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Automating the Fret Slotting Process Using a PLC Controlled 1.5 Axis Mill

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AUTOMATING THE FRET SLOTTING PROCESS USING A PLC CONTROLLED 1.5 AXIS CNC MILL

For the degree of Master of Science

Is approved by the final examining committee:

Dr. Richard Mark French
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Dr. Helen McNally

Dr. Haiyan Zhang

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AUTOMATING THE FRET SLOTTING PROCESS USING A PLC CONTROLLED 1.5 AXIS CNC MILL

A Thesis

Submitted to the Faculty

of

Purdue University

by

James Arthur Stratton

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

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West Lafayette, Indiana

I dedicate this work to my parents and my grandmother. Thank you for the encouragement and assistance throughout the years. I truly could not have done it without your love and confidence in my educational career.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

ABSTRACT

Stratton, James A. M.S., Purdue University, August 2011. Automating the Fret Slotting Process Using a PLC Controlled 1.5 Axis CNC Mill. Major Professor: Richard Mark French.

Can automation assist small job shops and hobbyists in the production of stringed instruments? This research set out to answer the question using a quantitative approach to determine if an economical CNC machine could be produced in such a fashion as to seamlessly join the workshop as an affordable, yet precise instrument to aid in the production of stringed instruments. The key was to incorporate common industrial automation equipment into the operation of the machine in an attempt to sever the dependency on outside resources, such as personal computers and shop utilities, while remaining compact enough as to not devour valuable workshop real estate. The fabricated 1.5 axis gantry mill was tested empirically by producing a population of fret boards which were measured for accuracy. Materials, methods, and statistical analysis are all included within this document. The results and conclusions of this study are provided in an attempt to answer the primary research question.

CHAPTER 1. INTRODUCTION

The information contained in this chapter will establish the research question for this thesis, as well as cover the scope, significance, assumptions, delimitations, and limitations.

1.1. Problem Statement

Automation rarely exists in the average personal woodshop. Research explored in this thesis explored the possibility of bringing industry-quality automation to the average home luthier by developing a piece of equipment to aid in the production of fret boards. The piece of equipment needed to be affordable enough that it could be obtained by any range of luthier, as well possess the craftsmanship to produce a quality fret board.

1.2. Research Question

The contents of this thesis are answered in respect to the following question:

- Is it possible to create an affordable and precise PLC controlled, 1.5 axis CNC mill to automatically cut fret slots into the fret board of a guitar while allowing for multiple, user defined, scale lengths?

1.3. Scope

The machine detailed in this thesis was designed to cut fret slots to scale lengths defined by the user. Using a human machine interface (HMI), users were able to enter any scale length, from which the appropriate fret spacing was automatically calculated. These scale lengths were available in either a chromatic or diatonic scale, in accordance with which instrument the user was creating. This allowed the luthier to create a variety of fret boards for instruments ranging from, but not limited to, the guitar, bass guitar, or mandolin. Each of these instruments naturally has multiple options for scale lengths depending on the style chosen by the user.

This machine was designed to be a desktop model. This will be useful as laboratory and workshop desktop real estate is typically scarce. A desktop design ensured that various end users would have an easily transportable machine that can be stowed when not in use. All parts incorporated in the device were to be readily available in the market place in order to keep the overall cost low, as well as provide easy options for upkeep and maintenance issues.

1.4. Significance

Automation is not a new field, and neither is a mechanical method for cutting fret slots. However, combining the two opened a slightly new door to the guitar manufacturing industry by offering on-the-fly scale length adjustments. This project aimed to create a completely automated method for cutting fret slots using a desktop sized machine that can be used by a range of users from the garage hobbyist to a full scale production company. The goal was to create a machine that was not only affordable, but offered the precision and repeatability required to produce a top-of-the-line stringed instrument. By satisfying these criteria, the hobbyist can abandon traditional manual methods of cutting fret slots, and incorporate this small machine into their arsenal of specialty tools. Typically, the hobbyist will cut each fret slot by hand, requiring precision on the order of merely thousandths of an inch in either direction, to produce a quality fret board. This machine was able to accurately produce this precision on a repeatable basis. Larger companies will also see benefit as many use outdated methods for this operation, and will greatly benefit from an automated station to accomplish the same task. The finished product offered a simple user interface with pre-programmed controls so that any number of operators could perform this high-level task typically performed by an experienced worker. This not only allows for a more diverse work force but can also lead to an increase in production size. Being that the unit was sized as a desktop model, multiple units would be able to be placed in various locations around a production facility in order to meet various levels of demand. While no “new” technology was being used, the implementation of combining standard industrial automation equipment with a 1.5 axis milling machine, set up to produce fret slots, was a new approach to guitar production that will greatly reshape the industry from the small scale garage luthier to the full scale industrial production line.

1.5. Definitions

Bridge – Component of a stringed instrument where the strings meet the body of the instrument.

Nut – The component of a stringed instrument, opposite of the bridge, where the strings enter the headstock of the instrument.

Scale Length – The distance, measured between the bridge and nut on a guitar. The scale length is critical in determining fret spacing.

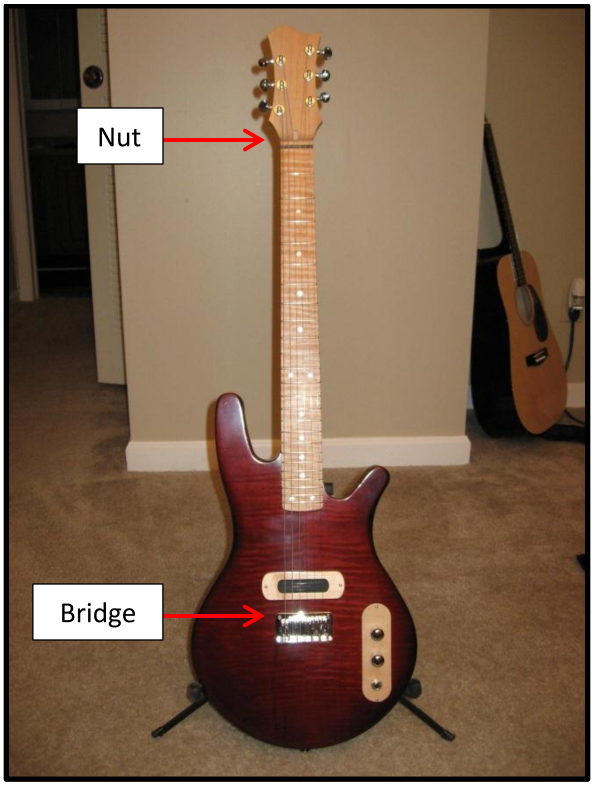

Figure 1.1. A schematic of the bridge and nut locations, where the distance between the two represents the scale length.

CNC – Acronym for computer numeric control and refers to computer controlled machining operations.

PLC – Acronym for programmable logic controller; a small processor used for controlling industrial automation systems.

HMI – Acronym for human machine interface; a graphical user interface used to aid in communication between the user of a machine and the PLC.

1.6. Assumptions

The following assumptions were stated as a basis for the research conducted in this thesis:

- There is a market for a home-use or small manufacturing fret slotting CNC machine.
- The most appropriate components will be chosen and incorporated into the bill of materials.

1.7. Delimitations

The following delimitations were identified by the researcher:

- The experiment was intentionally narrowed to be constrained by a maximum scale length. There was an infinite possibility of scale lengths offered by the machine, but the physical envelope of the machine limited the size of fret boards it can produce.

- The machine was constrained to 1.5 axes of motion control. Two complete axes of control would be preferred but due to a budget and time constraint, only one axis of motion will be precisely controlled. The third axis was fixed. This did not affect the overall accuracy of the machine.

- A budget of $2500 for raw materials was not to be exceeded. This allows the machine to remain a viable option for consumers.

1.8. Limitations

The following limitations were defined by the researcher:

- The overall size of the machine needed to be compact. An envelope of roughly 3’ x 2’ x 2’ (L x W x H) was established in order to ensure a desktop design was produced.

- The availability of the correct type of AC electric motor for the saw blade greatly inhibited both the budget as well as the design of the machine. The motor specified for the project did affect the quality of the research, however it should be noted that a more appropriate choice must exist; a smaller motor would be preferred for this application. A market search showed that the smaller AC motors were generally more expensive and did not meet the specifications needed. A smaller motor would have greatly reduced the size of

> the gantry apparatus as well as reduced the need for more expensive structural materials such as aluminum.

1.9. Chapter Summary

This chapter has helped establish grounds for which the research for this thesis will be conducted. The research question has been stated and the bounds of scope have been defined by the assumptions, limitations, and delimitations. To highlight the most important, the machine must fit a specific physical envelope, established as 3’ x 2’ x 2’. A budget of $2500 must not be exceeded.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

The premise of this thesis is to create an economical machine for cutting fret slots into the fret board of a guitar. The machine needs to be compact enough that it can be classified as a desktop work station that can be stored when not in use. This literature review will primarily cover the choices of hardware and basic machine design implemented in order to meet these parameters.

The design for the machine was chosen as a gantry style mill with the x-axis being controlled precisely and the y-axis performing a simple lateral operation. The x-axis will control the actual placement of each fret slot; therefore it needs to be extremely precise. The y-axis will actuate a saw blade back-and-forth to cut each slot. The z-axis of the machine was fixed, but adjustments were possible using shims. The components of each axis will be discussed and argued in the following section.

2.2. Automated Processes

As stated earlier, automation within the guitar industry is not exactly a new field. For instance, Taylor Guitars out of California switched from a two-man batch operation to a fully automated production facility employing over 350 people (Bates, 2005). It was interesting to note that in this particular case, automation helped the company grow. Producing more products in a shorter amount of time required more hands on deck to handle the demand. Taylor Guitars originally did not possess technical drawings for any of their instruments. As a result, the transition to an automated facility required the reverse engineering of every single one of their instruments in order to maintain the quality of which loyal patrons were accustomed (Bates, 2005). By choosing the correct machinery, Taylor Guitars was able to increase their quality through automation as each instrument was made to the highest expectations and standards, and identical to the next off of the line (Bates, 2005). While this source did not state the method by which Taylor Guitars produces fret boards, it should be noted that automated processes can bring profound quality increases to operations previously completed by hand.

2.3. Linear Motion

This machine depended greatly on the idea of linear motion control. Linear motion control is the concept of moving a load in a single linear direction with a level of control established by the user. Typically, the most precise type of control comes in the form of servo-motors that utilize a feedback loop to determine the ultimate position. Because this machine was constructed in an economical fashion, stepper motors were used as they are cheaper than servo-motors. However, with the right linear motion components, stepper motors can achieve the level of accuracy required to perform the fret slot cutting operation.

For high accuracy applications Glikin (2009) suggested using a lead-screw. Linear motion control systems, namely lead-screws, often require a higher level of component complexity as well as deliver higher orders precision (Cleaveland, 2002). Lead-screws are threaded rods that extend the length of the work area and are controlled by a stepper motor. A nut, attached to the load being moved, is threaded onto the lead-screw and travels the length of the screw depending on the direction of rotation. Lead-screws are available in a variety of styles and thread types and should be chosen appropriately for each individual application. For instance, an ACME type lead-screw provides higher levels of accuracy yet have a relatively low repeatability factor when compared to ball or roller type lead-screws. ACME nuts tend to wear heavily over time requiring higher maintenance. If left untreated, a significant loss in repeatability and accuracy can occur (Glikin, 2009). For this application, the machine demanded high resolution as well as high repeatability since it needed to produce the same results each time. Without this accuracy, a variance would occur between musical instruments. A roller type lead-screw provides the highest level of accuracy, repeatability, and resolution (Glikin, 2009). These characteristics were preferable given the application, but unfortunately roller type lead-screws are the most expensive of the three designs, which violate the constraint of economic feasibility. Of the lead-screws, the ball type lead-screw would be the most appropriate lead-screw for the x-axis control of the automated fret slot cutting machine.   Ball type lead-screws have the accuracy of a roller type lead-screw but a price closer to that of an ACME lead-screw (Glikin, 2009).

Another even less expensive form of linear motion is the rack-and-pinion mechanism. The rack-and-pinion operates by coupling a toothed gear, also known as the pinion, to the shaft of the stepper motor. The pinion is then mated to a straight gear rack, and operates in a linear fashion as the stepper motor is activated in either rotational direction. High precision systems can offer reliable, near zero-backlash linear motion (Stock, 2010). In an ideal scenario, two stepper motors can be used to operate the rack-and-pinion system with greater accuracy by providing opposing, or harmonic forces, to achieve motion. When working in opposition, two smaller stepper motors can generate a stronger holding torque, while the axis is stationary, by preloading the rotation of the stepper motors in opposite directions. When working together, the stepper motors can achieve faster acceleration, deceleration, and even hold more constant speeds (Stock, 2010). Stock (2010) also stated that adding gear ratios can allow machine designers to tune their axes of linear motion to allow for higher efficiencies and more accurate performance.

For this application, the rack-and-pinion offered the best performance for the money. In addition, the rack-and-pinion was chosen for its simple design and low maintenance operation.

The y-axis component of this machine needed to be stable, but does not require the precision of the x-axis. The y-axis simply needed to travel the length necessary to make a full cut through the fret board and then return to its home position. For this reason, precise control was not necessary and movement was controlled through the feedback from limit switches. According to Hahn (2001), selection of linear motion technology should be chosen appropriately as to not dramatically inflate a budget for unnecessary forms of control. Hahn (2001) suggested the lowest cost type of linear motion control comes in the form of pneumatic actuators. Due to the fact that the y-axis will only be extended to its limit, then retracted, a pneumatic cylinder would suffice as the control mechanism for the y-axis. In an attempt to keep the machine isolated from connecting to outside resources, the pneumatic cylinder showed the capability of being operated using the existing internal vacuum supply.

The fret slotting saw rode on a carrier supported by two parallel precision-ground rods via linear carrier bearings. A pneumatic actuator placed parallel to the guide rods acts as the mechanical force required to pass the saw blade through the fret board material. Figure 2.1 below details the cylinder placement on the saw carrier.

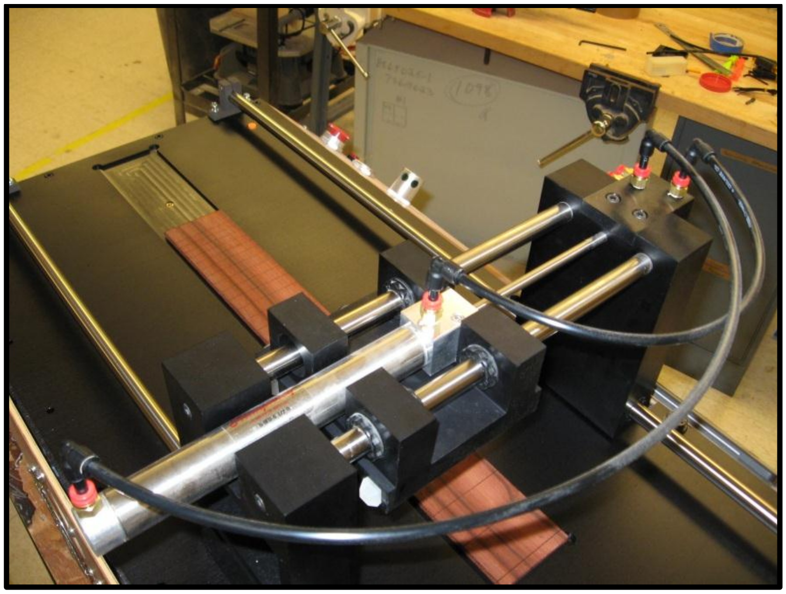

Figure 2.1. The pneumatic actuator was placed between the precision ground guide rods that supported the saw. This kept the design compact while maintaining functionality.

Simple mathematical equations provided by Mills (2007) determined the appropriate size of the cylinder and the air pressure at which the actuator operated. Mills (2007) outlined a design similar to that chosen for the y-axis, depicting a load supported by two parallel precision rods with a pneumatic actuator mounted between them.

2.4. Stepper Motors

A stepper motor was required to precisely control the position of the gantry along the x-axis of linear motion. Sheets and Graf (2002) stated that some advantages of stepper motors include open-loop and closed-loop operation, position error can be accounted for down to the single step, and that their design is highly reliable. Some disadvantages are that they can only operate in fixed increments of rotation, and choosing the correct driver for the stepper motor can make or break the effectiveness of the application (Sheets & Graf, 2002). Sheets and Graf (2002) also specified that for applications where budget is a concern, the stepper motor coupled with gear systems provides a reliable budget-friendly motion solution.

Stepper motors have what are called phases. Phases refer to the number of possible positions per rotation for which the stepper motor can operate. In general, the more phases a stepper motor has, the more accurate it becomes (McComb, 1999). A four-phase stepper motor consists of four windings. The shaft is positioned by energizing combinations of the windings, resulting in controlled motion. The amount of rotation from each pulse of energy provided to the windings is referred to as the step angle, which can range anywhere from 90 degrees to as small as 0.9 degrees (McComb, 1999). McComb (1999) stated for example, “A stepper [motor] with a 1.8-degree step angle...must be pulsed 200 times for the shaft to turn one complete revolution” (p. 65). This characteristic was important to note when coupling the stepper motor to a rack-and-pinion system because the rotation of the shaft must be translated into a linear distance proportional to the diameter of the gear. As one can see, the resolution can be greatly increased by increasing the number of phases within the stepper motor, as the steps per degree quickly grows. Each phase of the stepper motor has a respective wire that provides the phase with energy. These wires are then connected to a stepper motor controller that interfaces with a personal computer (PC), or in the case of this thesis, a programmable logic controller (PLC).

2.5. Feedback Loops

It was determined that a feedback loop could provide more precise control of the machine. Stepper motors typically operate using open loop control providing no feedback on the present location of the stepper motor's position. Closed loop control systems offer position feedback to verify that the correct motion has occurred.

One form of position feedback comes in the form of linear variable differential transformer (LVDT). The LVDT was first put use in industrial environments during World War II ("History of the LVDT," 2010). An LVDT operates by measuring a variable ac signal generated by a magnetic core material as it moves within cylindrical housing containing three coils. The center coil serves as the primary coil while the two outer coils offer the directional differential signal generated by the dynamic core (Titus, 2010). The core material is typically attached to a moving component of a machine, while the cylindrical housing is held stationary. This varying ac signal generated by movement of the core is used to compute the distance traveled in either direction. One benefit to LVDTs is that they offer extremely precise linear displacement measurements, with accurate resolutions of less than 1mm and

±0.25 percent error for the specified travel length (Titus, 2010). Bartos (2001) stated that LVDTs are typically designed for short travel applications. A brief market survey concluded that an LVDT with 3’ of travel, required for this application, would have solely exceeded the budget of the entire project.

The next most feasible alternative came in the form of optical rotary encoders. The most basic form of encoder is the incremental encoder. Incremental encoders operate by generating a square wave output, and can only be used to provide relative location in a single direction. A quadrature incremental encoder, however, can provide a relative home position, as well as two channels of square wave output for direction indication (Bartos, 2000). The home position marker counts each full revolution, while the other two channels provide an offset square wave that can be used to determine the direction of rotation, as well as track the angle of rotation. According to Gyorki and Monnen (1999), the square waves generated by an incremental encoder are created by detecting “alternating opaque or transparent segments” (p.186) on a disc using a source of light. The pulsing signal created by these segments generates the square wave output of the encoder (Gyorki & Monnen, 1999). A more advanced version of the optical encoder is known as an absolute encoder. A multitude of concentric tracks, each consisting of variably spaced segments, are individually counted using multiple light sources. This feature allows the absolute encoder to retain absolute positioning even if power is disconnected (Bartos, 2000). The more popular of the two, as indicated by Bartos (2001) is the quadrature encoder for its simple design and economical availability. Due to this recommendation, and availability from the chosen suppliers, the researcher chose the quadrature incremental encoder as the primary feedback device for the fret slotting machine.

2.6. Summary

Based on the information gathered in this literature review, the research conducted led the researcher to construct a 1.5 axis CNC gantry style mill. The motion system was specified as consisting of a stepper motor with rack-and-pinion linear motion transfer system, coupled with a PLC for precise motion control. The secondary axis was operated by the use of a pneumatic actuator, powered by vacuum pressure, to perform the cutting motion of the saw.

CHAPTER 3. PROCEDURES AND DATA COLLECTION

3.1. Study Design, Units & Sampling

The methodological approach for this quantitative thesis topic was rather simple. Upon completion of the automated fret slotting mill, a number of fret boards were produced for a guitar at a specific scale length. This tested the functionality of the machine, but also allowed for a quantitative study to be conducted on the accuracy of the machine. The distance from the nut to each fret slot was measured and recorded for each fret board. This was achieved using a manual vertical mill with digital readout. The location of the each fret slot was detected using a dial indicator. Measurements were recorded from the digital readout of the machine. The vertical mill chosen for the metrological aspect of this research was accurate to 0.0002”. A hypothesis test was then conducted once all of the data had been recorded to determine if there was a significant amount of variance between the machined fret boards and the theoretical location of the individual frets. Both Minitab and SAS version 9.2 were used as the statistical software to interpret the data. The null hypothesis stated that there is no significant difference of fret spacing between fret boards and the theoretical values for fret spacing and the alternative hypothesis stated that a significant difference between fret spacing exists. The fret distances were measured in inches. The results of this study were aimed to verify that the machine produced repeatable products as well verify the machine operated in a consistent manner with no mechanical malfunctions. Any issues pertaining to the mechanical operation of the machine were to be noted accordingly.

3.2. Machine Design

The following sections will cover aspects of the physical design of the machine. It will cover mechanical, electrical, and electromechanical design elements, from conception to fabrication. Analysis of the materials and components used will be provided in their respective sections.

3.2.1. Mechanical Design

Upon conception of the idea for an automated fret slotting machine, extensive design was required in order not to waste valuable materials. Based off of the original constraints for the system, the machine needed to fill an area of 3’x2’x2’ in order to be a desktop-sized machine. This constraint offered many challenges as materials and features needed to be compact, yet still functional for the task of slotting a fret board and be robust enough to survive the workshop environment.

Design began as simple sketches to establish the basic form of the machine. These sketches depicted the machine as a gantry style mill, anchored on a rectangular box to house the electronic components of the machine. Once the basic form was established, a computer aided model was created using Dassault Systems' SolidWorks Education Edition computer aided drawing (CAD) software package. This particular software package was chosen for its industry prevalence and robust modeling capabilities. By utilizing CAD software, the researcher was able to design the mechanical aspects of the machine in full without needing prototype components for fitting purposes. This helped keep material costs low while still allowing for modifications during the maturation of the machine's design. As stated earlier, a major limitation was the availability of an appropriate AC electric motor capable of being used as the saw motor. Therefore, the machine was designed specifically around the particular motor that was chosen for this application. The CAD software allowed the flexibility needed to make serious design changes as new components were specified. Once the individual components were drafted within the CAD software interface, the items were compiled into an assembly to verify that the components would mate without interference. Once the animated assembly was complete, the fabrication of parts began. Pictured below are the CAD assembly snapshots compared to the final fabricated machine.

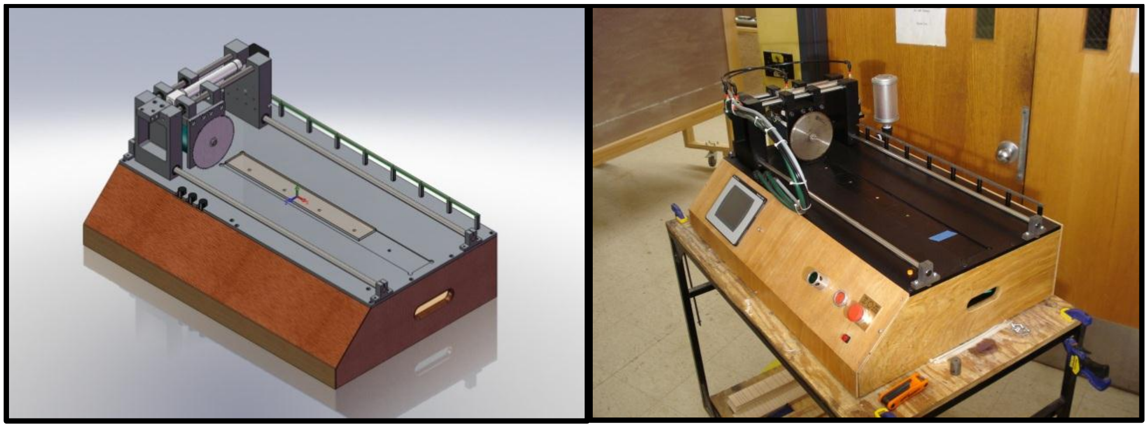

Figure 3.1. A side-by-side comparison of the original CAD model on the left and the finished product on the right is illustrated above.

A gantry style mill was chosen for its simplicity and well-suited capabilities for the application at hand. A gantry mill operates by traversing a single long axis, while actuating another. For this application, only two axes of motion were needed. Motion in both axes was achieved using precision-ground 5/8” stainless steel guide rods and linear ball bearings. Given, the 3’ of x-axis travel, the guide rods provided the most precise and most fluid form of motion that was available within the bounds of the budget. The following equation, with diagram, was used to determine the amount of deflection the x-axis guide rod would experience. The assumption of a point load applied directly to the mid-point of the rod predicted a worst case scenario for deflection. In reality, the load was distributed over a 5” length.

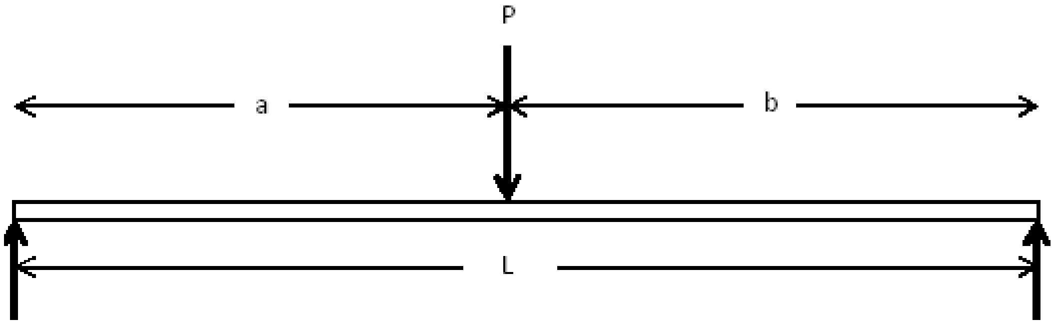

Figure 3.2. The free-body diagram used to calculate the deflection of the x-axis guide rod is shown above.

$$y = \frac{-Pa^2b^2}{3EIL}$$

The point load, P, was assumed as one half of the total weight of the saw carrier, given that two guide rods would support the gantry apparatus. Variables E and I represent the modulus of elasticity of stainless steel and the moment of inertia for a solid rod respectively. As a result of the calculation, it was determined that a 5/8" guide rod would be more than sufficient to support the weight of the saw carrier with negligible deflection.

The Advanced Micro Controls, INC. stepper motor, part number SM23-130-DE, was chosen for its compatibility with the stepper motor driver and the availability of a built-in rotary encoder. The stepper motor was mounted vertically on the rear support of the gantry and produced motion via a rack-and-pinion setup. This was implemented in place of a lead-screw for budgetary reasons as stated earlier. The y-axis of motion was traversed by a pneumatic actuator operated by vacuum. The reason for this will be discussed at a later point in this thesis. Due to the fact that the y-axis did not need precise control, the pneumatic actuator facilitated a simple down-and-back motion controlled by solenoid valves and limit switches.

According to the original design, the fret board was to be placed in a central pocket and held in place by a vacuum seal. This was achieved by milling port holes into the bottom face of the pocket and threaded to connect to the vacuum lines. Given that the vacuum force, measured in pounds per square inch, is dependent on area, channels were milled between the ports in order to increase the surface area of the vacuum underneath the fret board. Figure 3.3 shows the channels that were machined to a depth of 0.010” to increase vacuum force on the fret board.

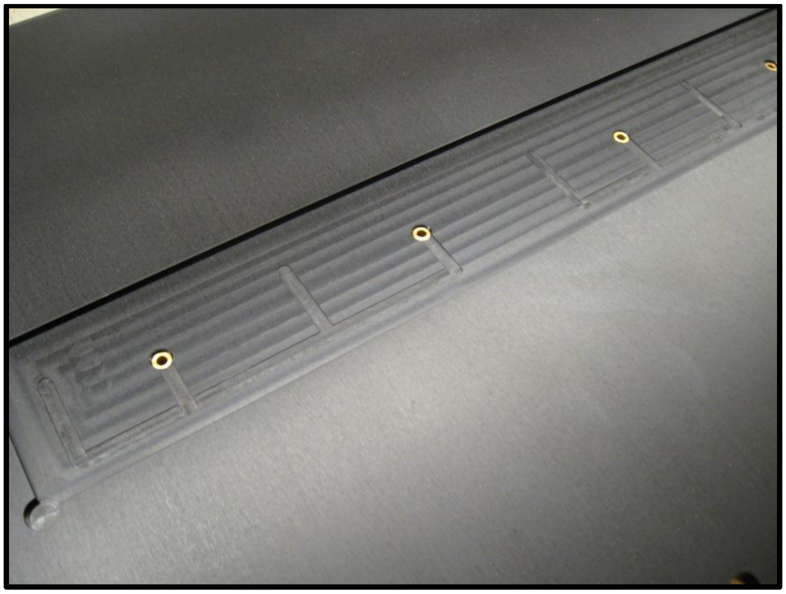

Figure 3.3. This image shows a detailed view of the vacuum channels machined into the top plate to provide greater holding force.

The vacuum chuck required a small vacuum pump to be installed within the substructure of the machine. Originally, the pneumatic cylinder required to push the saw was to be operated by a compressed air shop line. The downsides to this feature were that the machine could only operate near a source of compressed air and the machine would be limited by the capabilities of the compressor. As a remedy, the researcher calculated the minimum pressure required to operate the cylinder effectively using the following equation, where *A* equals the internal area of the cylinder, and *P* is the operating vacuum pressure. At the operating pressure of 10psi of vacuum, the cylinder chosen produced roughly 9 pounds of force.

$$F = PA$$

Through small experiments, it was determined that a small vacuum pump could produce sufficient vacuum pressure to operate the vacuum chuck and the cylinder simultaneously. This realization greatly simplified the overall design and compactness of the machine as a whole. No longer was the machine tied to any outside resources besides the standard 120VAC power outlet.

3.2.2. Materials

The materials chosen consist mainly of 6061-T6 aluminum and wood. The base was created from a half sheet of ¾” birch plywood. Plywood was the most economical and readily available material and provided the proper rigidity and weight necessary to support the main mechanism of the slotting machine.

As an added benefit, it provided a visually attractive appearance to the final product. The control panel was fabricated from ¼” plywood to allow the panel-mount HMI and control buttons to be installed. This structure was not load bearing, therefore the material properties were not a factor. The saw mechanism and main plate however needed to be able to span the 3’ width of the machine while remaining stable. Because rigidity was a major factor in the performance of the machine; 3/8” thick 6061-T6 aluminum plate was chosen for its lightweight properties, economic feasibility, machinability, and stiffness.

3.2.3. Fabrication

A majority of the components fabricated for this thesis were machined in-house by the researcher. Whenever possible, computer numerical controlled (CNC) machine operations were used to ensure proper dimensions and maintain specific hole locations. In this case, the Fryer MK 3300 vertical mill (Figure 3.4) was used as its accuracy is ±0.0001”. The main plate was machined on a larger Haas SR100 gantry sheet router (Figure 3.5) due to the size limitations of the Fryer MK3300 vertical mill.

Figure 3.4. The Fryer MK 3300 vertical mill used to machine precision pieces.

Figure 3.5. The top plate of the fret slotting machine is shown being machined on the Haas SR100 gantry sheet router.

A number of small components were machined on manual equipment when precision was not as necessary. These components were held to a ±0.005” specification limit. All of the fabricated aluminum components were outsourced to be anodized. The anodized finish provided a tougher exterior coating to protect against wear as well as provide an aesthetic uniform surface finish.

The extreme precision required for the saw blade arbor demanded tooling not available to the researcher. The arbor is the component of the machine needed to affix the saw blade to the shaft of the motor. This machining task was outsourced to a local machine shop to ensure the quality and safety needed for this particular component was accomplished.

3.2.4. Electrical Design

The premise of this thesis was to validate that a self-contained desktop fret slotting machine was possible. To accomplish this, the brain of the machine could not be a peripheral personal computer (PC). The most compact alternative solution was to use an industrial programmable logic controller (PLC). An Allen-Bradley Micrologix 1100 PLC (Figure 3.6) was chosen for its compact design, EtherNet readiness, and robust computing capabilities designed for the industrial environment.

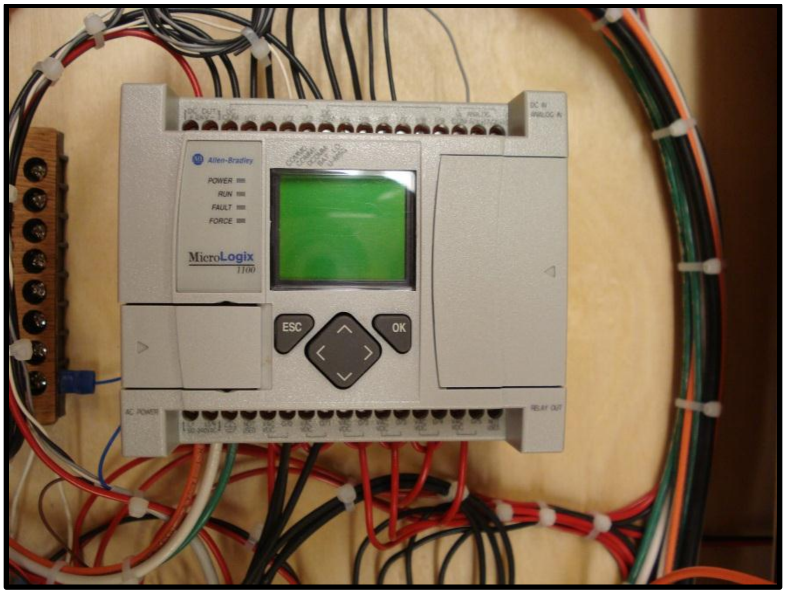

Figure 3.6. Allen-Bradley Micrologix 1100 PLC.

The PLC is, in its most basic form, an input/output controller. The Micrologix 1100 series offered ten digital input terminals, two analog input terminals, and six output relays. Larger industrial PLCs are available with more I/O capabilities, but the Micrologix 1100 was the best match for the application. Programmed with a language known as ladder-logic, the PLC is able to logically control inputs, and trigger outputs in accordance with the status of triggered inputs.

To facilitate a friendly user interface, the PLC was coupled with an Allen-Bradley PanelView C600 human machine interface (HMI) device, shown in Figure 3.7. This particular model boasts a 6” touchscreen monitor and EtherNet capabilities, making it a perfect match for the Micrologix 1100 PLC. This model also eliminated the need for complex programming software typically used to program such devices. The C600 connected via EtherNet to a PC and was programmed using internal programming software. This feature however does not sacrifice the functionality of the component when compared to its bigger brothers offered by Allen-Bradley. Once programmed, the PanelView HMI is connected directly to the PLC with the common EtherNet cable.

Figure 3.7. Allen-Bradley PanelView C600 monochrome human machine interface.

A stepper motor driver was sourced through Advanced Micro Controls, INC (AMCI). The PLC used in this application does not allow for expansion using Allen-Bradley stepper motor drivers designed for industrial applications. AMCI offers a solution with the SD17060E stepper driver designed specifically with the Micrologix 1100 PLC in mind (Figure 3.8). This device is also EtherNet-ready making communication simple. The operations are completely programmable and allow the user to incorporate stepper motor movement directly into the ladder logic program that controls the PLC. This stepper motor driver was coupled with the aforementioned AMCI stepper motor with built-in incremental quadrature rotary encoder. Both the stepper motor and encoder connected directly to the stepper motor driver and required no special adapters or additional programming. A feedback loop was pertinent to the precise linear position placement required by the x-axis of travel.

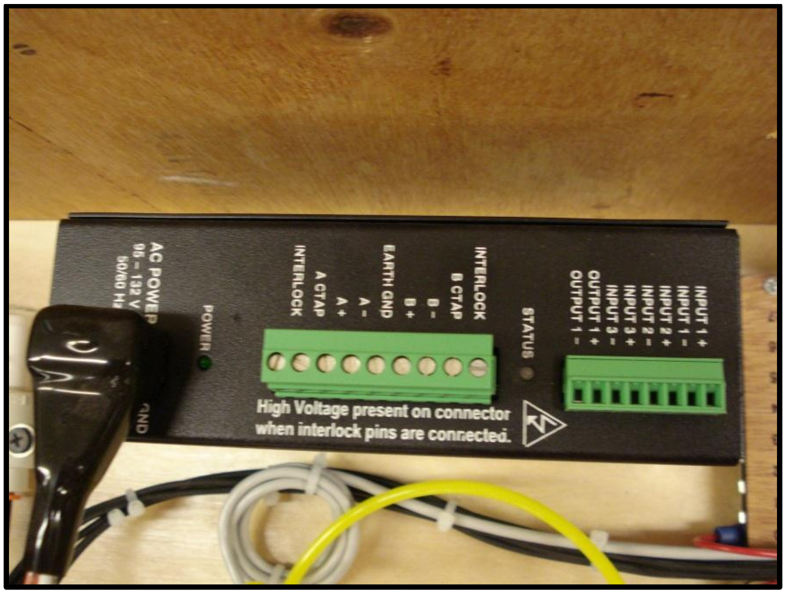

Figure 3.8. Advanced Micro Controls, INC SD17060E EtherNet-ready stepper motor controller.

Communication among these devices was essential. A non-wireless router was installed to accommodate the three EtherNet devices: The PLC, HMI, and stepper motor driver. Seamless integration of all three components meant multiple communication pathways would operate simultaneously. The router also allowed all three devices to be programmed by the same PC workstation.

Controlling the various inputs and outputs required a multitude of electromechanical devices. For the emergency stop circuit, hardwired Allen-Bradley push buttons were utilized to control a fail-safe method for halting machine operation. This allowed the user to mechanically isolate dangerous electrical equipment in the event of a catastrophic malfunction. Similar features were programmed into the HMI as a redundant form of machine control via PLC programming. The main saw motor and vacuum pump were controlled using 12VDC coil relays controlled by corresponding outputs on the PLC. These relays were also redundantly controlled by the mechanical buttons and HMI features to avoid an uncontrolled operation of the machine. The vacuum system consisted of three solenoid valves to control the direction and flow of the negatively pressurized system. Upon initialization of the slotting sequence, a vacuum pressure switch, programmed to activate only at a pre-programmed safe operating pressure, retarded the activation of the saw relay to ensure the fret board was securely fastened into the vacuum chuck before dangerous components were set into motion. In the event of an emergency stop, the vacuum table was allowed to remain under pressure in an attempt to retain the work piece firmly in the vacuum chuck.

3.2.5. Programming

The Allen-Bradley Micrologix 1100 was programmed using ladder logic within the RSLogix 500 software package. The program consisted of seven program files. The main program file handled basic system functions such as stepper driver communication, stepper driver configuration, homing procedures, manual jogging procedures, error resets, and basic machine operations. In order to use the absolute positioning capabilities of the stepper motor driver, the encoder needed to be preset to a home position. This was accomplished by enacting a manual jog procedure in the counterclockwise direction until the over-travel inductive proximity sensor was activated. This halted the movement of the machine and subsequently zeroed the machine to a home position. This home position naturally varies due to the reaction of the proximity sensor, but does not affect the overall functionality of the absolute positioning. Error resets were made available through the use of a physical push button located on the control panel. Basic machine operations, such as cylinder actuation and relay control, were established in the main program ladder.

Ladder programs two and three handled the calculations necessary to move the machine to each fret location using the scale length values sent to the PLC through the HMI. The function of these calculations will be discussed in section 3.2.6 of this thesis. These ladder programs were assigned to the handle both the chromatic and diatonic calculations, respectively and separately, in order to avoid inadvertent miscalculations. As each fret location was calculated, it was multiplied by 1000 and then moved to an internal integer register to be stored for later use.

Ladders five and six converted the integers created by ladders two and three to a format compatible with the AMCI stepper motor driver. The stepper driver reads what are called words, or 5-digit integers, that are used to control stepper motor position. Multiplying by 1000 in the previous ladder programs eliminated the decimal place created by the original calculation. The stepper reads these words in two parts: one for the 1000's place holder and a second for the 100's place holder. For example, the integer 14,564 would be split into two parts: 14 and 564. Ladder programs five and six perform the necessary mathematical operations required to split the integers created by ladders two and three. Once each integer is successfully split, an instruction moved the two parts of the integer to their respective locations within the internal PLC motion registers.

3.2.6. Music Theory Integration

Fret spacing on the neck of the guitar needs to be highly precise. Each fret is located at a calculated position that determines the frequency of a string after being plucked. According to French (2009), a guitar is tuned in a major chromatic scale, similar to that of a piano. The scale contains the following twelve notes: A-A$^{\#}$-B-C-C$^{\#}$-D-D$^{\#}$-E-F-F$^{\#}$-G-G$^{\#}$, of which any combination using all twelve in succession creates an octave. An octave, for example, is simply starting at note C, progressing twelve half-steps and arriving at the next higher frequency C. In the same respect, the spacing between each fret is also a half step, a common vocabulary term among musicians, which defines a progression from one note to another within the major chromatic scale. Additionally, two half steps create a whole step. It is the specific combination of whole steps and half steps that create the key of the scale being played by the musician (French, 2009).

In the simplest form, each note is founded on a specific frequency. Doubling the frequency of any given note will produce the same note, but one octave higher. This relationship is known as a frequency ratio, or more simply, the new frequency divided by the original frequency (French, 2009). As stated above, the progression of twelve half steps also produces the same note, but one octave higher. Therefore, one can deduce that by moving twelve frets on a fret board, the frequency doubles producing a note a single octave higher than the original. Due to this phenomena, it can be stated that the frequency ratio, r, is doubled by the twelfth half step. Because of this relationship, the value of r can then be derived by taking the twelfth root of 2. The resulting value for r is approximately 1.05946 (Fletcher & Rossing, 1991). This value is essential for calculating the position of frets in accordance with the scale length. The equation below was used to determine individual fret locations, where d_n represents the distance from the nut to the nth fret, L represents the scale length, and r^n represents the frequency ratio of nth fret.

$$d_n = L\left(1 - \frac{1}{r^n}\right)$$

In order to simplify the mathematical calculations required within the PLC program, the researcher calculated a portion of the equation above for each fret. The equation was broken into its respective parts and calculated in Microsoft Excel. Table 3.1 below shows these calculations for a 25.5” scale length. Performing these calculations in another program simplified PLC programming as the only calculation remaining was to multiply $(1\text{-}1/r^n)$ by the scale length L. When a user entered a scale length through the HMI, the calculation was done automatically through the ladder programs two and three. The example in Table 3.1 represents d_n for a 25.5” scale length only. Keep in mind that the machine was set up to calculate this value for any scale length chosen by the user.

Table 3.1. *Fret location calculations* (d_n) *for a 25.5” scale length fret board.*

r^n	Fret n	$(1\text{-}1/r^n)$	d_n for L=25.5”
1.05946	1	0.05612	1.43113
1.12246	2	0.10910	2.78195
1.18920	3	0.15910	4.05695
1.25991	4	0.20629	5.26040
1.33482	5	0.25084	6.39631
1.41419	6	0.29288	7.46846
1.49828	7	0.33257	8.48044
1.58736	8	0.37002	9.43563
1.68175	9	0.40538	10.33721
1.78175	10	0.43875	11.18819
1.88769	11	0.47025	11.99141
1.99993	12	0.49998	12.74955
2.11885	13	0.52804	13.46515
2.24483	14	0.55453	14.14058
2.37831	15	0.57953	14.77810
2.51972	16	0.60313	15.37985

Table 3.1. (Continued) *Fret location calculations* (d_n) *for a 25.5" scale length fret board.*

r^n	Fret n	$(1-1/r^n)$	d_n for L=25.5"
2.66955	17	0.62540	15.94782
2.82828	18	0.64643	16.48391
2.99645	19	0.66627	16.98992
3.17462	20	0.68500	17.46753
3.36338	21	0.70268	17.91834
3.56337	22	0.71937	18.34384
3.77524	23	0.73512	18.74547
3.99972	24	0.74998	19.12455

The machine has two available functions: to produce both chromatic and diatonic fret boards. At this point, only the chromatic version has been covered. To reiterate, the chromatic scale consists of twelve half steps. The diatonic scale, used to create instruments commonly referred to as dulcimers, utilizes the same equation as the chromatic however specific frets are omitted. Returning to the twelve half steps that create the chromatic scale, chords are created using simple recipes of combining individual portions of this chromatic scale. The most common, and the type used for the dulcimer guitar, is known as the major scale (French, 2009). The major scale is constructed by using the following formula:

Whole Step
Whole Step
Half Step
Whole Step
Whole Step
Whole Step
Half Step

This formula is used to create chords, and is the basis for the layout of the dulcimer's fret board. Unlike the standard chromatic fret board, which is comprised of twelve half steps, the dulcimer omits frets that are not in conformance with the major scale recipe. In accordance with tradition, the six-and-a-half fret is left in place to allow for a more diverse sound preferred by musicians.

3.3. Experiment

An experiment was conducted to verify that the machine built for this thesis was accurate enough to place fret slots in their correct locations. The following section will analyze the set-up and data collection methods for the experimental portion of this thesis. It will cover the metrology equipment and the methods used to collect accurate measurement data.

3.3.1. Experimental Set-up

In order to determine functionality, an experiment was conducted to measure fret slot locations. The researcher produced five raw fret boards measuring 20.5” x 2.75” x 0.25” (L x W x H). Each fret board was machined using a scale length of 25.5”, a common scale length used in industry for electric guitars. The fret slot being machined measures roughly 0.023” wide and 0.125” deep. The five fret boards were machined consecutively in an attempt to reduce the possible environmental factors that could affect the physical properties of the wood. The finished fret boards where then placed into a vice on a manual vertical milling machine, and squared using precision-ground parallels. The digital read-out of the machine, accurate down to 0.0002”, was zeroed to the leading edge of the slot machined for the nut. From this point, using a dial indicator as a feeler gauge, the x-axis of the milling machine was traversed until the dial gauge rested within a fret slot. The position of the machine head, as indicated by the digital readout, was recorded as the location of the first fret slot. This routine was repeated until the 24th fret slot was measured. It is important to note that this system of measurement was solely relative to the location of the nut, not relative to the previous fret. This method avoided compounding any present errors.

3.3.2. Data Collection

The researcher recorded data by hand in an attempt to remain unbiased to either the theoretical or previously recorded fret slot locations. A new sheet of paper was used for data collection of each fret board’s measurements. The machine is capable of measurement resolutions down to 0.0002”; therefore the slightest movements in either direction can cause rather significant measurement changes. If these previous data values had been present and visible, it could have been possible to sway results in the most beneficial direction in order to match the theoretical values. This “blind” method of measurement ensured that the measurements taken were not influenced by outside factors and researcher bias. The data collected was then entered into a Microsoft Excel spreadsheet for further analysis.

CHAPTER 4. PRESENTATION OF DATA & FINDINGS

4.1. Basic Statistics

For the study, a total of six fret boards were produced using a 25.5” scale length. The third fret board produced was used in a destructive test to determine whether or not the fret slots were reaching their correct depth. Since the z-axis of the machine was fixed, it was important to determine that the correct depth was being achieved. Therefore, data was only collected on the remaining five fret boards. Once the data had been recorded and transferred to Microsoft Excel, a barrage of basic statistical tools was utilized to obtain a generalized view of the data set recorded for the fret board measurements. Standard deviations of each of the samples for the individual fret slots were the first of the analytical tools employed in this study. Of the five observations for each sample of individual fret locations, the averages were recorded. This was used to calculate the percent error for the average of each fret location sample taken. Table 4.1 below depicts this information.

Table 4.1. *Percent error calculations for individual fret by sample.*

Fret	Standard Dev.	Average	% Error of Averages
1	0.008	1.425	0.412
2	0.007	2.780	0.063
3	0.009	4.052	0.131
4	0.006	5.254	0.119
5	0.008	6.390	0.099
6	0.006	7.461	0.093
7	0.005	8.469	0.135
8	0.003	9.428	0.083
9	0.005	10.328	0.087
10	0.006	11.179	0.079
11	0.006	11.981	0.083
12	0.004	12.745	0.033
13	0.006	13.452	0.099
14	0.008	14.134	0.049
15	0.005	14.763	0.099
16	0.005	15.370	0.062
17	0.003	15.938	0.064
18	0.005	16.477	0.042
19	0.005	16.979	0.066
20	0.006	17.460	0.044
21	0.006	17.913	0.031
22	0.004	18.337	0.040
23	0.007	18.734	0.060
24	0.004	19.118	0.037

While this information does not indicate the capability of the machine to produce a fret board to the theoretical dimensions, it does however display that the machine is capable of reproducible results. To provide means for comparison, a human hair is approximately 0.003” in diameter as measured by the researcher. Further statistical testing was required to determine if the results were centered on the theoretical values. At first, a simple scatter plot with connecting lines was created in Excel to see how well the measured values matched with the theoretical values. This plot is depicted in Figure 4.1 below.

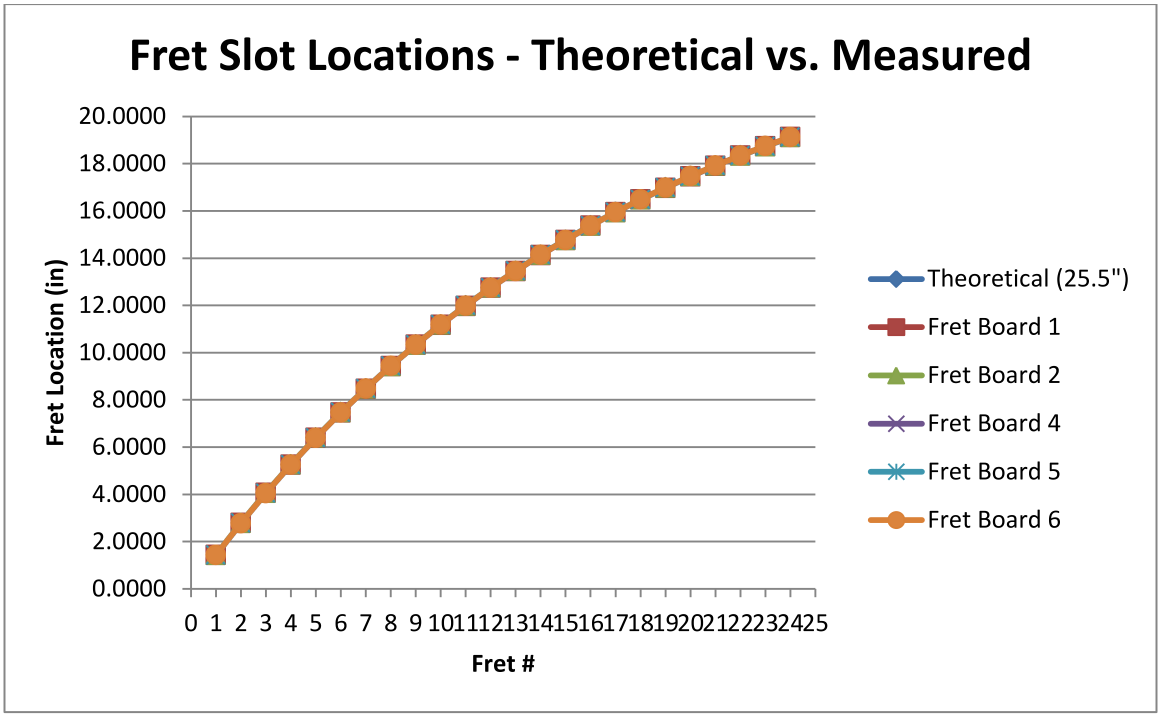

Figure 4.1. Fret slot locations graphed using a scatter plot with connecting lines. This figure was used to determine trends of measured values compared to theoretical values.

As one can decipher from the scatter plot, it was difficult to determine any statistical significance as to the spread of the data. The graph did, however, offer insight into the fact that the fret boards are extremely similar and error did not seem to compound as the length of travel grew. Each fret board seemed to follow the theoretical value to completion. In order to detect more detailed deviation, another scatter plot was created from the median of the measured fret locations and compared to the theoretical fret locations. This plot is shown below in Figure 4.2.

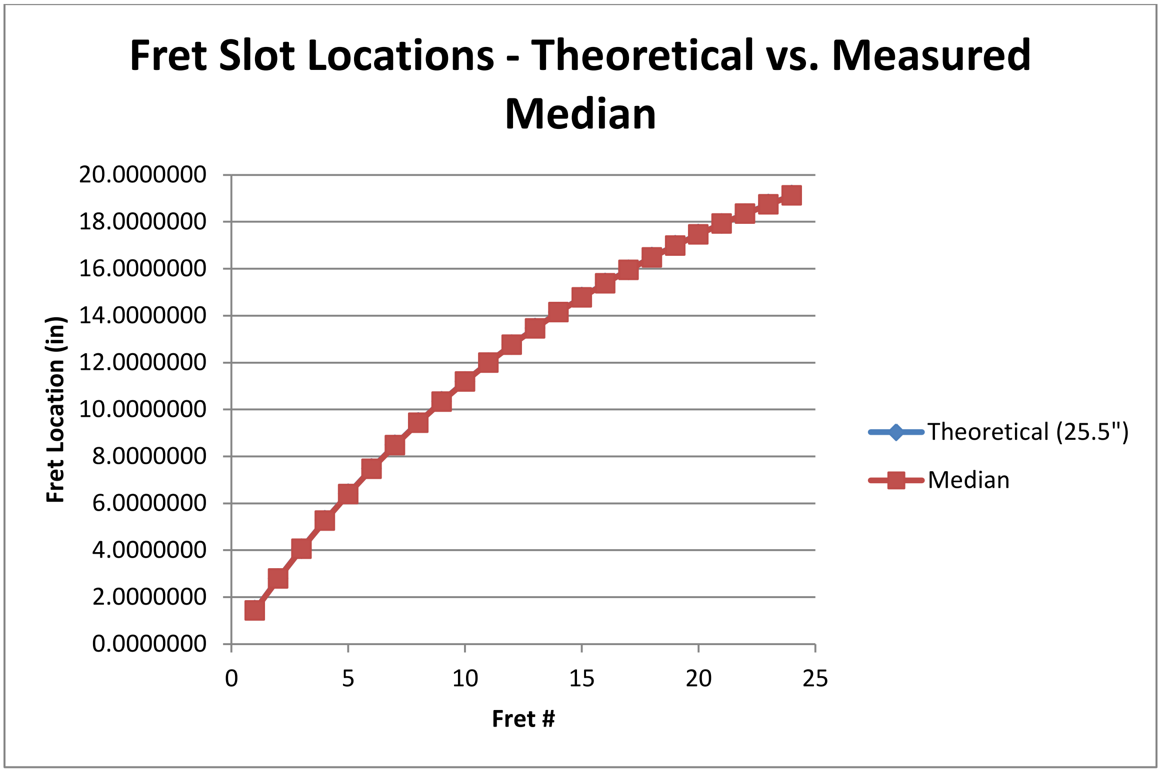

Figure 4.2. The theoretical fret slot locations were compared to the median values of each recorded sample.

Again, the differences between the theoretical and measured median values were difficult to decipher. At this stage, it was evident that more in-depth statistical analysis was required to either confirm or deny the functionality of the fret slotting machine.

4.2. The Normal Quantile Plot

Moore, McCabe, and Craig (2009) stated that the normal quantile plot is "the most useful tool for assessing normality" (p.68). While the researcher conducted this statistical analysis automatically using the SAS 9.2 software package, the normal quantile plot, also known as the QQ plot, is typically constructed by first arranging the observations in a sample from smallest to largest. Each sample observation in this ordered list represents the percentiles of the data set respectively. The z normal scores were calculated for each of the corresponding percentiles. These z-values are then graphed along with their corresponding measured values to create the QQ plot (Moore, McCabe, & Craig, 2009). If the data were collected from a normal distribution, the QQ plot will result in a straight line. For the application of this research, three QQ plots were formed from the data. Due to the fact that the initial statistical analysis showed that the fret slotting machine produced repeatable cutting operations, QQ plots were produced using the samples for the first, twelfth, and twenty-fourth frets. This ensured that the first, middle, and last measurements were taken from a normal distribution of data. As expected, the QQ plots returned favorable results and further statistical analysis could continue.

4.3. One-Sample t-Test

The next step of statistical analysis was to determine whether or not the collected fret location data was significantly different from the theoretical fret locations. The following hypotheses were tested:

H_o - There is no significant difference between the theoretical values of fret location and the measured values of fret location.

H_a - There is a significant difference between the theoretical values of fret location and the measure values of fret location.

Determining the results of this hypothesis was accomplished using a one-sample t-test. In order to test significance, an alpha value of 0.001 was chosen. This ensured that there is only a 0.1% chance of detecting that the fret slotting machine was accurate enough to produce a quality fret board. Using Minitab, the one-sample t-test was conducted on each of the fret location samples. The results of this test are detailed in Table 4.2 below.

Table 4.2. *One-sample t-test results and hypothesis test.*

Fret	**p-value**	**α**	**Accept H_o**
1	0.185	0.001	Yes
2	0.608	0.001	Yes
3	0.276	0.001	Yes
4	0.077	0.001	Yes
5	0.154	0.001	Yes
6	0.050	0.001	Yes
7	0.008	0.001	Yes
8	0.003	0.001	Yes
9	0.019	0.001	Yes
10	0.027	0.001	Yes
11	0.023	0.001	Yes
12	0.064	0.001	Yes
13	0.007	0.001	Yes
14	0.117	0.001	Yes
15	0.003	0.001	Yes

Table 4.2. (Continued) *One-sample t-test results and hypothesis test.*

Fret	**p-value**	**α**	**Accept H_o**
16	0.015	0.001	Yes
17	0.003	0.001	Yes
18	0.039	0.001	Yes
19	0.007	0.001	Yes
20	0.048	0.001	Yes
21	0.100	0.001	Yes
22	0.010	0.001	Yes
23	0.019	0.001	Yes
24	0.023	0.001	Yes

The choice of whether or not to accept the null hypothesis stems from the relationship of the p-value to the alpha value. If the p-value is greater than the alpha value, the null hypothesis that there is no significant difference between the measure values and the theoretical values exists can be accepted, and vice versa if the p-value is less than the alpha value. Based off of the results of this one-sample t-test, the researcher concluded that the fret slotting machine was more than capable of producing a quality fret board within the acceptable limits of the theoretical values, as is evident by the results.

CHAPTER 5. CONCLUSIONS, DISCUSSION, & RECOMMENDATIONS

5.1. Conclusion

The research of this thesis was aimed at the creation of a CNC machine capable of machining fret slots into the neck of the guitar. The project was deliberately constrained to limit the size of the machine to a 3’x2’x2’ physical envelope while retaining the functionality and proper motion flexibility to accurately machine fret boards. In addition, the machine was to remain self-contained and independent of peripheral equipment to allow for mobility. This was designed to allow for use in any environment with access to 120VAC electricity. To accomplish this, the machine needed to be independent from a PC workstation and compressed air supply, and remain small enough as to not inhibit valuable work space. An Allen-Bradley Micrologix 1100 PLC was used as the processor for the unit. A vacuum pump was installed within the machine to provide suction for the vacuum chuck and cylinder actuation. This feature eliminated the need for an external compressed air source. Its compact design and robust operation enabled the machine to operate autonomously.

The fabrication of the machine was done almost entirely in-house. Only two components were outsourced due to work piece size limitations and safety factors. To support the gantry, a plywood base was constructed to house the electronics and vacuum system. The gantry components themselves were fabricated from 6061-T6 aluminum. Aluminum possessed the most favorable physical properties for the application due to its machinability, low density, and structural rigidity.

Machine operations were programmed using the RSLogix 500 software package and the program was written using ladder logic. The PLC program for the machine controlled all of the basic machine functions, stepper driver communications, and calculated fret locations based off of user input through the Allen-Bradley PanelView C600 HMI.

The end result allowed the machine to cut both chromatic and diatonic scales, depending on user preference. The chromatic scale option machines twenty-four fret slots, equal to two octaves, where each fret slot translates to a half step on the chromatic scale. The diatonic scale option was added to allow for the creation of dulcimer style instruments. The diatonic scale omits frets in accordance with the major scale, but is founded on the same equation as the chromatic scale. Both scales allow for user-defined scale lengths limited by the capabilities of the machine.

5.2. Functionality

Upon completion of the physical and electrical systems, an experiment was conducted to validate the functionality of the machine. Five fret boards were produced using a 25.5” scale length. These fret boards were mounted into a manual vertical mill. Fret locations were located using a dial indicator and measured using the digital readout of the machine. This allowed for measurement accuracy on the order of 0.0002”. Statistical analysis was conducted using Excel, Minitab, and SAS version 9.2. Basic statistical analysis was completed using Excel functions. Once validated at the basic level, more advanced analysis was conducted using Minitab and SAS. SAS was used to confirm the normality of the data. The results permitted further analysis using a one-sample t-test within Minitab. An alpha value of 0.001 was chosen as the significance level for the hypothesis test. A comparison with the Minitab one-sample t-test output concluded that the fret locations machined were not significantly different than the theoretical fret locations. Figure 5.1 below was used to draw conclusions from the observed operation of the machine. The maximum recorded deviation from theoretical fret locations was around 0.020”. As well, oscillations are evident for each of the fret boards produced. It was concluded that these oscillations were attributed to faulty mounting mechanism for the saw blade. As indicated by the statistical analysis, the machine performed exceptionally well and was proven to be more than capable of producing a quality fret board.

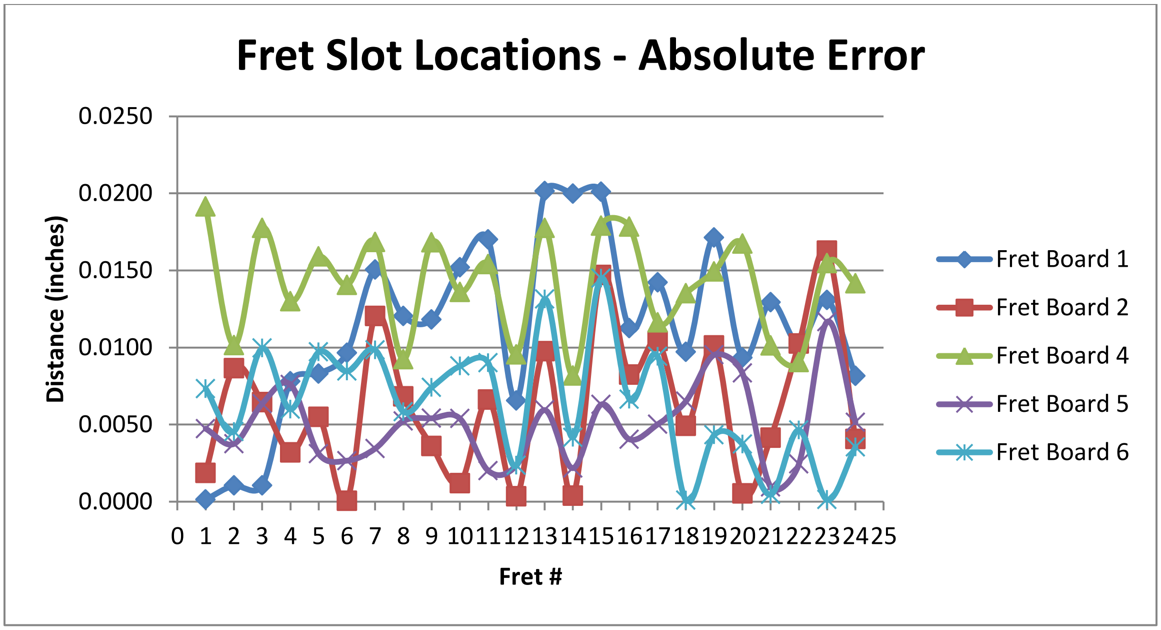

Figure 5.1. The absolute error for each fret board is shown graphically.

5.3. Economic Feasibility

Part two of this study was to determine whether or not the production of this machine would be feasible in the consumer market. With an initial $2500 dollar budget for materials, the theoretical retail price would range near $5000 dollars. This put the fret slotting machine in the same price range as other common woodworking equipment necessary for the production of stringed instruments. It would be reasonable to assume that functionality of this machine would allow it to be considered an invaluable addition to the average consumer home workshop. However, by utilizing the industrial equipment required to make this machine robust and self-contained, the real price of raw materials skyrocketed to just over $4000 dollars, not including the labor required to machine critical components as these tasks were performed by the researcher. As a result, the economic feasibility for the consumer market plummets to a very select niche of artisans. For the small scale production facilities and full blown industrial environments, this machine could still be considered a worthwhile investment, although no in-depth market research was investigated as a component of this research topic. Thanks to a generous donation on behalf of Advanced Micro Controls, INC, the research topic was allowed to continue under the sole funding of the research budget allotted to the researcher.

5.4. Future Work

Industrial controls greatly inflated the cost to build the fret slotting machine. While the equipment is robust and industry proven, the feasibility as a low cost control system is unrealistic. Future work could entail adding a PC workstation to replace the PLC and HMI, and could include lower grade stepper motors and drivers designed for non-industrial applications. Doing so could cut the cost of production by at least fifty percent.

The weakest link of this machine was the vacuum pump. A few minor oil leaks during testing raised concern that the vacuum pump is housed in the same area as sensitive electronics. This flaw was attributed to poor design of the pump. The given application required a more robust pump that could handle the constant run-time. As a replacement, a Venturi style pump could be used as they do not have moving parts. These pumps, however, require an external compressed air source. While this defeats the notion that the machine remains self-sufficient, it would greatly reduce the risk of either mechanical or electrical failure of the rest of the machine.

A provisional patent is planned to be obtained for the design and operation of this particular fret slotting machine. Due to these desires, the PLC programming and dimensioned engineering drawings were intentionally left out of this thesis.

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