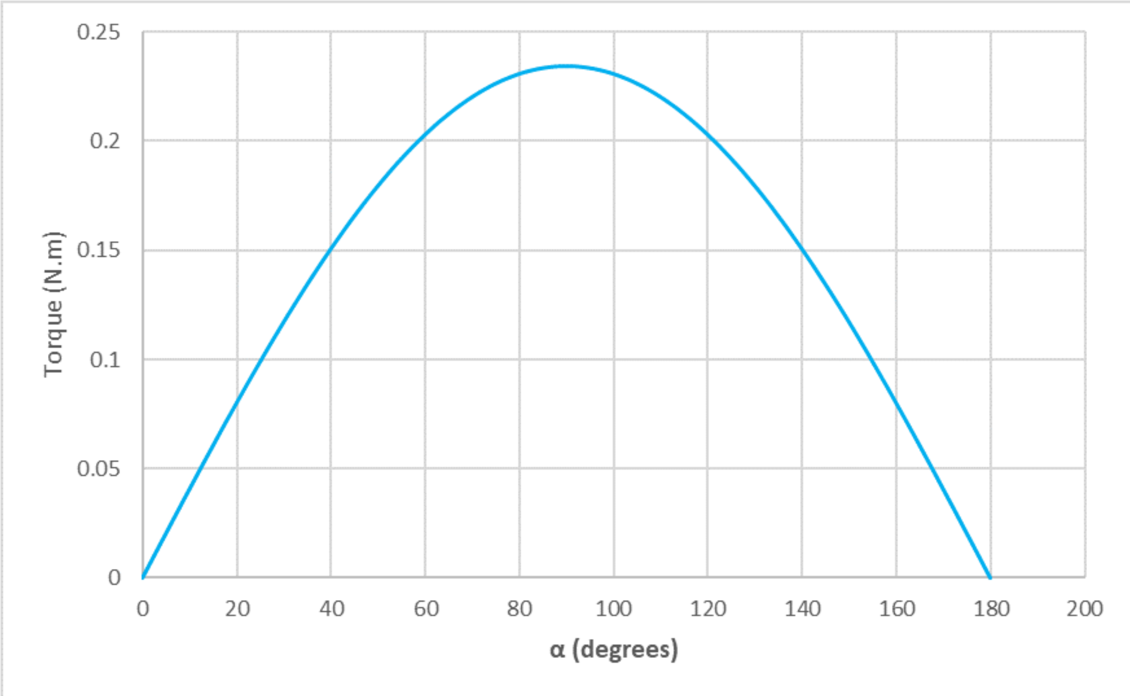


Figure 107: Graph showing the required torque at the different angles the disc arm makes with the horizontal

The maximum torque shown in Figure 107 is 0.235 N.m. This is the minimum torque that the servo motors need to produce. This occurs when the slider-crank is in the position shown by Figure 105. This maximum value will be shown by calculation. Calculating the minimum torque requirement of the servo motors:

$$T_{beat} = F_f \times d = 4.265 \times 0.055 = 0.235\ N.m = 2.396\ kg.cm$$

The servo motors require at least 0.235 N.m of torque in order to drive the beater. This torque requirement seems low and may be from an oversimplification of the real world application. Servo motors with higher rated torques will be used.

D.3 Horizontal linear actuator

D.3.1 Torque requirement of the servo motor mounted on the horizontal linear actuator

Table 7: Nomenclature for torque requirement of servo motor mounted on linear actuator

Symbol	Description
F_{but}	Force required to push the push button and change its state
m_{but}	Mass measured off the kitchen scale
g	Gravitational acceleration
L_{horn}	Approximate length of servo horn
T_{select}	Torque requirement of selector servo motor

These calculations were important in specifying the servo motor for this sub-assembly.

The required force to push the push button in and out was determined using a click pen and a kitchen scale as seen in Figure 108. The pen that was used was the Pilot G-2 0.7. This is the pen from which the necessary parts will be extracted. The pen was selected based on its apparent strength when in the extended position. The inability to access laboratories and the necessary equipment, in this case a spring balance, meant that this could only be confirmed through inspection. The pen did not break when a large force was placed on it in the direction as shown in Figure 109.

Figure 108: The way the necessary force to click the pen in and out was determined

Figure 109: The direction in which the force was applied to the pen

The scale read 550 g, using a safety factor of 2. The mass, m_{but} , becomes 1.1 kg. This was used to determine the required force, F_{but}. The calculation is shown below:

$$F_{but} = m_{but}g = 1.1 \times 9.81 = 10.791\ N$$

Assuming the length of the servo horn, L_{horn}, in the worst case, is approximately 30 mm. The torque, T_{select}, requirement of the servo motor is found:

$$T_{select} > F_{but}L_{horn} = 10.791 \times 0.03 = 0.324\ N.m$$

Or

$$T_{select} > m_{but}L_{horn} = 1.1 \times 3 = 3.3\ kg.cm$$

The torque of the selected servo motor should be above 0.324 $N.m$ or 3.3 $kg.cm$. This is a conservative estimate of the torque requirement. Research conducted has shown that most servo motors, other than micro servo motors, would be suitable for this application.

D.3.2 Specifying the stepper motor used to control the horizontal linear actuator

Table 8: Nomenclature for the horizontal linear actuator calculations

Symbol	Description
$\mathrm{m_{total1}}$	Total mass to be moved by horizontal linear actuator
$\mathrm{m_{smm}}$	Mass of the servo motor mount
$\mathrm{m_{sm}}$	Mass of the servo motor
ρ_{PLA}	Density of PLA
$\mathrm{V_{smm}}$	Volume of servo motor mount
$\mathrm{W_1}$	Weight of mass of servo motor and its mount
g	Gravtitational accelerations
$\mathrm{d_m}$	Mean diameter of lead screw
$\mathrm{d_o}$	Outer diameter of lead screw
$\mathrm{P_s}$	Pitch of lead screw
f	Coefficient of running friction between lead screw and nut threads
f_{start}	Coefficient of starting friction between lead screw and nut threads
η_3	Safety factor used in specifying the stepper motor used to control the horizontal linear actuator
$\mathrm{d_c}$	Collar diameter
f_c	Collar coefficient of running friction
f_{cstart}	Collar coefficient of starting friction
$\mathrm{L_s}$	Lead of lead screw
α_n	Thread angle measured from the normal plane
$\mathrm{M_{trunninghor}}$	Running torque requirement for stepper motor controlling the horizontal linear actuator
$\mathrm{M_{tstartinghor}}$	Starting torque requirement for the stepper motor controlling the horizontal linear actuator

The load on the power screw is from the mass of the servo motor and servo motor mount. The mass of the servo motor mount was found from the volume of the Solidworks part model as well as the density of PLA. According to the Solidworks model the volume of material used for the servo motor mount equates to 69399.82 $\mathrm{mm^3}$. The density of PLA is commonly 1.24 $\mathrm{g/cm^3}$ [38]. The mass of the servo motor mount is determined below:

$$m_{smm} = \rho_{PLA} \times V_{smm} = 1.24 \times 10^{-6} \times 69399.82 = 0.08606\ kg$$

The mass of the servo motor was taken from the motors specification sheet. The total mass calculation can be seen below:

$$m_{total1} = m_{smm} + m_{sm} = 0.08606 + 0.055 = 0.141\ kg$$

The total load on the motor becomes:

$$W_1 = m_{total1} \times g = 0.141 \times 9.81 = 1.384\ N$$

Table 9 shows the characteristics of the lead screw.

Table 9: Characteristics of lead screw

Symbol	Value
α_n	14.5 deg
L_s	8 mm
d_o	8 mm
P_s	2 mm

Calculating the mean diameter of the lead screw, d_m, from the known characteristics of the lead screw.

$$d_m = d_o - 2 \times \frac{P_s}{4} = 8 - 2 \times \frac{2}{4} = 7\ mm$$

The coefficient of friction that exists between the brass nut threads and the steel threads of the lead screw is between 0.15 and 0.19 running [39]. In order to be conservative it will be assumed that the friction coefficient is the upper limit of the range, i.e. 0.19, for the coefficient of running and that the coefficient of starting friction is 4/3 of the running coefficient of friction. A safety factor of 4 will be added to the coefficient of running friction. The final values for the coefficients of friction that will be used in calculation can be seen below:

$$f = 0.19 \times \eta_3 = 0.19 \times 4 = 0.76$$

$$f_{start} = \frac{4}{3} \times f = \frac{4}{3} \times 0.76 = 1.013$$

There is no collar present in the arrangement and thus d_c, f_c and f_{cstart} are set to zero. This power screw is operating horizontally, therefore there is no raising or lowering of the load. Instead the equation for the torque required for raising the load will be used as this would be the worst case scenario. The torque requirements during the different modes of operation can be seen below:

$$M_{trunninghor} = \frac{W_1 d_m}{2} \times \frac{f \pi d_m + L_s \cos(\alpha_n)}{\pi d_m \cos(\alpha_n) - f L_s} + \frac{W_1 f_c d_c}{2} = 0.00779\ N.m$$

$$M_{tstartinghor} = \frac{W_1 d_m}{2} \times \frac{f_{start} \pi d_m + L_s \cos(\alpha_n)}{\pi d_m \cos(\alpha_n) - f_{start} L_s} + \frac{W_1 f_{cstart} d_c}{2} = 0.0110\ N.m$$

The condition for self locking need not be checked as the motor will be energized and this will prevent the undesired turning of the lead screw. The motor therefore must supply a minimum torque of 0.011 N.m. This seems like a reasonable torque requirement for a motor in this application.

D.4 Heddle plates/warp threads

D.4.1 The vertical displacement of the warp threads necessary

Table 10: Nomenclature for the vertical displacement of warp threads

Symbol	Description
A	Location of breast beam
B	Location of beater during picking
C	Location of heddle plate
D1	Distance between breast beam and beater during picking
D2	Distance between beater and heddle plate during picking
H1	Height of shed
H2	Vertical height of lifted warp threads

The warp threads at the point where they interface with the heddle plates need to move vertically in order to create a shed of a sufficient height for picking to take place.

The boat shuttle designed has a height of 20 mm. The shed height was set to 60 mm. This shed height is generous and could be made smaller if necessary. This height is represented by 'H1' in Figure 110.

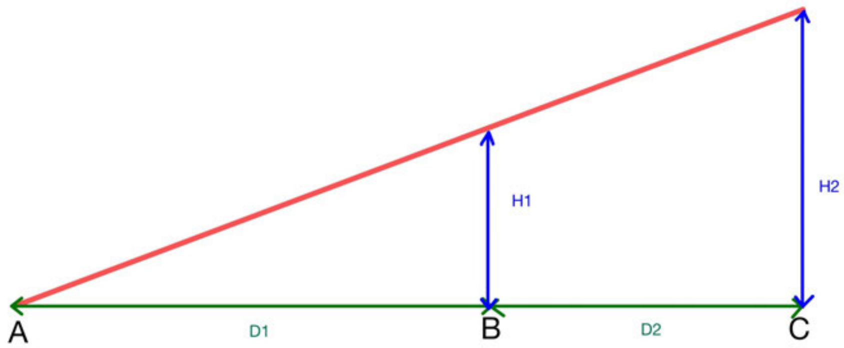


Figure 110: The distances and location of components

Distance D1 and D2 seen in Figure 110 were determined from the Solidworks model. The necessary vertical displacement of the heddle plates, H2, in order to create the desired shed height, H1, could be calculated as shown below.

$$\frac{H2}{D2 + D1} = \frac{H1}{D1}$$

$$\frac{H2}{98 + 155} = \frac{60}{155}$$

$$H2 = 97.94\ mm$$

There is to be more than 97.94 mm of space above the frame that holds the pen click mechanisms for the vertical linear actuator to move the frame in order to create a sufficient shed for the picking operations to take place.

D.4.2 Specifying the stepper motor used to move frame that houses the pen click mechanisms (vertical linear actuator)

Table 11: Nomenclature for the vertical linear actuator calculations

Symbol	Description
m_{total2}	Total mass to be raised and lowered by vertical linear actuator
m_{frame}	Mass of the meranti frame
m_{plates}	Mass of perspex heddle plates
$m_{pushact}$	Mass of pen click mechanisms
W_2	Weight of mass of frame, plates and pen click mechanisms
g	Gravtitational acceleration
T_{warp}	Tension in warp threads
d_m	Mean diameter of lead screw
d_o	Outer diameter of lead screw
P_s	Pitch of lead screw
f	Coefficient of running friction between lead screw and nut threads
f_{start}	Coefficient of starting friction between lead screw and nut threads
η_4	Safety factor used in specifying the stepper motor used to control the vertical linear actuator
d_c	Collar diameter
f_c	Collar coefficient of running friction
f_{cstart}	Collar coefficient of starting friction
L_s	Lead of lead screw
α_n	Thread angle measured in the normal plane
$M_{traisingrunning}$	Raising running torque needed from the stepper motor used to control the vertical linear actuator
$M_{traisingstarting}$	Raising starting torque needed from the stepper motor used to control the vertical linear actuator
$M_{tloweringrunning}$	Lowering running torque needed from the stepper motor used to control the vertical linear actuator
$M_{tloweringstarting}$	Lowering starting torque needed from the stepper motor used to control the vertical linear actuator

The load on the power screw is from the tensions in the warp threads as well as the mass of the components that the power screw supports.

The mass of the total system that the power screw supports is made up of the frame that holds the pen click mechanisms, the pen click mechanisms and the heddle plates. The masses of the frame that holds the pen click mechanisms and the heddle plates were determined from the Solidworks model and the mass of the pen click mechanisms was determined using a kitchen scale. The total mass calculation can be seen below:

$$m_{total2} = m_{frame} + 38 \times m_{plates} + 38 \times m_{pushact} = 0.189 + 38 \times 0.006 + 38 \times 0.002 = 0.493\ kg$$

Assuming the maximum force from the warp threads in tension, i.e. when all threads have been lifted, the total load on the power screw can be determined:

$$W_2 = m_{total2} \times g + 38 \times T_{warp} = 0.493 \times 9.81 + 38 \times 2.747 = 109.221\ N$$

Table 12 shows the characteristics of the lead screw.

Table 12: Characteristics of lead screw

Symbol	Value
α_n	14.5 deg
$\mathrm{L_s}$	8 mm
$\mathrm{d_o}$	8 mm
$\mathrm{P_s}$	2 mm

Calculating the mean diameter of the lead screw, $\mathrm{d_m}$, from the known characteristics of the lead screw.

$$d_m = d_o - 2 \times \frac{P_s}{4} = 8 - 2 \times \frac{2}{4} = 7\ mm$$

The coefficient of friction that exists between the brass nut threads and the steel threads of the lead screw is between 0.15 and 0.19 running [39]. In order to be conservative it will be assumed that the friction coefficient is the upper limit of the range, i.e. 0.19, for the coefficient of running friction and that the coefficient of starting friction is 4/3 of the running coefficient of friction. A safety factor of 4 will be added to the coefficient of running friction. The final values for the coefficients of friction that will be used in calculation can be seen below:

$$f = 0.19 \times \eta_4 = 0.19 \times 4 = 0.76$$
$$f_{start} = \frac{4}{3} \times f = \frac{4}{3} \times 0.76 = 1.013$$

There is no collar present in the arrangement and thus $\mathrm{d_c}$, f_c and f_{cstart} are set to zero. The torque requirements during the different modes of operation can be seen below:

$$M_{traisingrunning} = \frac{W_2 d_m}{2} \times \frac{f \pi d_m + L_s \cos(\alpha_n)}{\pi d_m \cos(\alpha_n) - f L_s} + \frac{W_2 f_c d_c}{2} = 0.615\ N.m$$

$$M_{traisingstarting} = \frac{W_2 d_m}{2} \times \frac{f_{start} \pi d_m + L_s \cos(\alpha_n)}{\pi d_m \cos(\alpha_n) - f_{start} L_s} + \frac{W_2 f_{cstart} d_c}{2} = 0.871\ N.m$$

$$M_{tloweringrunning} = \frac{W_2 d_m}{2} \times \frac{f \pi d_m - L_s \cos(\alpha_n)}{\pi d_m \cos(\alpha_n) + f L_s} + \frac{W_2 f_c d_c}{2} = 0.125\ N.m$$

$$M_{tloweringstarting} = \frac{W_2 d_m}{2} \times \frac{f_{start} \pi d_m - L_s \cos(\alpha_n)}{\pi d_m \cos(\alpha_n) + f_{start} L_s} + \frac{W_2 f_{cstart} d_c}{2} = 0.189\ N.m$$

The condition for self locking need not be checked as the motor will be energized and this will prevent the undesired turning of the lead screw. The motor therefore must supply a minimum torque of 0.871 N.m. This seems like a reasonable torque requirement for the motor in this application.

Appendix E Prototyping

Due to the pandemic it was difficult to complete any kind of detailed prototyping before the final design was completed. However, it was essential to verify the operation of the pen click mechanism in its ability to operate as a selector for the warp threads as well as its ability to carry the load of the warp threads in tension.

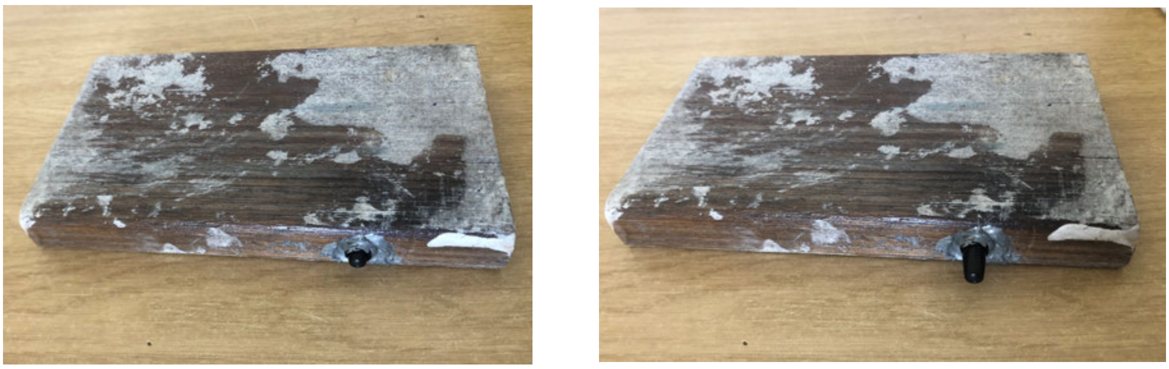
E.1 Pen click mechanism as a selector

The pen click mechanisms ability to retract and extend when the pen was dismantled and press fitted into wood was essential to this project. In order to test this, a pen was dismantled using a Dremel. The parts of the pen that were used can be seen in Figure 111 which is a repeated image.

Figure 111: A dismantled pen

A hole was then drilled into a scrap piece of wood. The intention for the final part that holds all the pen click mechanisms was to have them press fit into the holes. Due to the lockdown and not having the correct drill bit a slightly larger hole needed to be made for the prototype. The pen click mechanism then had to be held in place with Pratley's Putty.

The prototype was successful. The pen click mechanism was able to click in and out while mounted in the wooden frame. An image of the pen click mechanism in its two states, i.e. retracted and extended, can be seen in Figure 112a and Figure 112b.



(a) The pen click mechanism retracted

(b) The pen click mechanism extended

Figure 112: The pen click mechanism mounted in wood in its two states

E.2 Pen click mechanisms ability to carry a load

The pen click mechanisms ability to carry the load of the warp threads in tension was another vital part of the design. For this test the same cup that had been used to estimate the tension in warp threads, as described in Section D.1.1, was allowed to hang from the pen that had been mounted in the scrap piece of wood (in its extended state). This can be seen in Figure 113.

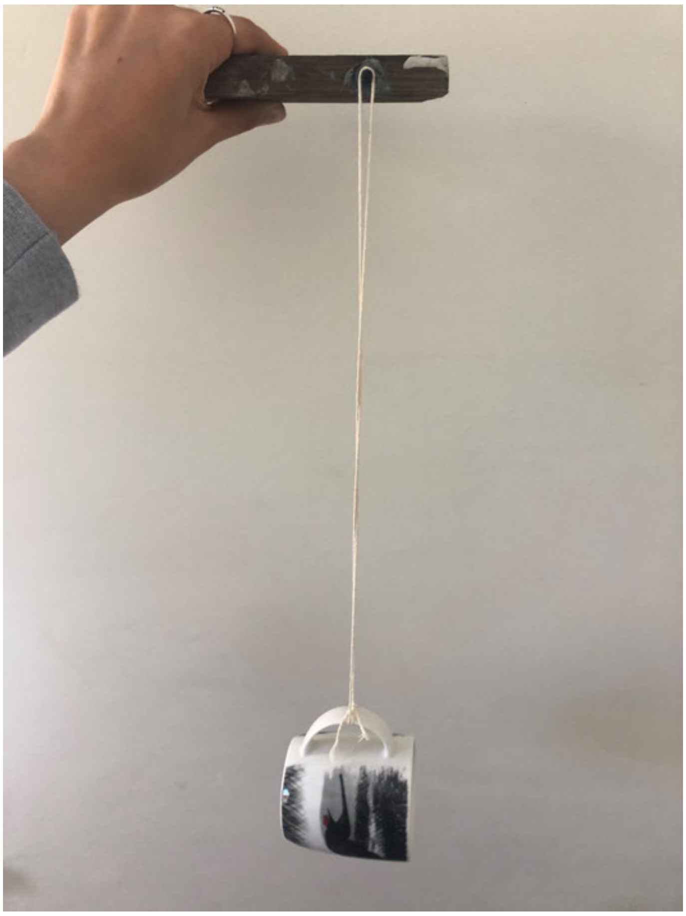


Figure 113: The pen click mechanism supporting a load

Importantly the pen click mechanism was not only able to support the load but exhibited no permanent deformation to its shape i.e. it could still be clicked in and out after the load had been removed.

Appendix F Budget and budget variance

The budget allocated to this project by the University of Cape Town (UCT) was R1500. The initial budget allocation can be seen in Table 13. The total is R2115.57 including tax and excluding tax is R1798.23. This total is just above the budget allocated by UCT. The amount the project was over budget by can be attributed to the cost of the motor drivers.

The final budget breakdown can be seen in Table 14. Table 14 shows the purchases made through UCT and the purchases made for future use and that were low-cost. If the university decides to use this project as a demo model for the department most of these expenses listed under the purchases for future use and other low-cost purchases will be reimbursed.

Table 14 shows costs including tax. Including tax the purchases through UCT are R1754.01. Excluding taxes the purchases through UCT are calculated to be R1490.91. Thus, the expenses to UCT for this project were within the prescribed allocation. However, as can be seen in Table 14 the overall project costs were over the allocated budget by the University. The overall cost being R4852.50 including tax. This can mainly be attributed to the number of actuators and drivers that needed to be used. In order to achieve the level of desired automation this required extra funding.

The final budget breakdown varies quite dramatically from the initial budget breakdown. One reason for the differences was the inability to borrow motors from UCT. Another reason for the difference can be attributed to under-budgeting for certain items. For example, the heddle plate guide was expected to cost approximately R100. However, the final cost was almost triple that amount. It was assumed that sufficient wool could be found from leftover wool, however, this was not the case and wool had to be purchased.

It should be noted that the costs for this project would have been higher had Pilot Pens not sponsored this project with 50 of their G-2 07 Pilot Pens. Thus, the price per unit for the G-2 07 Pilot Pens is reflected as R0.00 in Table 14.

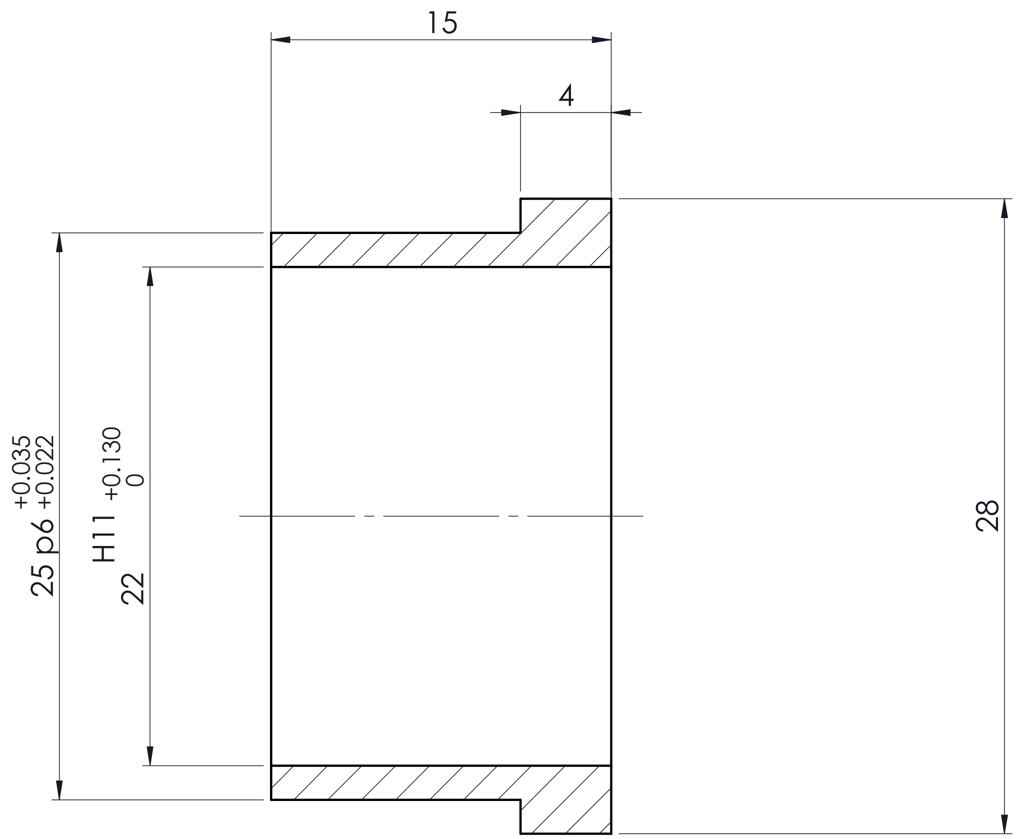
Table 13: Initial Budget Allocation

Part	Intended vendor	Price per unit	QTY	Total price
Raw materials				
Hardboard for frame and beater	Leroy Merlin	R114.00	2	R228.00
Perspex for heddle plates	Maizey Plastics	R278.00	1	R278.00
Flexible coupler for stepper motor, leadscrew connection	Netram	R40.00	2	R80.00
Leadscrew and nut for linear actuator and frame	Netram	R195.00	2	R390.00
GT2 timing belt	Netram	R39.00	2	R78.00
Aluminium bar for frame	Netram	R40.00	3	R120.00
Wool	From home	R0.00	0	R0.00
Motors				
Servo motor	Borrow from UCT	R0.00	3	R0.00
Stepper motor	Borrow from UCT	R0.00	3	R0.00
Stepper motor driver	Netram	R204.00	3	R612.00
3D printing by mass	**(R700/kg)**			
Ratchet	UCT	R14.08	2	R28.16
Pawl	UCT	R6.22	2	R12.45
Pulley	UCT	R34.05	2	R68.11
Dual pulley	UCT	R19.63	1	R19.63
Shuttle boat	UCT	R33.18	1	R33.18
Bobbin	UCT	R3.95	1	R3.95
Servo motor mount	UCT	R60.24	1	R60.24
Vertical limit switch mount	UCT	R2.23	1	R2.23
Horizontal limit switch mount	UCT	R1.62	1	R1.62
Vulcan steel				
Aluminium Heddle plate frame	Vulcan Steel	R100.00	1	R100.00
Total cost				R2 115.57

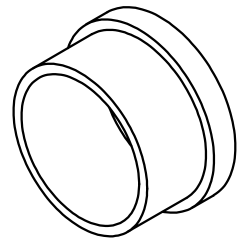
Table 14: Budget Allocation

Purchases through UCT				
Part	**Purchased from**	**QTY**	**Price per unit**	**Total price**
3mm Hardboard sheet (1.22m x 1.4m)	TimberCity	1	R 243.65	R 243.65
2mm Perspex sheet (720mm x 400mm)	Maizey Plastics	1	R 119.59	R 119.59
TB6600 stepper motor driver	Netram Technologies	1	R 205.10	R 205.10
Smooth round bar (8mm diameter, 500mm length)	Netram Technologies	3	R 40.00	R 120.00
6mm GT2 open ended timing belt (1m)	Netram Technologies	2	R 39.00	R 78.00
Flexible couple (6.35mm - 8mm)	Netram Technologies	1	R 40.30	R 40.30
Flexible couple (5mm - 8mm)	Netram Technologies	1	R 40.30	R 40.30
Stainless steel lead screw 500mm Tr8x8 and brass nut	Netram Technologies	2	R 195.00	R390.00
Heddle Plate Guide	Vulcan Steel	1	R287.50	R287.50
3D printing (this cost is an estimation)	UCT	N/A	R 229.57	R 229.57
			Total	R 1 754.01

Purchases for future use and other lowcost purchases				
Part	**Purchased from**	**QTY**	**Price per unit**	**Total price**
Arduino Mega 2560 R3	Netram Technologies	1	R 264.20	R 264.20
TB6600 stepper motor driver	Mantech	1	R 230.00	R 230.00
NEMA17	Netram Technologies	1	R 247.65	R 247.65
DRV8825	Netram Technologies	1	R 75.00	R 75.00
DRV8825 breakout board	Netram Technologies	1	R 40.00	R 40.00
DC power supply 12V2A out 220V AC input	Netram Technologies	1	R 79.90	R 79.90
DC barrel jack adapter	Netram Technologies	1	R 12.00	R 12.00
Vero board	Netram Technologies	1	R 85.74	R 85.74
Fasteners	Bolt It & Mica	N/A	R 300.00	R 300.00
Wool	Woolworld	4	R 88.00	R 352.00
Wood	Builders Warehouse	N/A	R 300.00	R 300.00
NEMA23	Communica	2	R 340.00	R 680.00
BSK servo motor MG995	Communica	3	R 144.00	R 432.01
GT2 Pilot Pens	Pilot Pens	50	R0.00	R0.00
			Total	R 3 098.49
			Overall total	R 4 852.50



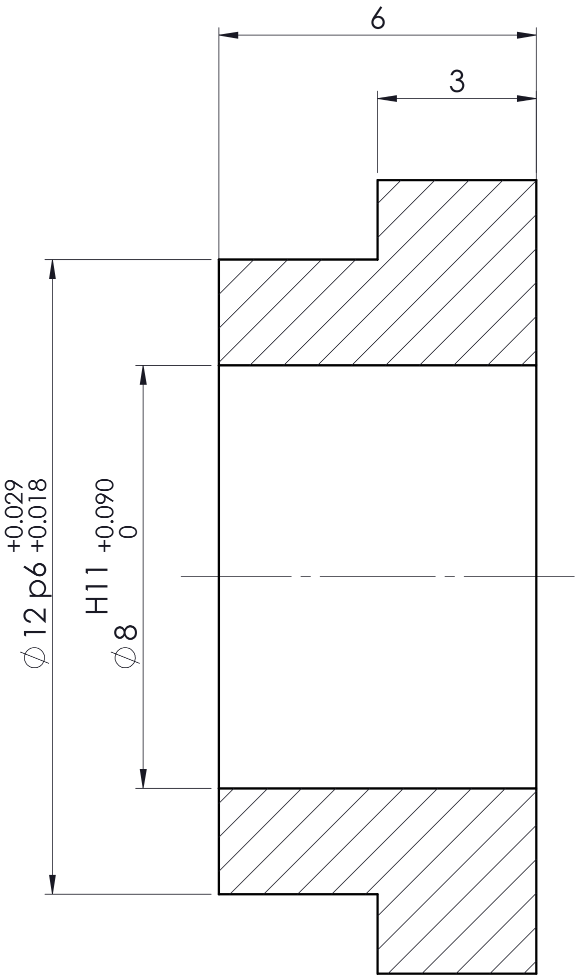
SECTION A-A
SCALE 3 : 1



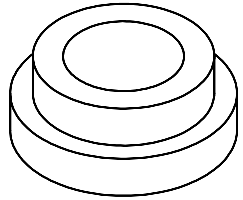
SCALE 1:1

4 OFF

Scale: 3:1 on A4	University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Cloth Roll and Warp Beam Bushing		
Checked :	Material : Nylon 101	Drawing Number : YDKANJ001-013	Rev. : A	Sheet : 1 of 1



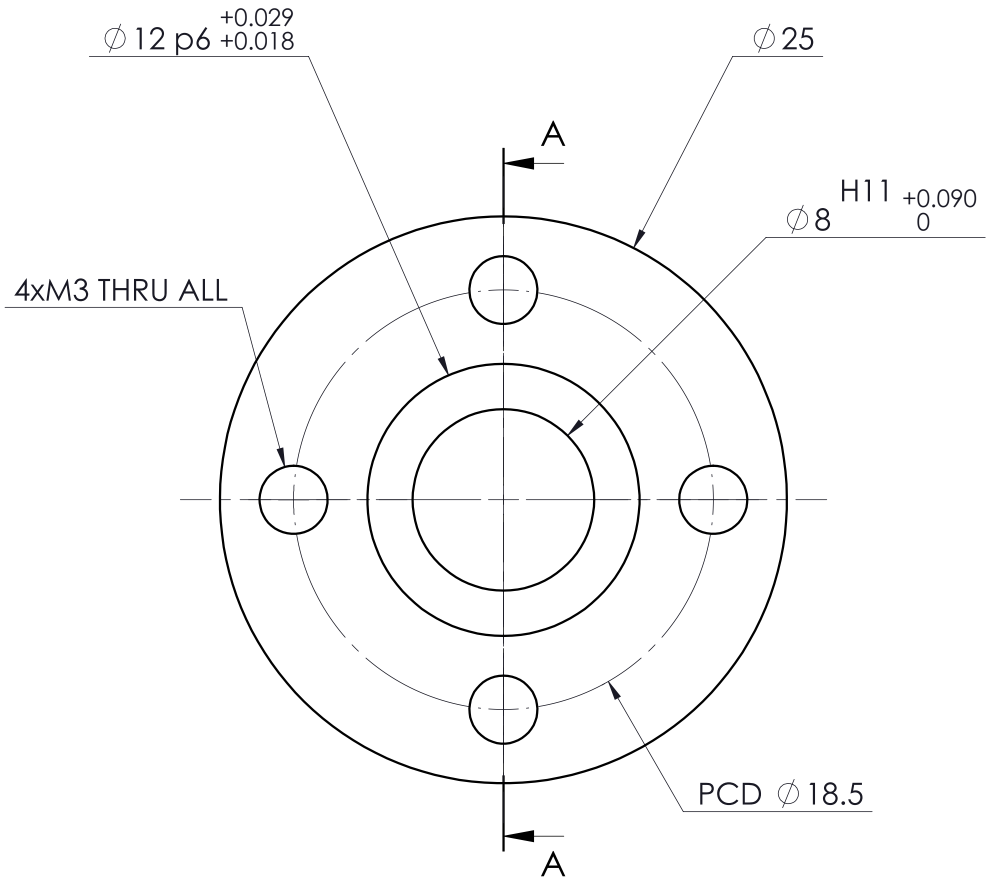
SECTION A-A

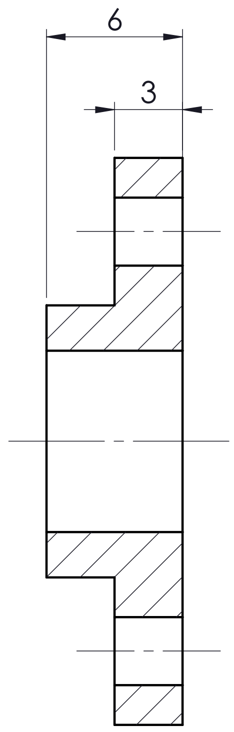


SCALE 2:1

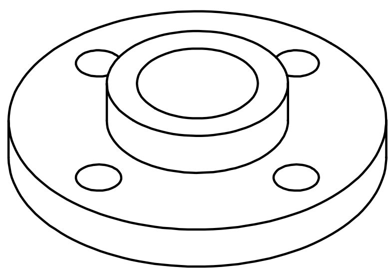
4 OFF

	Scale: 7:1 on A4	University of Cape Town Department of Mechanical Engineering		
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Horizontal Linear Actuator Bushing		
Checked :	Material : Nylon 101	Drawing Number : YDKANJ001-032	Rev. : A	Sheet : 1 of 1





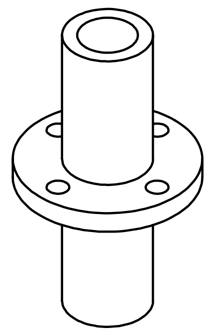
SECTION A-A



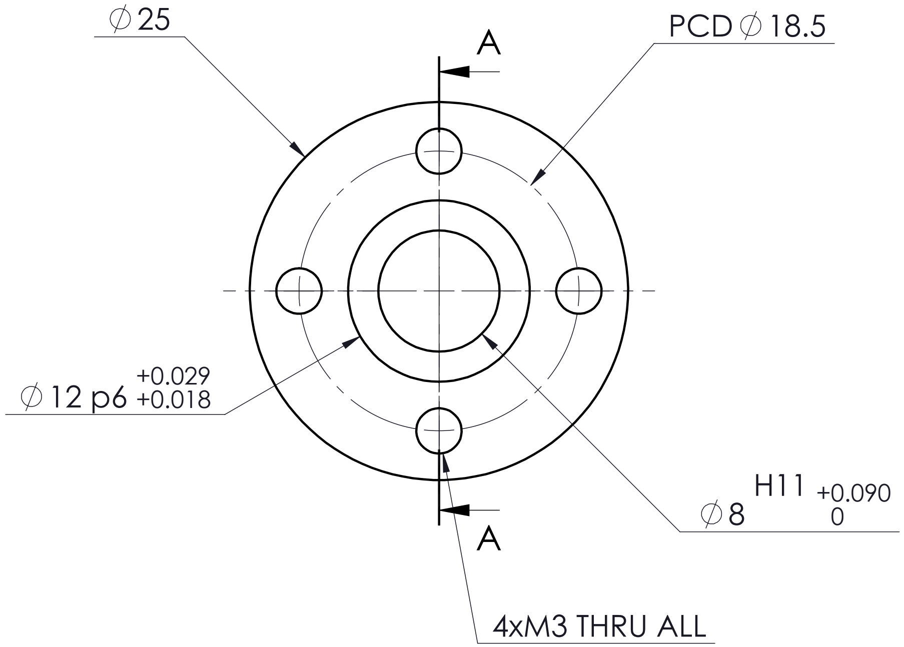
SCALE 2:1

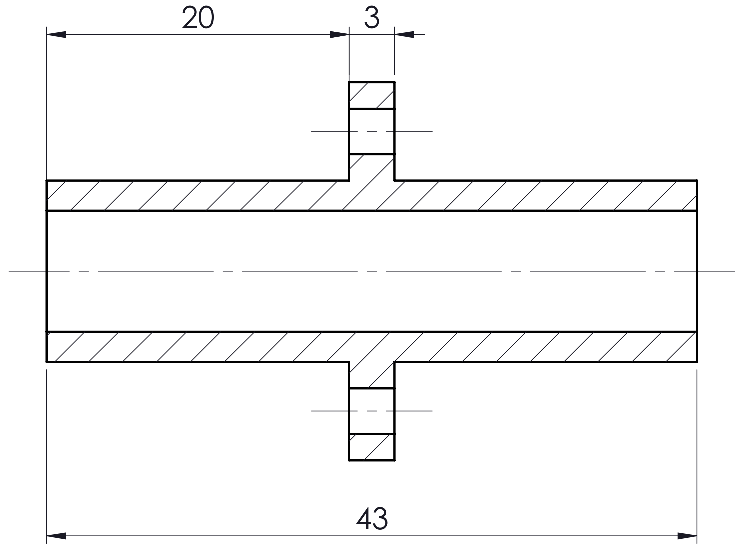
7 OFF

	Scale: 3:1 on A4	University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Vertical Linear Actuator Bushing			
Checked :	Material : Nylon 101	Drawing Number : YDKANJ001-027	Rev. : A	Sheet : 1 of 1	



SCALE 1:1

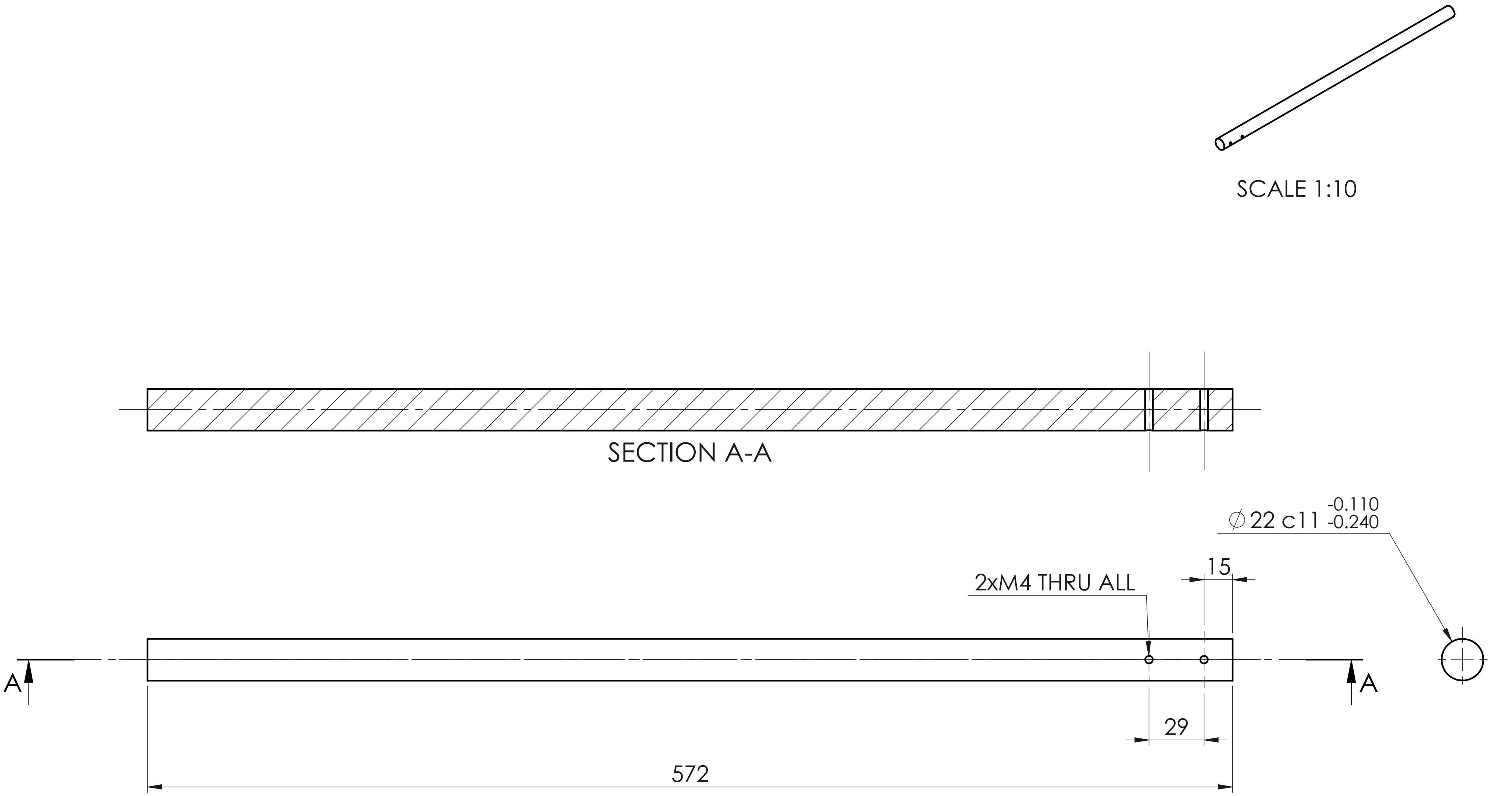




SECTION A-A

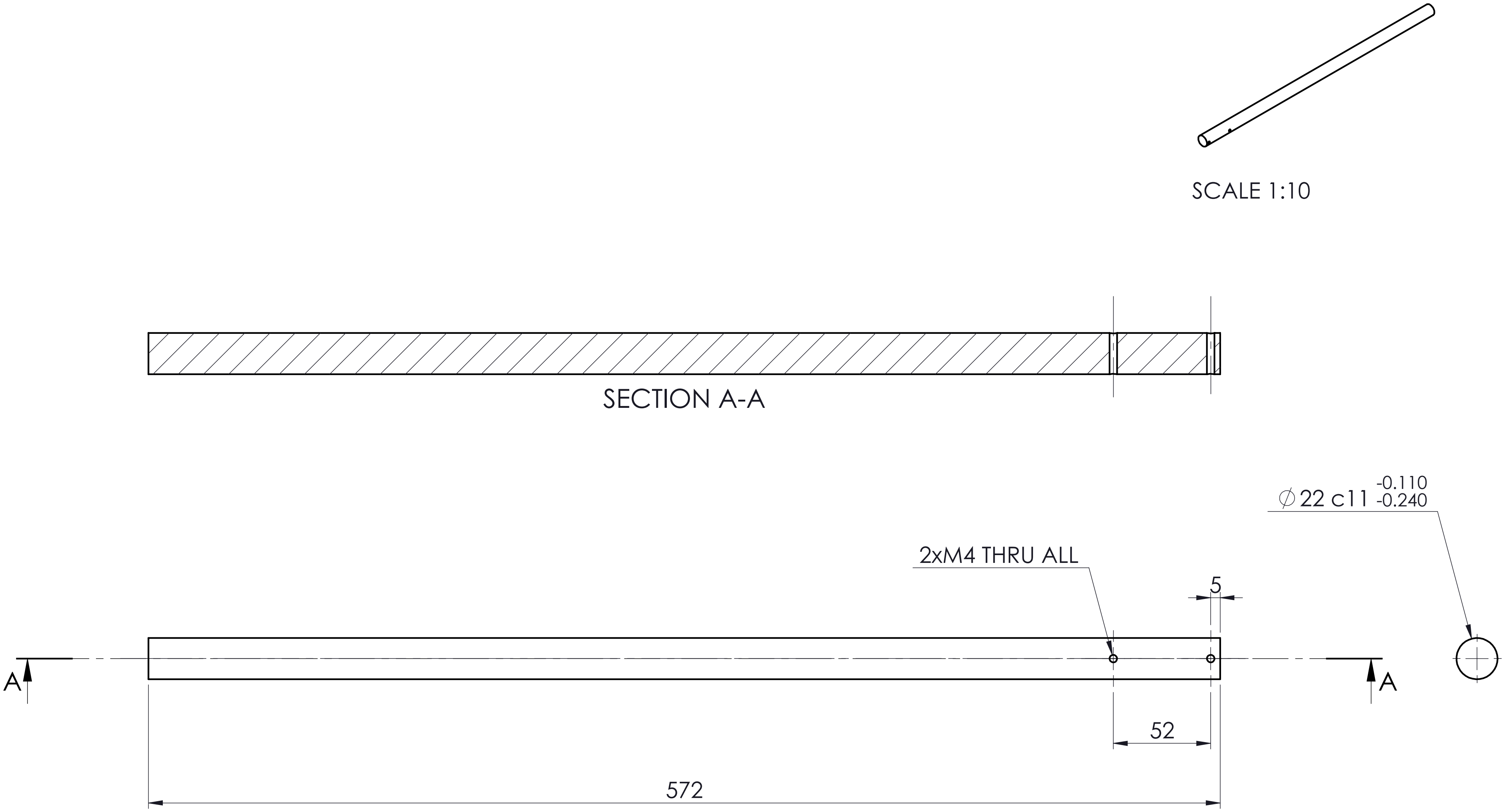
2 OFF

	Scale: 2:1 on A4	University of Cape Town Department of Mechanical Engineering		
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Vertical Linear Actuator Bushing Long		
Checked :	Material : Nylon 101	Drawing Number : YDKANJ001-066	Rev. : A	Sheet : 1 of 1



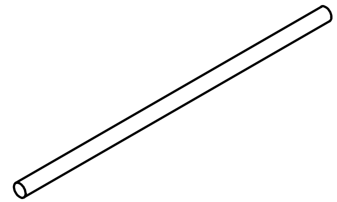
1 OFF

Scale: 1:3 on A4	University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Warp Beam		
Checked :	Material : 22 mm Wooden Dowel	Drawing Number : YDKANJ001-059	Rev. : A	Sheet : 1 of 1

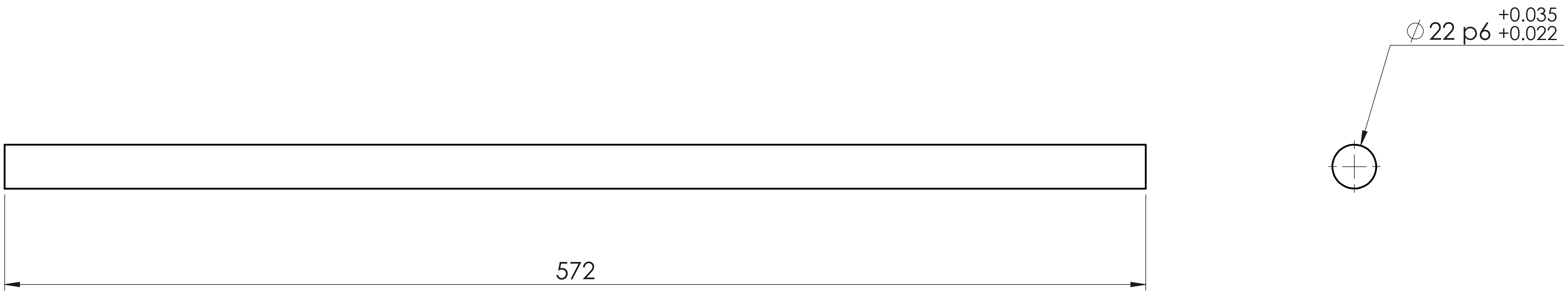


1 OFF

Scale: 1:3 on A4	University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Cloth Roll		
Checked :	Material : 22 mm wooden dowel	Drawing Number : YDKANJ001-012	Rev. : A	Sheet : 1 of 1



SCALE 1:10



2 OFF

University of Cape Town
Department of Mechanical Engineering

Scale: 1:3 on A4

Drawn By: YDKANJ001 Anjana Yodaiken

All un-toleranced dimensions to adhere to ISO 2768-m

Title: Back Rest and Breast Beam

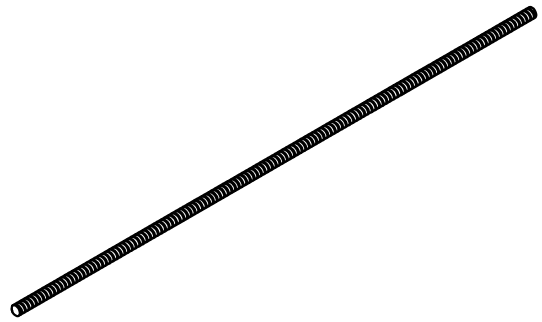
Checked :

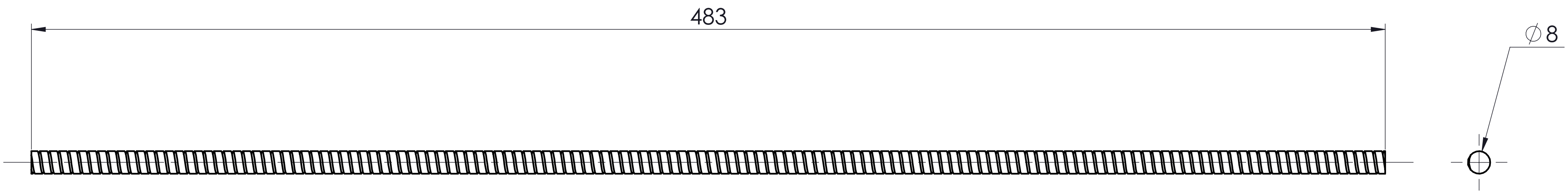
Material : 22 mm wooden dowel

Drawing Number : YDKANJ001-011

Rev. : A

Sheet : 1 of 1

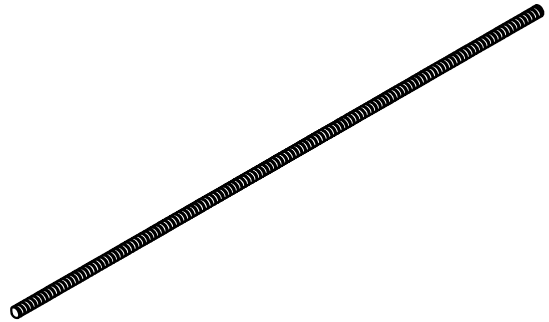




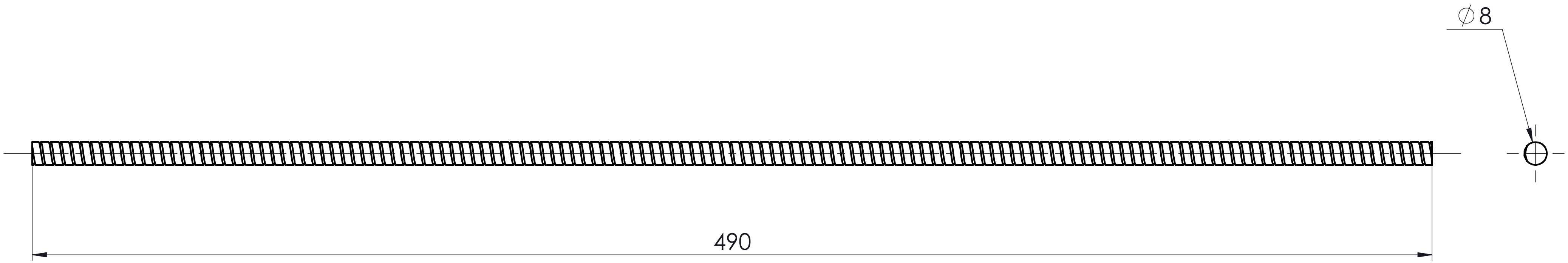
1 OFF

NOTES:
THIS IS A MODIFICATION OF AN EXISTING PART

Scale: 1:2 on A4	University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Vertical Linear Actuator Lead Screw		
Checked :	Material : Stainless Steel	Drawing Number : YDKANJ001-030	Rev. : A	Sheet : 1 of 1



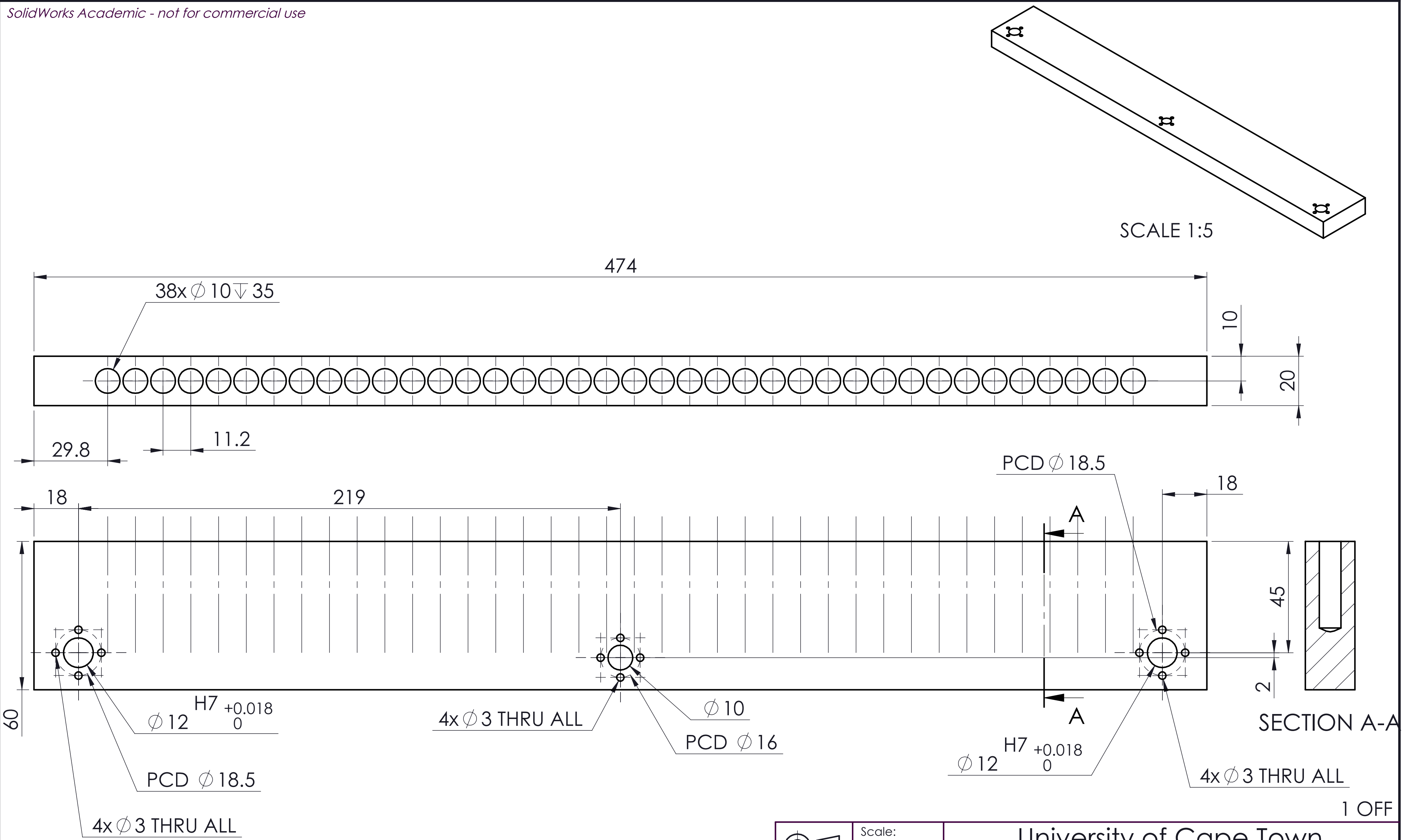
SCALE 1:5



1 OFF

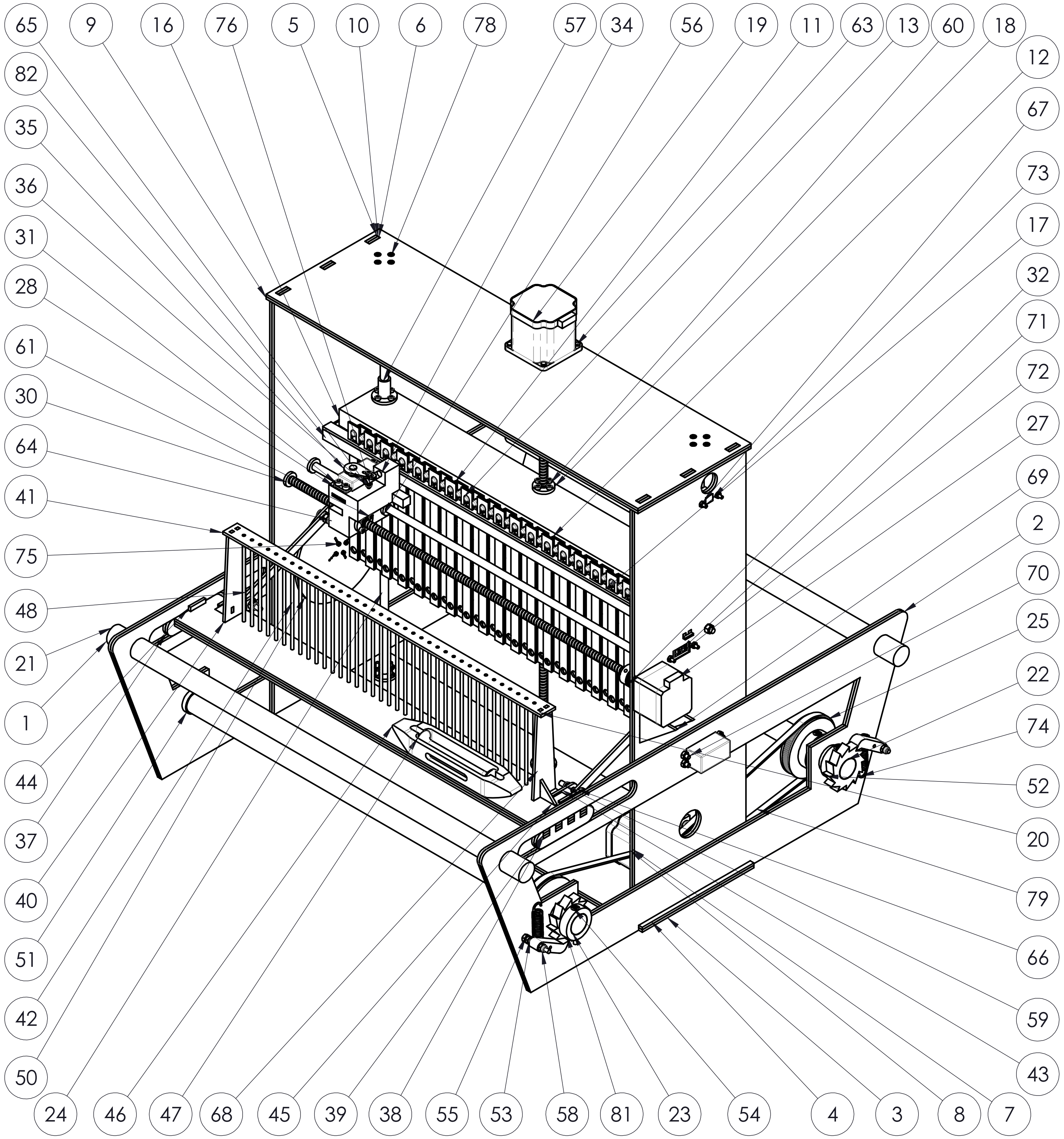
NOTES:
THIS IS A MODIFICATION OF AN EXISTING PART

	Scale: 1:2 on A4	University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Horizontal Linear Actuator Lead Screw			
Checked :	Material : Stainless Steel	Drawing Number : YDKANJ001-035	Rev. : A	Sheet : 1 of 1	



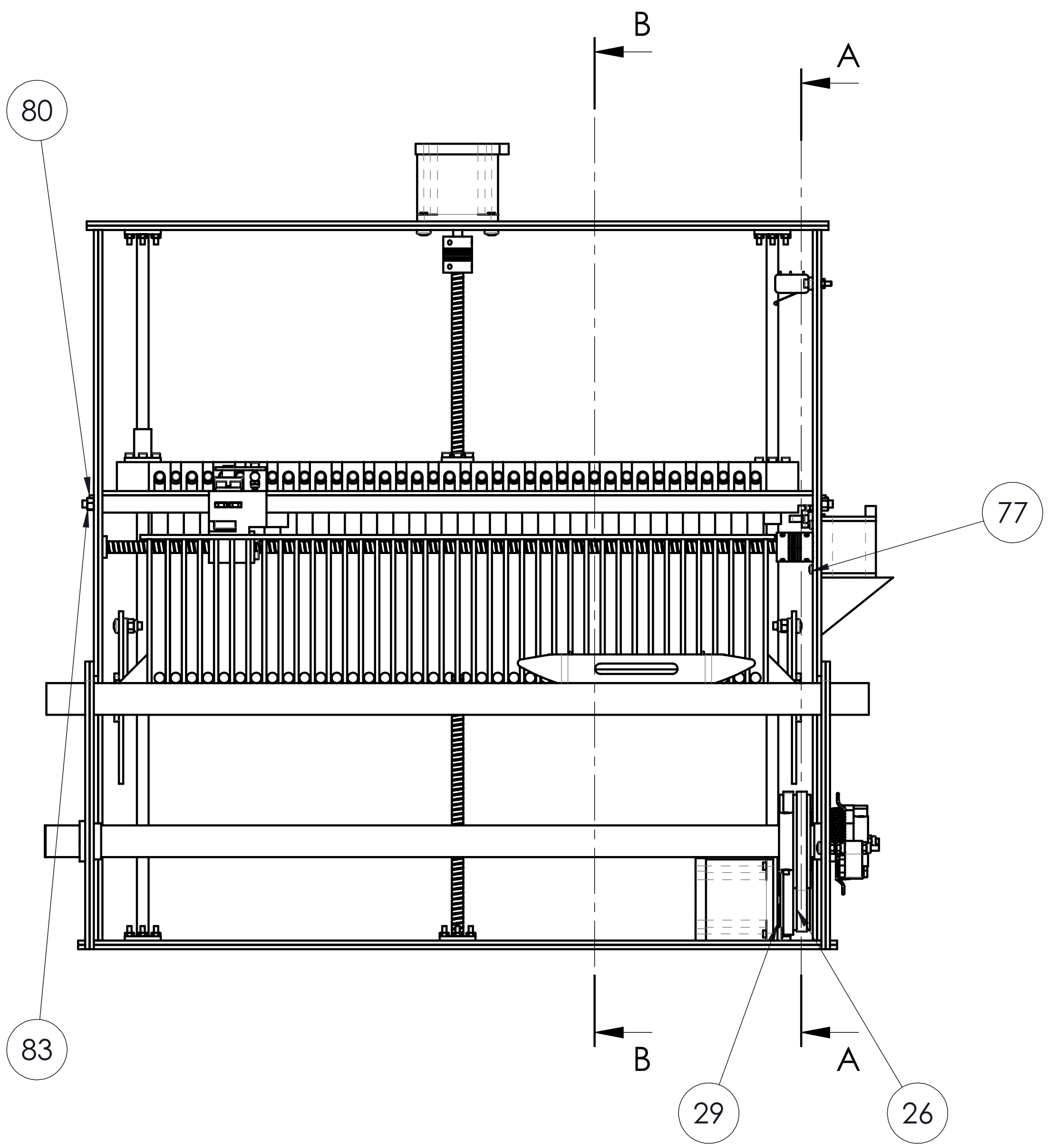
1 OFF

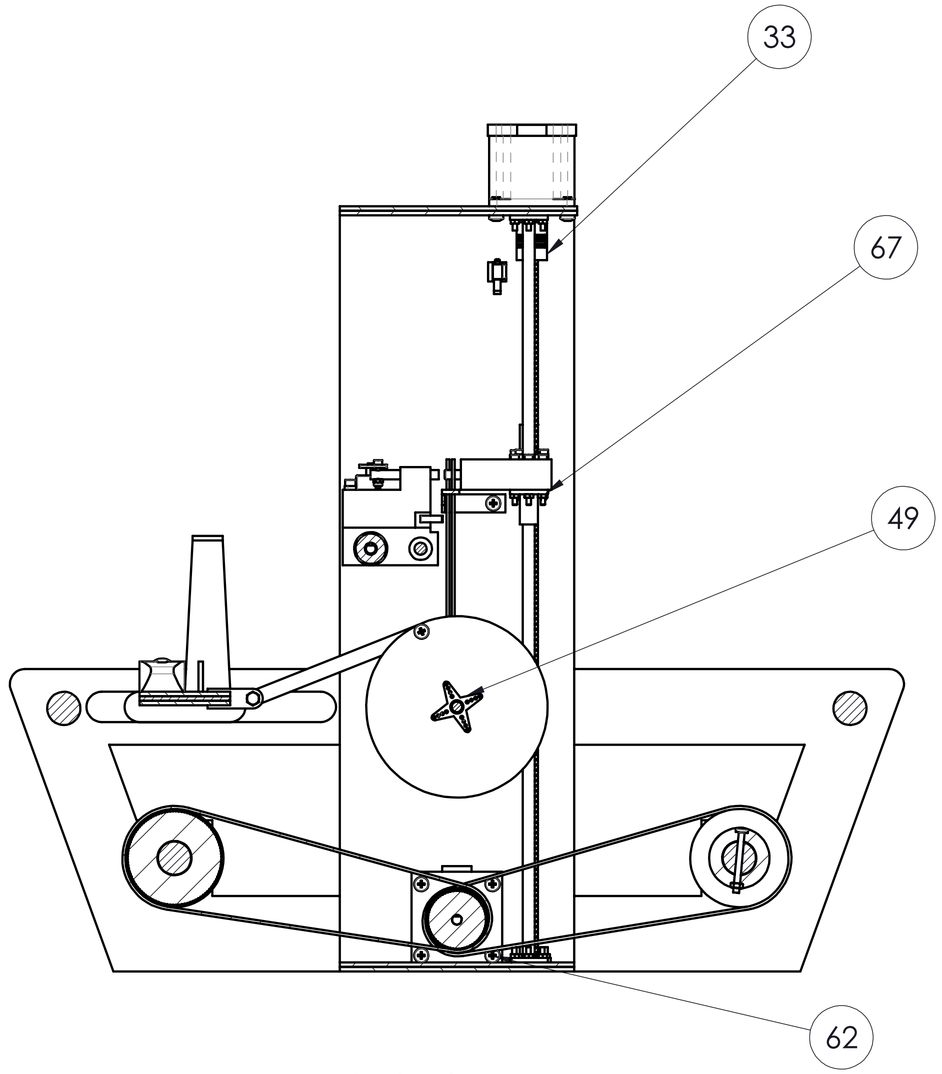
Scale: 1:2 on A4	University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Push Actuator Frame		
Checked :	Material : Meranti	Drawing Number : YDKANJ001-022	Rev. : A	Sheet : 1 of 1



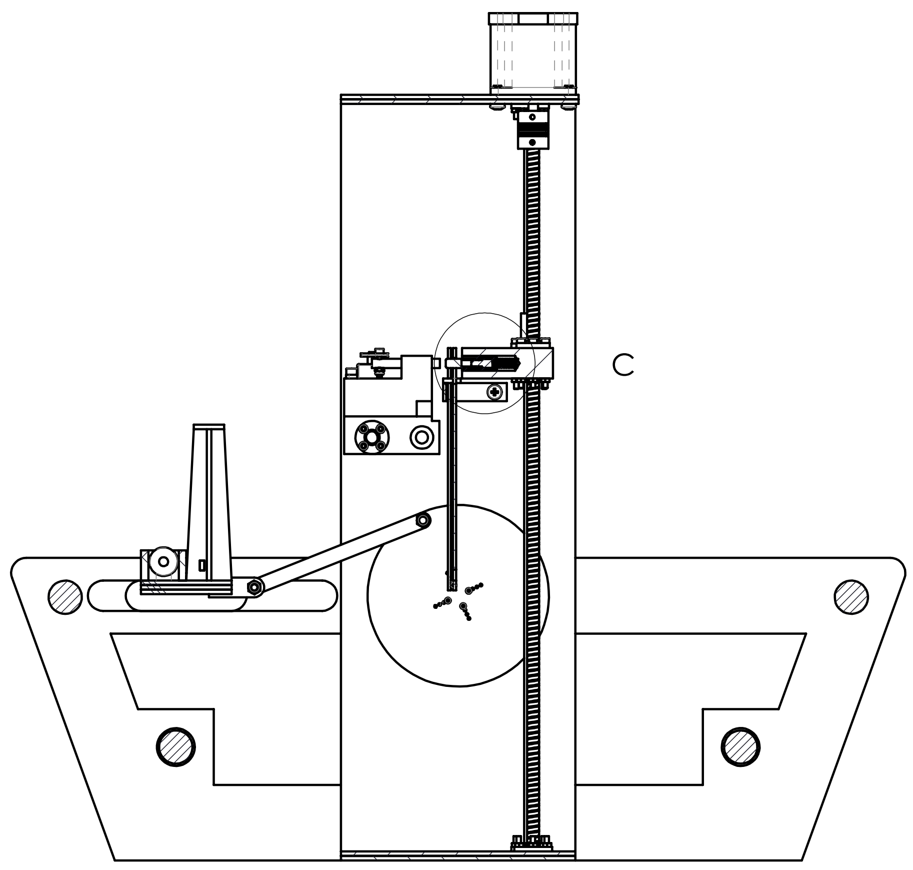
NO.	PART NUMBER	DESCRIPTION	SPECIFICATION	QTY
1	YDKANJ001-002	Side Frame 2	See DWG for details, Hardboard	2
2	YDKANJ001-001	Side Frame 1	See DWG for details, Hardboard	2
3	YDKANJ001-003	Vertical Frame Base 1	See DWG for details, Hardboard	1
4	YDKANJ001-004	Vertical Frame Base 2	See DWG for details, Hardboard	1
5	YDKANJ001-005	Vertical Frame Side 1	See DWG for details, Hardboard	1
6	YDKANJ001-006	Vertical Frame Side 2	See DWG for details, Hardboard	1
7	YDKANJ001-008	Vertical Frame Side 4	See DWG for details, Hardboard	1
8	YDKANJ001-007	Vertical Frame Side 3	See DWG for details, Hardboard	1
9	YDKANJ001-009	Vertical Frame Top 1	See DWG for details, Hardboard	1
10	YDKANJ001-010	Vertical Frame Top 2	See DWG for details, Hardboard	1
11	YDKANJ001-021	Heddle Plate	See DWG for details, Perspex (TM) GS Acrylic Cast Sheet	38
12	YDKANJ001-026	Push Actuator Guide	See DWG for details, N/A	38
13	YDKANJ001-023	Push Actuator Pin	See DWG for details, N/A	38
14	YDKANJ001-024	Push Actuator Cam	See DWG for details, N/A	38
15	YDKANJ001-025	Push Actuator Spring	See DWG for details, Spring Steel	38
16	YDKANJ001-022	Push Actuator Frame	See DWG for details, Meranti	1
17	YDKANJ001-057	Heddle Plate Frame	See DWG for details, Aluminium	1
18	YDKANJ001-028	Lead Screw Nut	See DWG for details, Brass	2
19	YDKANJ001-054	NEMA23	See DWG for details, N/A	2
20	YDKANJ001-030	Vertical Linear Actuator Lead Screw	See DWG for details, Stainless Steel	1
21	YDKANJ001-011	Back Rest and Breast Beam	See DWG for details, 22 mm Wooden Dowel	2
22	YDKANJ001-059	Warp Beam	See DWG for details, 22 mm Wooden Dowel	1
23	YDKANJ001-012	Cloth Roll	See DWG for details, 22 mm Wooden Dowel	1
24	YDKANJ001-029	Vertical Linear Actuator Support	See DWG for details, Stainless Steel (ferritic)	2
25	YDKANJ001-014	Pulley	See DWG for details, PLA	2
26	YDKANJ001-015	Dual Pulley	See DWG for details, PLA	1
27	YDKANJ001-056	NEMA17	See DWG for details, N/A	1
28	YDKANJ001-053	Servo Motor	See DWG for details, N/A	3
29	YDKANJ001-037	Stepper Motor Mount	See DWG for details, Hardboard	1
30	YDKANJ001-035	Horizontal Linear Actuator Lead Screw	See DWG for details, Steel	1
31	YDKANJ001-034	Horizontal Linear Actuator support	See DWG for details, Stainless Steel (ferritic)	1
32	YDKANJ001-058	Flexible Couple (5mm - 8mm)	See DWG for details, Aluminium	1
33	YDKANJ001-036	Flexible Couple (6.35mm - 8mm)	See DWG for details, Aluminium	1
34	YDKANJ001-031	Horizontal Linear Actuator Servo Mount	See DWG for details, PLA	1
35	YDKANJ001-052	Servo Horn	See DWG for details, N/A	1
36	YDKANJ001-033	Servo Pin	See DWG for details, Teak	1
37	YDKANJ001-040	Beater Side	See DWG for details, Hardboard	4
38	YDKANJ001-046	Beater Base 1	See DWG for details, Hardboard	2
39	YDKANJ001-047	Beater Base 2	See DWG for details, Hardboard	1
40	YDKANJ001-044	Beater Vertical Side	See DWG for details, Hardboard	2
41	YDKANJ001-045	Beater Top	See DWG for details,Hardboard	1
42	YDKANJ001-048	Beater Wire	See DWG for details, Stainless Steel (ferritic)	38
43	YDKANJ001-042	Beater Crank Interface	See DWG for details, Hardboard	4
44	YDKANJ001-041	Beater Locating Piece	See DWG for details, Hardboard	2
45	YDKANJ001-043	Beater Vertical Support	See DWG for details, Hardboard	2
46	YDKANJ001-049	Boat Shuttle	See DWG for details, PLA	1
47	YDKANJ001-050	Bobbin	See DWG for details, PLA	1
48	YDKANJ001-039	Crank Slider Arm	See DWG for details, Teak	2
49	YDKANJ001-051	Circular Servo Horn	See DWG for details, N/A	2
50	YDKANJ001-038	Crank Slider Disc	See DWG for details, Hardboard	2
51	YDKANJ001-013	Cloth Roll and Warp Beam Bushing	See DWG for details, Nylon 101	4
52	YDKANJ001-017	Ratchet Warp Beam	See DWG for details, PLA	1
53	YDKANJ001-018	Pawl	See DWG for details, PLA	2
54	UCT-08048	Cross pan HD screw M4	ISO 7045 - M4 X 40 x 40, Carbon Steel Gr 8.8	6
55	UCT-11104	Hex nut M4	ISO 4032 - M4, Carbon Steel Gr 8.8	16
56	YDKANJ001-032	Horizontal Linear Actuator Bushing	See DWG for details, Nylon 101	4
57	YDKANJ001-066	Vertical Linear Actuator Bushing Long	See DWG for details, Nylon 101	2
58	UCT-11301	Lock nut M4	ISO 7040 - M4, Carbon Steel Gr 8.8	4
59	UCT-11302	Lock nut M5	ISO 7040 - M5, Carbon Steel Gr 8.8	4
60	UCT-05039	Socket HD Bolt M3	ISO 4762 - M3 X 30 x 18, Carbon Steel Gr 8.8	12
61	UCT-05037	Socket HD Bolt M3	ISO 4762 - M3 X 25 x 18, Carbon Steel Gr 8.8	4
62	UCT-08051	Cross pan HD screw M5	ISO 7045 - M5 X 10 x 10, Carbon Steel Gr 8.8	4
63	UCT-08052	Cross pan HD screw M5	ISO 7045 - M5 X 12 x 12, Carbon Steel Gr 8.8	4
64	UCT-08053	Cross pan HD screw M5	ISO 7045 - M5 X 16 x 16, Carbon Steel Gr 8.8	4
65	UCT-05034	Socket HD Bolt M3	ISO 4762 - M3 X 16 x 16, Carbon Steel Gr 8.8	5
66	UCT-01037	Hex Bolt M5	ISO 4015 - M5 X 30 x 16, Carbon Steel Gr 8.8	2
67	UCT-11103	Hex nut M3	ISO 4032 - M3, Carbon Steel Gr 8.8	40
68	YDKANJ001-027	Vertical Linear Actuator Bushing	See DWG for details, Nylon 101	5
69	YDKANJ001-055	Stepper Motor Support	See DWG for details, Hardboard	2
70	UCT-05044	Socket HD Bolt M4	ISO 4762 - M4 X 16 x 16, Carbon Steel Gr 8.8	12
71	YDKANJ001-060	Limit Switch	See DWG for details, N/A	2
72	YDKANJ001-061	Limit Switch Mount Horizontal	See DWG for details, PLA	1
73	YDKANJ001-061	Limit Switch Mount Horizontal	See DWG for details, PLA	1
74	YDKANJ001-063	Hook Spring	See DWG for details, Spring Steel	2
75	UCT-05013	Socket HD Bolt M2	ISO 4762 - M2 X 8 x 8, Carbon Steel Gr 8.8	8
76	UCT-11300	Lock nut M3	ISO 7040 - M3, Carbon Steel Gr 8.8	1
77	UCT-08031	Cross pan HD screw M3	ISO 7045 - M3 X 10 x 10, Carbon Steel Gr 8.8	4
78	UCT-07033	Cross CSK HD screw M3	ISO 7046-1 - M3 X 16 x 16, Carbon Steel Gr 8.8	20
79	YDKANJ001-064	Timing Belt	See DWG for details, NEOPRENE	2
80	YDKANJ001-067	Shim	See DWG for details, Perspex (TM) GS Acrylic Cast Sheet	2
81	YDKANJ001-016	Ratchet Cloth Roll	See DWG for details, PLA	1
82	YDKANJ001-068	Heddle Guide Support	See DWG for details, Aluminium	1
83	UCT-11105	Hex nut M5	ISO 4032 - M5, Carbon Steel Gr 8.8	2

Scale: 1:5 on A3		University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken		All un-toleranced dimensions to adhere to ISO 2768-m	Title: Weaving Loom		
Checked :		Assembly drawing	Drawing Number : ASM1	Rev. : A	Sheet : 1 of 1

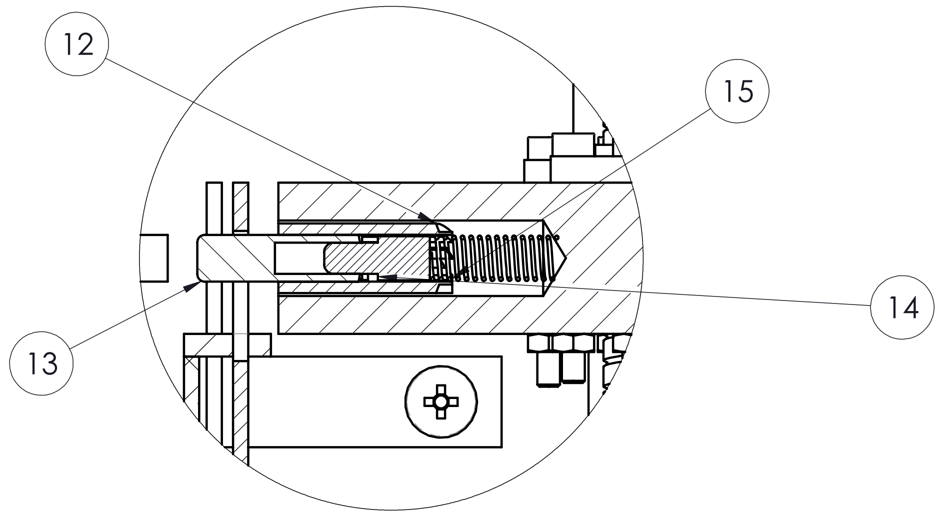




SECTION A-A

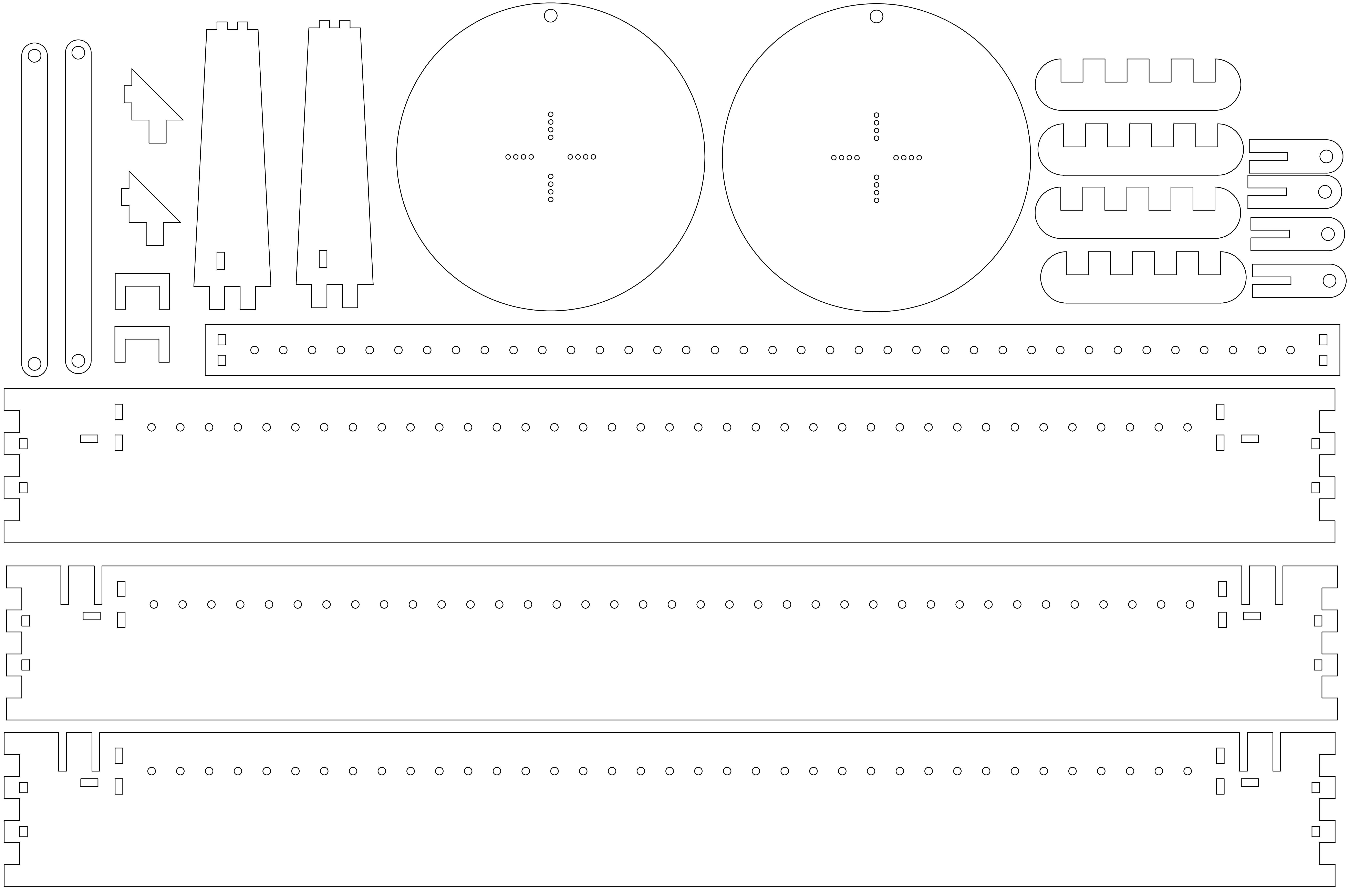


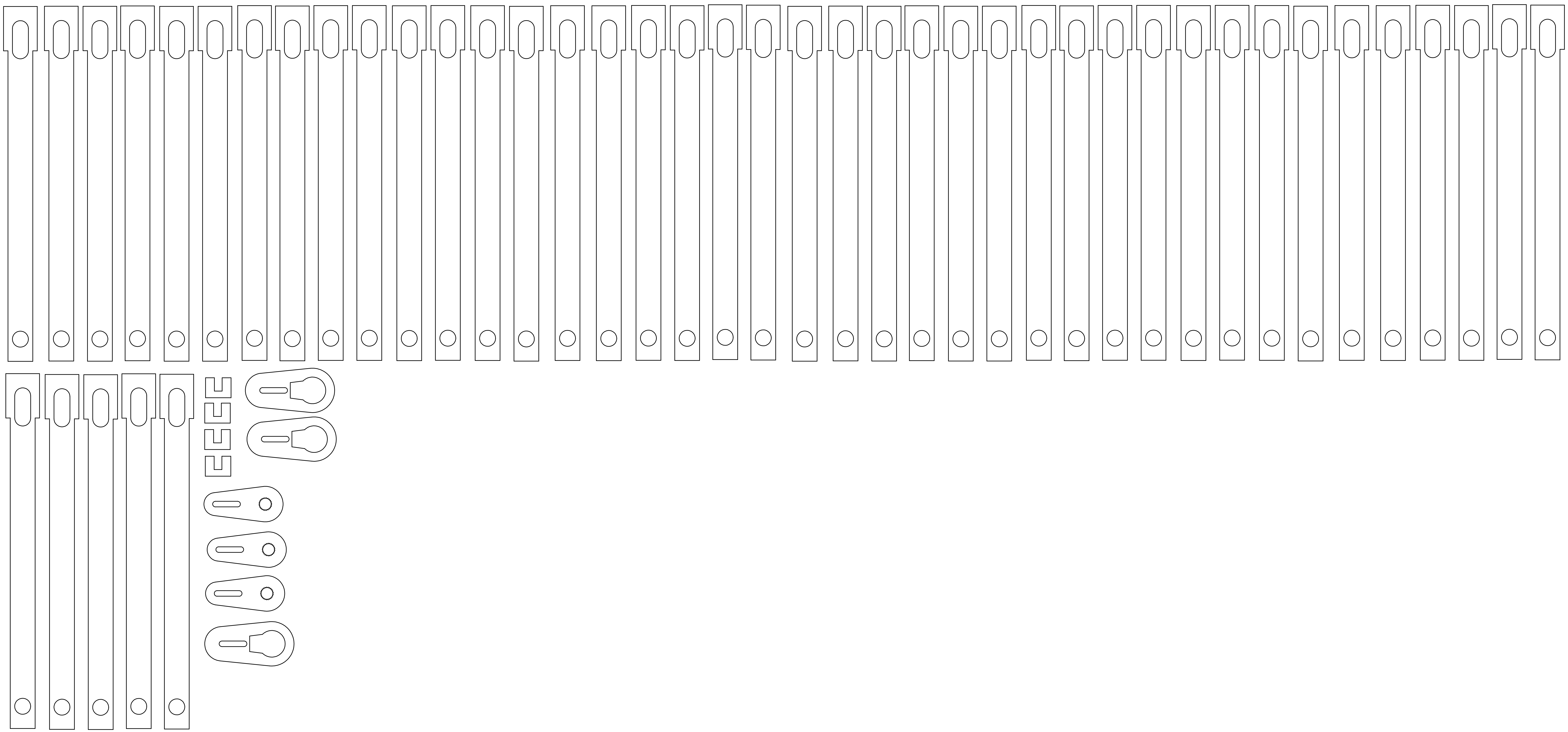
SECTION B-B

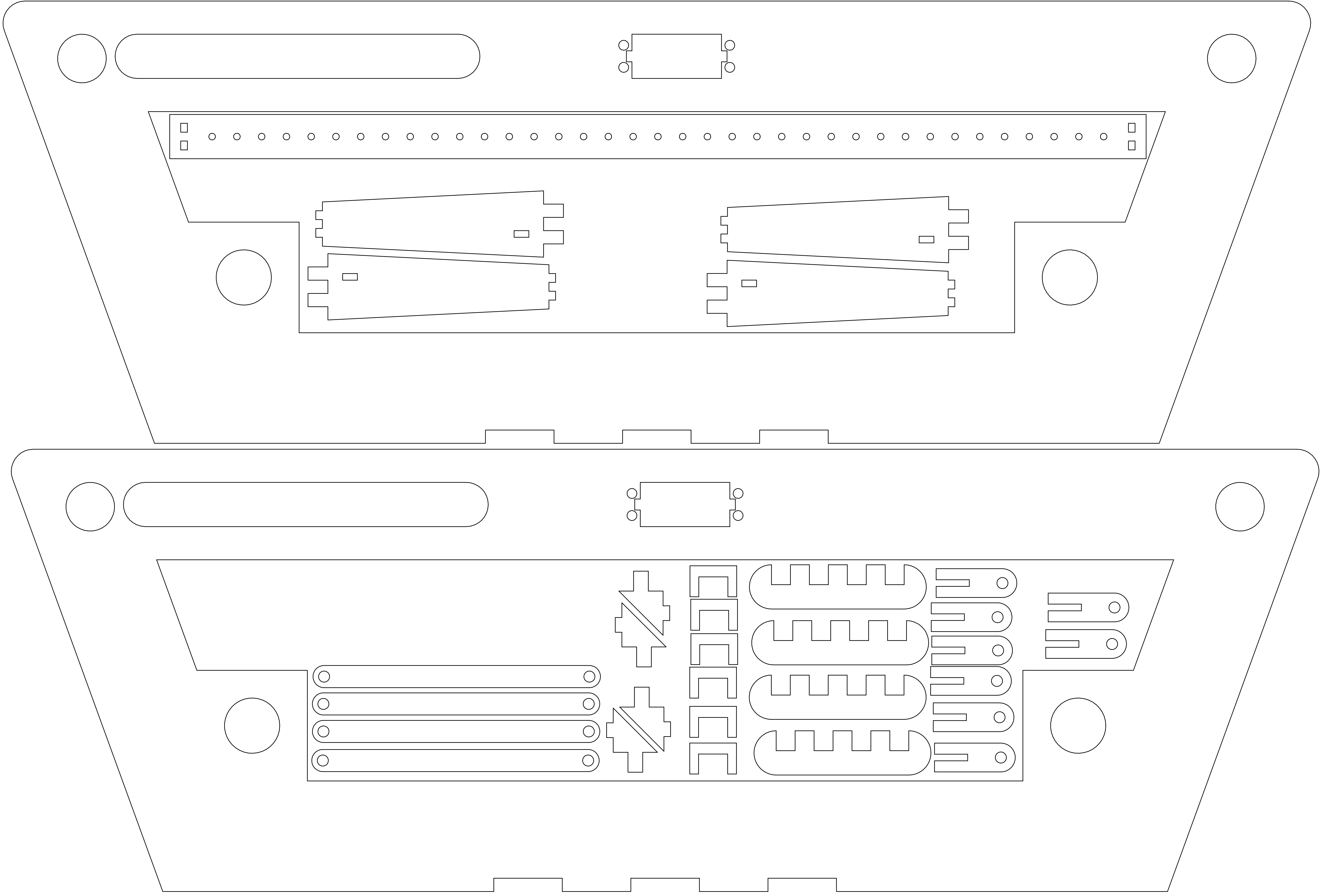


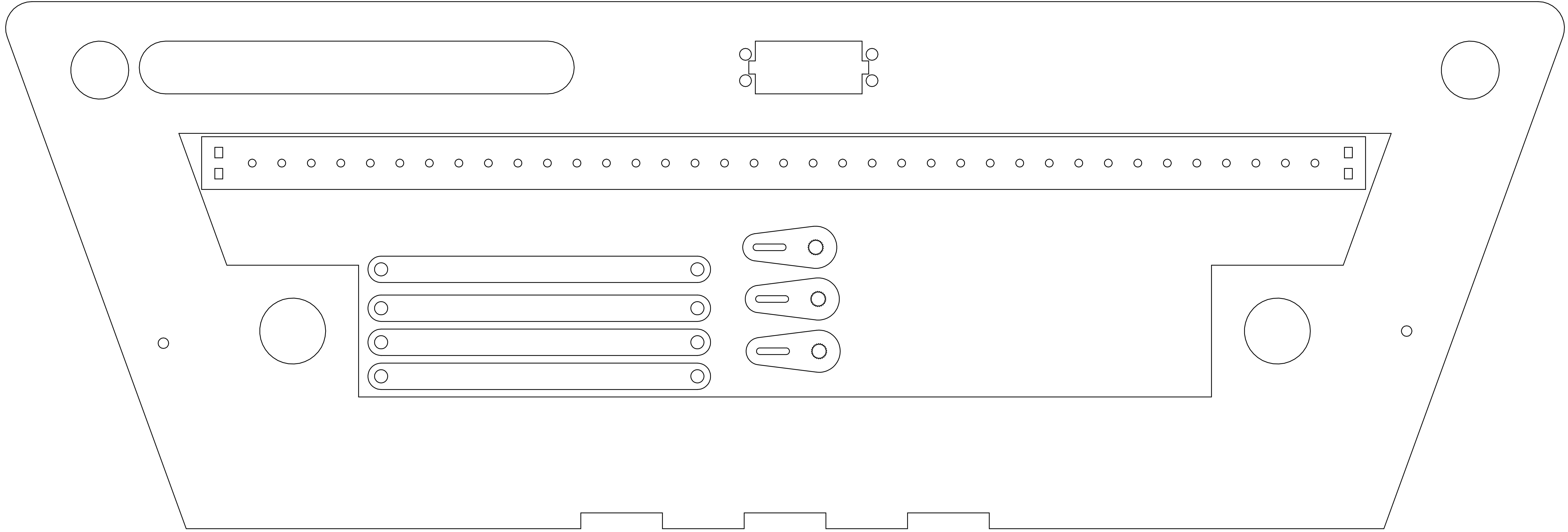
DETAIL C
SCALE 1 : 1

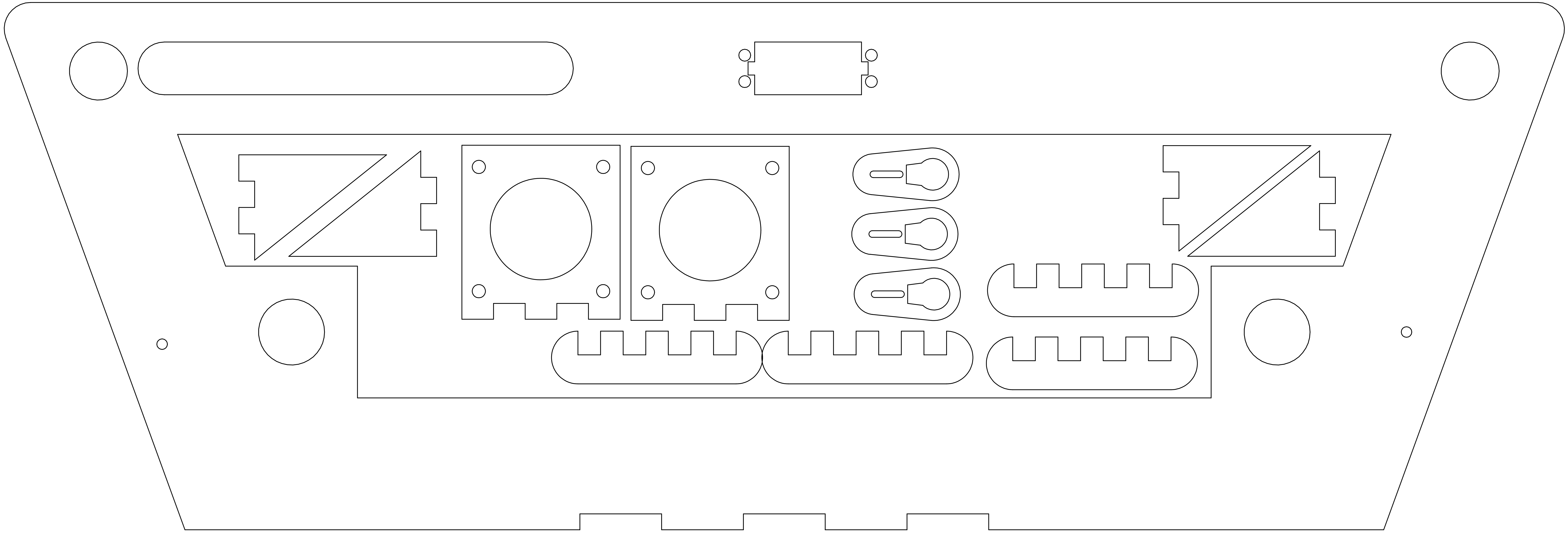
Scale: 1:5 on A3	University of Cape Town Department of Mechanical Engineering			
Drawn By: YDKANJ001 Anjana Yodaiken	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Weaving Loom		
Checked :	Assembly drawing	Drawing Number : ASM2	Rev. : A	Sheet : 1 of 1

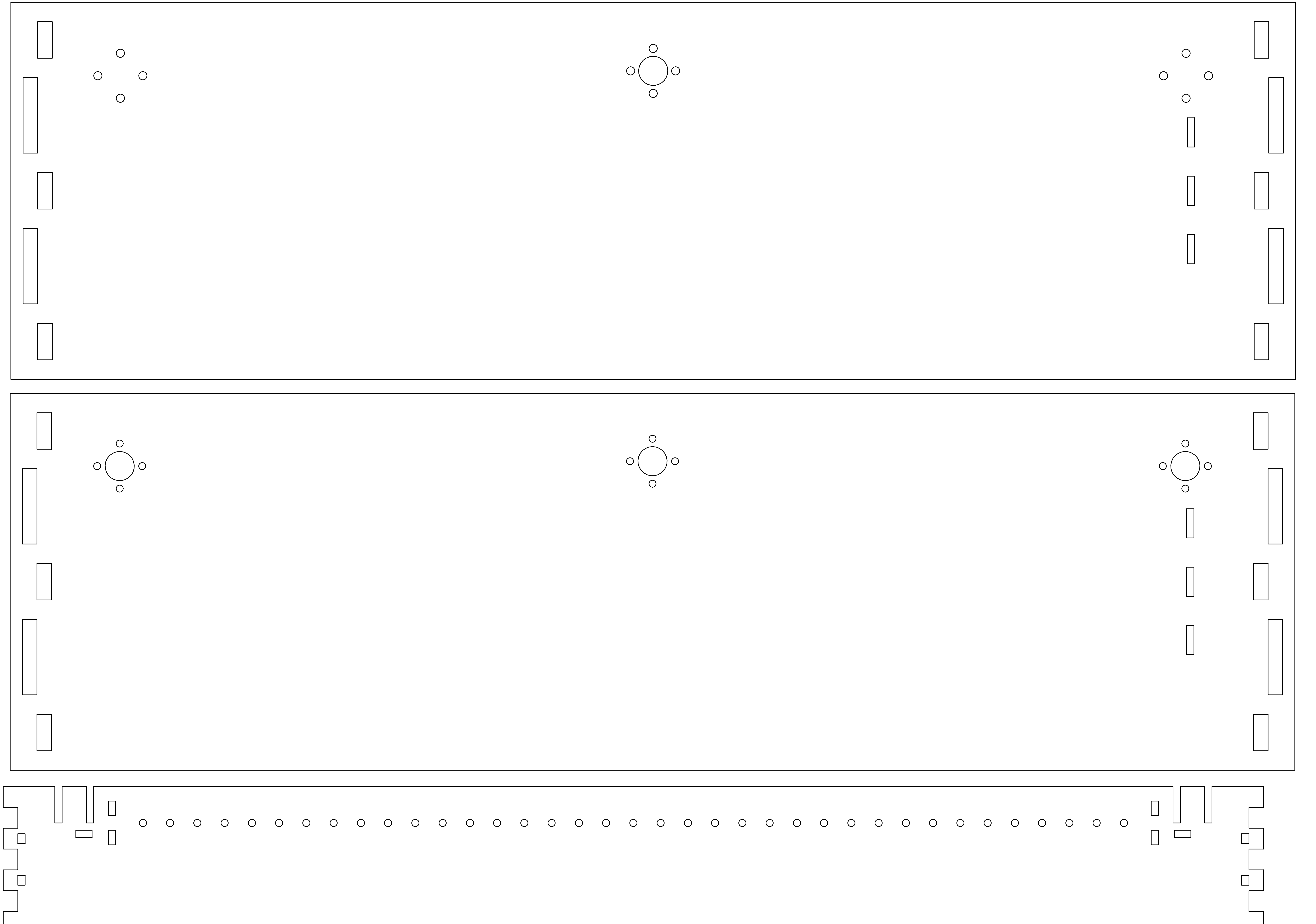


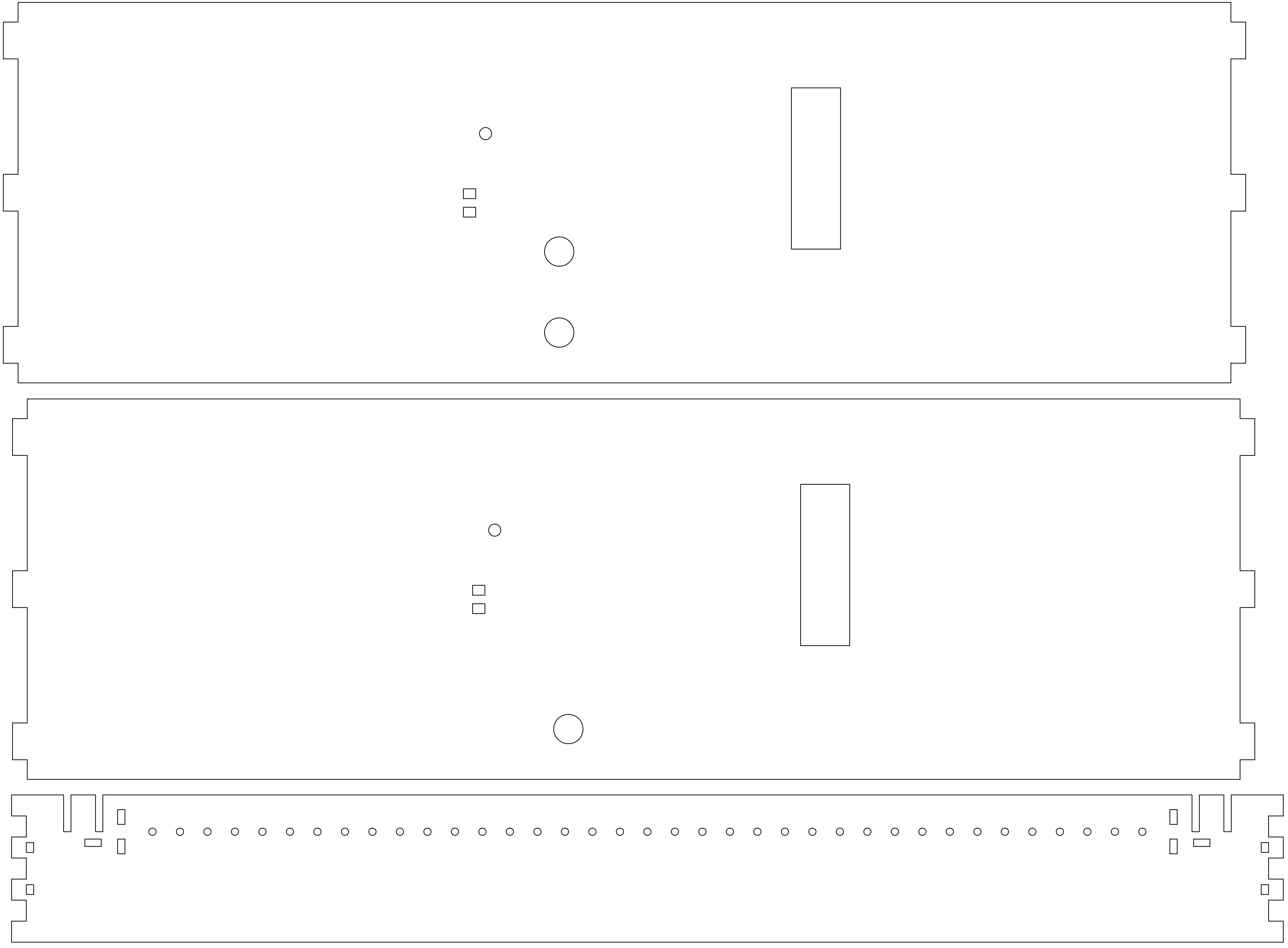


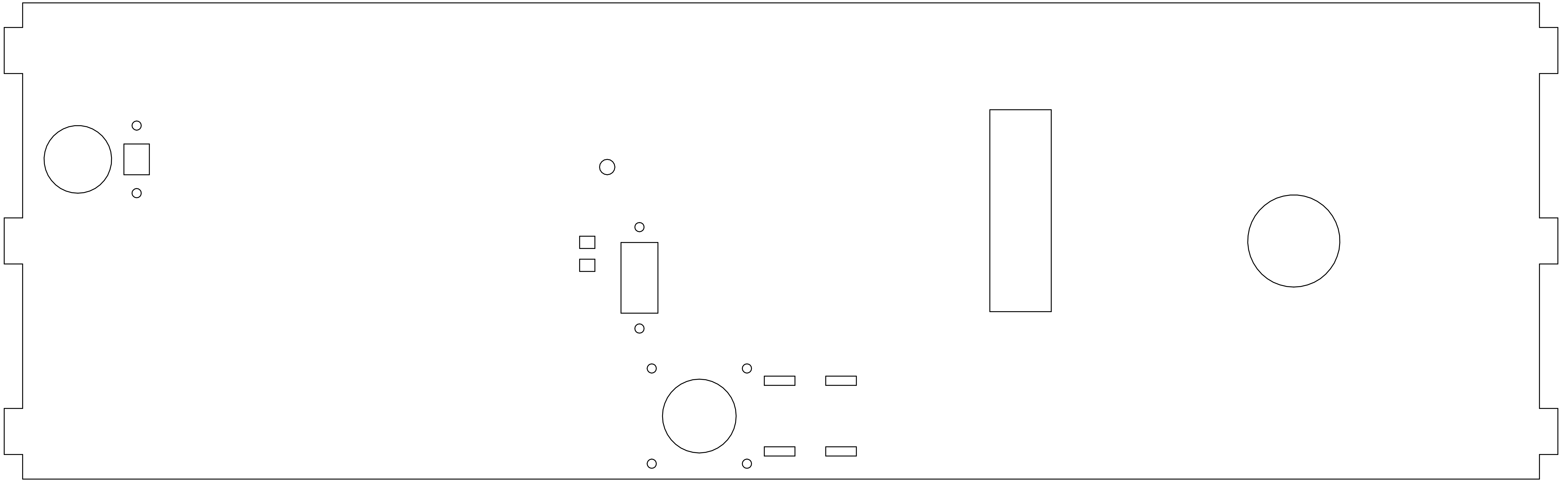
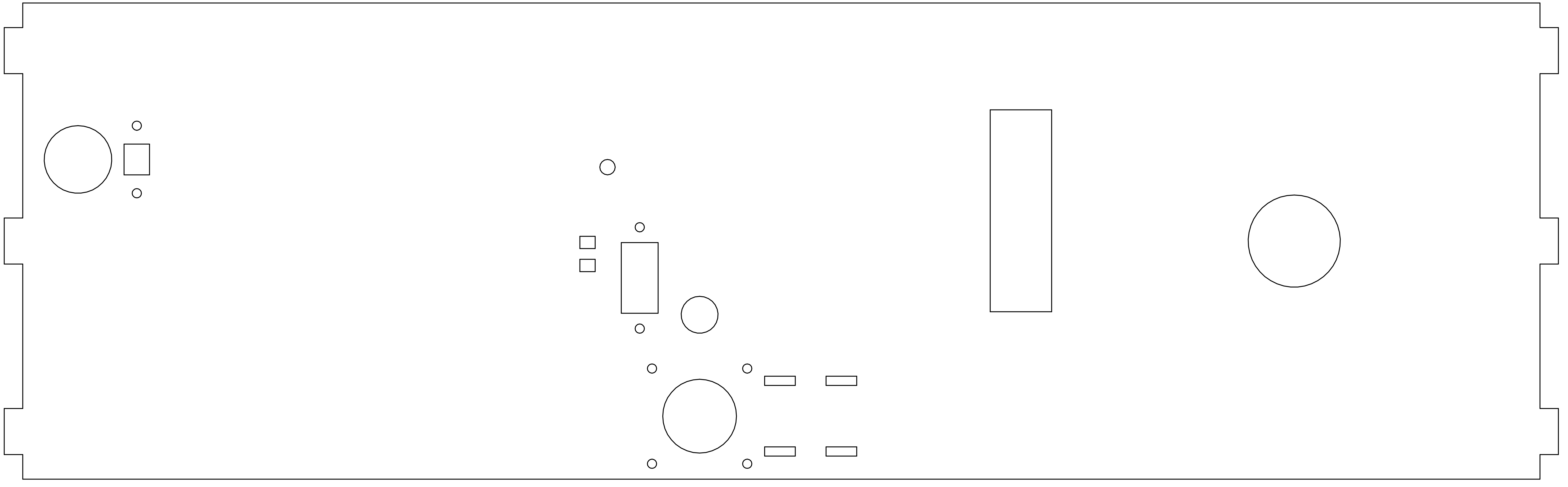


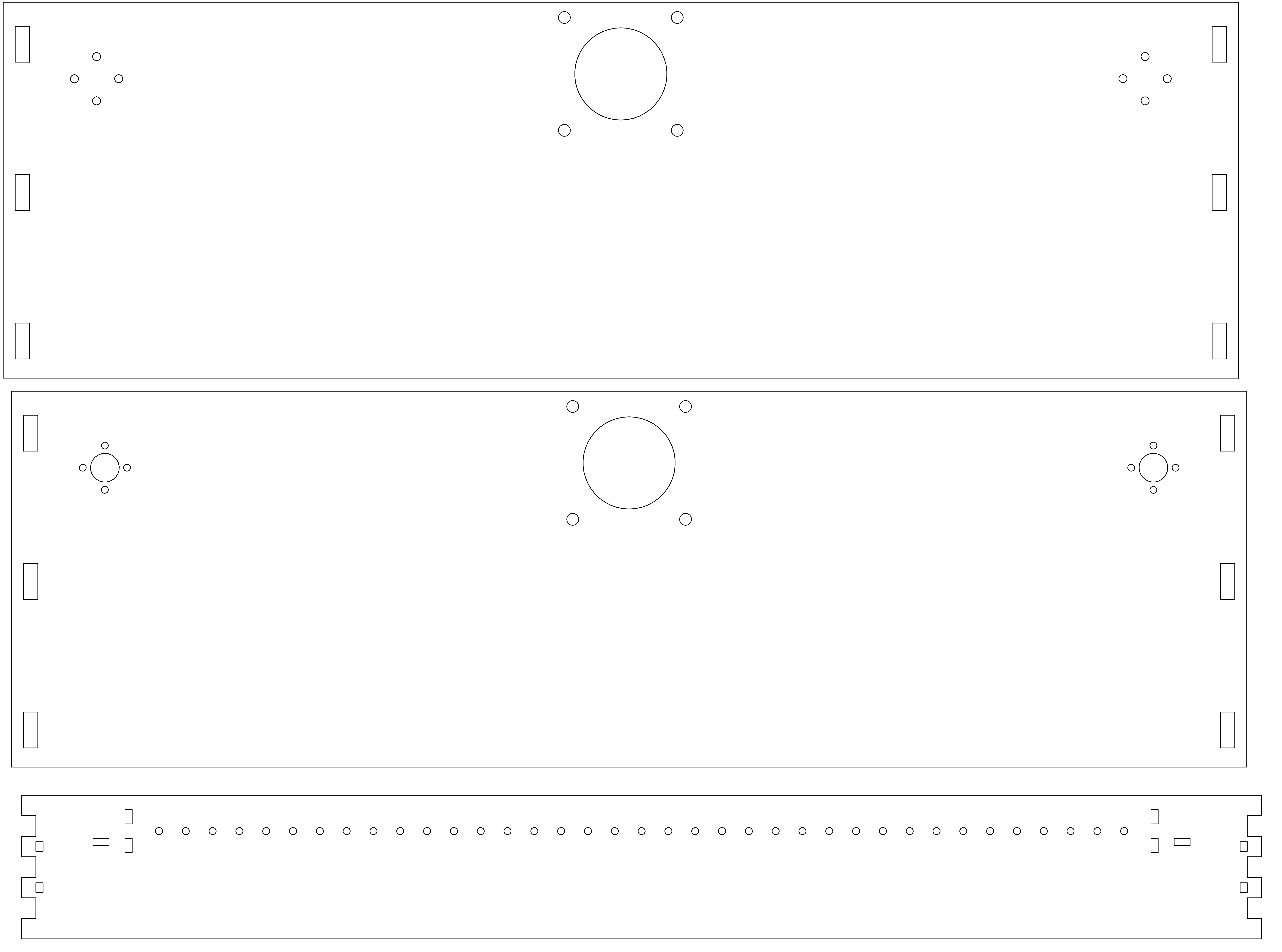


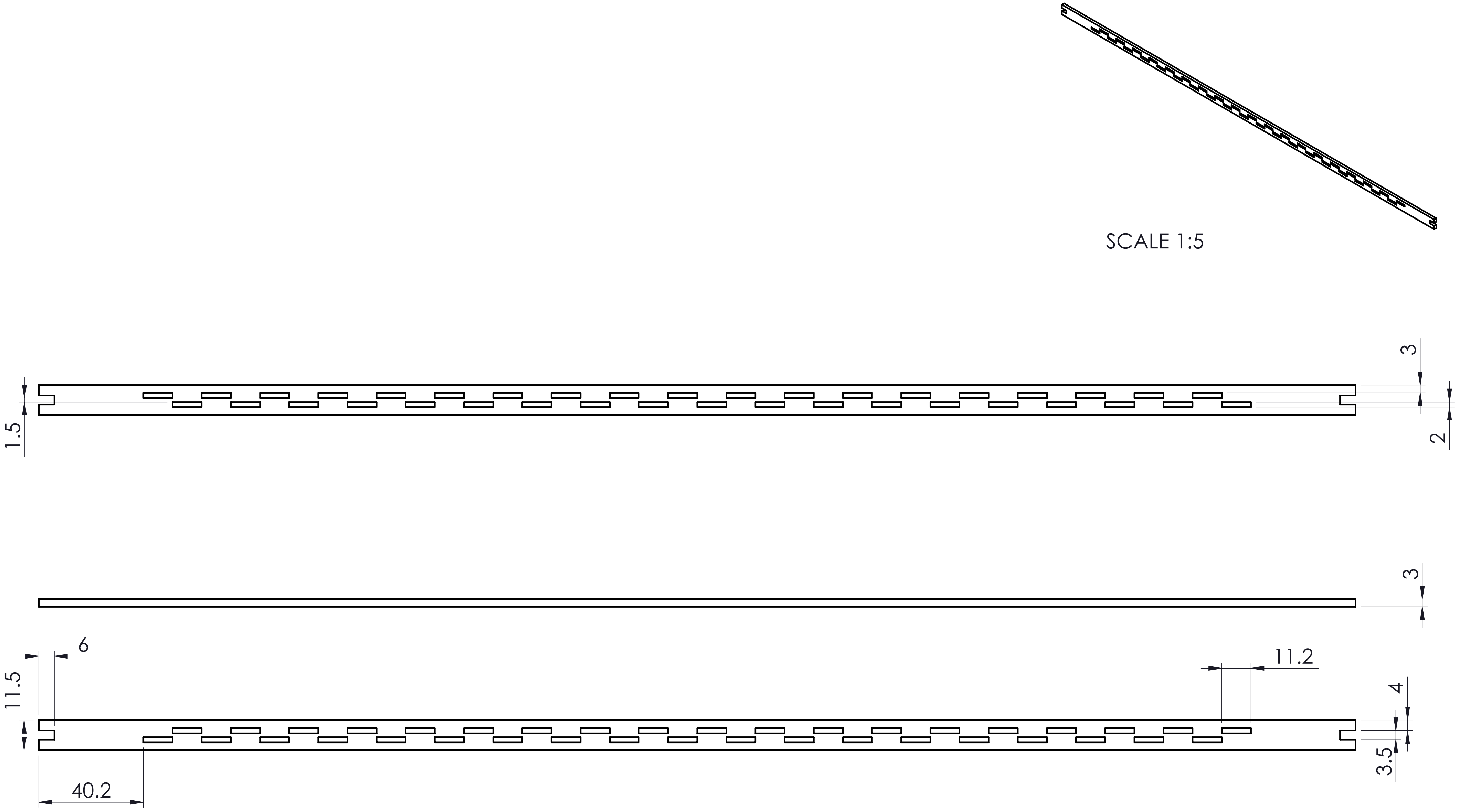










Scale: 1:2 on A4	University of Cape Town Department of Mechanical Engineering	
Drawn By: Anjana Yodaiken YDKANJ001	All un-toleranced dimensions to adhere to ISO 2768-m	Title: Heddle Plate Frame
Checked :	Assembly Drawing	Drawing Number : YDKANJ001-057 / Rev. : A / Sheet : 1 of 1

Risk Assessment Form

- **Risk Assessments are not required for simple workshop activities covered by the Safety Declaration. However permission must be obtained from the Workshop Manager before commencing any activity in the Workshop.**
- **A new Risk Assessment form needs to be completed for each major activity within your project.**
- **You are required to include this document (signed) in your bound project submission and mount a copy next to any rig / apparatus you are using.**

Your Name	Anjana Gabrielle Martin Yodaiken
Your Supervisor	Ernesto Bram Ismail Urban
Project title and number	Programmable Weaving Loom #135
Area Safety Warden	

This Section to be completed by the student (Must be typed and the declaration signed)			
Location where the activity will be done	At home		
Describe the activity (use attachment with diagrams if needed)	Handling and powering of electronics		
Names of persons involved in this activity	Anjana Gabrielle Martin Yodaiken		
Describe in detail the risks you (and others) will face during this activity and the potential consequences of your activities	Possibility of a small electric shock.		
Does this activity involve the use of any materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment	No		*If Yes list the chemicals / gasses to be used and attach the MSDS(s) for these materials.*
Does this activity involve any equipment / device designed or built by you which is to be plugged into mains electricity?	No		*If Yes please consult with Mr Richard Whittemore or* Mr Maysam Soltanian (Electrical Machines Lab) *before connecting to the mains / switching on.*
Does the activity involve any new equipment / devices designed by you which will be pressurized with a gas or volatile liquids?	No		*If Yes please check the relevant SANS Pressurised Equipment Regulations and consult with A/Prof Fuls before testing.*
What precautions are required to protect against the risks detailed above?	Increased awareness of surroundings and remaining focused.		
Describe the personal protective equipment (PPE) required during this activity – specify in detail.			
Describe the shutdown procedure in detail.	In the event of a shock the electronics will be disconnected from the power supply, the power supply will be turned off and unplugged from mains.		
Describe any relevant emergency procedures, e.g. spillage response etc.	In the event of a shock the shutdown procedure will be followed. If the shock causes a burn the burn will be treated with disinfectant and dressed in bandages. Depending on the severity of the shock the injured person may need to be transported to the emergency room for further assessment. This can be facilitated by my parents who work from home as this would be the location of injury.		

I declare that I am aware of the risks associated with this activity and will take all necessary steps to mitigate these risks.	**Student Signature** Yodaiken	**Date** 20/10/2020

I am aware of the student's intended activity, and have provided the necessary guidance, inputs, and oversight.	**Supervisor Signature**	**Date** 20/10/2020

This section to be completed by the Area Safety Warden		
Level of supervision required (Please tick relevant block)	A = work may not take place without supervisor/warden present.	X
	B = work may not take place without a 2nd party present.	
	C = no specific extra supervision requirements.	
I am satisfied that the student is aware of the risks associated with this activity and grant approval for it to proceed.	**Signature**	**Date**

Department of Mechanical Engineering

Risk Assessment Form

rev 1.0

- **Risk Assessments are not required for simple workshop activities covered by the Safety Declaration. However permission must be obtained from the Workshop Manager before commencing any activity in the Workshop.**
- **A new Risk Assessment form needs to be completed for each major activity within your project.**
- **You are required to include this document (signed) in your bound project submission and mount a copy next to any rig / apparatus you are using.**

Your Name	Anjana Gabrielle Martin Yodaiken
Your Supervisor	Ernesto Bram Ismail Urban
Project title and number	Programmable Weaving Loom #135
Area Safety Warden	

This Section to be completed by the student (Must be typed and the declaration signed)			
Location where the activity will be done	At home		
Describe the activity (use attachment with diagrams if needed)	Use of soldering iron for soldering of electronic components to Veroboard.		
Names of persons involved in this activity	Anjana Gabrielle Martin Yodaiken		
Describe in detail the risks you (and others) will face during this activity and the potential consequences of your activities	Coming into contact with the heated end of the soldering iron, which could result in a burn.		
Does this activity involve the use of any materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment	No		*If Yes list the chemicals / gasses to be used and attach the MSDS(s) for these materials.*
Does this activity involve any equipment / device designed or built by you which is to be plugged into mains electricity?	No		*If Yes please consult with Mr Richard Whittemore or* Mr Maysam Soltanian (Electrical Machines Lab) *before connecting to the mains / switching on.*
Does the activity involve any new equipment / devices designed by you which will be pressurized with a gas or volatile liquids?	No		*If Yes please check the relevant SANS Pressurised Equipment Regulations and consult with A/Prof Fuls before testing.*
What precautions are required to protect against the risks detailed above?	Increased awareness of surroundings and remaining focused.		
Describe the personal protective equipment (PPE) required during this activity – specify in detail.	N/A		
Describe the shutdown procedure in detail.	In the event of a burn the soldering iron will be turned off by unplugging it and moved to an area where it can cool down safely.		
Describe any relevant emergency procedures, e.g. spillage response etc.	In the event of a burn the above shutdown procedure will be followed. The burnt area will then be allowed to run under cold water for 5 minutes. The burnt area will then be covered in burn shield and wrapped in gauze.		

I declare that I am aware of the risks associated with this activity and will take all necessary steps to mitigate these risks.	**Student Signature** Yodaiken	**Date** 16/10/2020

I am aware of the student's intended activity, and have provided the necessary guidance, inputs, and oversight.	**Supervisor Signature**	**Date** 16/10/2020

This section to be completed by the Area Safety Warden		
Level of supervision required (Please tick relevant block)	A = work may not take place without supervisor/warden present.	X
	B = work may not take place without a 2nd party present.	
	C = no specific extra supervision requirements.	
I am satisfied that the student is aware of the risks associated with this activity and grant approval for it to proceed.	**Signature**	**Date**

Department of Mechanical Engineering

Risk Assessment Form

rev 1.0

- **Risk Assessments are not required for simple workshop activities covered by the Safety Declaration. However permission must be obtained from the Workshop Manager before commencing any activity in the Workshop.**
- **A new Risk Assessment form needs to be completed for each major activity within your project.**
- **You are required to include this document (signed) in your bound project submission and mount a copy next to any rig / apparatus you are using.**

Your Name	Anjana Gabrielle Martin Yodaiken
Your Supervisor	Ernesto Bram Ismail Urban
Project title and number	Programmable Weaving Loom #135
Area Safety Warden	

This Section to be completed by the student (Must be typed and the declaration signed)			
Location where the activity will be done	At home		
Describe the activity (use attachment with diagrams if needed)	Use of power tools in the construction of the loom.		
Names of persons involved in this activity	Anjana Gabrielle Martin Yodaiken		
Describe in detail the risks you (and others) will face during this activity and the potential consequences of your activities	Entrapment of clothing or hair in moving parts or direct contact with moving parts.		
Does this activity involve the use of any materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment	No		*If Yes list the chemicals / gasses to be used and attach the MSDS(s) for these materials.*
Does this activity involve any equipment / device designed or built by you which is to be plugged into mains electricity?	No		*If Yes please consult with Mr Richard Whittemore or* Mr Maysam Soltanian (Electrical Machines Lab) *before connecting to the mains / switching on.*
Does the activity involve any new equipment / devices designed by you which will be pressurized with a gas or volatile liquids?	No		*If Yes please check the relevant SANS Pressurised Equipment Regulations and consult with A/Prof Fuls before testing.*
What precautions are required to protect against the risks detailed above?	Increased awareness of surroundings and remaining focused. As well as the use of eye protection in cutting, grinding or sanding operations.		
Describe the personal protective equipment (PPE) required during this activity – specify in detail.	Eye goggles.		
Describe the shutdown procedure in detail.	In the event of injury, the power tool will be turned off by unplugging it.		
Describe any relevant emergency procedures, e.g. spillage response etc.	In the event of a burn the above shutdown procedure will be followed. The wound will then be treated with disinfectant and bandaged. Depending on the severity of the wound the injured person may need to be transported to the emergency room for further assessment. This can be facilitated by my parents who work from home as this would be the location of injury.		

I declare that I am aware of the risks associated with this activity and will take all necessary steps to mitigate these risks.	**Student Signature**	**Date**
	Yodaiken	20/10/2020

I am aware of the student's intended activity, and have provided the necessary guidance, inputs, and oversight.	**Supervisor Signature**	**Date**
		20/10/2020

This section to be completed by the Area Safety Warden			
Level of supervision required (Please tick relevant block)	A = work may not take place without supervisor/warden present.		X
	B = work may not take place without a 2nd party present.		
	C = no specific extra supervision requirements.		
I am satisfied that the student is aware of the risks associated with this activity and grant approval for it to proceed.	**Signature**	**Date**	

Department of Mechanical Engineering rev 1.0

Risk Assessment Form

- **Risk Assessments are not required for simple workshop activities covered by the Safety Declaration. However permission must be obtained from the Workshop Manager before commencing any activity in the Workshop.**
- **A new Risk Assessment form needs to be completed for each major activity within your project.**
- **You are required to include this document (signed) in your bound project submission and mount a copy next to any rig / apparatus you are using.**

Your Name	Anjana Gabrielle Martin Yodaiken
Your Supervisor	Ernesto Bram Ismail Urban
Project title and number	Programmable Weaving Loom #135
Area Safety Warden	

This Section to be completed by the student (Must be typed and the declaration signed)			
Location where the activity will be done	At home		
Describe the activity (use attachment with diagrams if needed)	Use of a Dremel and different bits to dismantle pens and cut aluminium.		
Names of persons involved in this activity	Anjana Gabrielle Martin Yodaiken		
Describe in detail the risks you (and others) will face during this activity and the potential consequences of your activities	Pieces of plastic or aluminium being flung by the turning of the Dremel bit, there is particular risk to one's eyes in this event. Coming into contact with the end of the Dremel bit while the Dremel is on and injuring oneself. The fumes created by the cutting of the aluminium could cause damage to ones lungs or respiratory tract.		
Does this activity involve the use of any materials (chemicals, gasses, etc.) which may be hazardous to health, or the environment	No		*If Yes list the chemicals / gasses to be used and attach the MSDS(s) for these materials.*
Does this activity involve any equipment / device designed or built by you which is to be plugged into mains electricity?	No		*If Yes please consult with Mr Richard Whittemore or* Mr Maysam Soltanian (Electrical Machines Lab) *before connecting to the mains / switching on.*
Does the activity involve any new equipment / devices designed by you which will be pressurized with a gas or volatile liquids?	No		*If Yes please check the relevant SANS Pressurised Equipment Regulations and consult with A/Prof Fuls before testing.*
What precautions are required to protect against the risks detailed above?	Increased awareness of surroundings and remaining focused. Turn off the Dremel when it is not in use.		
Describe the personal protective equipment (PPE) required during this activity – specify in detail.	Safety goggles and mask.		
Describe the shutdown procedure in detail.	In the event that a piece of material enters one's eye or coming into contact with the Dremel bit while it is on, the Dremel will be turned off and the Dremel will be placed in a secure location.		
Describe any relevant emergency procedures, e.g. spillage response etc.	In the event of a piece of material entering one's eye, the above shutdown procedure will be followed. The affected eye will then be washed out with water and if necessary, further medical attention will be sought out. In the event that one comes into contact with the Dremel bit while it is on, the above shutdown procedure will be followed. The wound will be sterilized and dresses and depending on the severity of the wound further medical attention will be sought out.		

I declare that I am aware of the risks associated with this activity and will take all necessary steps to mitigate these risks.	**Student Signature**	**Date**
		12/11/2020

I am aware of the student's intended activity, and have provided the necessary guidance, inputs, and oversight.	**Supervisor Signature**	**Date**
		12/11/2020

This section to be completed by the Area Safety Warden		
Level of supervision required (Please tick relevant block)	A = work may not take place without supervisor/warden present.	
	B = work may not take place without a 2nd party present.	
	C = no specific extra supervision requirements.	
I am satisfied that the student is aware of the risks associated with this activity and grant approval for it to proceed.	**Signature**	**Date**