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Threading Mechanism for a Home Warp Knitting Machine

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Executive Summary

Home knitting machines are great ways to produce custom garments in the home without taking the large amount of time needed to knit by hand. Various weft knitting machines (horizontal knitting, like your grandma does) do exist, but weft knitting remains inferior to warp knitting (vertical knitting - many interlocking vertical threads) in terms of quality and longevity. However, warp knitting essentially only exists on an industrial scale because it requires each thread to be loaded by hand - not feasible for a home machine. Our machine provides a solution to this problem by using the normal motions of a warp knitting machine and only one additional fixture to load each thread. It can load all the threads at once in far less time than a conventional machine might, and requires far less input from the user. This combination of features makes home warp knitting technology possible by removing the most difficult, most arthritis-inducing component of this particular knitting process.
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1 INTRODUCTION AND BACKGROUND INFORMATION

This section was created in the very beginning when the project was focused on making seamless clothing in multiple colors.

1.1 INITIAL PROJECT DESCRIPTION

This product should be able to create a 3D garment that contains multiple colors. A 3D garment does not simply stitch a flat garment and sew them together at the seams, but is able to create a single seamless garment. It must also be able to provide a multi-color capability, like stripes or patterns. Additionally, this product should take a reasonable amount of time to create a garment, be safe to use with minimal pinch points, and reliable enough to not require constant maintenance.

1.2 EXISTING PRODUCTS

1) Mach2XS Wholegarment Machine (www.shimaseiki.com/product/knit/mach2xs/)

Figure 1.1: Mach2XS Wholegarment Machine

This machine is a specialty machine for professionals to create 3D garments. It contains four distinct needle beds so that it can create stitching patterns and keep a high quality on complex garments. It is made for industrial use, attempting to achieve the maximum efficiency by using software to eliminate excess carriage returns and optimize the knitting path. It is shipped as a whole unit and many parts, like the knitting needles, are special made for this machine. This
allows the customer greater flexibility in the type of garment to make, while removing any control the user has over the machine itself.

2) Kniterate (http://www.kniterate.com/)

![Figure 1.2: Kniterate Machine](image)

Kniterate is a start-up company that has tried to incorporate many of the features we wish to include in our product. They are attempting to be able to create multi-color or patterned fabric, while maintaining an industrial feel. This design is much more industrial and relies on industrial knitting machines more than open-source materials. However, this machine is still in development, though it professes to be able to do many of these things currently. It is meant to attract a knowledgeable customer base, but not necessarily the industrial/manufacturing base of the Wholegarment machines. The design is robust enough to act like an industrial machine, but small and versatile enough to cater to a “maker” audience.
3) Silver Reed SK280 Knitting Machine

This machine has been around for decades, and it is a common manual industrial knitting machine. By hand, one may move the carriage by the handle back and forth over the needle bed which will automatically knit a sheet of fabric. More complicated versions use punch cards to create patterns or designs in the fabric.

1.3 RELEVANT PATENTS

1) US5487281A – Method and Apparatus for Joining Two Edges of a Knitted Tubular Article

Figure 1.4: Patent US5487291A Images
This patent describes a machine able to join the toe of a sock to the tubular section. The device is able to deftly sew together the two sections with minimal input from the user. The proposed machine is able to utilize a set of cams to allow the needles to sew the two parts together even in a semicircular path.

2) US3262285A – Electromagnetic Needle Selection Mechanism

This patent describes a mechanism by which knitting needles may be selected and triggered electromagnetically. Generally, when a carriage goes by, needles are activated mechanically, allowing them to grab the thread and knit it into the fabric. However, this mechanism changes this process by making it electromagnetic, allowing a potentially more computerized knitting process.
1.4 Codes & Standards

The codes and standards obtained for this project ended up being empty of useful information on the design of the system. However, some relevant codes and standards for a home warp knitting machine likely revolve around appliances. The final design iteration for the class did not involve electronics, but a true final design ready for market would include a power supply from a home outlet. Much like any other home appliance, this knitting machine would be subject to codes and standards in this way. Regarding safety, the warp knitting machine would have numerous standards about the accessibility and labeling of pinch points in the device. A motorized final design would look more like a manufactured product and the current open design would give way to a more closed, easily pinched design which would need labeling.

1.5 Project Scope

The purpose of this project is to create an automated knitting machine that can print in multiple colors. This will not be an industrial product, but a product for home-scale use by an individual. That customer is intended to be a “maker” or someone otherwise interested in building their own knitting machine to create their own 3D garments. The automated knitting machine would be able to produce two-colored knitted garments faster than a person might be able to by hand. It also will be able to produce garments of higher quality than by hand. This is to say, it will be of higher accuracy and involve fewer errors. The machine, which would be scalable and thus could be adjusted to fit the user’s need with minor effort, will provide homemade custom products with store-bought quality.

This machine would have three specific goals: to knit a pattern in two colors, to knit a small garment, such as a scarf, and to knit faster than a person, assuming the same grade yarn, needle size, etc. Within scope on this machine would be small personal knitwear like a multicolored scarf, rudimentary software to run the machine, and 2D sheets of fabric knit by the machine. Ideas that are out of scope include a full-sized design of an industrial machine, which is to say that the machine can be assembled and changed by the user. The machine also will not be focused on the software aspect of the development. Programming and software are secondary to the mechanical build of the machine. Lastly, the machine does not need to knit large garments to demonstrate the capability of knitting.
## 1.6 PROJECT PLANNING

This is the current, up to data version of the group’s Gantt Chart.

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**Table 1.1: Gantt Chart**
1.7 **REALISTIC CONSTRAINTS**

These realistic constraints apply to our final, finished product.

1.7.1 **Functional**

Functional constraints for this knitting machine are limited. The machine shouldn’t encounter any conditions that would prohibit the use of certain materials, except by cost. Some cooling in the form of heat sinks might be needed for the stepper motors, especially if the entire section in the future is enclosed. Motors shields will be necessary, but no significant electronic controls as of yet. Other than these, the major functional constraints that must be considered at all times are the consistent linear motion of the various axes, and the size/weight constraint that the machine be able to fit in a user’s home or design space.

1.7.2 **Safety**

This machine will have several safety warnings, all resulting from pinch points inherent in the knitting design. No radiation or other hazardous material will result from the machine, but several places could pinch and injure a user’s hand or fingers. The design will need to reflect this reality by restricting access while in operation to those high-risk areas.

1.7.3 **Quality**

Our machine in terms of quality restraints would have to conform to various appliance rules and regulations. It would need to be able to plug into a wall safely, not overheat such that it is dangerous to touch or catch fire, and be sufficiently shielded from pinch points. The machine should also be able to handle very many usage cycles without failure. Nothing will fail from stress in the machine, but misalignment or burnout is always possible and must be avoided.

1.7.4 **Manufacturing**

The knitting machine should be easily produced, as it is made up of easily manufactured components, or purchased parts from specific knitting vendors. Assembly is also simple and can be done by hand even with only bolting required, no welding or complicated assembly. The machine should also be easily carried around and packaged so that the user can handle it as needed.

1.7.5 **Timing**

Regarding timing constraints, assembly and manufacture is not a limiting factor. Both are relatively simple and could be fit into a normal production schedule. It is possible that some specialty purchased components would be behind schedule, like the knitting needles. Because the
machine is primarily marketed to people, not companies, it is also necessary to remember that users will expect the product to arrive like any other product - on time and functional.

1.7.6 Economic

The knitting machine’s market may be constricted to “makers” and others interested in the quick manufacture of their own clothing. While the product is designed to be easily made, with very few specialty parts, it should also be well-made, so that the cost of warranty, spare parts, and other after-delivery costs are minimized.

1.7.7 Ergonomic

The user should be able to easily lift and move the machine as well as find a place for it to fit within their home or design space. In this, the height and weight of the machine are restricted. However, it should also be very easy to use, with an interface that would allow anyone with the ability to create their own design on a computer system to upload that design to the machine. Clarity will be extremely important for users, as not everyone who uses the machine will be a technical wizard.

1.7.8 Ecological

Currently the fashion industry is one of the most polluting industries in the world today. Taking any section of their market and directing them to a new alternative would have a positive benefit on the fashion industry’s ecological footprint. Small scale clothes production, like small scale production of most any product, there is less waste because of the closer attention to detail. Knitting machines, as they are now, do not use any environmentally harmful chemicals or materials and taking knitting machines to a small scale will not change that.

1.7.9 Aesthetic

Because this machine will be based in a home, the aesthetic constraints are that it should not look like the industrial knitting machines used today where you see all the inner working and the motors of the machine, it needs an aesthetically pleasing housing that will fit in a home setting or will fit in a design studio type setting. It does not need to be the centerpiece of a room, It simply needs to visually fit in a home setting so as not to deter customers based on the appearance.

1.7.10 Life Cycle

These knitting machines, once purchased, are designed to to stay in a house or a design studio, so they cannot be so big that it can’t be moved by one person (hence our performance goals). In normal operating conditions (such as indoors, in an air-conditioned and dry protected environment) the knitting function should be able to create millions and millions of stitches in its
life cycle, this will retrain what materials we use to materials that will not break down or degrade over 10 years. The actual loading function should have a life cycle of a few thousand iterations at least as you would want this machine to make at least a few thousand garments over its life.

1.7.11 Legal

Currently, there are no copyrights, patents or trademarks that would inhibit us from making the physical knitting mechanism. Realistically, the final idea of our knitting machine incorporates a computer program and an interface that lets the user tell the mechanism what to make, and there are non-expired patents on that type of a program that we would have to work around.

1.8 Revised Project Description

A home warp knitting machine has a huge disadvantage compared to weft knitting in that it is very difficult to start up. Though it can provide better quality garments, each needle requires a thread to be individually loaded. If this problem could be mechanically solved, a home warp knitting machine would be feasible. Our machine should be able to spool out the appropriate amount of thread onto smaller spools which can then be loaded into the various needles. However it is able to do this, it should not take up more space than reasonably allocated by thread volume itself, and not require many motors. Additionally, it should be able to essentially load itself to be able to begin knitting. Human involvement should be extremely curtailed from the current version of warp knitting to be a successful machine.
2 Customer Needs & Product Specifications

Customer interviews were conducted when this project was still focused on creating seamless garments with multiple colors.

2.1 Customer Interviews

Table 2.1: Customer Interview

<table>
<thead>
<tr>
<th>Question</th>
<th>Customer Statement</th>
<th>Interpreted Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>What type of knit stitches should the machine make?</td>
<td>Weft knitting machine should include at least purl and knit stitches. Warp knitting would be very innovative.</td>
<td>KM knits in purl and knit stitches OR KM uses warp knitting</td>
<td>5</td>
</tr>
<tr>
<td>Do you see a market for an at-home knitting machine?</td>
<td>Market for real knitters requires a social aspect; market for makers requires easy/custom pattern creation</td>
<td>KM allows for custom patterns</td>
<td>4</td>
</tr>
<tr>
<td>What features should the machine have?</td>
<td>Machine needs to be beautiful, an accessory to the home; a modern, streamlined design</td>
<td>KM is aesthetically pleasing</td>
<td>1</td>
</tr>
<tr>
<td>What challenge do you see making this machine?</td>
<td>Size, should be as compact as possible</td>
<td>KM is compact</td>
<td>3</td>
</tr>
<tr>
<td>How fast should the machine knit?</td>
<td>Faster than by hand</td>
<td>KM knits garments quickly</td>
<td>4</td>
</tr>
<tr>
<td>What type of garments should it make?</td>
<td>Ready-to-wear garments, knitted without seams</td>
<td>KM produces garments without seams KM produces completed cloth (castoff ends)</td>
<td>3 4</td>
</tr>
<tr>
<td>What size thread should the machine knit?</td>
<td>Garments should look commercially made</td>
<td>KM uses small gauge thread</td>
<td>2</td>
</tr>
</tbody>
</table>
What kind of safety features would you expect on the machine?  

It should have a kill switch based on tension, and should have all pinch points enclosed.

KM adheres to basic safety standards 5

What sort of garments should the machine minimally make?  

It should at least make scarves; hats and sweaters are a plus.

KM knits scarves 5
KM knits multiple types of clothing 3

What other capabilities are necessary?  

Many colors

KM knits in many colors 4

### 2.2 Interpreted Customer Needs

<table>
<thead>
<tr>
<th>Need Number</th>
<th>Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KM knits in purl and knit stitches</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>OR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>KM uses warp knitting</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>KM allows for custom patterns</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>KM is aesthetically pleasing</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>KM is compact</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>KM knits garments quickly</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>KM produces garments without seams</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>KM produces completed cloth (castoff ends)</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>KM uses small gauge thread</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>KM adheres to basic safety standards</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>KM knits scarves</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>KM knits multiple types of clothing</td>
<td>3</td>
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</table>
### 2.3 Target Specifications

**Table 2.3: Target Specifications**

<table>
<thead>
<tr>
<th>Metric Number</th>
<th>Associated Needs</th>
<th>Metric</th>
<th>Units</th>
<th>Acceptable</th>
<th>Ideal</th>
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<tr>
<td>1</td>
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<td>Stitch Used</td>
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<td>2</td>
<td>2</td>
<td>Custom Patterns Possible</td>
<td>Binary</td>
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<td>1</td>
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<td>3</td>
<td>3</td>
<td>Focus Group agrees on beauty</td>
<td>%</td>
<td>&gt;50</td>
<td>&gt;75</td>
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<tr>
<td>4</td>
<td>4</td>
<td>Footprint of Machine</td>
<td>$m^2$</td>
<td>&lt;1.25</td>
<td>&lt;1</td>
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<tr>
<td>5</td>
<td>5</td>
<td>Time required for 9 in x 4 ft scarf</td>
<td>Hours</td>
<td>&lt;6</td>
<td>&lt;3</td>
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<tr>
<td>6</td>
<td>6</td>
<td>Seams per sweater</td>
<td>Integer</td>
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<td>0</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>Non-castoff Ends</td>
<td>Integer</td>
<td>2</td>
<td>0</td>
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<tr>
<td>8</td>
<td>8</td>
<td>Threads per inch</td>
<td>Integer</td>
<td>5</td>
<td>15</td>
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<tr>
<td>9</td>
<td>9</td>
<td>Pass safety codes</td>
<td>Binary</td>
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<td>1</td>
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<tr>
<td>10</td>
<td>10</td>
<td>Ability to knit a scarf</td>
<td>Binary</td>
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<td>1</td>
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<td>11</td>
<td>11</td>
<td>Types of garments</td>
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<td>4</td>
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<td>12</td>
<td>12</td>
<td>Colors available</td>
<td>Integer</td>
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<td>7</td>
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<tr>
<td>13</td>
<td>Codes</td>
<td>Rated Voltage</td>
<td>Integer (Volts)</td>
<td>220</td>
<td>110</td>
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<tr>
<td>14</td>
<td>Codes</td>
<td>Motor Run Temperature</td>
<td>Celsius</td>
<td>110</td>
<td>60</td>
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</table>
3 Concept Generation

3.1 Functional Decomposition

3.2 Morphological Chart

Table 3.1: Morphological Chart

<table>
<thead>
<tr>
<th>Bobbin Rotation</th>
<th>Diagram</th>
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<tbody>
<tr>
<td>Bearing on Bobbin</td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Attachment to Peg</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Driven Rotation</td>
<td><img src="image3.png" alt="Diagram" /></td>
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<tr>
<td>Keeps Yarn Distinct</td>
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<tr>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Thread Reception</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image2.png" alt="Diagram" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Move Yarn</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Grab Yarn</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4.png" alt="Diagram" /></td>
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</table>

<table>
<thead>
<tr>
<th>Move with Eyelet Bed</th>
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<tbody>
<tr>
<td><img src="image5.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Keep Threads Distinct</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Some of these are exceedingly difficult to draw, so will be explained here. The wheel method of moving yarn looks more like a large wheel seen in looms from another era. Thread would sit on the rim of that wheel. The screw method of moving the eyelet bed is just that - a screw attached to a stepper motor. The tether with a track method of moving the eyelet bed runs the eyelet bed on a track as a tether attaches to a single stepper motor, pulling it from both sides along the track. Last, the beard insertion method involves the use of beard needles, which look stranger and more elongated, allowing a particular motion to wrap the thread through the loop in the beard needle (which is not a closed eyelet).
3.3 Concept #1 – “Drum”

This method utilized the driven roller method of thread reception and the drum/groove method of thread movement. The eyelet bed in this case acts as a funnel in order to achieve thread insertion, requiring only the natural shape of the bed to insert threads into their various tubes. These tubes take the place of eyelets in this design.
3.4 Concept #2 – “Roller”

The roller concept uses a driven bobbin and a single roller to feed the thread from the bobbin into a flexible tube. This tube doubles as both a method for thread movement and the eyelet as in the previous concept. The eyelet bed in this case could be driven by any of the methods, as it is rigid and doesn’t require particular stability as the flexible tubes provide options. The roller itself could incorporate multiple different ideas to achieve thread reception and insertion. One of these options is a sticky roller of some sort in order to maintain control over the thread as it changes direction.
3.5 Concept #3 – “Standard”

The standard concept is based heavily on the current designs of industrial warp knitting machines. Otherwise, it is simply smaller so that it could be used in the home. Eyelets are the standard industry-grade needles and the thread is not moved in any way from the various bobbins to the eyelet. Rather, it could be loaded by hand as the current industrial machines are, and the eyelet bed can be moved in any of the ways listed above.
3.6 Concept #4 – “Tubes and Funnel”

The tubes and funnel concept is similar to the roller concept, except the eyelet bed is redesigned. In this concept, the eyelet bed is modeled as a set of funnels that might be able to act better than the eyelet bed with just tubes. Though there is concern that the individual “eyelets” would not be as close in this scenario, the funnel may be easier for the threads to make it through the system as it would provide less friction. The tubes are useful for redirecting threads, but added friction on the thread makes for poor knitting. This concept also uses the roller concept, perhaps sticky in order to maintain control over the threads.
3.7 **Concept #5 – “Beard”**

![Figure 3.6: Beard Concept](image)

The beard concept utilizes a different type of knitting needle, the beard needle, as its eyelet. The beard needle has a differently shaped hook than usual needles which would allow it to act as an eyelet but allow easy manual loading. It does not have a closed eyelet, but a rather deep hook which allows it these qualities. This concept only affects the eyelet bed, so the thread movement and reception functions could still be addressed by previous concepts like the roller. However, this concept could actually still be loaded manually, which bypasses the functions in this area and focuses the mechanical problems on the function of thread attachment and thread tension.
3.8 Concept #6 — “Horizontal Eyelet”

The horizontal eyelet concept relies on a difference in loading and eyelet design. In this concept, a stepper motor unloads all the bobbins horizontally all at once. The eyelets are designed like the tube concept, but they are in fact small holes in the eyelet bed. This is far simpler, but might increase the risk of misloading the threads. This sort of eyelet bed would be moved by a CNC setup rather than the tether methods.
## 4 Concept Selection

### 4.1 Concept Scoring Matrix

Table 4.1: Concept Scoring Matrix

<table>
<thead>
<tr>
<th>Selection Criterion</th>
<th>Weigh t (%)</th>
<th>R at ing</th>
<th>Weigh ted</th>
<th>Rati ng</th>
<th>Weigh ted</th>
<th>Rati ng</th>
<th>Weigh ted</th>
<th>Rati ng</th>
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<th>Weigh ted</th>
<th>Rati ng</th>
<th>Weigh ted</th>
</tr>
</thead>
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<td>0.22</td>
<td>2</td>
<td>0.22</td>
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<td>4</td>
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<td>5</td>
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<td>Ease of Loading</td>
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<td>0.37</td>
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<td>0.11</td>
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<tr>
<td>Cost of parts</td>
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<td>0.56</td>
<td>2</td>
<td>0.22</td>
<td>5</td>
<td>0.56</td>
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<tr>
<td>Loading Accuracy</td>
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<td>0.56</td>
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<td>0.11</td>
<td>3</td>
<td>0.11</td>
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</tbody>
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|          | 0.00        | 0.00     | 0.00       | 0.00     | 0.00      | 0.00     | 0.00       | 0.00     | 0.00      | 0.00     | 0.00      | 0.00     | 0.00     |
| Total score | 3.333   | 2.889    | 3.000      | 3.185    | 3.926     | 3.444    |
| Rank        | 6         | 5        | 4          | 3        | 1         | 2        |
Table 4.2: Analytic Hierarchy Process

<table>
<thead>
<tr>
<th></th>
<th>Mechanical Safety</th>
<th>Ease of Loading</th>
<th>Weight</th>
<th>Space</th>
<th>Noise</th>
<th>Cost of Parts</th>
<th>Loading Accuracy</th>
<th>Assembly Simplicity</th>
<th>Durability</th>
<th>Human Loading time</th>
<th>Yarn size Adaptability</th>
<th>Row Total</th>
<th>Weight Value</th>
<th>Weight (%)</th>
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</thead>
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<td>6.73</td>
<td>0.04</td>
</tr>
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<tr>
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4.2 **Explanation of Winning Concept Scores**

The bearded needle bed design had the highest score with a score of 3.926 out of 5 when the highest weighting was given to the ease of loading and the amount of human input time required. The safety was slightly better than the reference because there was no major difference between the two designs in terms of safety risks, but the bearded needle design does keep fingers further from the moving parts. The ease of loading is a 5 because you just need to pull each thread to an attachment point, not tie anything off or feed it through any holes. The weight is a 4 because it will weigh less than a bunch of plastic dividers. The space is a 5 because the design is incorporated into the needle bed, not added around the knitting machine. Noise is a 3 because it should be equally as quiet as the reference; bearded loading doesn’t make much noise. The cost of parts will increase with this method and assembly will not be as simple, but that may be the
only two downsides. Loading accuracy is a 4 because it should load the threads with a higher success rate than by hand (think about how many tries it takes to thread a needle by hand). Durability shouldn’t be too much of an issue because the loading mechanism is contained within the knitting machine, not on the surface, so should not be damaged by dropping the machine. The human loading time is a 5 because it only requires the person attach each thread to a rack (by a pinch mechanism maybe), not actually thread anything. The yarn size adaptability is a 3 because it is still limited by the eyelet size, not by the loading mechanism itself.

4.3 **Explanation of Second-Place Concept Scores**

The hanging yarn on driven spools design had a score of 3.44 out of 5 to take second place. The mechanical safety is a 5 because the only moving part of the loading mechanism is the motor that the spools are mounted on. The criteria that got 3s because they will be the same as the reference are Ease of Loading, Space, Noise, Assembly Simplicity and Yarn size adaptability. The weight was given a 4 because it should be a lighter setup than the plastic divider design. The cost of parts should be lower since we would only need one motor instead of lots of dividers, hence the 5. The loading accuracy is a 2 because with hanging thread there is more room for the thread to move out of line before loading or get tangled. The durability is also a 2 because with the spools and motor out above the knitting machine it will be more exposed to damage. The human loading time is a 4 because with all of the threads tied together, there shouldn’t be any time spent on having to pull out the threads separately; pulling the first one out to thread pulls all of the threads to the proper length.

4.4 **Explanation of Third-Place Concept Scores**

The standard roller into tubes design took third place with a score of 3.185 out of 5. This design scored a 3 (so should have very similar performance to our reference design) in 4 criteria, mechanical safety, noise, ease of loading, weight and human load time. The standard roller into tube design would improve in 4 areas. Cost of parts, with how cheap tubing can be, would make this a very inexpensive design. Assembly simplicity, because of how the tubes control and protect the threads, show that the roller and spools could be put anywhere relative to the needle and eyelet beds. Durability is high as this is not a design you could “knock out of alignment;” you would have to actually break the roller or disconnect a tube to stop this design. Yarn size adaptability means that the roller and tube should be able to handle a vast array of thread sizes, limited only by the eyelets size. This design will take up more space than others, hence its 2 on the space criteria. Additionally, it will also be a step back in loading accuracy, because if the tubes get too long, the roller may not be able to push a thread all the way through the eyelet or any number of snags or bunches may happen in the tubing.
4.5 Summary of Evaluation Results

At the end of the day however, a different design won out, as the existing designs were simply not good enough to surpass the existing designs. Ultimately, the alternative designs did not create a better product than simply a shrunken industrial, hand-loaded machine. We ended up going a different direction entirely, utilizing the natural motions of the two beds of a warp knitting machine in order to load the strings. Thus, only one extra axis of motion is needed to load the machine all at once. These threads will be partially loaded by the user, though the input will be decreased as much as possible. This is a large break from the previous designs which were far more involved in the loading of the eyelets from a mechanical perspective. These mechanical complexities result in an unreliable, nearly unusable machine. In the end, this forced the design change forward to this new paradigm.
5 EMBODIMENT & FABRICATION PLAN

5.1 ISOMETRIC DRAWING WITH BILL OF MATERIALS

Figure 5.1: Isometric Drawing with Bill of Materials
5.2 Exploded View

Figure 5.2: Exploded View
Figure 5.3: Eyelet Bed Movement Assembly

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Figure 5.4: Exploded Eyelet Bed Movement Assembly
6 ENGINEERING ANALYSIS

6.1 ENGINEERING ANALYSIS RESULTS

6.1.1 Motivation

Our design is influenced hardly at all by codes and standards, but primarily by collision and motion analysis. This is because of the machine’s focus on knitting, which is a mechanical endeavor that is incredibly complex, but quite light on the usual engineering stresses and strains. The four axes of motion are required to operate all at the same time, not just individually, and small components like the eyelets and hooks operate in very close proximity to each other. If those components were to collide while knitting, it would likely cause irreparable damage to that component and it would need to be replaced. Therefore, we sought to make sure by way of Solidworks motion analysis that no components could collide during normal operation of the machine. Since there are so many small parts, it is possible that a design flaw allowing collisions could be overlooked. While we may be able to stop such a collision in our prototype, the design would require a user to look on as the machine did the knitting. No such allowance would exist, so a good fundamental design with minimized risk for collision is required.

6.1.2 Summary Statement of the Analysis

The Motion Analysis showed that our knitting machine will have the full designed range of motion and will have no collisions. This is in agreement with our first draft mock up build of the two beds. Together, these two tests showed that we need a high level of accuracy in the movement of the hook bed to have a smooth interaction between the bed of eyelets and the bed of hooks. In our final design we will put a large emphasis on making a precise and structurally
sound connections between parts. This SolidWorks Motion Analysis required a complete understanding of SolidWorks Motion tools, and an understanding of dynamics.

### 6.1.3 Methodology

The analysis was done by using our computer aided design model in a SolidWorks Motion Analysis and by building a “first draft mock up” build of our design. The first draft mock up build we did a few weekends ago, we built a small eyelet bed of approximately 9 eyelets and a hook bed also of 9 hooks. We, by hand, moved the two beds in the way that would test their motion in one of the most precise sections of our design. This mock up build allowed us to learn the tolerances for collision while the hooks pass through the eyelets and then return to their previous position. Next we ran a SolidWorks Motion Analysis on our computer aided design model. This allowed us to test the whole design for collisions, not just the hook and eyelet interaction. In the Motion Analysis, we tested every single single axle for its full range of motion in both directions, forward and backwards.

### 6.1.4 Results

We performed a SolidWorks Motion analysis on our CAD model to test for interferences. The only motions tested were for the threading of the eyelets. No interferences were found.

The first motion is for the lowering of the grabber. The user first places all of the thread ends in their respective receptacles in the grabber. The grabber is then lowered approximately 3 in to increase tension in the threads. This motion can be seen in Figure 6.2.

![Figure 6.2: Motion of the Needle Bed](image)

The next motion is for the hooks to move through the eyelets. As seen in Figure 6.3, the hooks move roughly one inch through the eyelets to receive the threads. With the all of the hooks position fully through the eyelets, the threads can be grabbed by the hooks in the next motion.
The carriage then moves over the grabber and to the right, as seen in Figure 6.4. This motion forces the threads into the head of the hook and also provides additional tension. At this point the user can also fix any threads that might have gotten missed by the hooks. The user simply places the threads across the head of its respective hook.

The final motion is for the hooks to retract. This retraction motion pulls all of the threads through the eyelets. This motion can be seen in Figure 6.5.
6.1.5 Significance

The Solidworks motion analysis primarily tells us that the design is on the right track, so there is no change in the embodiment drawings. There are no collisions detected due to the normal motion of the various beds, although this was expected from the style of design we had chosen. However, the motion analysis does show, if nothing else, that it is quite easy to produce an accidental collision. The tolerances for motion are quite low and small parts are moving around in close proximity to each other. The future design of this knitting machine will pay careful attention to this important issue not just in making sure that the hooks and eyelets are perfectly aligned, but also have a difficult time getting misaligned. This could be achieved through use of more precise aluminum structural components and a unified hook bed rather than individual hooks. By and large however, the successful Solidworks motion analysis shows us that our current prototype has a viable design concept.

6.2 Product Risk Assessment

6.2.1 Risk Identification

Risk Name: Pinch Points
Description: This knitting machine contains many small parts and both movement with bearings and small hooks inserted into eyelets. If the user were to have their fingers poking around the machine while the machine was on and loading, they could get their fingers pinched in various places. There isn’t necessarily a certain condition where this would be possible; perhaps a machine that was slow or prone to failure or unreliable would cause a user to poke around.
Impact = #: 4. This pinching problem would not be catastrophic as they would likely not do irreparable harm to the user, but it certainly could cause significant injury in its worst iteration.
Likelihood = #: 4. This seems like something that a user would be careful with, especially if warnings were placed on the machine. However, there are any number of situations where a simple failure (e.g. machine misses a thread) could lead to more significant injury for the user if the user gets caught trying to fix the problem.

Risk Name: Overheating
Description: Stepper motors can get hot, especially if the motors are inadequately ventilated or too confined. The thread is technically a flammable material, although it is extremely unlikely this would catch fire, as the two are not located near one another. However, the motors could fail because of this, or burn circuitry, wiring, or even structural components if overheating.
Impact = #: 4. If a motor were to fail, the machine would be unusable. The only saving grace is that motor failure is not at all likely to cause catastrophic failure. The machine will not explode or spit acid, just stop working properly.
Likelihood = #: 2. Stepper motors do get hot, and a future design would likely hide these motors and belts to reduce pinch points, but it is unlikely that heat exhaust would not be accounted for in such a design.

Risk Name: Caught Thread
Description: Depending on the type, a thread can get caught at any number of places, from the tensioner to the eyelet bed. If this were to happen, the knitting process could be thrown off or even hampered significantly.
Impact = #: 2. Even if this were to happen, failure would be insignificant and would not damage the operation of the machine.
Likelihood = #: 2. Thread is difficult to get caught, and even the thread that catches the most would likely be simply ripped off whatever snag was catching it.

Risk Name: Snagged Hook
Description: The hook bed inserts through the eyelet holes to grab the threads and pull them through. By any number of misalignment problems, a hook might catch on the edge of an eyelet and be unable to complete the retraction back through the eyelet. If the hook bed were one piece and anchored like a future design might be, the hook may rip off the offending eyelet or break itself.
Impact = #: 3. Failure of this sort would not be catastrophic failure of any sort, as the machine would still be fine. However, each eyelet is necessary for knitting, so a damaged eyelet would need a replacement before continuing. A damaged hook though would not cause the machine to be unusable, as any thread could be loaded by hand if absolutely necessary.
Likelihood = #: 4. This is a problem encountered during building the prototype. Alignment is a tricky issue and could pop up in many ways. However, any working machine would have this in mind, so would be less likely to happen. No major forces are torquing the hook bed into misalignment either.

Risk Name: Electrical Failure
Description: Either by overheating or physical damage, the wiring or circuitry may fail, leaving the motors without a power source.
Impact = #: 3. This sort of failure would not damage the physical components of the machinery, but an average user would almost certainly not be able to fix this problem. The entire machine likely would need to be sent in for repairs if such a problem were to occur. Luckily, the fix would not be terribly hard.
Likelihood = #: 1. Perhaps overheating could cause this, but the motors may fail before this. Perhaps it could happen if the user dropped the machine, this failure could occur, although the
user may have larger problems at this point. Lastly, it could occur with some electrical surge, but this could be protected as well. The failure seems unlikely.

**Risk Name:** Axle Failure  
**Description:** The system of beds and four axes of motion rely on a series of axles for success. There are collars on the ends of the axles to prevent beds from going too far, but they could be pushed off. Additionally, a set of linear bearings align the axles, but they could fail by misalignment or some other issue.  
**Impact = #:** 4. This axle failure would almost certainly render the knitting machine inoperable. Luckily, it would not hurt the user, but the machine would need to be replaced or repaired by professionals.  
**Likelihood = 1.** This mechanical failure is incredibly unlikely to occur, especially if the motors were not actively trying to make the beds run off track. It might only occur by user input, and even that is unlikely.

### 6.2.2 Risk Heat Map

![Risk Assessment Heat Map](image)

**Figure 6.6: Risk Assessment Heat Map**
6.2.3 Risk Prioritization

This heat map analysis shows that the two most important risks to mitigate are the pinch point and misaligned hook risks. Our Solidworks analysis is focused primarily on mitigating the snagged hook problem by ensuring perfect alignment between the eyelet and hook beds. This will have to be forefront in any future iteration of this design if the design concept is to be successful. Second, there is a huge potential for pinch point injuries inherent in our design. While this prototype relies on common sense for safety, a future iteration with motors and other essential components will need to have barriers to access that can hide the most severe pinch points.
7 DESIGN DOCUMENTATION

7.1 PERFORMANCE GOALS

1 - The threading assembly will thread 80% or more of the total eyelets of the knitting machine in one loading cycle.

2 - The threading assembly requires less human time input to thread all eyelets than if the threading assembly did not exist. This is estimated to be one minute per eyelet.

3 - The knitting machine will weigh less than 60 lbs.

4 - The knitting machine will take up less volume that the restraining box measuring 30in x 40in x 40in.

5 - If the threading assembly breaks, the knitting machine will be able to be loaded by hand in less than (or equal to) one minute per eyelet.

7.2 WORKING PROTOTYPE DEMONSTRATION

7.2.1 Performance Evaluation

During the prototype demonstration, the machine missed three out of the twenty threads on the first run and only one on the second, giving it a 90% success rate. Given a more precise design, we believe we could raise this to nearly 100%. The whole assembly most certainly required less time to thread using the assembly than by hand, as was proven in the demonstration. The machine as a whole weighed fewer than 40 pounds all together, less than 20 per part. This means it is easily moved. Last, the machine falls in a 28in x 43in x 32in box. Ultimately, the frame was slightly too wide and ended up exceeding the width target, though the mechanism itself was within the required space. Last, the machine could also be loaded by hand in a reasonable amount of time quite easily as the open design allowed this to occur if necessary.

7.3 FINAL PRESENTATION – VIDEO LINK

The final presentation video is located in the Group J WUSTL Box folder. Because we are looking to get this project funded and furthered, we decided to not publish it publicly on YouTube for public disclosure reasons. Hopefully the reader will understand. You should still have access through WUSTL Box however.


8 **DISCUSSION**

8.1 **DESIGN FOR MANUFACTURING – PART REDESIGN FOR INJECTION MOLDING**

8.1.1 **Draft Analysis Results**

The part that makes the most sense to injection mold would be the thread catcher. This is the part to which the Velcro is attached and the thread pulled down for loading.

![Figure 8.1: Before Design Change](image1)

![Figure 8.2: After Design Change](image2)

If injection comes from the bottom of the part, giving the vertical walls a positive draft (i.e. narrower at the top where the humps are located), the injection process will allow for a clean release and the best shaped humps. Injection from the bottom should work the best because that
is both the least visible face and does not need to be perfectly flat like the side walls need to be which allows the divots from the injection to remain.

Further components with potential for injection molding are the 3D printed pieces that act as a collar for the axles which attach to the 80/20. The before (left) and after (right) photos show the extent to which it is possible to design this component for injection molding. As the photos show, this piece and the others like it are functionally impossible to injection mold (or at least draft) as they require vertical walls to act as the inserts for both the 80/20 channels and the axles themselves.

![Figure 8.3: Before (left) and After (right) Injection Mold Design Change](image)

8.1.2 Explanation of Design Changes

The first component, the thread catcher, is easy to redo for injection molding. The vertical sides of the pieces are simply given a three degree draft in order to allow for injection molding. This piece could be easily mass-produced in this way, as it is a perfect candidate for such a procedure. However, some of the other components analyzed like the 80/20 inserts and collars for the axles are not injection moldable in their current form. These pieces and more likely, the entire junction of these components would need to be redesigned in order to incorporate injection molded components.

8.2 Design for Usability – Effect of Impairments on Usability

8.2.1 Vision

Visually impaired people (fully blind) do not typically take up knitting, however, if they are familiar with the machine and its set up, it would still be possible for them to operate the knitting
machine once it has motors. Pulling the thread from the spool, over the tensioner to the Velcro is a movement that can be tracked by touch. Now, without motors, this would not work, catching the threads by feel while technically possible would be difficult.

Red-Green color blindness should have no effect on usability as there are no red vs green controls. Red-green color blindness may affect their choice in thread colors, but should not affect operation. Presbyopia (like blindness) could make the fine motor skills required to load the threads more difficult but, with sufficient familiarity with the machine, would pose no major obstacles.

8.2.2 Hearing

The only effect a hearing impairment would have on using the knitting machine would be once the machine actually starts knitting, loading would be unaffected. Typically you would want to listen as the machine knits to hear if anything goes wrong, because you would no longer be able to listen, you would have to keep an eye on it instead.

8.2.3 Physical

For those in a wheelchair with full range of motion in their arms, as long as the machine is located low enough for their reach, operating it would be no problem. Moving the machine may present challenges, but not operating it. For those that are handicapable with only one arm, operation would be relatively the same as anyone else, they just won’t have a second hand to load two threads at one time. For those without the use of both arms, there is unfortunately no feasible way to operate the knitting machine.

Muscle weakness may impact one's ability to move the knitting machine, but not to load and operate it. Arthritis could present difficulty in loading the mechanism because of the fine motor skills required, however, loading the machine takes far less fine motor skills than knitting by hand so the machine would prolong someone’s ability to knit far beyond when they could no longer knit by hand.

8.2.4 Language

Someone who speaks little to no English would be able to load the knitting machine with no trouble. A simple demonstration is all that would be required, or a few illustrated directions could serve the same purpose. Depending on how the final user interface for the actual knitting is designed, a language barrier may not matter in using the machine to knit.
8.3 **OVERALL EXPERIENCE**

8.3.1 Does your final project result align with the initial project description?

Our final project result really ended up very different from our initial ideas about this project. We started wanting to build a 3D knitting machine, then along the way kind of changed gears. During an interview to determine customer needs, the weft versus warp knitting distinction was brought to our attention. At that point we shifted over to working on a warp knitting machine for the home instead of the 3D weft knitting machine. We felt this would be more innovative and present a better design challenge. As we dug into warp knitting we realized the biggest challenge facing warp knitting was simply the loading system and just that problem in and of itself could (and would) be our senior design project.

8.3.2 Was the project more or less difficult than you had expected?

Honestly, more difficult than expected. One of the best benefits of the design we chose was that it incorporated the movements of actually knitting into the loading mechanism, but, at the same time, this made visualizing the mechanism very difficult because it was such a complicated motion. In the early stages, visualizing the movement that would work best was difficult, and designing the machine around that fuzzy mental image was difficult.

8.3.3 In what ways do you wish your final prototype would have performed better?

I wish we could have had a better built hook bed. That would have made the motion of the hooks through the eyelet much smoother, and much cleaner. As of now, there is enough slack in the hook bed that you have to move it just so for it to cleanly pass through the eyelet bed. Additionally, I would have liked if the spools of thread sat on the bobbins better, right now they can be pulled off just a little too easily for my taste, giving the spools some kind of grip to the bobbins would solve this.

8.3.4 Was your group missing any critical information when you evaluated concepts?

We weren’t missing any information. Like at the time of the assignment we were missing the critical revelation of how to incorporate the motion of the knitting into the loading mechanism, but that is about it.

8.3.5 Were there additional engineering analyses that could have helped guide your design?

I really don’t know how you could do this analysis except empirically testing it, but one analysis that would have helped is determining the an upper limit to the force required to pull the yarn off the spool under normal conditions without a hard stop snag. Like even a perfectly spooled yarn
will snag and come off the spool unevenly, that’s the nature of yarn. We would like to know what is the max force required to pull that “hitch” off of the spool.

8.3.6 How did you identify your most relevant codes and standards and how they influence revision of the design?

We were unable to identify any relevant codes. However, all of the specifications of our machine must be able to meet the standards for any home appliance.

8.3.7 What ethical considerations (from the Engineering Ethics and Design for Environment seminar) are relevant to your device? How could these considerations be addressed?

There aren’t any really major issues with providing people a way to knit their own cloth, the biggest concern would be introducing a machine with many moving parts and possible pinch points to a home that could possibly have children. To address this, I would make sure that the housing for the market ready product covers as many of the moving parts as possible, the shield for unsupervised operation is childproof, and that the knitting machine came with lots of warnings and directions.

8.3.8 On which part(s) of the design process should your group have spent more time? Which parts required less time?

We should have spent more time coming up with and doing initial sketches of our designs. We honestly could not come up with an actually good design idea for how to easily load the knitting machine for the longest time (until after the assignment was turned in) and our sketches reflected how we felt about our first ideas. Thankfully a better idea did come to us but I think we should have spent more time on the initial concept generation. I think we spent too much time on the customer needs assignment, not to say understanding customer needs is unimportant, but I think the very specific way we analyzed needs was overkill.

8.3.9 Was there a task on your Gantt chart that was much harder than expected? Were there any that were much easier?

I have a feeling that programming the arduinos would have been a huge headache had we not cut them due to budgetary concerns. None of us have much programming experience beyond using matlab as a super calculator so it would have been a learning experience for all of us. Besides that, the part that was easier than expected was the actual build. Danny and Andrew have years of experience in high school robotics building, and Sam spent years working for a company building everything from tables to decks to cabinetry to car doors. Between the three of us, we had the knowledge and experience to address every speed bump that came up.
8.3.10  Was there a component of your prototype that was significantly easier or harder to make/assemble than you expected?

The hardest part of our prototype to assemble was the hook bed, it had to be fine tuned to align with the eyelet bed and still grab the threads. It currently has more slack than I would like because the level of accuracy it needs is so much higher than most every other part in the mechanism. And it doesn’t just have to be aligned in one spot with the eyelet bed, it has to be aligned along its whole path which is harder than it seems, especially when the hooks and slide track are displaced from each other in the y direction by such a relatively large distance.

8.3.11  If your budget were increased to 10x its original amount, would your approach have changed? If so, in what specific ways?

I don’t think our approach would have changed all that much, I do think our design might have changed a bit though. With more money we could have made more of the framing out of 80/20 instead of wood, and most importantly we could have actually purchased motors and mechanised the knitting machine. Making the framing out of 80/20 would have reduced the slack and wiggle in everything, which would have been important for the hook bed.

8.3.12  If you were able to take the course again with the same project and group, what would you have done differently the second time around?

Doing this over again, I would have liked to not change our project idea so many times early in the course. Getting dialed in earlier on in the semester would have helped a ton, it especially would have helped with this report, because a lot of our early work is no longer relevant. Other than that, we wouldn’t have done a whole lot different, being able to work at TechShop was awesome. Maybe we would have 3D printed more of our connections for the 80/20, especially for the hook bed mount, reducing slack and wiggle in that would have been a good focus.

8.3.13  Were your team member’s skills complementary?

Oh absolutely. All three of us have lots of experience making things, but none of us have the exact same background or have worked on all the same projects so while we all know what we are doing, we all have a different view and can solve different problems. Danny and Andrew did high school robotics, Andrew has a background in knitting and 3D printing, Danny also knows 3D printing and woodwork, Sam has a history working with wood and metal, we had a nice balance of skills but also have enough overlap in skills so we can still bounce ideas off each other.
8.3.14 Was any needed skill missing from the group?

The only skill missing from the group was programming, and that only would have come into play if we had purchased motors. As for everything that did fall into our project scope, there weren’t any skills that our team was missing.

8.3.15 Has the project enhanced your design skills?

I think it has enhanced our design skills. This project has gotten us to focus more on finding those one or two issues in any project that are going to cause most of the issues and focusing on the earlier in the process. Like for us, the one or two issues initially was the loading mechanism when we were trying to build the whole knitting machine, that ended up becoming our whole project. learning how to recognize that earlier I think is an important step for us. Also we learned how to look at user needs and not just base our design off the image we have in our head but also what other potential users may be envisioning which we think is important.

8.3.16 Would you now feel more comfortable accepting a design project assignment at a job?

Yes I think all of us would feel more comfortable accepting a design project at work now that we have more experience doing it and we’ve done it start to finish now.

8.3.17 Are there projects you would attempt now that you would not have attempted before?

I think there are. We plan to continue working on this project and hopefully take it to the next step of actually being able to knit a sheet and I don’t think this was a project I would have felt comfortable taking on in its entirety 6 months ago. But now it is something we feel is definitely manageable.
## Appendix A - Parts List

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Table 9.1: Cost Accounting
Figure 10.1: Bearing to 80-20 Adapter
Figure 10.2: Dual Shaft Collar Adapter
Figure 10.3: Shaft Collar for Vertical Motion
Figure 10.4: Dual Bearing Adapter for X-Axis Motion
Figure 10.5: Bearing to 80-20 Adapter for Y-Axis Motion
Figure 10.6: Tensioner
Figure 10.7: Eyelet Bed
Figure 10.8: Half Hump
Figure 10.9: Hooks