Miniature Tensile Stage For Fibre Testing in XRD

Composites Innovation Centre Manitoba Inc.
– FibreCITY

MECH4860 Engineering Design
Final Design Report

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December 6, 2015

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Dear Dr. Choo-Smith,

Enclosed is the Final Design Report – Miniature Tensile Stage For Fibre Testing in XRD – for the Capstone Design Project. The report provides a possible solution to applying tensile load to a fibre inside the x-ray diffractometer. Details regarding the functionality and application of each component, as well as costs, instructions, and recommendations are included.

It should be considered that data acquisition and x-ray shielding unfortunately fell out of scope in this project, and further research and assessment is required.

It has been a great pleasure working with you and your company. This has been a valuable experience for our group, and we thank you for the opportunity.

With Regards

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December 6, 2015

Dr. Paul Labossiere
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Executive Summary

Composites Innovation Centre (CIC), a company based in Winnipeg, Manitoba, Canada, uses X-ray diffractometry (XRD) and tensile testing separately to evaluate different fibres and observe if they are usable in composite materials. In order to increase efficiency and view how the molecular structure of the fibre changes as force is applied, it is ideal to combine the two tests within the XRD machine. Approaching this problem requires an assessment on the size constraints imposed by the XRD, as well as the precision required from the test. This report provides both the necessary background information and presents a final design for such a system with recommendations to proceed forward.

The final design consists of two purchased components, the LP512 load cell from Cooper Instruments & Systems which costs $795 and the PQ12 Micro Linear Actuator from Firgelli Technologies Inc. which costs $65. Four fastener components whhich are the two M3 Machine Screws, one 40 mm and one 20 mm, along with two M3 Nylock Nuts are required with an expected cost of approximately $6. The remaining three components are 3-D printed from ABS plastic. They are a base mount, a lower tab slot, and an upper support with a tab slot. The base consists of a hole with a cover to insert the load cell into. The lower tab slot threads onto the load cell, securing it to the base while providing a point of load application. The linear actuator inserts into another hole in the base, and is secured via the 40 mm screw and nut. The upper support and slot is secured to the actuator via the 20 mm and nut. The total cost in time, labour, and materials for these three parts is expected to be approximately $50. A Personal Daq/54 by Measurement Computing is recommended as a possible solution for data acquisition.

This final design has dimensions of 23 mm × 49 mm × 40 mm width, height, and depth respectively, and has been tested to fit within the XRD machine. The total cost of the chosen components is approximately $919.98, with an additional $829.00 for a recommended data acquisition module, which below the total budget of $2000. The design is capable of applying a tensile load to a fibre while inside the XRD, allowing the examination of the crystalline structure during the application of a tensile load.

1. Introduction

This report will provide a summary of the project statement, background, and objectives. Client needs and technical specifications will be provided, with a brief overview of the conceptual designs chosen to proceed into the final design stage. The specific details of the final design will be focused on, along with recommendations for moving forward.

2. Problem Statement and Background

The client is the FibreCITY laboratory at the Composites Innovation Centre Manitoba Inc. (CIC). CIC is a not-for-profit corporation dealing in the research and development of composite materials and technologies [1]. The FibreCITY lab in particular deals with biofibre applications [2]. The client currently uses an x-ray diffractometer (XRD) to study the crystallinity of fibres to help evaluate their potential for future applications. The machine does this by shining x-rays through the fibre, allowing a user to observe a diffraction pattern through computer software while visualizing the fibre through a camera. A picture of the XRD can be seen in Fig. 1.

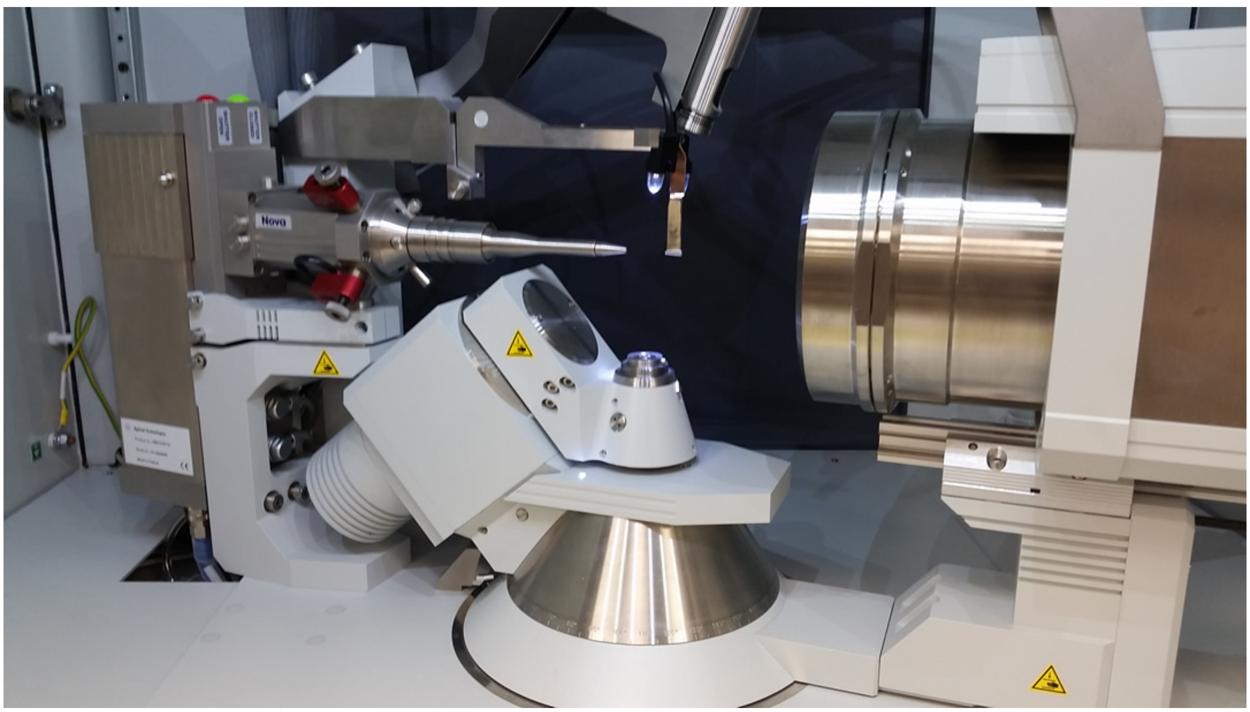


Figure 1: X-ray Diffraction Machine [3].

The client has expressed the desire to observe the microstructure of the fibre with the XRD while a tensile load is simultaneously being applied *in situ*. The current mode of operation involves observing the fibre before and after a tensile stress test performed on a separate machine.

The client has previously taken part in the Capstone design course, tasking the students from the previous year to design and build a fixture to hold fibres within the XRD during testing. Last year's team was successful in creating a fixture that the client still uses today. The fixture, which is shown in Fig. 2, is installed on the goniometer, the device which controls the angular position of the specimen in the XRD. The fixture features a rack and pinion with magnets on the top and bottom. The fibres are glued onto plastic tabs. These are coated in a magnetic finish so the magnets on the fixture can hold them in place. The tabs are then attached to the magnets and the rack and pinion is tightened by hand before the fixture is placed in the XRD.

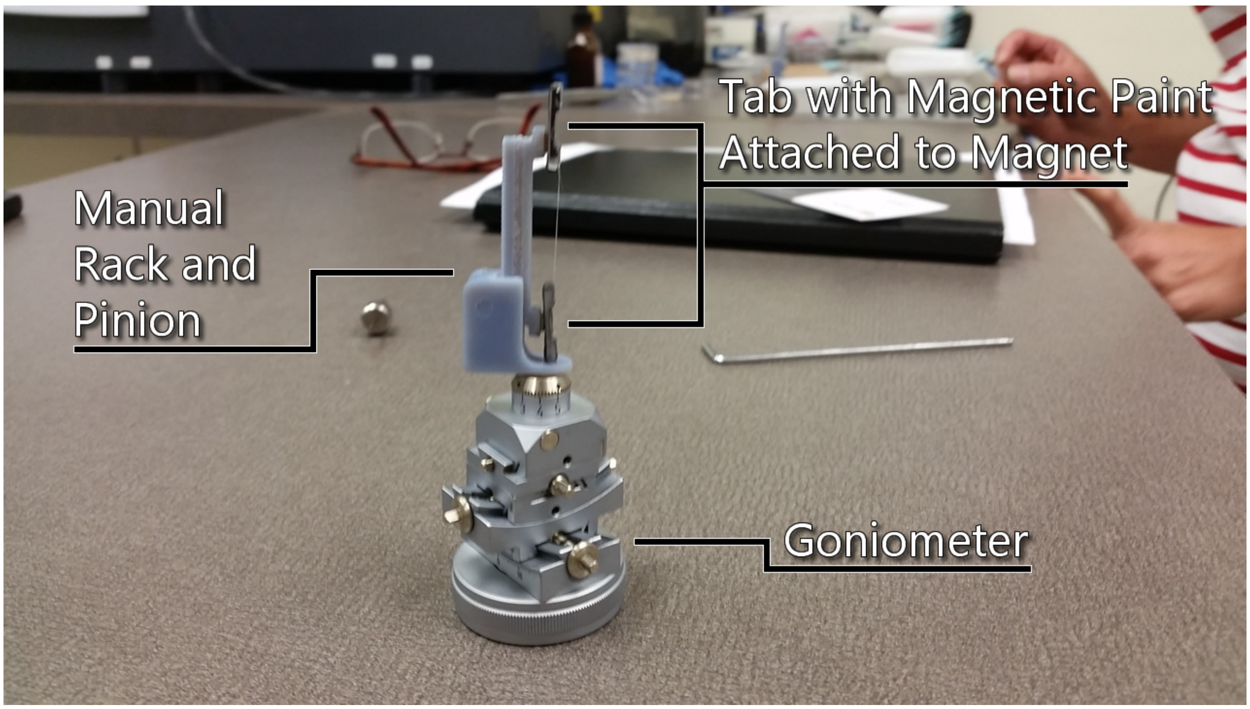


Figure 2: Fixture atop the Goniometer [4].

This current design fulfills the need of positioning the fibre in an observable location from the XRD and camera, but is not capable of applying a load on the fibre, nor is it capable of measuring any loads.

3. Project Objective

The objective of this project is to design a device that will hold a fibre in the XRD during testing, while simultaneously applying a measurable tensile stress. The device must accommodate the 12 mm gage length of the fibres, as well as account for 10 % elongation. In its fully elongated state the device must be small enough to fit within the XRD while it is running, and not interfere with any of the XRD's moving parts. Finally, due to the volume of fibres being tested each day (10 to 20), the device must allow the operator to insert new fibres quickly and efficiently. As Fig. 3 shows, there are many immovable obstacles that must be worked around.

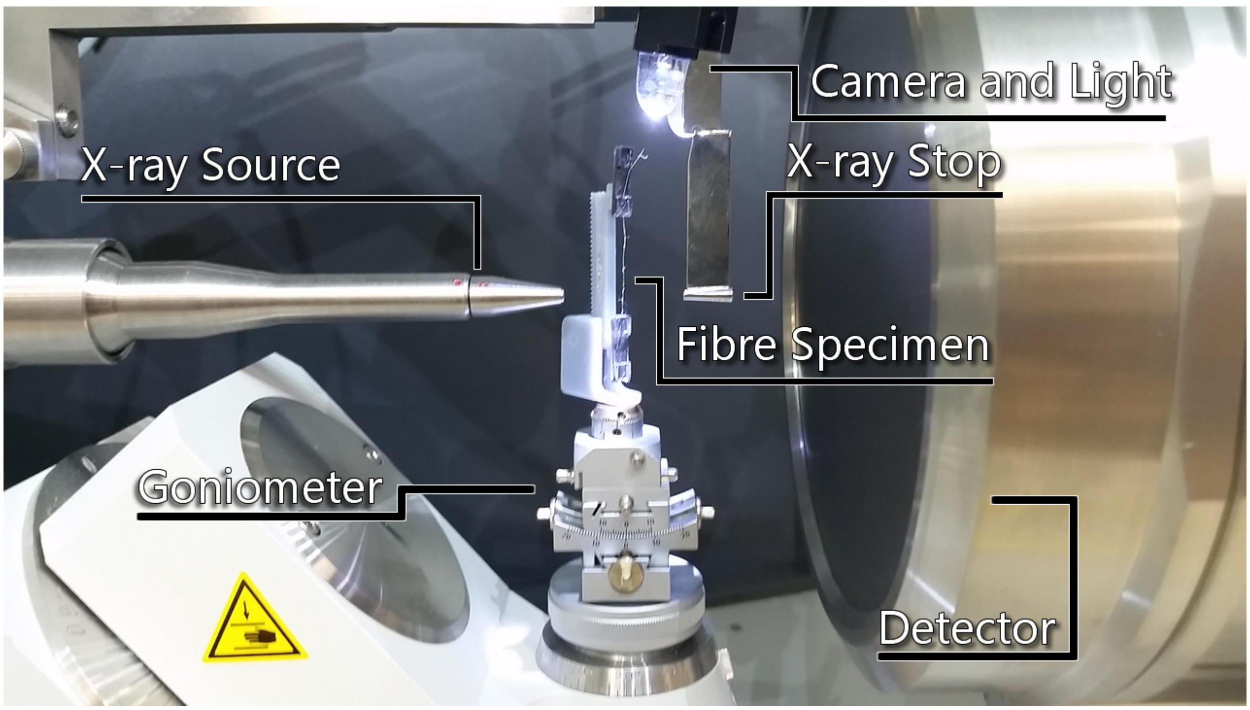


Figure 3: XRD with fixture and loaded specimen [5].

The x-ray source and x-ray stop create a maximum width constraint of approximately 25 mm, while the camera and light position give a maximum height constraint of approximately 55 mm.

3.1. Client Needs

The needs for the design were defined after meetings with the client and are shown in Table I. The most important criteria are weighted with a 5, while less important criteria were weighted with a 1. These criteria were then used to compose concept screening and scoring matrices, with the relevant need descriptors in brackets.

TABLE I: CLIENT NEEDS HIERARCHY

Need	The Design...	Weight
Applies Tensile Load	Can apply a sufficient tensile load	5
(Range)	Can apply a range of tensile loads	5
(Stability)	Can apply a load in a controlled manner	5
	Can apply a load over a long period of time	5
	Conforms to ASTM and/or ISO standards	5
	Can apply a load that can break a fibre	3
Measures Data	Can measure tensile loads	5
(Accuracy)	Can measure tensile load during XRD experiment	5
(Resolution)	Can measure displacements and elongations	5
(Repeatability)	Can measure data accurately	5
	Can output data in a readable format	5
	Can measure data in an automated manner	3
	Shows repeatability	3
Fits in Current System	Fits in the XRD	5
(Size)	Can manage auxiliary parts such as cables, wires, supports	3
	Is self contained	3
	Uses the current tab system	3
	Is able to rotate partially or fully	2
Durability	Can be exposed to x-ray radiation	5
(Durability)	Can perform multiple tests before failure	5
	Can survive falling on the floor	3
Cost Effective	Is inexpensive to replace *or*	4
(Cost)	Is replaced infrequently	4
	Has a lower cost than the commercial alternative	4
Safe	Can be used in an x-ray environment	5
(Safety)	Can be used without specialized safety equipment	5
	Can break a fibre without catastrophic failure	5
	Can shield auxiliary ports from x-ray	5

Need	The Design...	Weight
Fast (Speed)	Operating time is comparable to current procedure	5
	Loads specimens quickly	5
	Loads into the XRD quickly	5
	Can apply preload quickly	5
Usability (Ease of Implementation) (Ease of Use)	Is easy to set up	4
	Is easy to learn to use	3
	Is easy to load specimens into	3
	Is easy to remove specimens from	3
	Is easy to load into the XRD	3
	Is easy to remove from the XRD	3
	Expands on current design	2
	Can operate in other testing equipment	2
Secures Specimen (Stability)	Keeps the fibre specimen in place	5
	Is stable during tensile test	5
	Is stable in both vertical and horizontal positions	5
Environmentally Friendly	Uses environmentally friendly manufacturing methods	3
	Is recyclable	3

As the design space includes x-ray emissions and expensive hardware, safety is a top priority. The work requires measurable input and output to provide meaningful information. Thus, the application of a load and its measurement are also high priority needs.

One of the goals of this design is to also reduce the time it takes for both the tensile testing and XRD experiment to be completed. The current procedure is performed on two different pieces of equipment, leading to inefficiencies carrying out setup on two separate machines. Performing both tests simultaneously allows for the technician to observe the microstructure of the specimen inside the XRD while a load is applied. This new testing procedure will allow for a better understanding of how the microstructure changes as a tensile load is applied to a specimen.

3.2. Constraints and Limitations

Table II and III describe the constraints and limitations found in this project.

TABLE II: CONSTRAINTS

Constraint	Description
Safety	The design should not have any inherent risk in operation. It should be self-containable to the XRD and any auxiliary components should be unaffected by x-ray radiation or properly shielded.
Time	A tight time frame for research, concept development, design, prototyping, and testing was given.
Available Space	Approximately rectangular dimensions are 25 mm by 53 mm for width and height. Depth was not thoroughly measured, but had excessive space comparative to others. At least 50 mm if not more.
Labour Time	Labour time to insert fibre into fixture and install into XRD should be comparable to one minute.
Manufacturing	The final design must be manufacturable at the University of Manitoba or in-house for ease of prototyping and future orders.

TABLE III: LIMITATIONS

Limitation	Description
Mechanical Design	Due to the large scope encompassed by this project, the design details had to focus on the mechanical design.
XRD Motion	The complex geometry of the XRD and its motion requires prototyping to perform analysis on possible obstructions.
Fibre Gage Length	Gage length is set to 12 mm.
Maximum Elongation	Maximum elongation has been capped to 10% by the client.
Minimum Exposure Time	The test must be held in place after load application for two minutes.
Ports Accessible on XRD	A port in the back left of the XRD chamber is available for external access for cables.
Cost	Budget is estimated to be $2000 CAD, with an ideal approaching $5000 CAD.

3.3. Deliverables

The following is a list of deliverables expected by the client.

- Final Design for Miniature Tensile Testing Stage
- Technical Drawings (Appendix B)
- SolidWorks Files of Components
- Bill of Materials
- 3-D Printed Prototype
- Recommendations for Components Out of Scope

The final design will be detailed in the following section with a bill of materials. The technical drawings are included in Appendix B. A 3-D printed prototype dimensioned to the expected size of the final design will be provided to confirm the size requirements have been met. Additional components necessary for full functionality are required, but were out of scope for this design. Due to the limitation of focusing on the mechanical design, the electrical component and shielding of the design could not be thoroughly analyzed. Further recommendations for components and direction are provided.

4. Final Design

This section will describe the details of the final design, how it was chosen, iterated upon, and finalized. The final design that was chosen is depicted in Fig. 4.

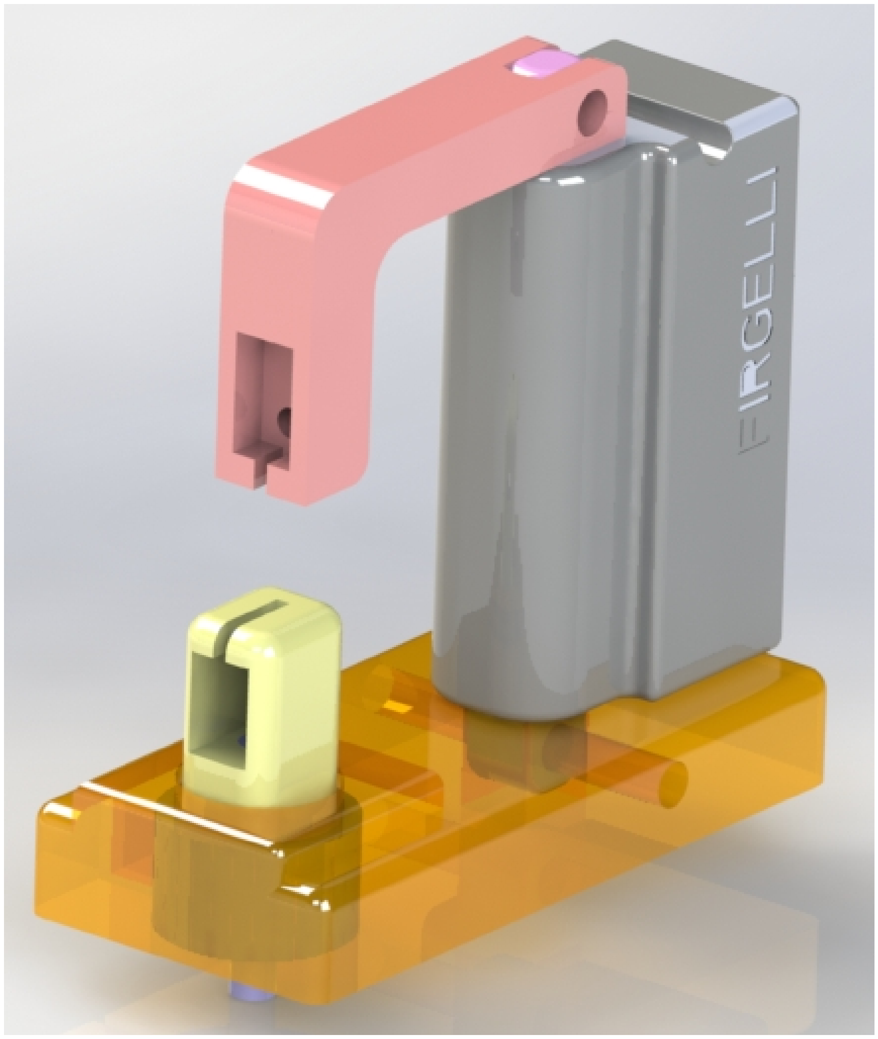


Figure 4: Final Design with Transparent Base [6].

The final design consisted of five major components and uses the current fibre and tab setup used by the client. The three designed pieces which require 3D printing are the base, the upper tab holder and the lower tab holder. The two parts sourced externally were the load cell, the LPM512 by Cooper Instruments, and the Firgelli PQ12 linear actuator. The base is used as an aligning and supporting piece for the entire apparatus. It aligns the load cell with both tab holders and keeps the actuator and load cell stationary. The bottom tab holder is threaded onto the load cell for a solid interface which can withstand the tension applied by the linear actuator.

The upper tab holder is bolted to the actuating end of the actuator and sits flush against it. The fibre is strung between the tab holders which sits directly in the line of the x-ray beam.

A morphological design process was used to reach this final design. This involved dividing the design into the aforementioned five separate components which perform a certain function and selecting a method which worked best. More details of this process can be found in Appendix A.

4.1. Details of Design

After the concept development process, which is detailed in Appendix A, testing inside the XRD was performed to determine if the chosen designs could fit within the alloted space. Unfortunately, the conceptual designs that were chosen were still too large, and further refinement of the design was required to meet the target size specifications. Two different load cells were considered for the final design; however, the vertical height of one load cell, the S251, was too large and could not be adapted to the system. The positioning of the displacement mechanism, which was a lead screw and motor also contributed too much height for the design to properly fit within the workspace.

Redesigns were necessary to combat these issues. Further details will be given in the subsections ahead, but a brief summary is as follows. The lead screw concept was replaced with a linear actuator which is functionally identical. The linear actuator chosen also functions as the vertical support. To further conserve vertical space, the load cell no longer sits atop a base. The bottom thread of the load cell is fixed within the goniometer and the base is fitted around the load cell to connect the linear actuator to it.

4.2. Load Cell

We have recommended the LPM 512 tension/compression load cell [7] seen in Fig. 5 to measure the load on the fibre. This load cell was chosen due to its ability to measure small loads (under 20N), and for being the smallest and most compact load cell available from research.

Figure 5: Image of LPM 512 Load Cell by Cooper Instruments [7].
Stamp for scale.

This load cell is capable of measuring loads between 150 g and 444.8 N [7]. The load cell has a diameter of 0.50 in and a height of 0.29 in, excluding the threads. The threads add an additional 0.18 in to each side. In metric, this is a total diameter of 12.7 mm, a sectional height of 7.37 mm and a total height of 16.51 mm. The product specifications for the load cell is provided in Table IV.

TABLE IV: SPECIFICATIONS FOR SUGGESTED LOAD CELLS [7]

Product	LPM512	
	Metric	Imperial
Range	0 – 444.8 N	0 – 100 lbf
Output	2 mV/V	
Diameter	12.7 mm	0.50 in
Midsection Height	7.37 mm	0.29 in
Thread Height	4.57 mm	0.18 in
Total Height	16.51 mm	0.65 in
Excitation	5 V DC	
Nonlinearity	± 0.5%	
Repeatability	± 0.10%	
Hysteresis	± 0.5%	
Cost	$795	

4.3. Linear Actuator

The Firgelli PQ12 linear actuator was chosen to create the load for this tensile test. A SolidWorks render of the CAD model is shown in Fig. 6.

Figure 6: Render of Linear Actuator [6].

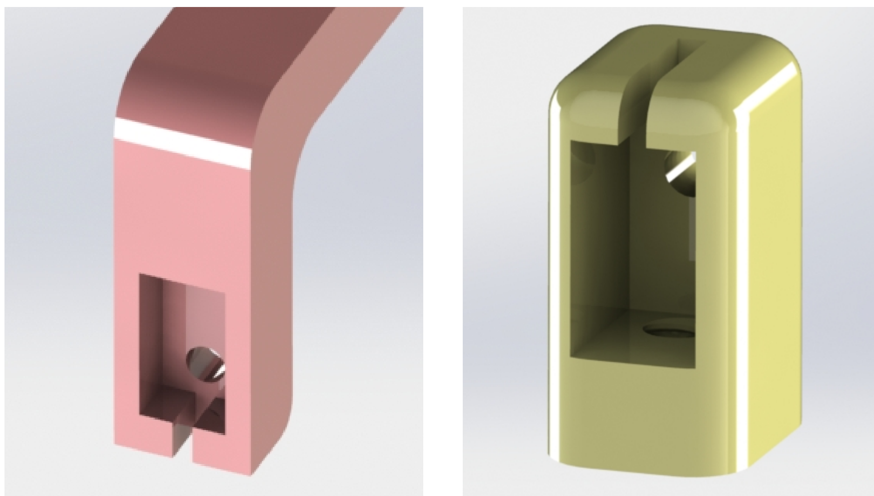
The initial concepts used a lead screw that was placed in-line with the fibre. This lead screw would be driven by a stepper motor, allowing for precise movement based on the thread type used for the lead screw and the resolution of the stepper motor. By having the lead screw in-line with the fibre, issues with regards to bending were non-existant; however, vertical space constraints could not be overcome with this design, and a new approach was required.

A linear actuator applies a measurable displacement on one end of the fibre by moving a supporting component, allowing a force to be exerted. The PQ12 has an unextended height of 47.5 mm which allows it to fit parallel to the fibre being tested. The maximum height available was measured to be approximately 53 mm, allowing for up to 5.5 mm of extension which is more than needed. It has a width of 15 mm which is thin enough to not impede on the instruments. Its depth is 21.5 mm which is still low and depth is not a significant constraint compared to the other directions.

The PQ12 also features 3 mm holes at one end of the driving shaft and another at its base. These allow for easy mounting of the device onto a base, and an additional support to the moving actuator to enable driving.

4.4. Tab Slot

Our method of securing the tabs in the device is a vertical slot system and can be seen in Fig. 7. The tabs are slid in from the front and are held in place during tension. The slots consist of a cut away section that the tab fits into, with a lip that holds the tab in place while allowing the fibre to travel through. The lower tab also needed to be relatively thick so that a hole in the bottom can be drilled and used to hold the slot to the load cell. The upper tab slot will be manufactured as part of the upper support connected to the linear actuator. Both systems will be 3D printed from ABS plastic.



(a) Top Tab Holder (b) Bottom Tab Holder

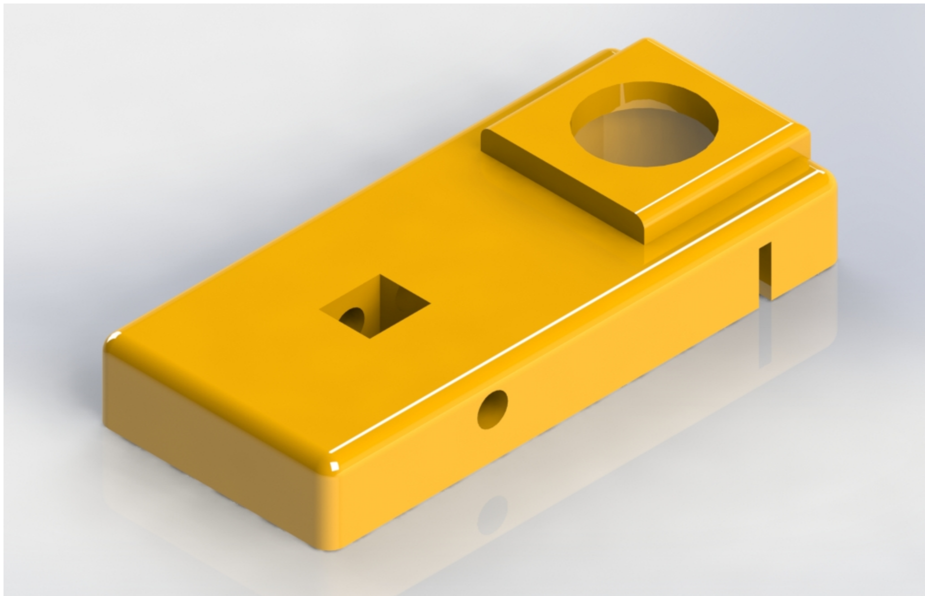
Figure 7: Render of Slot System [6].

An additional hole at the back of the slots allows for the removal of an inserted tab. This slot system was chosen due to its simplicity and because it allowed the fibre to be held completely vertical in the center of the XRD. To save on space constraints, the slots are only large enough to fit half a tab. Therefore the unused half of the tab will need to be removed before being inserted.

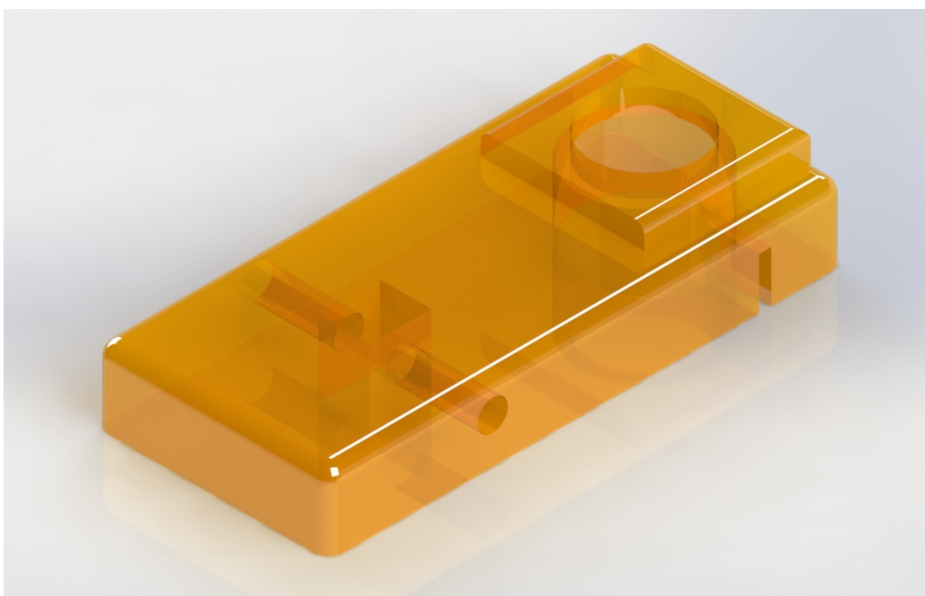
It is expected that the tabs stay in place due to gravity and friction alone by conforming to the shape of the slot. If there is a need to introduce more securing features, the addition of magnets to work with the current metallic paint that is being applied to the tabs will be sufficient. Alternatively, an added cover to prevent the tab from falling out of the slot can be manufactured.

4.5. Base

The design is supported by the bottom thread of the load cell being clamped in the goniometer. This allows the design to rest atop the goniometer. An additional base made of ABS plastic is used to connect the linear actuator to the load cell. A support also connects the top of the linear actuator to a slot which holds a tab and fibre. A SolidWorks render of this base is shown in Fig. 8 with a solid view and a transparent view to show the interior extrusions.



(a) Base



(b) Transparent Base

Figure 8: Render of Base [6].

The base is a rectangular shaped piece of ABS plastic. The height is the same as the load cell excluding threads, 7.37 mm. Three slots exist to house the components. A vertical circular hole with the same diameter of the load cell beneath the raised square fits the load cell inside. The load cell is inserted into this bottom hole with the thread fitting through the smaller opening in the raised square. The top opening is not large enough for the entire load cell to fit through, thereby supporting the base on top of the load cell. The lower tab slot can be secured on the thread of the load cell and tightened to be flush against its surface. A small notch on the side allows the wires of the load cell to protrude out.

A vertical rectangular hole is present to fit one end of the linear actuator. A horizontal screw hole passes through this rectangular hole which allows a screw to secure the linear actuator to the base. The position of this hole was determined through a combination of prototyping and calculations, described in the following section. A certain minimum distance from the center of the fibre to the face of the actuator must be achieved for a given initial position, such that after rotation the actuator does not contact the XRD stop.

4.6. Support

The top support is an L-shaped component as shown in Fig. 9. As described in Section 4.4, a slot exists to hold the tab and fibre in place. A screw hole is present to attach this support to the linear actuator. The entire upper support is displaced by the actuator while it is holding the tab with fibre in a slot.

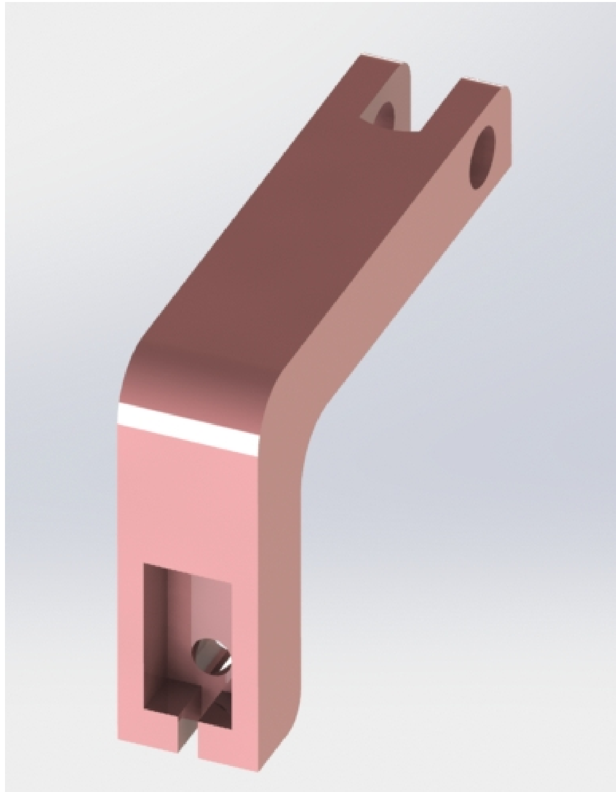


Figure 9: Render of Top Support [6].

By approximating this component as a simple beam in bending, the expected deflection caused by the maximum load from the fibre can be determined. The moment of inertia is found from the following equation.

$$I = \frac{bh^3}{12}$$

$$I = \frac{(0.021)(0.006)^3}{12} = 3.78 \times 10^{-10}\,\mathrm{m}^{-4}$$

Young's modulus for ABS plastic is given as ranging from 1.4 GPa to 3.1 GPa while Steel is given as 200 GPa [8]. Assuming a maximum load of 20 N, the maximum possible deflection can be found for each material.

$$y_{max} = \frac{wL^3}{3EI}$$

Weak ABS:

$$y_{max} = \frac{(20)(0.030)^3}{3(1.4 \times 10^9)(3.78 \times 10^(-10))}$$

$$= 0.3401\,\mathrm{mm}$$

Strong ABS:

$$y_{max} = \frac{(20)(0.030)^3}{3(3.1 \times 10^9)(3.78 \times 10^(-10))}$$
$$= 0.015\,36\,\text{mm}$$

Steel:

$$y_{max} = \frac{(20)(0.030)^3}{3(200 \times 10^9)(3.78 \times 10^(-10))}$$
$$= 0.002\,381\,\text{mm}$$

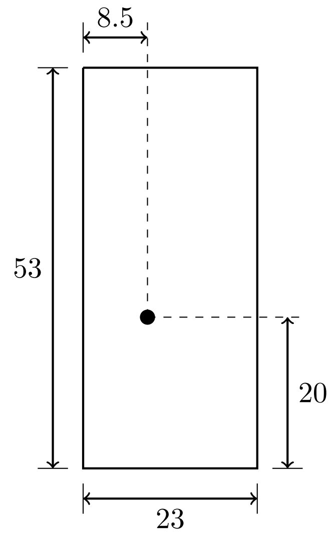
Comparing the maximum deflection to the maximum elongation, the expected error for weak ABS is too high. Strong ABS is 1.25%, while steel is 0.2%.

4.7. Prototyping

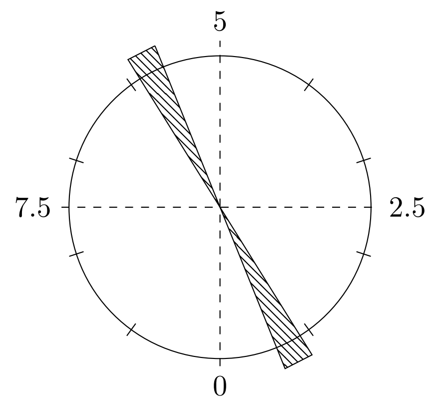
Due to the complex path of the goniometer, it was decided that a physical prototype would be necessary due to difficulties modeling the movement of the arm and the obstacles which it cannot interfere with. In addition, the arm which holds the goniometer takes a different path of motion when it moves from its resting position to the alignment position compared to moving from the alignment position to the resting position.

For a preliminary measurement for width and height, a simple piece of cardboard was cut and attached to the current fixture and placed within the XRD machine. This testing allowed the evaluation some of the movements of the goniometer arm and illustrated how it took two different paths depending on whether it was going up or down.

The cardboard's initial dimensions used rough measurements from the XRD space. The initial height was approximately 60 mm with a width of 25 mm. The cardboard piece was initially too large for the XRD since the height did not consider the fixture it sat upon. As the arm rotated through its movement and met obstacles, the interfering area of the cardboard was cut allowing the arm to proceed further. The other variable that was changed was the angle at which the cardboard sat relative to the goniometer. The goniometer has its circumference marked in tenths, which an be used to denote the angular position of an object placed inside. The initial position facing the viewer when the XRD is at rest is 0. The side that faces the x-ray beam (left) is marked 7.5, and the side that faces the XRD stop (right) is 2.5. After rotation, the side that faces the x-ray (left) is 0. The side facing up is 2.5, and the side facing the XRD stop (right) is 5.0. The cardboard piece was adjusted to an angle range where it did not require any readjustment during movement to prevent it from hitting an obstruction. The final dimensions of our prototype are given by Fig. 10. The figure shows the major dimensions as well as the area of contact with the x-ray beam, where the fibre will sit visible to the camera. The angle at which the prototype could be the largest was roughly between 22° and 32°.



(a) Cardboard width and height with x-ray location

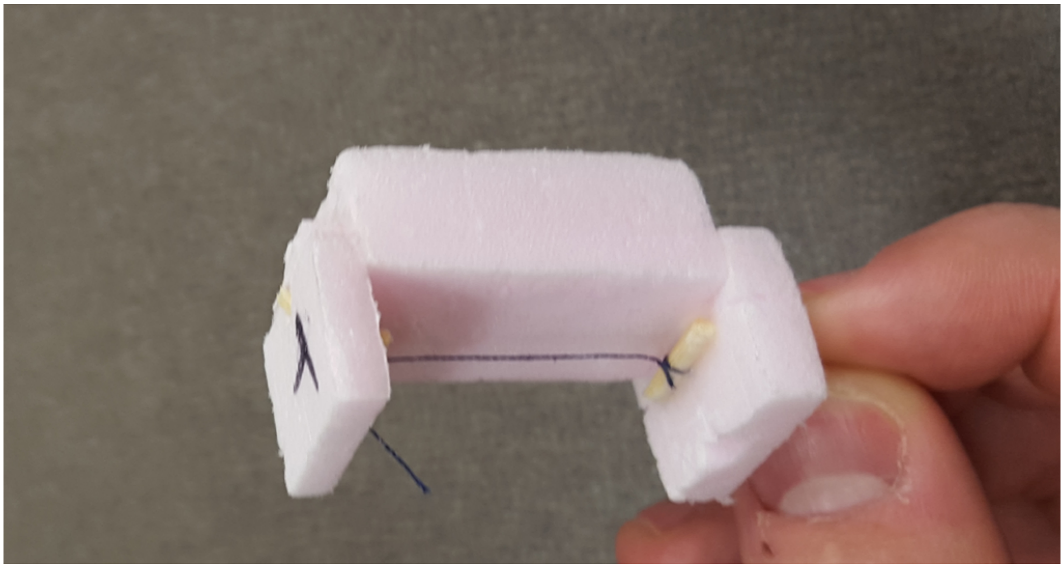


(b) Goniometer angle denoted in 10ths of circumference

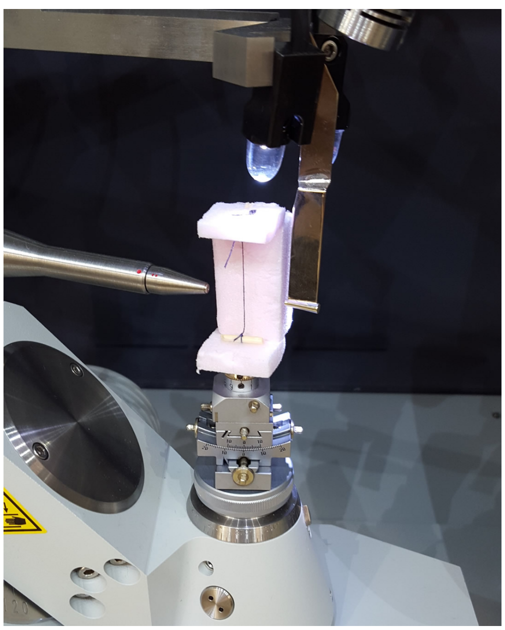
Figure 10: Approximate dimensions and position of cardboard prototype in mm

This prototype provided reliable constraints in two dimensions, and during testing it was observed that the last dimension, depth, had large amounts of clearance from any obstacles within the XRD.

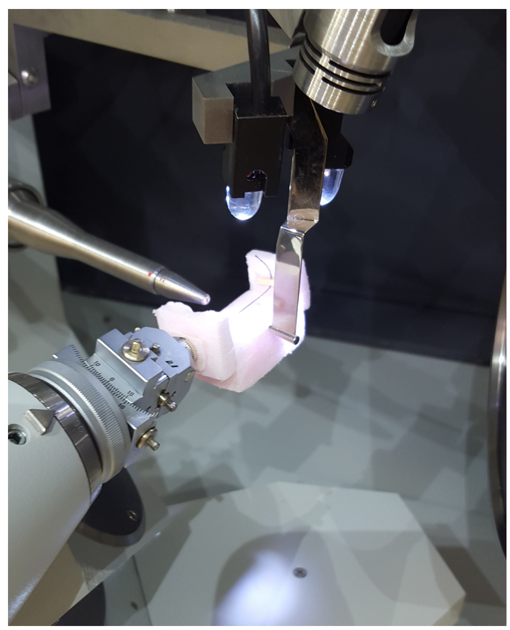
The second phase of prototyping involved creating a more realistic, 3-dimensional model to place within the XRD. The construction material chosen was foam board insulation for its easy manipulation and reasonable accuracy for a prototype. The prototype used was placed into the machine as shown in Fig. 11.



(a) Initial Foam Prototype



(b) In setup position



(c) In alignment position

Figure 11: Initial Foam Prototype [9].

The model successfully fit in the setup position as shown above, but was not able to complete the movement into the alignment position. By implementing the same iterative method as the cardboard prototype, material was cut from the prototype until it was able to successfully move through both paths without external adjustment from the operator. The successful prototype is shown in Fig. 12. The cardboard was used as structural support as the insulation was very thin in the centre section after cutting.

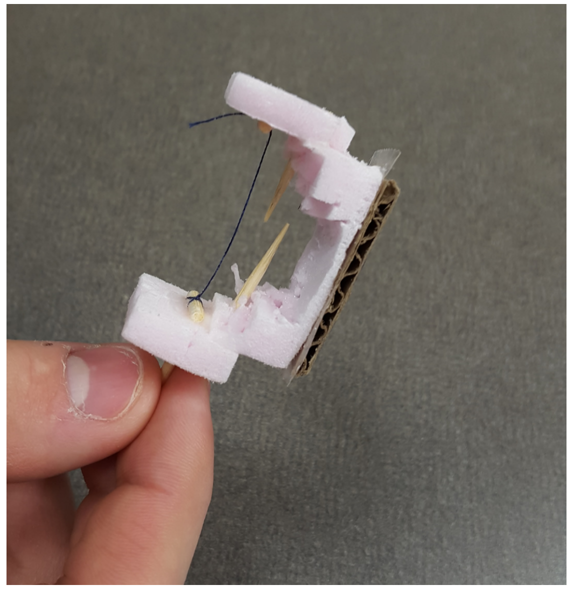


Figure 12: Final Foam Prototype [9].

This approximate prototype and additional calculations were used to help verify the final placement of the linear actuator in the design. The position of the linear actuator from Fig. 11c is conceptually represented with a straight ahead view in Fig. 13.

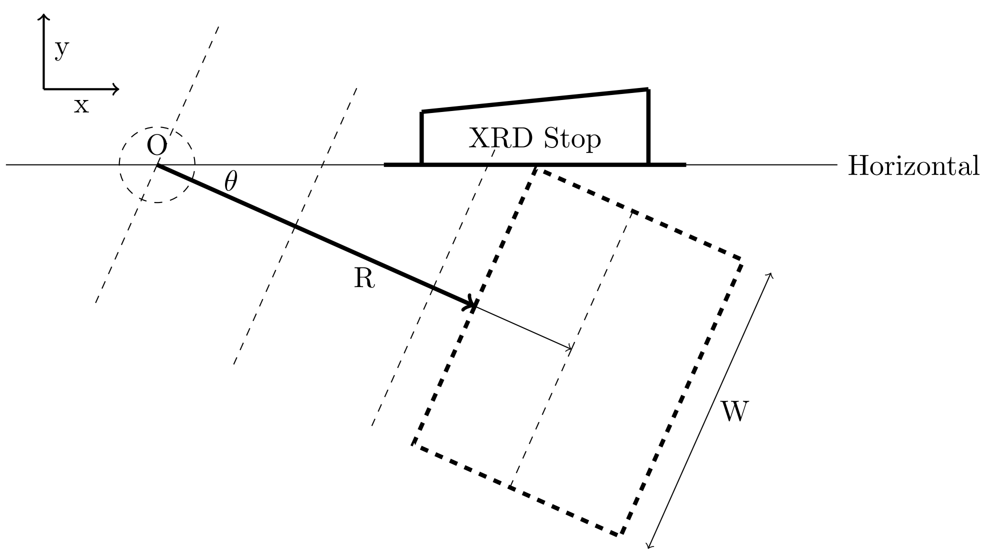


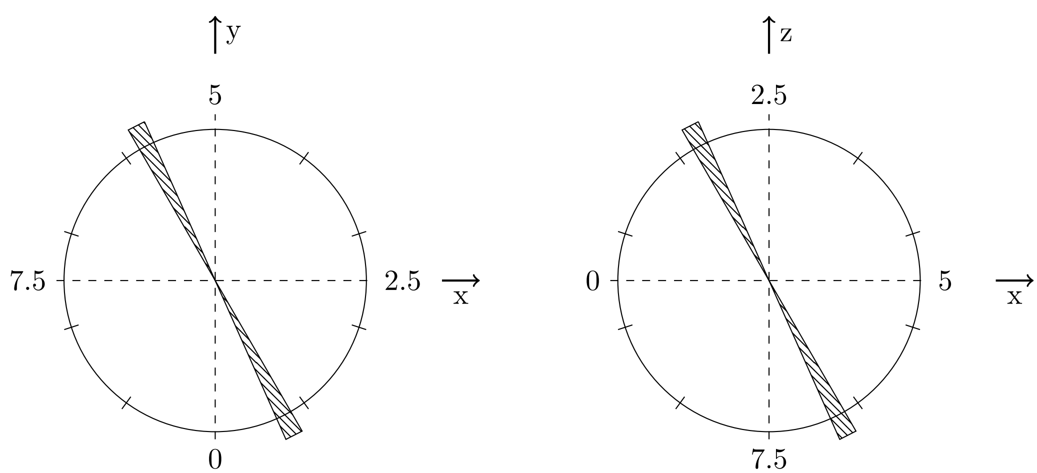
Figure 13: Position of the Actuator, not to scale

Fig. 13 shows a cross-sectional view of the actuator, comparing its position to where it may obstruct the XRD stop when the goniometer is in the horizontal position. The point of rotation, denoted O is the center of the goniometer. The face of the actuator is a certain distance away from that point, which is denoted R and potential positions are marked with dashed lines to illustrate how distances shorter than the shown R pass through the XRD stop. The thick dashed rectangle represents the position where the actuator no longer contact the XRD stop. The actuator has a width of W, centered and perpendicular about R. As the position of the actuator away from O becomes larger, the distance above the horizontal line begins to decrease to the point where it no longer extends through the XRD stop.

The distance required between the center of the fibre to the face of the actuator such that the x-ray stop is not struck while rotating can be found using the following formula

$$R = \frac{0.5W}{\tan\theta}$$

where W is the width, and θ is the initial angle offset that the tensile tester is placed on the goniometer. Fig. 14 compares the rotation of the goniometer and the relative position of the center line of the device, where xyz axes indicate width, depth, and height respectively. Note that in Fig. 14a, the z-axis which indicates height points into the page, whereas 14b shows the y-axis or depth pointing into the page.



(a) Top-down view of goniometer

(b) Frontal view of goniometer

Figure 14: Comparison of goniometer position before and after rotation

The initial position of the device in the goniometer is estimated to be between 0.666 and 0.833, or 24° to 30°. Based on the actuator width of 15.00 mm, the minimum distances for R

from the given angles can be found as follows

$$R = \frac{7.5}{\tan 24}$$
$$= 16.85\,\mathrm{mm}$$
$$R = \frac{7.5}{\tan 30}$$
$$= 12.99\,\mathrm{mm}$$

The distance must be between 12.99 mm and 16.85 mm if the initial position of the tensile tester inside the goniometer is between 30° and 24° respectively to prevent the actuator from impeding on the XRD stop.

4.8. Recommendations

Due to limitations in time and technical knowledge, assessment for x-ray shielding and data acquisition could not be performed in depth. The following are recommendations for the client which provide a general direction for possible solutions.

4.8.1. Shielding

The load cell and actuator contain wiring that will need to be run through panels in the back of the XRD. The panel can be seen in Fig. 15. The wiring of these two components may also need to be extended to exit the XRD.

Figure 15: Photograph of XRD Auxiliary Panel [10].

To properly shield the wires, it is recommended the client pursue a vendor that has a proper shielding rubber material. They can then create small holes through the rubber to insert the wires through for a tight fit. In order to ensure that they is no leakage, test the radiation with the use of a Geiger counter.

4.8.2. Data Acquisition

A data acquisition module is necessary to collect data from the test. The Personal Daq/50 Series by Measurement Computing offers a possible solution. The Personal Daq/54 shown in Fig. 16 is recommended. It has a cost of $829 [11]. This data acquisition system is compatible with the current load cell and actuator selections.

Figure 16: Personal Daq/54 [11].

The data sheet can be found in Appendix C. This system will be able to transfer the data being processed in the XRD from the tensile testing stage to a nearby computer to document and review the results.

4.9. Design Summary

A summary of the design is as follows. A fully assembled view is shown in Fig. 17, and an exploded view is shown in Fig. 18.

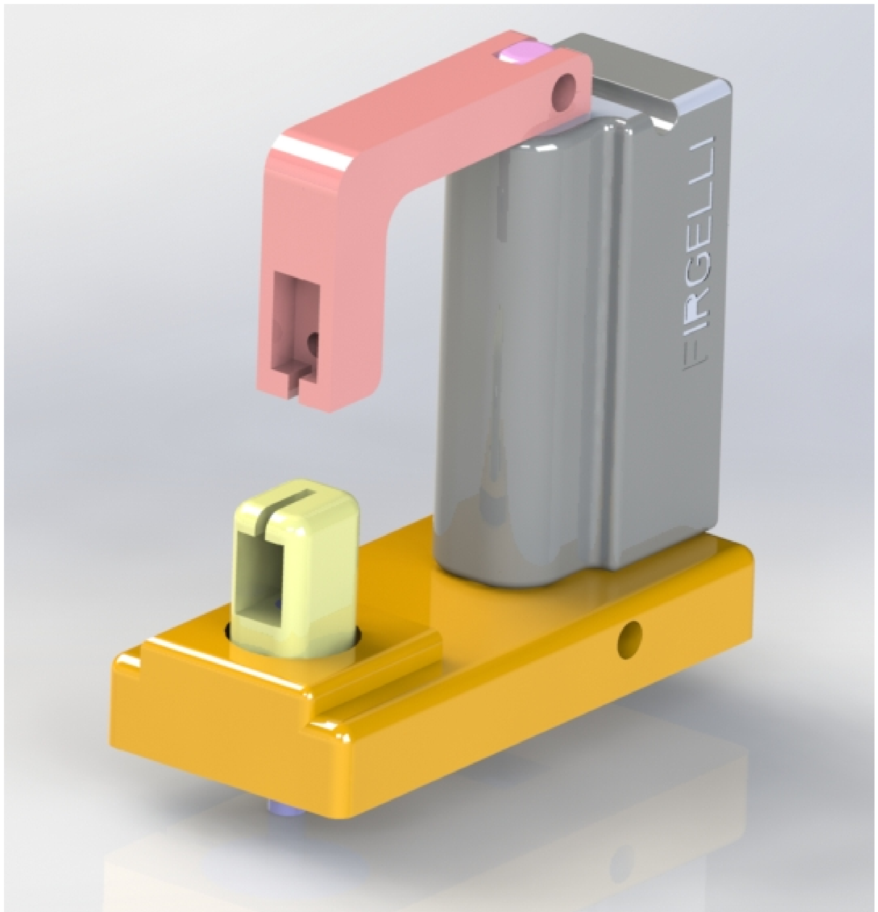


Figure 17: Final Design [6].

Pink:	Upper Support and Slot
Yellow:	Lower Slot
Orange:	Base
Blue:	Load Cell
Silver:	Linear Actuator

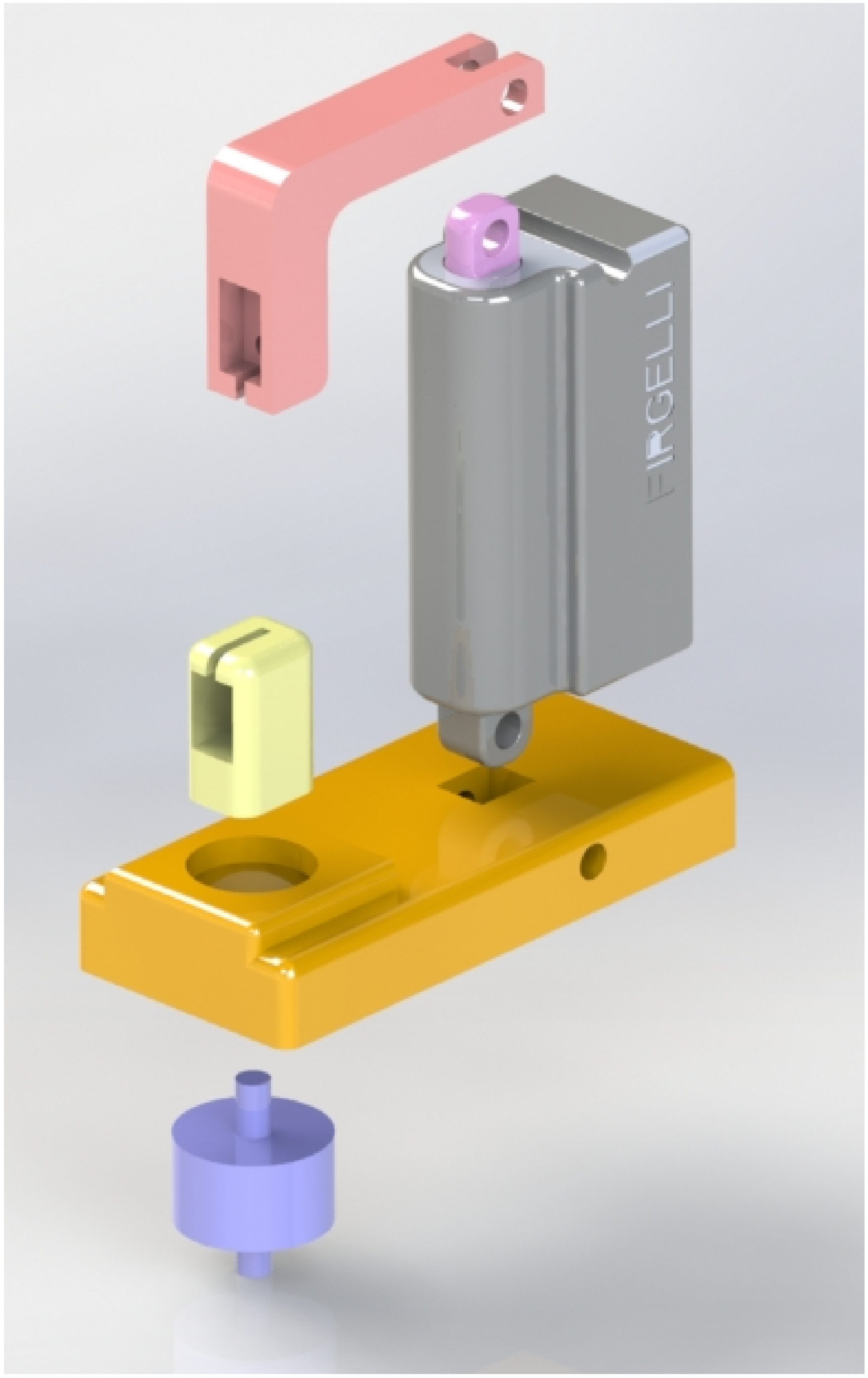


Figure 18: Exploded View [6].

The status of the client needs described in Table I are shown in Table V. A dash indicates not enough information to determine whether this need has been met.

TABLE V: CLIENT NEEDS BEING MET

Need	The Design...	Met?
Applies Tensile Load	Can apply a sufficient tensile load	Yes
(Range)	Can apply a range of tensile loads	Yes
(Stability)	Can apply a load in a controlled manner	Yes
	Can apply a load over a long period of time	Yes
	Conforms to ASTM and/or ISO standards	—
	Can apply a load that can break a fibre	Yes
Measures Data	Can measure tensile loads	—
(Accuracy)	Can measure tensile load during XRD experiment	—
(Resolution)	Can measure displacements and elongations	—
(Repeatability)	Can measure data accurately	—
	Can output data in a readable format	—
	Can measure data in an automated manner	—
	Shows repeatability	—
Fits in Current System	Fits in the XRD	Yes
(Size)	Can manage auxiliary parts (cables, wires, supports)	—
	Is self contained	Yes
	Uses the current tab system	Yes
	Is able to rotate partially or fully	Yes
Durability	Can be exposed to x-ray radiation	—
(Durability)	Can perform multiple tests before failure	Yes
	Can survive falling on the floor	No
Cost Effective	Is inexpensive to replace *or*	Some
(Cost)	Is replaced infrequently	Some
	Has a lower cost than the commercial alternative	Yes
Safe	Can be used in an x-ray environment	—
(Safety)	Can be used without specialized safety equipment	Yes
	Can break a fibre without catastrophic failure	Yes
	Can shield auxiliary ports from x-ray	—

Need	The Design...	Met?
Fast	Operating time is comparable to current procedure	Yes
(Speed)	Loads specimens quickly	Yes
	Loads into the XRD quickly	Yes
	Can apply preload quickly	No
Usability	Is easy to set up	Yes
(Ease of	Is easy to learn to use	Yes
Implementation)	Is easy to load specimens into	Yes
(Ease of Use)	Is easy to remove specimens from	Yes
	Is easy to load into the XRD	Yes
	Is easy to remove from the XRD	Yes
	Expands on current design	No
	Can operate in other testing equipment	No
Secures Specimen	Keeps the fibre specimen in place	Yes
(Stability)	Is stable during tensile test	—
	Is stable in both vertical and horizontal positions	—
Environmentally Friendly	Uses environmentally friendly manufacturing methods	Yes
	Is recyclable	Yes

Certain needs were not adequately met. The 3D printed ABS plastic, and the purchased components are not expected to survive an impact after falling from the height of a desk. Application of a preload requires extending the actuator by a small amount which could take more time. This final design does not expand on the previous design nor can it operate in other testing equipment.

Whether the design meets the data measurement needs is not immediately clear. Testing is required to determine if these needs are met with the recommended data acquisition module. Management of auxiliary parts is unclear since the actual components are not available to test with. There should be sufficient space and positioning for the wires available though. More research into x-ray shielding is required to determine what is necessary to achieve the safety necessities.

4.10. Assembly

The device should be assembled by first inserting the load cell into the circular hole in the bottom of the base. Its thread should enter an opening, while the wiring should be tucked through a gap in the side. Next, the lower slot can be screwed onto the load cell until it is flush with the base. The upper support can be screwed to the actuating side of the linear actuator first using an 20 mm M3 machine screw, being secured with an M3 nylock nut. The support should be pointing away from the power cable, and the slot pointing downwards. The linear actuator can then be inserted into the base, screwed in with a 40 mm M3 machine screw, and secured by another M3 nylock nut.

When the arm of the actuator moves upwards, it will in turn displace the upper support and slot. The lower slot is threaded onto the load cell which remains stationary due to the base. Only the threaded rod of the load cell protrudes through the base. Due to these threads, it is necessary for the lower tab slot to be larger when compared to the upper support. When a specimen is placed within the fixture and is subjected to a tensile force, the actuator is accurate to ± 0.1 mm and a data acquisition system will allow you to control and monitor this value and the load cell will output the force being applied. The bill of materials, pricing and final measurements and specifications are included in the Table VI and VII.

TABLE VI: BILL OF MATERIALS

Name	Quantity	3D Printed?	Price	
Top Support	1	yes	Total Price Approx. $50.00	
Lower Tab Slot	1	yes		
Base	1	yes		
LPM512-10 Load Cell	1	no	$795.00	[12]
Firgelli PQ12 Linear Actuator	1	no	$65.00	[13]
M3 Machine Screw (40mm)	1	no	$1.00	[14]
M3 Machine Screw (20mm)	1	no	$1.00	[14]
M3 Nylock Nut	2	no	$3.99	[15]
Personal Daq/56	1	no	$829.00	[11]
Total			$1748.98	
Budget			$2000.00	

TABLE VII: FINAL SPECIFICATIONS

Width (mm)	23
Depth (mm)	40
Height (mm)	49
Fibre Length (mm)	12
Max Tensile Force (N)	35
Max Displacement (mm)	20
Total Cost ($)	1748.98

5. Conclusion

In conclusion, with all of the final parts sourced from various vendors, a solution for a miniature tensile stage in XRD has been provided. Below is a summary of the design, its key components, and recommendations for CIC going forward.

The LPM 512 load cell from Cooper Instruments is the smallest and most versatile load cell found from research that fits into the small working envelope, while still maintaining the accuracy needed for the small force applied to the fibre. However, since the space constraint is the most difficult to meet, one side of the load cell's threads must be placed into the goniometer itself and tightened in order to meet the height requirement.

The slot system used to secure the fibre and tab into the tensile stage was chosen due to its simplicity and space constraints. The current plastic tabs used by the client to secure fibres can be cut in half and inserted into the slot. Once the force is applied to the fibre the slot will hold the tabs in place. If the tabs have any tendency to slip forward out of the slot, it is recommend to continue using the metallic paint on the tab system and magnets will be added to the slot design to secure them.

The PQ12 actuator from Firgelli was chosen because it was able to be used as not only the driving force to elongate the fibre with the accuracy necessary, it also acts the vertical support of the tensile tester. A simple beam in bending analysis was performed on the upper support to determine the error from using the linear actuator in this method. From these results, strong ABS recommended as the weak ABS provided too large of a vertical deflection for the accuracy required. If the strong ABS still does not meet the accuracy needs of the application, it is then recommend to make the support out of steel as it provides such a low vertical deflection that the error will be practically negligible in the elongation process. In addition, the base must have a small hole near the load cell to allow the wires to be run through it.

The Personal Daq/54 by Measurement Computing Inc. is recommended as a starting point for investigating possible data acquisition modules. The total expected cost of the design is approximately \$919.98 with an additional \$829.00 for the data acquisition unit. The 3D printed components can be manufactured at the University of Manitoba.

6. References

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Appendix

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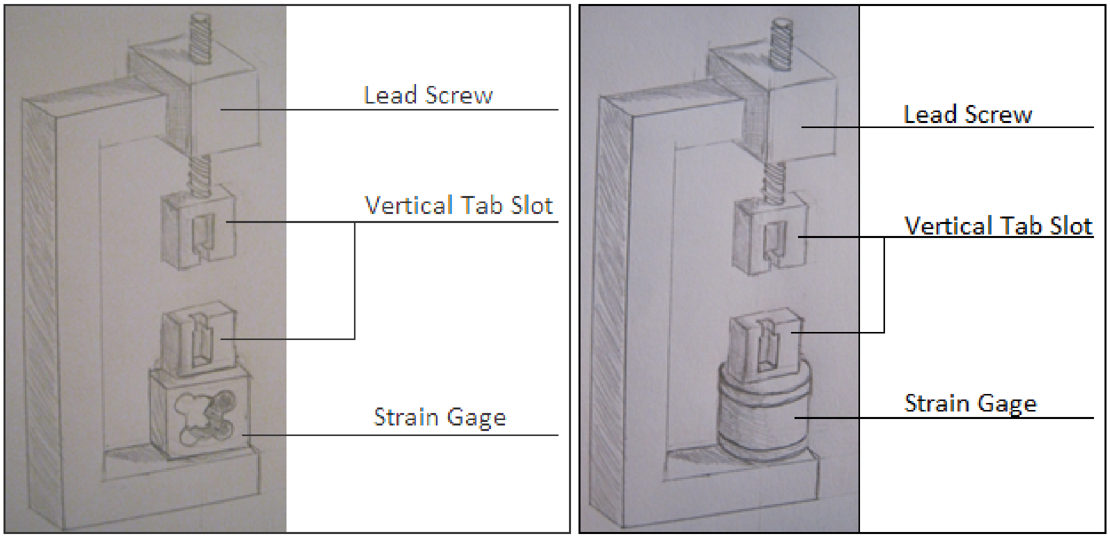
Appendix A. Overview of Concept Development

This appendix covers an overview of the concept development phase for this project. The final concepts chosen to pursue into the final design stage are shown in Fig. 1.



(a) L-Shape with S251 (b) L-Shape with LPM512

Figure 1: Selected Concepts [1].

The final concepts consisted of an L-shaped bracket for support. Two different load cells, the S251, and LPM512 were considered, and mounted at the bottom of the support. Above the load cell is a vertical tab slot. At the top of the support is a lead screw which holds a second vertical tab slot. The fibre attached to tabs are inserted into these tab slots, and the lead screw, powered by a stepper motor which is not visualized in Fig. 1 applies a displacement, causing a load. The following sections outline how these concepts were developed.

Appendix A.1. Conceptual Designs

The conceptual design divided the concept into five components. These components were designated based on their function – pulling, driving, gripping, load cell, and support. The pulling mechanism applies a tensile load or displacement on the fibre. The driving mechanism provides power to the pulling mechanism. The gripping mechanism holds the fibre in place. The load cell measures the applied load. The support component holds all these mechanisms together. Concepts for each component and a small description are shown in Tables I to V.

TABLE I: PULLING MECHANISMS

Lead Screw	A type of screw that converts a rotational movement into a linear movement, powered by a stepper motor or servomotor. The linear distance traveled can be controlled by the fineness or resolution of the threads, and the resolution of what is driving it.
Ball Screw	Functionally similar to a lead screw, but larger due to its design.
Rack and Pinion	Converts rotation by the pinion into linear motion by the rack. Easily manufacturable, accuracy depends on the quality of printing for small components and gear ratio.
Pneumatics	A possible method suggested by the client from availability of pressurized air. Concerns arose over size and stability.
Manual	Manually apply a tensile load on the fibres. Low cost option, but excessively time consuming and inaccurate.

TABLE II: DRIVING MECHANISMS

Manual	Manually apply a driving force to power one of the pulling mechanisms, such as manually turning a lead screw, or rack and pinion. Low cost option, but excessively time consuming and inaccurate.
Stepper Motor **Servomotor**	Two types of motor with small discretized steps capable of high resolution rotation. Provides an accurate and controllable method of powering a lead screw, ball screw, or rack and pinion. Many low cost high accuracy possibilities available.
Electromagnet	An unorthodox method for providing a driving force. This proved to be too complicated to implement.

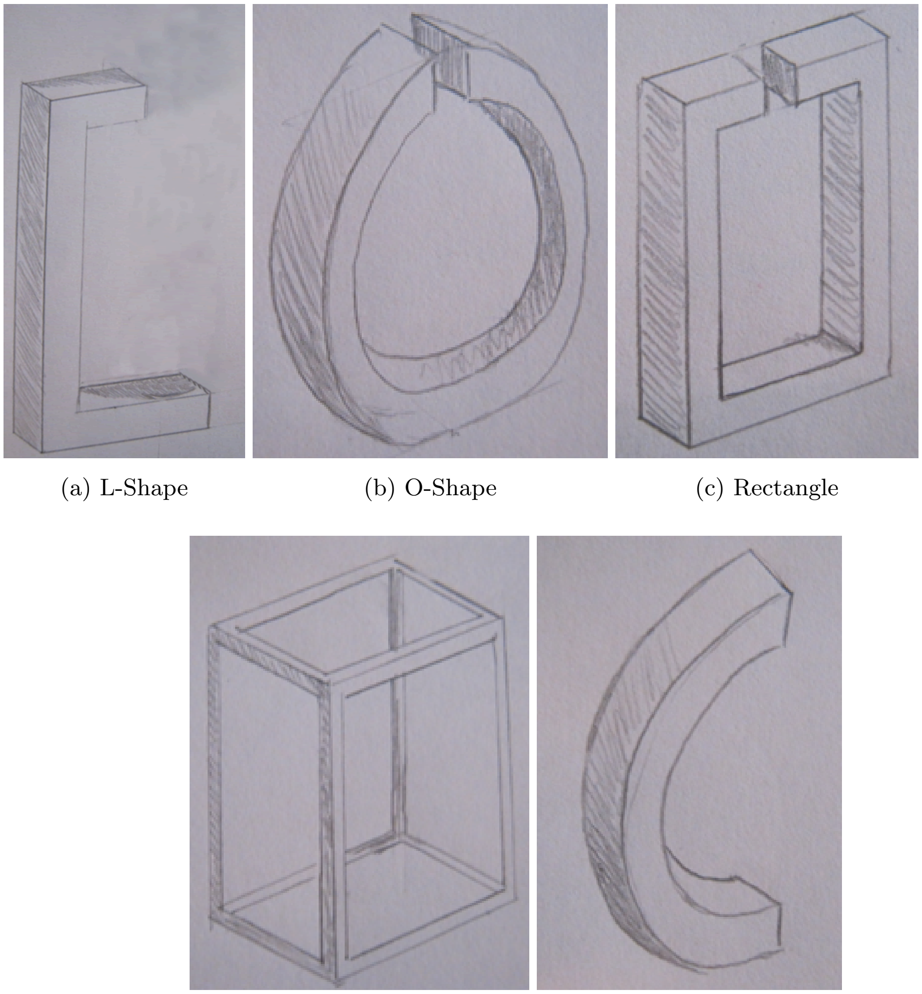
The following load cells were recommended by their respective companies for an application requiring minimizing space and achieving small loads.

TABLE III: SPECIFICATIONS FOR SUGGESTED LOAD CELLS

Product	LPM512 [2]	LPM530 [3]	RES2 [4]	S251 [5]
Range	0 – 22 N	0 – 22 N	0 – 2000 N	0 – 20 N
Output	2 mV/V	1.5 mV/V	2 mV/V	2 mV/V
Size	13 x 17 mm	25 x 25 mm	18 x 19 mm	32 x 18 mm
Excitation	5 V DC	5 V DC	10 to 20 V DC	5 to 20 V DC or AC
Nonlinearity	± 0.5%	± 0.15%	± 0.5%	0.04%
Repeatability	± 0.1%	± 0.1%	± 0.5%	0.02%
Hysteresis	± 0.5%	± 0.2%	± 0.5%	0.02%
Cost	$795	$750	$450	$193

TABLE IV: GRIPPING MECHANISMS

Vice Clamp	A clamping mechanism that requires tightening to hold the fibre or a tab which it is attached to.
Vertical Slot	A recessed hole where the fibre attached to a tab fits vertically.
Horizontal Slot	A recessed hole where the fibre attached to a tab fits horizontally.
Tying	Tying a fibre to secure it. Extremely difficult given the overall length, while adding additional stresses and loss of accuracy.
Screwing	Placing the fibre through a screw and tightening it to secure it. Poses challenges in damaging the thread and applying a torque.
Threading	Threading the fibre through a small opening to secure it. May be too manually intensive for such a small and fine procedure to be repeated frequently.
Spring Clamp	A clamp that secures the fibre or tab by using a spring.
Magnet	Continued use of magnets to hold magnetically painted tabs.



(a) L-Shape (b) O-Shape (c) Rectangle

(d) Prism (e) C-Shape

Figure 2: Structural Support Illustrations [1].

TABLE V: SUPPORT MECHANISMS

L-Shape	A simple geometry that takes up minimal space. May have issues with bending an unbalanced load depending on the rigidity.
O-Shape	A larger geometry that tries to combat possible bending issues due to unbalance.
Rectangle	Two L-Shapes put together to combat possible bending issues.
Prism	A larger frame like structure. Due to the additional supports, the beams can be thinner, but the overall effective volume is larger.
C-Shape	Similar to the L-Shape but rounded.

Appendix A.2. Concept Scoring

The criteria shown in Table VI were chosen based on the customer needs. A plus sign (+) indicates the criteria on the left is more important than the one above. A minus sign indicates it is less important. The grayed out cells show duplicate comparisons. The scores were then summed, and weights are calculated using the score for a criteria divided by the total points given for all criteria. As an example, for pulling *accuracy*, the weight is $^{9}/_{66} = 0.13636... = 13.636\%$.

The criteria are broad overarching concepts of the complete design, but each component does not necessarily correspond to a certain criteria. As an example, the driving mechanism does not have a corresponding *range* criteria. As such, every other criteria cannot compare a score with *range*. The pulling mechanism *accuracy* scores a 9 from a possible 11, whereas the driving mechanism only scores 8 from a possible 10 since it cannot compare *accuracy* with *range* to get a score.

TABLE VI: CRITERIA WEIGHING MATRIX

Criteria														Component Score				
	Accuracy	Resolution	Size	Cost	Implementation	Ease of Use	Durability	Speed	Safety	Range	Repeatability	Stability		Pulling	Driving	Load Cell	Gripping	Support
Accuracy		+	-	+	+	+	+	+	-	+	+	+		9	8	8		
Resolution			-	+	+	+	+	+	-	+	-	+		7	6	6		
Size				+	+	+	+	+	-	+	+	+		10	9	9	8	5
Cost					+	-	-	-	-	+	-	+		3	2	2	3	2
Implementation						+	+	+	-	-	-	-		3	3	3	3	2
Ease of Use							+	-	-	+	+	+		5	4	4	5	3
Durability								-	-	+	-	-		2	1	2	2	1
Speed									-	+	-	-		4	3	4	4	
Safety										+	+	+		11	10	10	9	6
Range											-	-		1		1	1	
Repeatability												-		6	5	6	6	
Stability														5	4		5	2
Total														66	55	55	45	21

A concept screening process resulted in the concepts shown in Tables VII to XI to be scored. The weights achieved from Table VI are used to score each concept. The highest scoring pulling mechanism is shown to be the Lead Screw in Table VII. While the ball screw is similar in design and scoring for many criteria compared to the lead screw, it scored less favourably in size and cost, leading to a larger difference in points. The rack and pinion showed less promise in accuracy and resolution.

TABLE VII: PULLING MECHANISM SCORES

	Total Points		Lead Screw		Rack and Pinion		Ball Screw	
	Weight	% Weight	Score	Weight	Score	Weight	Score	Weight
Accuracy	9	0.136	5	0.682	3	0.409	5	0.682
Resolution	7	0.106	5	0.530	3	0.318	5	0.530
Size	10	0.152	3	0.455	4	0.606	2	0.303
Cost	3	0.045	3	0.136	4	0.182	2	0.091
Implementation	3	0.045	3	0.136	4	0.182	2	0.091
Ease of Use	5	0.076	4	0.303	4	0.303	4	0.303
Durability	2	0.030	4	0.121	3	0.091	2	0.061
Speed	4	0.061	3	0.182	4	0.242	3	0.182
Safety	11	0.167	5	0.833	5	0.833	5	0.833
Range	1	0.015	5	0.076	5	0.076	5	0.076
Repeatability	6	0.091	5	0.455	3	0.273	5	0.455
Stability	5	0.076	5	0.379	3	0.227	5	0.379
Total	66	1.00	50	**4.288**	45	3.742	45	3.985

Table VIII shows the stepper motor concept scored the highest for driving mechanisms. The score was very similar to the servomotor concept though, only proving more favourable for implementation. The final choice would have to be decided based on specific models available on the market, as there can be large variances for specific products on any of these criteria.

TABLE VIII: DRIVE MECHANISM SCORES

	Total Points		Stepper Motor		Servomotor		Manual	
	Weight	% Weight	Score	Weight	Score	Weight	Score	Weight
Accuracy	8	0.145	5	0.727	5	0.727	2	0.291
Resolution	6	0.109	4	0.436	4	0.436	2	0.218
Size	9	0.164	3	0.491	3	0.491	5	0.818
Cost	2	0.036	3	0.109	3	0.109	5	0.182
Implementation	3	0.055	4	0.218	3	0.164	5	0.273
Ease of Use	4	0.073	4	0.291	4	0.291	3	0.218
Durability	1	0.018	4	0.073	4	0.073	2	0.036
Speed	3	0.055	5	0.273	5	0.273	1	0.055
Safety	10	0.182	4	0.727	4	0.727	3	0.545
Repeatability	5	0.091	5	0.455	5	0.455	1	0.091
Stability	4	0.073	4	0.291	4	0.291	1	0.073
Total	55	1.00	45	**4.091**	44	4.036	30	2.800

Two concepts showed significantly higher promise after scoring of the gripping mechanisms in Table IX. The vertical slot and horizontal slot scored very similarly to each other, with the horizontal slot being more favourable for meeting size constraints; however, the horizontal slot faced an issue that was categorized under repeatability. By placing the tab horizontally but keeping the fibre vertical, excess stress is applied at the corner where the fibre is bent. This could lead to repeatability issues in testing.

The spring clamp mechanism scored the worst due to issues in all categories. The addition of a spring and some method of compressing it detracted from its size, cost, implementation, ease of use, and speed scores. Due to the moving parts, durability, repeatability, and stability were affected as well.

The magnet concept showed strengths in size and durability, but were considered more costly than the alternatives with possible poor stability and repeatability on its own.

TABLE IX: GRIPPING MECHANISM SCORES

	Total Points		Vertical Slot		Horizontal Slot		Spring Clamp		Magnet	
	Weight	% Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight
Size	8	0.178	3	0.533	4	0.711	2	0.356	5	0.889
Cost	3	0.067	4	0.267	4	0.267	3	0.200	1	0.067
Implementation	3	0.067	5	0.333	4	0.267	2	0.133	3	0.200
Ease of Use	5	0.111	4	0.444	4	0.444	3	0.333	4	0.444
Durability	2	0.044	5	0.222	5	0.222	3	0.133	5	0.222
Speed	4	0.089	3	0.267	3	0.267	3	0.267	3	0.267
Safety	9	0.200	5	1.000	5	1.000	4	0.800	5	1.000
Repeatability	6	0.133	4	0.533	3	0.400	2	0.267	1	0.133
Stability	5	0.111	5	0.556	5	0.556	3	0.333	1	0.111
Total	45	1.00	38	4.156	37	4.133	25	2.822	28	3.333

The load cell scores in Table X show the S251 to be the preferred choice due to its expected accuracy and extremely low cost. The LPM512 showed more promise in regards to its small profile though, and was considered as an alternative should the size of the S251 prove to be too large.

The rounded concepts for support did not make it through concept screening to Table XI due to the more complex geometries while providing no significant benefit compared to their right angled analogs. The L-Shaped support proved to be the preferred choice. It uses less material and covers a smaller effective volume. As such, it would be less costly to 3D print. Its smaller size also improves its ease of implementation.

TABLE X: LOAD CELL SCORES

	Total Points		S251		LPM512		LPM530		RES2	
	Weight	% Weight	Score	Weight	Score	Weight	Score	Weight	Score	Weight
Accuracy	8	0.145	5	0.727	3	0.436	4	0.582	3	0.436
Resolution	6	0.109	4	0.436	3	0.327	3	0.327	4	0.436
Size	9	0.164	3	0.491	5	0.818	3	0.491	4	0.655
Cost	2	0.036	5	0.182	2	0.073	2	0.073	4	0.145
Implementation	3	0.055	4	0.218	5	0.273	5	0.273	4	0.218
Ease of Use	4	0.073	4	0.291	4	0.291	4	0.291	4	0.291
Durability	2	0.036	3	0.109	3	0.109	3	0.109	4	0.145
Speed	4	0.073	4	0.291	4	0.291	4	0.291	4	0.291
Safety	10	0.182	4	0.727	4	0.727	4	0.727	4	0.727
Range	1	0.018	5	0.091	4	0.073	4	0.073	3	0.055
Repeatability	6	0.109	5	0.545	4	0.436	4	0.436	3	0.327
Total	55	1.00	46	**4.109**	41	*3.855*	40	3.673	41	3.727

TABLE XI: STRUCTURAL SUPPORT SCORES

	Total Points		L-Shape		Rectangle		Prism Frame	
	Weight	% Weight	Score	Weight	Score	Weight	Score	Weight
Size	5	0.238	5	1.190	3	0.714	2	0.476
Cost	2	0.095	5	0.476	4	0.381	4	0.381
Implementation	2	0.095	5	0.476	4	0.381	2	0.190
Ease of Use	3	0.143	5	0.714	4	0.571	2	0.286
Durability	1	0.048	4	0.190	5	0.238	5	0.238
Safety	6	0.286	5	1.429	5	1.429	5	1.429
Stability	2	0.095	3	0.286	4	0.381	5	0.476
Total	21	1.00	32	**4.762**	29	4.095	25	3.476

Appendix B. Technical Drawings

Technical drawings for the base, bottom tab holder, and connector model for the final design are included. They are to be 3D printed using ABS plastic. Drawings for the LPM512 load cell and PQ12 linear actuator are available from the manufacturers [2][6].

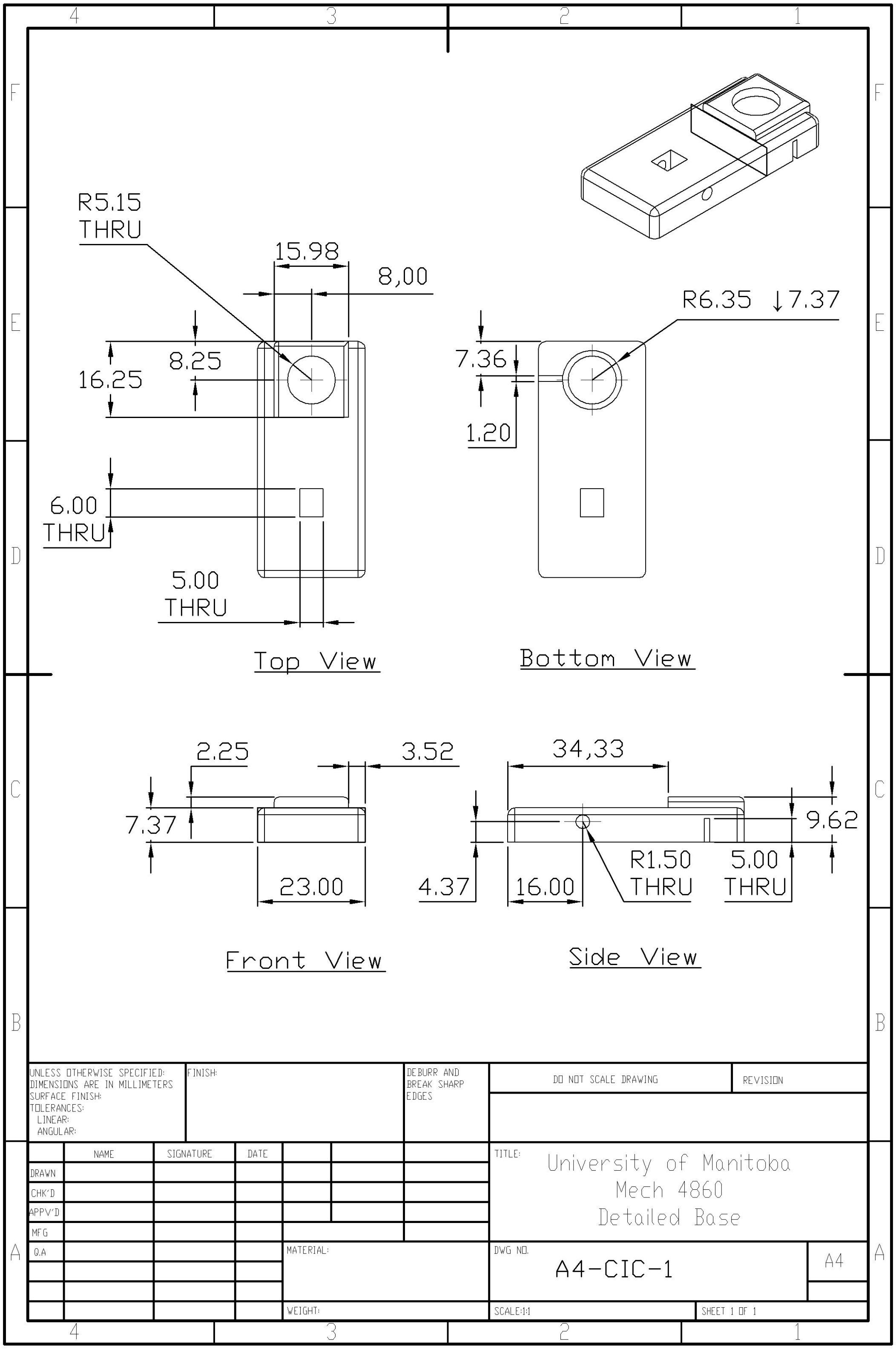


Figure 3: Technical Drawing of Base [7]

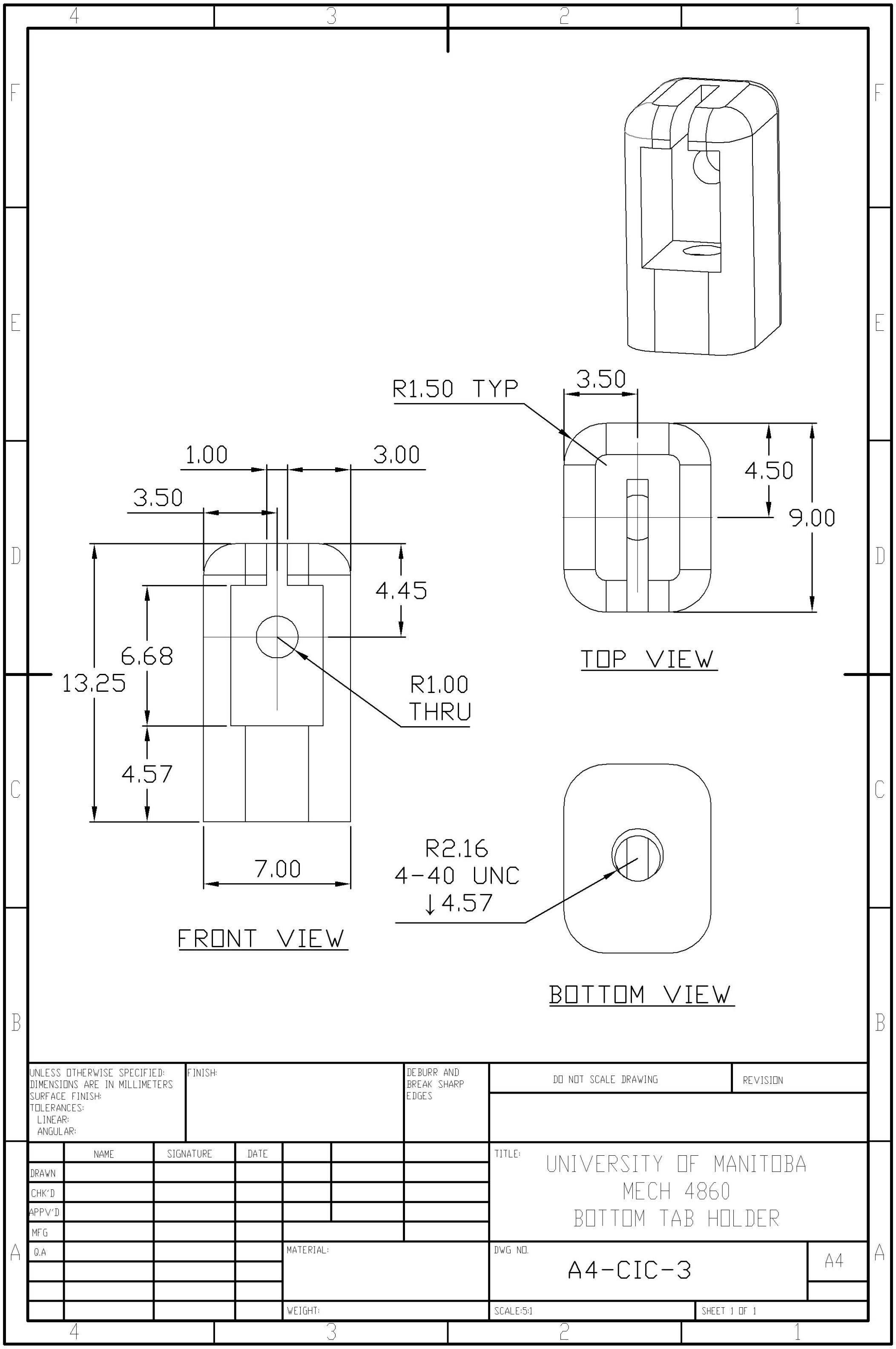


Figure 4: Technical Drawing of Bottom Tab Holder [7]

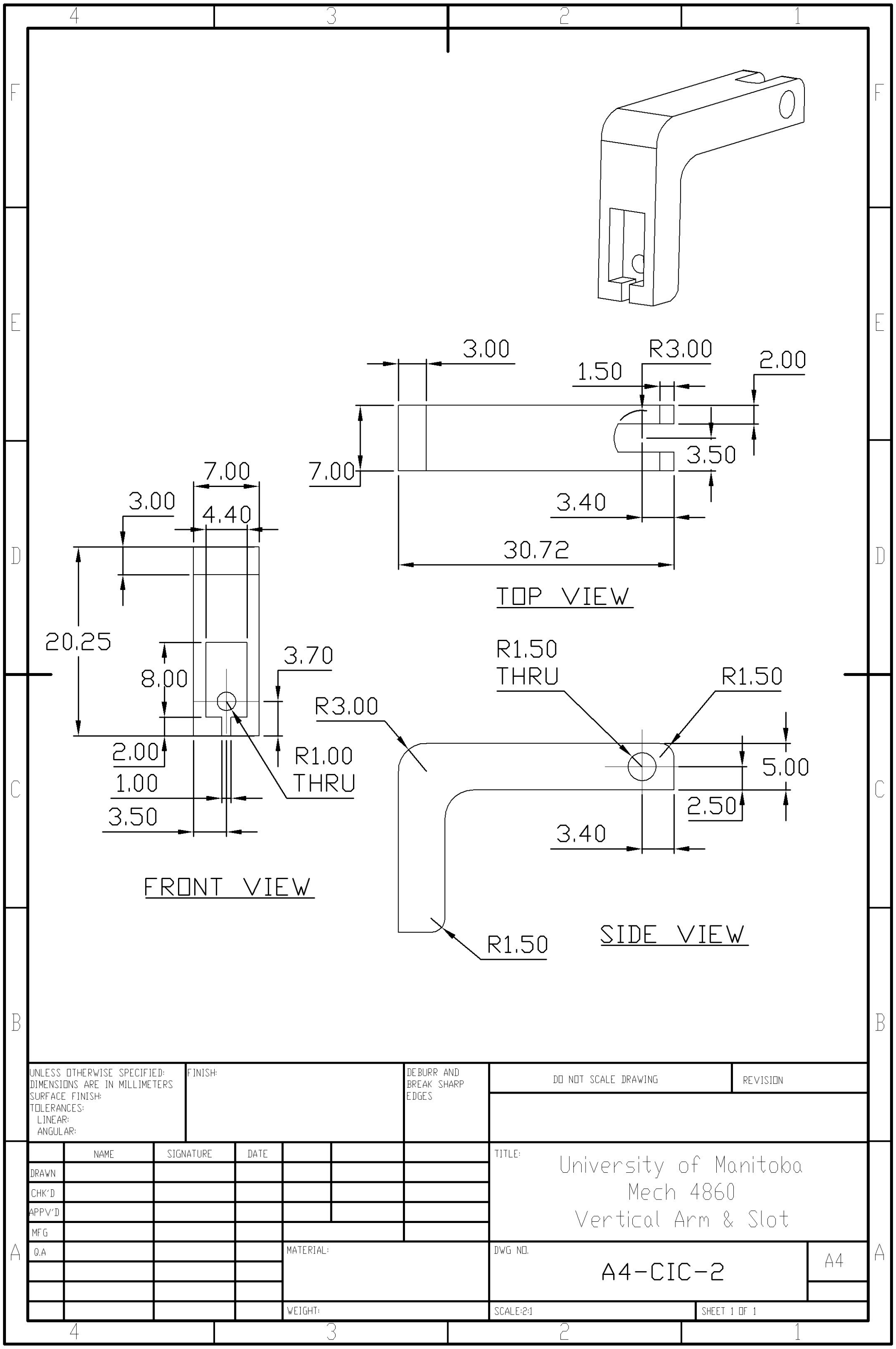


Figure 5: Technical Drawing of Connector Model [7]

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Figure 6: LPM512 Specifications [2]

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Figure 7: Firgelli Technical Drawing [6]

Appendix C. Personal Daq/50 Series Data Sheet

The following are pertinent excerpts from the Personal Daq/50 Series data sheet relevant to the recommendations for client use. The full document with examples and general instructions is available from the citation [8].

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Figure 8: Personal Daq/50 Series Data Sheet Excerpts [8]

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