GONZAGA UNIVERSITY

School of Engineering

FINAL REPORT

FOR

KIMBALL ALUMINUM TUBE ROUTER

Center for Engineering Design

Project ME08

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1.0 INTRODUCTION

1.1 Project Overview

Kimball Office is a company located in Post Falls, Idaho that specializes in the manufacturing of office cubicle systems and other office furniture. Over the last few years, the company has been adopting Lean Manufacturing techniques, and with this, the engineering team has been responsible for designing and creating small, moveable machines that fit well with the lean manufacturing mode of production.

Kimball’s method for producing the Xsite Model office furniture is the next to be reformed. Within the system, there are extruded aluminum tubes that act as corner posts. Pictures of the Xsite model and its corner posts are located in Appendix D. These posts have the cubicle walls anchored to them, and there are slots cut in the side to act as wire passageways. There are three different shapes of extruded aluminum tube, and multiple different cut patterns used in the Xsite Model. Currently, these slots are manually cut from the tubes by a woodworking router being dragged through a template. This process is lengthy and extremely labor intensive, and the volume of machined aluminum chips that is produced from the routing contact the worker and pile up on the floor, making it unsafe.

The Gonzaga Design Team’s responsibility is to design a computer controlled machine that will cut all routed portions of the Xsite corner posts without any needed manual labor. The machine will be able to clamp and rotate the tube for the entire duration of the process while keeping the operator safe from machined chips, and reducing the total time necessary to complete the part to under 180 seconds.
1.2 Possible Solutions

The first problem that needed to be solved was the cutting process. There are many cutting processes that can be viable solutions. The main concepts that were considered along with their pros and cons are listed in the table below.

<table>
<thead>
<tr>
<th>Cutting Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive Waterjet</td>
<td>Clean Cut; New process for Kimball</td>
<td>Large Space Requirement; Expensive</td>
</tr>
<tr>
<td>Laser</td>
<td>Clean, Fast, Efficient</td>
<td>Very Expensive</td>
</tr>
<tr>
<td>Plasma</td>
<td>Multi-axes cutters available</td>
<td>Expensive; High heat could warp metal</td>
</tr>
<tr>
<td>Router</td>
<td>Most Cost Effective; new engineering endeavor</td>
<td>Large volume of chips produced</td>
</tr>
</tbody>
</table>

1.3 Final Concept

From the possible methods described in the earlier section, the design team chose to pursue using a router to cut the pockets in the aluminum tube. The router will have three axes of linear motion that will have the ability to conform to any variation of corner post that needs to be produced. In order to prevent any human contact during the machining process the tube will be able to rotate while being clamped so all faces can be easily machined.

Along with its movement capabilities, the finished machine will have all necessary safety features that allow 90% of all machined chips to be captured, and the total cycle time will be reduced to 180 seconds per part.
1.3.1 Scope

The Gonzaga Design Team's responsibilities to Kimball include:

- All mechanical design features
- All necessary 3-D modeling
- A complete 2-D drawing package
- A list of all required purchased parts

1.3.2 Budget

The team's instructions were to keep the price of producing the machine as low as possible. As a benchmark, Ken Lambie, liaison for Kimball, limited the budget to $20,000. Major design decisions hinge on purchase price and fabrication costs.

2.0 Design Phase

2.1 Research

To begin this project, the team spent a large amount of time researching and deciding on design ideas including how best to orient the machine, how the router would move, and how to clamp the part in the machine. Our team brainstormed many different ideas and worked closely with the faculty advisor and Kimball in order to gather necessary information to come to the best decision. Kimball was interested in using this project as a learning process for them as well as for us and for that reason they wanted to build and fabricate as much of the machine and parts in house as possible.
In addition to assisting the design process, Kimball specified router requirements so that our group could find a suitable router and they did cutting tests to determine which router bit would be best.

2.2 Functional Breakdown

2.2.1 Clamping and Rotation

The part will be clamped on both sides of the routed area. One side of the aluminum extrusion will be slid around a support, or part drive arbor, of the same geometry and clamped in place using a manual toggle clamp. On the other side of the routed area the aluminum extrusion will be held by an insert in a ‘clamshell’ shape clamp which will hold the part in place with a second manual toggle clamp. These clamping methods will allow the part to be rotated a full 360 degrees so the router can machine on all faces of the part as needed. Kimball produces corner post of three different geometries so there are three different clamshell inserts and three different support shapes which can easily be replaced. The part drive arbor will be connected using three alignment pins and two set screws while the clamshell inserts can be replaced simply by opening the clamshell. To load the part, the part will be slid through the clamshell insert and over the part drive arbor then clamped in place by the two manual toggle clamps.

2.2.2 Linear Motion

The Linear Motion facet of the project consists of three separate axes of motion; one axis to travel the length of the part, one axis to travel across the width of the part, and the final axis to travel up and down the height of the part. Please
reference Appendix A for detailed pictures of each axis and their respective components.

**X-Axis:**
The X-Axis of motion is the largest range of motion present within the machine. The length of travel for the X-Axis comes in at approximately 54”, where 36” are intended to be utilized for the actual cutting of the aluminum tube stock. The difference of travel lengths is due to the length of the saddle which sits on the bearings placed along the X-Axis, the need to be able to move the router completely away from the part itself, and due to the associated acceleration and deceleration speeds that will be present when the machine is cutting.

The X-Axis consists of 2 support rails and bearing shafts at \( \frac{3}{4}" \) thick, which are mounted on a steel base \( \frac{3}{4}" \) thick. Also mounted on the base is a \( \frac{3}{4}" \) ball screw with a threaded ball nut, a flange which attaches to the threaded ball nut and the saddle that sits along the bearings, an end mounting block that contains a standard sleeve roller bearing which the ball screw rotates and is supported.

The ball screw is tapered at one end to allow for connection to a stepper motor which will actually provide the drive motion along the X-Axis. This tapered end sits in a floating mounting block, which not only keeps the ball screw supported throughout the motion of the router, but also allows the ball screw to freely rotate without moving back and forth through the mounting block. The stepper motor is press fit into an in house fabricated mounting plate which screws into the X-Axis base. The ball nut, which is actually screwed onto the ball screw, has a threaded end which is attached to a flange which screws into a saddle. The
ball nut, in conjunction with the saddle, facilitates the movement of the remaining axes. As the ball screw rotates in either direction, the ball nut travels along its length. This allows for the saddle to move in any direction specified. The saddle sits on four pillow blocks with open faced ball bearings that move along the linear bearings that traverse the length of the base. Both the saddle and the flange are to be fabricated in house and made of MIC-6 Aluminum. MIC-6 Aluminum is a lighter metal and easier to machine.

**Y-Axis:**

The Y-Axis is a scaled down version of the X-Axis. However, instead of utilizing ¾” linear bearings and ¾” ball screw, the Y-Axis utilizes ½” linear bearings and ½” ball screw and facilitates motion across the width of the aluminum tube stock. The end mounting block setup is also identical to that of the X-Axis. The bearing length along the Y-Axis is 14”, where approximately 8” will be utilized in the cutting of the aluminum tube stock. The Y-Axis saddle sits on four pillow blocks with open faced ball bearings that move along its linear bearing rails as well. As is the case with the X-Axis saddle, the Y-Axis support base is made of MIC-6 Aluminum.

The Y-Axis support base is attached to the X-Axis saddle with two ½” gussets that utilize two ¼” alignment pins and five ¾” socket head cap screws. The Y-Axis extends over both sides of the X-Axis saddle. Not only do the gussets keep the Y-Axis and X-Axis attached, the gussets also help also help with the weight imbalance due to the router, linear bearings, and the Z-Axis. The Stepper motor for the Y-Axis will press fit into an in house fabricated motor mounting
plate which will attach to the top of the Y-Axis base plate and to the ends of side support plates.

Side support plates are placed along the top edges of the Y-Axis base in order to help reduce the vibration forces expected to occur during the machining of the aluminum tube stock. These support plates run the length of the Y-Axis and screw in from the side of the Y-Axis base with 3/8” socket head cap screws.

**Z-Axis:**

The Z-Axis has the smallest range of motion present within the machine, measuring only 8”. Of that 8”, approximately 4” or less will be utilized during the cutting of the aluminum tube stock. Once again, the difference in lengths is due to the saddle present on the bearings, which for the Z-Axis, has to be able to support the weight and length of the router. The Z-Axis utilizes two 3/8” linear bearings and a 1/2” ball screw, a nearly identical setup to that of the Y-Axis. However, the lengths have been reduced. Just as with the X-Axis and Y-Axis, the Z-Axis is attached to the Y-Axis with gussets and utilize 3/8” alignment pins and 3/8” socket head cap screws.

The Z-Axis saddle has several holes placed throughout its surface to accommodate not only the four pillow blocks that rest on the linear bearings, but also for the router that cuts the aluminum tube stock. The Z-Axis also utilizes the same end mounting block setup, however, the end block closest to the floor extends across the length of the axis in order to prevent any component placed on the Z-Axis from falling to the ground if anything were to become detached. As with the other two axes, the motor that drives the motion of the Z-Axis is press fit into an in house fabricated mounting plate attached to the top of the Z-Axis.
2.2.3 Tube steel base

The CNC Router will be mounted on a tube steel frame made from 2"x2"x1/4" steel tubing. The frame will hold the machines base plate in the vertical position so that gravity can be utilized to remove machine chips from the work area. The legs of the frame will be fitted with large industrial casters that will allow the machine to be moved around the manufacturing floor more easily and the casters will also be fitted with brakes to ensure that the router stays in place while it is in use. The legs of the machine will have height adjustments in order to accommodate several different machine operators.

2.3 Calculations

During the course of the project, certain calculations had to be made to verify designs. These calculations ranged from power requirements to structural analyses. These are listed below.

2.3.1 X-axis moment on bearing rails and cantilever deflection

When the choice was made to design and build linear motion systems rather than purchasing them, calculations concerning the forces imparted on the bearing rails. This calculation finds the maximum value of deflection on the cantilevered base and the moment force imparted on the two X-axis bearing rails.

2.3.2 Router requirements

They also have done calculations to specify the requirements for a router. These calculations are located in Appendix B. Desired characteristics for the router are listed below.
• Spindle speed of 20,000 RPM
• 1.3 Horsepower motor
• Compressed air cooled

2.4 Informational meetings

On January 19th, thanks in part to the help of Ken Lambie, the group met with a representative from Danaher who specialize in motion systems. During the meeting, the team gained significant insight into what components were necessary for the project’s specific needs. The representative showed the group with actual pieces the group was able to inspect in hand, and explained to the group the recommended application associated with the different components and additional ones initially inquired about. He also gave the group telephone numbers to call if additional questions or concerns regarding components we intended to incorporate within our machine arose.

On March 17th, thanks to the help of the team advisor, Jeff Nolting, the group met with a representative from Kaman Industrial Services, who once again helped by guiding the team to choosing the correct bearing specific to the loads and forces they would be exposed to. The Kaman representative was extremely knowledgeable regarding the application of bearings in many different types of systems, and was able to walk the group through what the group needed to accomplish and the bearings that could be used to help reach that goal. The Kaman representative also presented the group with a plethora of catalogs and manuals that had in-depth information regarding not only bearings, but also lubrication and locknuts. This meeting was helpful and had it occurred several months earlier, the project may have been much closer to completion entering 2010.
2.5 Design Decisions

2.5.1 Linear Motion Systems vs. Building own

At present, there are many different types of prebuilt linear actuator systems that could fit our needs. However, there were a couple factors the group considered which led to the development of a linear motion system designed to fit the project’s applications.

**Design Dimensions:**
As much as the group attempted to keep all of the parts at standard lengths and dimensions, due to the range of the project’s applications, the group was unable to realistically keep some of the dimensions at the lengths offered for prebuilt linear motion systems. For example, the longest axis of motion utilizes bearings that are over 50” long. Without a special order, many of the linear actuator systems researched did not go past a length of 48”. To keep the machine as simple as possible, the group tried to keep each axis as close to each other as possible.

**Cost:**
Furthermore, each of the linear actuator systems cost drastically more than the cost of ordered and machining standard parts from distributors ourselves. For example, each ball screw needs two end mounting blocks to function appropriately. To fit into these mounting blocks, the ends need to be machined to fit within the bearings that are placed within the mounting blocks. From Thomson Linear, the company the group intended to purchase our linear bearings from has ball screws that come machined to fit into mounting blocks. However, the most expensive ball screw without machined ends is approximately $200. Kimball has
every resource needed to machine the ends of the ball screw themselves to any dimension they specify.

2.5.2 Standard Bearings vs. Angular Contact bearings

During the finalization of the project modeling phase, the group met with a representative from Kaman Industrial Technologies who helped to answer some of the questions regarding the construction of the end mounting blocks. One of the questions had to do with the bearings required within the mounting blocks.

The group initially believed, due to initial research and bearings found to be placed within the end mounting blocks sold pre-assembled, that tapered roller bearings were needed to keep the ends of the ball screw stabilized because of the back and forth motion we anticipated during the machining of the aluminum tube stock. However, the Kaman representative informed the group that standard roller bearings were more than sufficient to meet the needs of the project’s ball screw application. Tapered roller bearings can handle associated thrust forces of up to 3000 lbs. The project’s application will not exceed 1000 lbs of force.

2.5.3 Thomson End Blocks vs. Fabricating own

Ball screws were decided to be the method of linear motion early in the project. A complete ball screw systems includes the following components:

- Ball screw
- Ball nut
- Two end blocks
- Motor
End blocks consist of a machined block of metal that houses various roller bearings that enable the ball screw to spin. Variations of end blocks can be purchased from ball screw manufacturers, i.e. Thomson Linear, but the price of these are rather high. This high price is due to the fact that the blocks are not specifically designed for every application. Therefore, these blocks are equipped with high-priced angular contact and deep groove bearings that are used in applications where the ball screw will experience high thrust and axial loads.

After examining the loads that would be imparted on the bearing blocks for the router application, it was found that Thomson’s end blocks are unnecessarily over designed. From this, the team set out to design various end blocks for all three linear motion systems. Variations of designs can be seen in Appendix C. Below is a table comparing the differences between the designed ¾” ball screw blocks and Thomson’s block.

<table>
<thead>
<tr>
<th>Component</th>
<th>Kimball</th>
<th>Thomson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing</td>
<td>Double sealed ball bearing</td>
<td>Deep Groove</td>
</tr>
<tr>
<td>Material</td>
<td>MIC - 6 Aluminum/Steel (machinist's choice)</td>
<td>Steel</td>
</tr>
<tr>
<td>Extra Components</td>
<td>Extra seals can be added as necessary</td>
<td>Inner and outer seals</td>
</tr>
<tr>
<td>Total Price per Block</td>
<td>$135.11</td>
<td>$535.00</td>
</tr>
</tbody>
</table>

2.5.4 Manual vs. Automatic Clamping

Two options were discussed for holding the extruded aluminum tubing in place while being cut. The first option was to automate the clamping procedure with either pneumatic or electronic clamps. This method allows for minimal
interaction between the machines moving parts and the operator. Several
difficulties arise trying to implement this option due to the need for the clamps to
rotate. The air lines and electrical wires would need couplers that would allow for
360 degree rotation without pinching or binding. Also, the electronic and
pneumatic clamps are much larger than their manual counterparts which would
require larger clearances around the tubing. The one difficulty of using manual
clamps to secure the aluminum tubing is that it creates a safety concern for the
operators. This could be overcome by using safety shields and sensors to ensure
that the operators are clear of the machine before it is allowed to start. The final
consideration of the clamping method is the cost of the individual clamps. A
typical manual clamp costs around 15 dollars whereas pneumatic or electric
clamps are closer to 100 dollars. Taking all of these differences into
consideration, manual clamps were chosen for the project in order to reduce costs
and increase the simplicity of the design.

3.0 Budget

3.1 Purchased Parts

The CNC Router will be fabricated and constructed in Kimball Office’s machine shop
in Post Falls, ID. However, many of the machines components will be purchased through
outside suppliers and manufacturers. The linear motion systems, including linear
bearings, support rails and ball screws, will be purchased through the Kaman Industrial
Technologies office in Spokane, WA. The manual toggle clamps and latches will be
ordered from the CarrLane Manufacturing Company or one of its vendors. Many
components including the ball bearings will be ordered from McMaster Carr. Spider
Couplers that will be used between the stepper motors and the ball screws will also be purchased from either Kaman or McMaster. Four stepper motors will be used to control the motion of the machine and will be purchased from Anaheim Automation in Anaheim, CA along with a planetary gearbox for part rotation. The router motor will be ordered from Ekstrom Carlson in Rockford, IL. The raw materials needed to complete the design will be ordered by Kimball from their supplier and machined to the proper dimensions.

Table 1 shows a list of all purchased part required for the design.

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Description</th>
<th>Part Number</th>
<th>Quantity</th>
<th>Price ($)</th>
<th>Total ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carr Lane</td>
<td>T-Handle Toggle Clamp</td>
<td>CL-300-VTC</td>
<td>3</td>
<td>14.55</td>
<td>43.65</td>
</tr>
<tr>
<td>Carr Lane</td>
<td>Latch Action Toggle</td>
<td>CL-100-PA</td>
<td>1</td>
<td>11.55</td>
<td>11.55</td>
</tr>
<tr>
<td>Carr Lane</td>
<td>Horizontal Handle Toggle Clamp</td>
<td>CL-200-VTC</td>
<td>4</td>
<td>9.85</td>
<td>39.4</td>
</tr>
<tr>
<td>McMaster</td>
<td>Urethane Spider</td>
<td>2410K13</td>
<td>1</td>
<td>8.18</td>
<td>8.18</td>
</tr>
<tr>
<td>McMaster</td>
<td>Metric Spider Coupling Hub 19 mm to 28 mm Bore, 2-7/64” Outside Diameter</td>
<td>6413K15</td>
<td>1</td>
<td>10.52</td>
<td>10.52</td>
</tr>
<tr>
<td>McMaster</td>
<td>Standard Spider Coupling Hub 7/16” to 1-1/8” Bore, 2-7/64” Outside Diameter</td>
<td>6408K15</td>
<td>1</td>
<td>9.86</td>
<td>9.86</td>
</tr>
<tr>
<td>McMaster</td>
<td>Sealed 3/4” Ball Bearing</td>
<td>6384K790</td>
<td>2</td>
<td>11.73</td>
<td>23.46</td>
</tr>
<tr>
<td>McMaster</td>
<td>Shoulder Screw 3/8” Shoulder Dia, 1-1/4” L Shoulder, 5/16”-18 Thrd</td>
<td>91259A626</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>McMaster</td>
<td>10mm Double Sealed Ball Bearing</td>
<td>6153K74</td>
<td>4</td>
<td>24.27</td>
<td>97.08</td>
</tr>
<tr>
<td>McMaster</td>
<td>15mm Double Sealed Ball Bearing</td>
<td>6153K76</td>
<td>2</td>
<td>31.22</td>
<td>62.44</td>
</tr>
<tr>
<td>Supplier</td>
<td>Description</td>
<td>Part Number</td>
<td>Quantity</td>
<td>Unit Price</td>
<td>Total Price</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------</td>
<td>----------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td>McMaster</td>
<td>Flexible Spider Coupling Hub 1/4&quot; to 5/8&quot; Bore, 1-5/64&quot; Outside Diameter</td>
<td>6408K11</td>
<td>6</td>
<td>2.33</td>
<td>13.98</td>
</tr>
<tr>
<td>McMaster</td>
<td>Buna-N Spider for 1-5/64&quot; Outside Diameter Flexible Spider Shaft Coupling Hub</td>
<td>6408K84</td>
<td>3</td>
<td>1.52</td>
<td>4.56</td>
</tr>
<tr>
<td>Anaheim Automation</td>
<td>NEMA 34Y Series Stepper Motor</td>
<td>34Y0</td>
<td>3</td>
<td>113.2</td>
<td>339.6</td>
</tr>
<tr>
<td>Anaheim Automation</td>
<td>NEMA 23Y Series Stepper Motor</td>
<td>23Y3</td>
<td>1</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Anaheim Automation</td>
<td>GBPH-090X-NP Series Gearbox</td>
<td>GBPH-0901-NP</td>
<td>1</td>
<td>504</td>
<td>504</td>
</tr>
<tr>
<td>Kaman</td>
<td>3/4&quot; Bearing Rail Assembly</td>
<td>2</td>
<td>552.23</td>
<td>1104.46</td>
<td></td>
</tr>
<tr>
<td>Kaman</td>
<td>1/2&quot; Bearing Rail Assembly</td>
<td>2</td>
<td>222.57</td>
<td>445.14</td>
<td></td>
</tr>
<tr>
<td>Kaman</td>
<td>3/4&quot; Ball Screw</td>
<td>1</td>
<td>164.79</td>
<td>164.79</td>
<td></td>
</tr>
<tr>
<td>Kaman</td>
<td>Wiper Kit</td>
<td>3</td>
<td>34.57</td>
<td>103.71</td>
<td></td>
</tr>
<tr>
<td>Kaman</td>
<td>1/2&quot; Ball Nut</td>
<td>2</td>
<td>163.57</td>
<td>327.14</td>
<td></td>
</tr>
<tr>
<td>Kaman</td>
<td>3/4&quot; Ball Nut</td>
<td>1</td>
<td>198.88</td>
<td>198.88</td>
<td></td>
</tr>
<tr>
<td>Kaman</td>
<td>24&quot; x 1/2&quot; Ball Screw</td>
<td>1</td>
<td>79.42</td>
<td>79.42</td>
<td></td>
</tr>
<tr>
<td>Kaman</td>
<td>12&quot; x 1/2&quot; Ball Screw</td>
<td>1</td>
<td>56.27</td>
<td>56.27</td>
<td></td>
</tr>
<tr>
<td>Ekstrom Carlson</td>
<td>Model SM2-C54 Spindle Motor, 1.34 HP at 24000 RPM, 220 Volts, 5.5 Amps</td>
<td>SM2-C54</td>
<td>1</td>
<td>1946.43</td>
<td>1946.43</td>
</tr>
</tbody>
</table>

**Total= $5684.02**

Table 1: Purchased Parts List
3.2 Raw Materials

Table 2 shows the estimated cost of raw materials for the project based on prices from Alcobra Metals of Spokane Valley. Most parts will be machined from MIC-6 aluminum tooling plate.

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Quantity</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>24&quot; x 72&quot; x 3/4&quot; x-axis Baseplate</td>
<td>Steel</td>
<td></td>
<td>$562.70</td>
</tr>
<tr>
<td>12&quot; x 24&quot; X .75 plate for x-saddle</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$152.51</td>
</tr>
<tr>
<td>4 - 1&quot; thick PB total area &lt; 1 sq. ft</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$131.72</td>
</tr>
<tr>
<td>16 g. cable trough 12&quot;x60&quot;</td>
<td>Sheet Steel</td>
<td></td>
<td>$29.12</td>
</tr>
<tr>
<td>X &amp; Y Motor Mounts 1 - 12&quot;x12&quot;x 3/4&quot;</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$99.10</td>
</tr>
<tr>
<td>Z-motor mount .5&quot; scrap</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$54.03</td>
</tr>
<tr>
<td>Z saddle 0.25&quot; x 12&quot; sq</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$4.68</td>
</tr>
<tr>
<td>Z support 0.5&quot; x 1.5&quot; x 12&quot;</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$99.10</td>
</tr>
<tr>
<td>Y saddle 3/4&quot; x 12&quot; x 12&quot;</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$205.93</td>
</tr>
<tr>
<td>Y-axis Base</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$18.88</td>
</tr>
<tr>
<td>Y-axis Base side support 0.5&quot; x 2.5&quot; x 36&quot;</td>
<td>6061-T6 aluminum</td>
<td></td>
<td>$111.89</td>
</tr>
<tr>
<td>z base 0.5&quot;x 12&quot; x 24&quot;</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$111.89</td>
</tr>
<tr>
<td>large gusset 0.75&quot; x 12&quot; x 12&quot;</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$99.10</td>
</tr>
<tr>
<td>small gusset 0.5&quot; x 12&quot; x 12&quot;</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$73.70</td>
</tr>
<tr>
<td>Rotating Block 3&quot; sq x 12&quot; extruded</td>
<td>6061-T6 aluminum</td>
<td></td>
<td>$62.63</td>
</tr>
<tr>
<td>Clamp Insert 12&quot; x 36&quot; x 0.5&quot;</td>
<td>Delrin</td>
<td></td>
<td>$135.00</td>
</tr>
<tr>
<td>Clamp Mount 2.5&quot; sq x 12&quot;</td>
<td>6061-T6 aluminum</td>
<td></td>
<td>$42.03</td>
</tr>
<tr>
<td>Wear Plate 0.25&quot; x 2&quot; x 12&quot;</td>
<td>1018 CR steel</td>
<td></td>
<td>$4.57</td>
</tr>
<tr>
<td>Clamshell 1.25&quot; x 12&quot; sq</td>
<td>MIC-6 aluminum</td>
<td></td>
<td>$166.59</td>
</tr>
<tr>
<td>Bearing Block 1&quot; x 4&quot; x 12&quot;</td>
<td>6061-T6 aluminum</td>
<td></td>
<td>$26.00</td>
</tr>
<tr>
<td>Gearbox Mounting Plate</td>
<td>6061-T6 aluminum</td>
<td></td>
<td>$26.00</td>
</tr>
<tr>
<td>Shaft 1&quot; x 12&quot; round</td>
<td>6061-T6 aluminum</td>
<td></td>
<td>$4.68</td>
</tr>
</tbody>
</table>

Table 2: Estimated Raw Material Costs

3.3 Budget Analysis

As it was stated earlier in this report, a limit of $20,000 was granted to the Gonzaga design team to produce the multi-axis programmable router. From above, the total cost of
raw materials and purchased parts sums to be $7886.15, and the only factor that was not accounted for in this listed cost is the cost of labor to manufacture the in-house parts and assemble the machine. Of the allotted $20,000, nearly two-thirds, $12,113.85, remains to be expended on machining and assembling the machine. From early estimates, the cost of labor will not exceed the remaining budget; therefore, it is projected that the total cost of the project will be thousands of dollars less than $20,000.

4.0 Schedule

The goal at the start of this project was to have the machine designed and built by the end of the school year. During the course of this project, however, our team has slowly slipped behind schedule. This is due to our team being a little ambitious about what we could do and how quickly we could do it and due to Kimball being unable to get the budget for the project approved. Completing the 3-D models set us back a couple weeks due to some difficulties in the design and determining specific purchase parts. Although we tried to make that time up, the 2-D drawings also took a good amount of time. As a result our team will be turning in the 2-D drawing package a little behind schedule.

We have been worried about the budget not being approved for some time now, but recently were told that it would in fact not be approved and therefore the machine would not be built before the end of the school year as we had originally planned. Kimball will build the machine sometime in the near future pending the approval of the budget.

5.0 Recommendations

5.1 Safety

Safety for the operator of the machine is the number one priority for Kimball. There are a number of features that need to be added to the machine prior to its
implementation onto the manufacturing floor. A number of suggested safety features are listed below.

5.1.1 Chip Collection

One of the major problems with the previous method of routing the side pockets in the extruded aluminum tubes is the quantity of machined chips that are produced and thrown. With the use of the new CNC router, there will still be machined chips that are thrown, but there have already been steps to reduce their quantity. First, the router will be using a ¼” two flute cutting bit that will travel around the outline of the desired pocket. By cutting around the outline of the pocket, large slugs will drop out, either into the interior of the tube or to the floor below, thus reducing the total volume of machined chips. For the chips that will be expelled during the process, a plexi-glass hood/shield needs to be placed over the Z-axis motion components including the router to encourage the chips to fall to a desired location on the ground.

5.1.2 Operator Safety

Along with preventing chips from hitting the operator, other features need to be added to ensure operator safety. First, there are many moving components that can catch an inattentive operator off guard. To prevent this from occurring, safety sensors located at various points on the machine will be a valuable asset. These would include light curtains on the front base (see figure below), sensors that detect the chip guards are correctly in place, and sensors that detect the
correct loading of the aluminum tube. These small safety features will ensure that no injuries will happen when operating the machine.

5.2 Testing

Numerous tests need to be performed on the router before it is fully implemented into production. First, after the machine is assembled all motion components need to be run the full length of their stroke, and the router controls need to be tested, as well. Each individual program needs to be tested with the aluminum tube in place.

After these preliminary tests, a vibration analysis should be performed on the cantilevered base during a complete cut on an aluminum tube. This analysis will place accelerometers at its connection point to the x-axis saddle and the end of the base. This needs to be performed to make sure that resonant frequencies will not be an issue during operation. The machine is designed to reduce the effects of vibration with the side rails, but this test will show if other measures need to be taken before implementation.

6.0 Conclusion

Overall, the project between Kimball Office and the Gonzaga team was successful even though it did not accomplish all of the initial goals that were set at the beginning of the school year. The Gonzaga team was able to complete the design of the mechanical components of the CNC router for Kimball. A complete SolidWorks model and drawing package will be provided to the engineers at Kimball who will complete the design and construction of the machine once a budget has been approved.
Appendices

Appendix A Drawing Package
APPENDIX B - Calculations
CALCULATE Router Power

13/4" per Revolution (1,203"/Rev)
20,000 RPM
120"/min Feed
1/4" Dia 2 flute cutter

KP = HP / in³/min
KP Aluminum = .25 HP / in³/min

Determine Feed Factor, C

\[
\text{Feed} = \frac{120 \text{ in} / \text{min} \times \frac{1}{20,000 \text{ RPM}}}{\frac{1}{2} \text{ "/ tooth}} \Rightarrow C = 1.3 \quad (\text{Table 4, page 1087})
\]

Determine Total Removal Rate, Q

\[
Q = f_m \cdot w \cdot d = 120"/\text{min} \cdot .25" \cdot .080" = 2.4 \text{ in}^3/\text{min}
\]

W = Work Factor = 1.25 \quad (Table 5, page 1087)

\[
P_c = \text{Power @ cutter} = KP \cdot C \cdot Q \cdot W = .25 \text{ HP} / \text{in}^3/\text{min} \cdot (1.3) \cdot (2.4 \text{ in}^3/\text{min}) \cdot (1.25) = .975 \text{ HP}
\]

\[
P_m = \text{Power @ motor} = \frac{P_c}{E} \quad E = \text{Efficiency}
\]

\[
E = .75 \quad (\text{Table 4, page 1088})
\]

\[
P_m = \frac{.975}{.75} = 1.3 \text{ HP} \quad \text{Router HP}
\]
CALCULATE X AXIS POWER

ASSUMPTIONS:

Rapid Speed = 2 ft/sec
CUTTING SPEED = 120 in/min = .147 ft/sec
ACCELERATION = 2 ft/sec/sec = 4 ft/sec^2

X-AXIS & Y-AXIS

30 LB LOAD / 32.2 ft/sec^2 = 0.93 s l w / s
FORCE READ TO ACCELERATE:
\[ F = ma = (0.93 \text{ slw} / \text{s}) \times (4 \text{ ft/sec}^2) \]
\[ F_{accel} = 3.73 \text{ lbs} + \text{FORCE READ TO ACCEL 30 LB LOAD} \]

ESTIMATE: FORCE READ TO CUT: 20 LB

TOTAL FORCE TO CUT & ACCELERATE
\[ F_t = F_{cut} + F_{accel} = 20 + 4 \]
\[ F_t = 24 \text{ lbs} \]

Z AXIS

ROTOR + Z AXIS HARDWARE = 15 LB

BALL SCREW

6/8 Dia x 13/44" / Rev (2031 in/rev)
Rapid speed = 2 ft/sec x 1 rev x 2031 in
\[ \text{RPM} = \frac{118 \text{ in} / \text{sec} \times 60 \text{ sec}}{\pi} \approx 7090 \text{ RPM} \]
Determine Power

\[ \text{Power} = \text{Torque} \times \text{Rotational Speed} \]

\[ = 2/3 \times 240 \text{ RPM} \times 1 \text{ Min/Rev} \times 2 \text{ Ft} \]
\[ = 12 \times \frac{16}{5} \text{ M/P} \times 40 \text{ Sec/Rev} \]

\[ = 4.2 \text{ Ft-Lb/sec} \]

1 HP = 550 FT-LB/sec

\[ \frac{4.2 \text{ Ft-Lb/sec}}{550 \text{ FT-LB/sec}} \]

\[ = 0.008 \frac{\text{HP}}{\text{sec}} \]

Calculate Power to Raise:

\[ \theta = 50^\circ \]
\[ \sin \theta = 0.83 \]
\[ \text{Torque} = 0.375 \times 0.83 = 0.31 \text{ LBS} \]
\[ = 0.5 \text{ LBS}\]

\[ \text{Power} = \frac{5 \text{ Min/HR} \times 1 \text{ FT} \times 1440 \text{ RPM} \times 1 \text{ Min/Rev} \times 2 \text{ Ft} \}
\[ = 12 \times \frac{16}{5} \text{ M/P} \times 40 \text{ Sec/Rev} \]
\[ = 4.3 \text{ Ft-Lb/sec} \times 550 \text{ FT-LB/sec} \]

\[ = 0.011 \text{ HP} \]
Stress Analysis of Cantilever Base

Objective:
1) Find Maximum deflection of Base
2) Obtain Force Data on x-axis bearing rails

Assumptions:
* Properties of y-axis motion (MIC-6 Aluminum)
  * Tensile Strength = 24 ksi
  * Yield Strength = 15 ksi
  * Mod. of Elasticity = 10.3 x10^6 psi
* Distributed load is 11 lb/in of cantilever
* Load of Z-axis motion components is at end of cantilever
* Router weight = 9.6 lb
* Z axis includes
  * Plate
  * Motion components w/ motor
  * Router
2) All components are considered Rigid bodies
* Force Required to Cut: Fcut = 20 lb
Analysis:

1) Deflection

\[ F_{\text{dist}} = F_{\text{components}} + F_{\text{weight}} \]
\[ = (11.5)(18^-) + (0.098 \text{ lb/in}^2)(18^-)(0.5^-)(0.75^-) \]
\[ = 18 \text{ lbf} + 8.6 \text{ lbf} \]
\[ F_{\text{dist}} = 26.6 \text{ lbf} \]

\[ F_2 = F_{\text{dist}} + F_{\text{rot}} + F_{\text{motor}} \]
\[ = [(0.098)(12^-)(0.5^-)(5^-) + 1 \text{ lbf}] + 3 \text{ lbf} \]
\[ \text{weight of plate} \]
\[ \text{components} \]
\[ \text{motor} \]
\[ \text{rotor} \]
\[ F_2 = 23.54 \text{ lbf} \]

\[ R_y = F_0 + F_2 \]
\[ R_y = 50.14 \text{ lbf} \]
\[
\delta_{\text{max}} = -\frac{pL^3}{3EI} + \frac{F_d}{2EI} (3b-a)
\]
\[
\gamma = 9''
\]
\[
\delta_{\text{max}} = \frac{(23.6^3)(18')^3}{3(10.3\times 10^4)(0.286)} - \frac{(26.4)(9)^3}{6(10.3\times 10^4)(0.286)} - (3(18') - 9)
\]
\[
\delta_{\text{max}} = .1553'' + .0549
\]
\[
\delta_{\text{max}} = .2102\text{ in}
\]

2) Moment on \(x\)-axis, \(F\) bearings

\[
R_y = 50.14\text{ lbf}
\]
\[
R_z = 20\text{ lbf}
\]
\[
T_o = \frac{I_t}{J} = \frac{J=I+y^2A}{J} = \frac{.0284 + (.75)(.75)}{2.777} = 187.73\text{ lbf-in}
\]

The torsion will act on the bearing rails as a Couple

\[
F = 17.88\text{ lbf on each rail}
\]
Appendix C

Z - Axis Bottom Block

X - Axis End Block

Movable Bearing End Block
Appendix D

Aluminum Corner Posts

Kimball Office “Xsite Model”