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5-axis Milling for Micro-machining of Implantable Flow Sensor

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5-axis milling for micro-machining of Implantable Flow Sensor

An Honors Thesis Submitted to the Department of Biomedical Engineering, University of Connecticut, in Partial Fulfillment of the Requirements for the Bachelor of Science Degree in Biomedical Engineering with Honors

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Abstract:

5 axis milling is a manufacturing process utilizing CNC technology. It has been widely supported as an effective tool for micro machining throughout multiple industries. In medical manufacturing specifically, there is a large demand for high accuracy at the microscale level as the geometries of medical devices are often highly complex. 5-axis milling offers the means to develop such complex features including curved faces and steep walls. This thesis covers the conversion of a generic 3-axis milling machine into a 5-axis machine. Through testing, the modified device effectively demonstrated its ability to run 5-axis tool paths required for complex designs. As it is still in the development stage, errors in the generated machine code highlighted disagreement between the CAM software and machine geometries which will be addressed in the future. The thesis provides insight into the practicality of modifying a generic 3-axis milling machine into a 5-axis milling machine. With many applications including the machining of a Senior Design team's implantable sensor, 5 axis mills such as the one developed in this thesis are clearly effective tools for medical device development.

Introduction:

Numerical control (NC) machine tools are mechatronics devices that are frequently used in manufacturing. One category of such machines is “cutting NCs”. These machines remove material from a stock to form a finished product. The use of computers in conjunction with NC machines allows for commands to activate motors through motor drives and control the movement of the toolpath. This combination of technologies is known as Computerized Numerical Control or CNC.

This thesis focuses on CNC milling machines, specifically the addition of rotary axes beyond the traditional linear XYZ scope. There are three potential rotary axes that can be included on milling machines. These are the A, B, and C axes **Fig 1**.

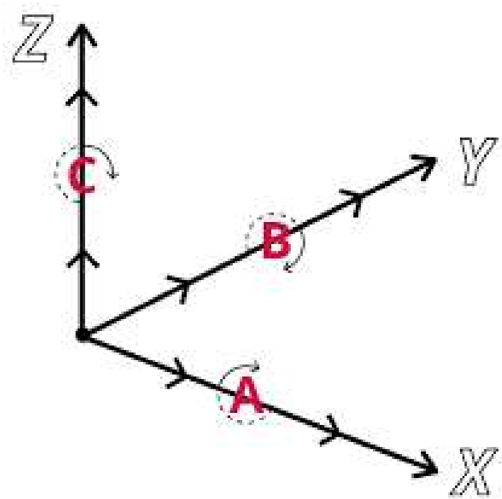

Fig. 1. Linear and rotary axes

The A axis is rotation around the X axis, the B axis is rotation about the Y axis, and the C axis is rotation about the Z axis. The addition of these rotary axes is advantageous in several ways. For example, a common issue in CNC milling fabrication is determining the exact zero coordinate of the model in correlation with the machine. This step is vital in the accuracy of the fabrication process and to avoid crashing any axes. For designs

that require milling on several faces, the part must be re-clamped and the zeros must be set yet again before continuing the milling process. This vastly increases the time of fabrication and the chance for potential error. The avoidance of these complexities along with the added benefit of fast material removal rate and improved surface finish are perhaps the most obvious advantages of 5-axis milling. Another perhaps less discussed advantage of 5-axis CNC technology is in the manufacturing of spatially complex geometries. Often, more complex toolpaths can be generated that allow for these geometries to be fabricated without manual readjustments and frequently traditional 3-axis milling may not allow for the fabrication of certain contoured surfaces. This is often a result of the toolpath being forced to interpolate spatial locations leading to inaccuracies and often failure in the reproduction of complex geometries [1].

Many scientific fields rely heavily on the ability to fabricate complex devices. Often there is an additional need to minimize the footprint of these devices which further complicates the fabrication process. A common manufacturing technique for such a fine level of detail is etching. Etching is the reductive fabrication process in which layers of material are selectively removed. Etching can frequently be categorized as either Wet or Dry. Wet etching involves selective removal of material by immersing it in a chemical solution which will lead it to dissolve. Dry etching is similar but uses reactive ions or a vapor phase etchant to remove material [2]. A limitation of Etching is that it is a strictly 2D fabrication process. The manufactured product is solely the result of using a protective mask on different areas of the stock during each reduction stage [1]. These structures will have depth and dimension but not curved surfaces indicative of a 3D manufacturing process. This is unfortunate as curved surfaces are necessary in

microfluidics and micro sensing applications. And etching is an established and affordable manufacturing technique for micro and nano scale devices. Herein lies the potential of using 5-axis micro machining.

Introduction 1.1: Implantable Flow Sensor

The work done in this thesis was to investigate 5-axis milling as a manufacturing technique for biomedical devices. This study considered the steps in machining a miniature fluid sensor by a Senior Design team as well as other micro and nanoscale manufacturing research studies. The need for this design is due to the frequency of malfunction in current Hydrocephalus shunts.

Hydrocephalus is a disease affecting the ventricles within the brain. This disease leads to the buildup of cerebrospinal fluid within these cavities creating extreme levels of pressure. In a healthy functioning body cerebrospinal fluid will flow normally through the ventricles providing cushioning to the brain and removing waste. This disease can occur for a number of reasons including obstructions in the ventricles, poor absorption, and overproduction. It most frequently occurs in infants and adults over 60. For infants, complications with the birthing process can frequently lead to the development of Hydrocephalus. These include: abnormal development of the central nervous system, bleeding within the ventricles, and infection of the uterus during pregnancy. For older age groups, tumors of the brain or spinal cord, central nervous system infections, or stroke can all be contributing factors. The method of most commonly treating Hydrocephalus is implanting a shunt for directing cerebrospinal fluid from the ventricles to the abdomen or heart where the fluid can be easily reabsorbed. These shunts consist

of 2 long flexible tubes and a one way valve to direct flow. This simple design is effective but requires frequent monitoring due to mechanical problems, blockage and infections [3].

The goal of the Senior Design team was to develop a not intrusive implantable device that could transfer data on cerebrospinal fluid flow rate within the shunt to an externally monoritable device. The SolidWorks design of the proposed flow sensor can be seen in **Fig 2.**

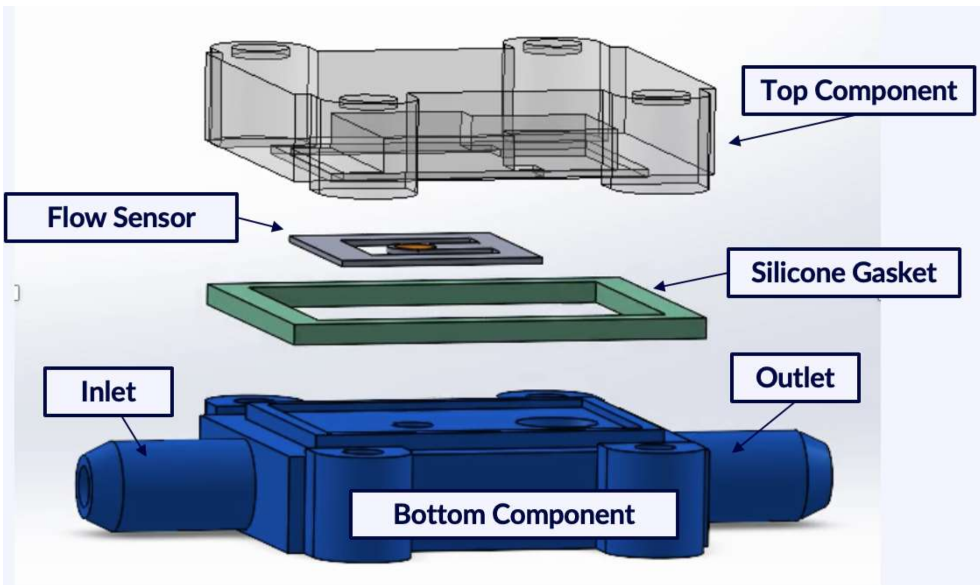

Fig. 2. SolidWorks design for the implantable flow sensor

In the Materials and Methods section, the mechanistics of the device as well as considerations during the milling process will be discussed. As can be seen, the design is 2 parts with geometrically complex cylindrical components. In a typical 3-axis milling machine, the only way to create this component is by manually re-clamping the workpiece twice. Obviously, this is extremely inefficient and adds a lot of potential for error in the manufacturing process. The purpose of this study is to examine the potential of 5-axis milling to improve efficiency and ease of manufacturing on biomedical devices

such as this. A general approach to developing a 5-axis milling system will also be examined.

Another study demonstrating the utility of 5-axis milling in medical sciences: *Comparison of 3-D Printing and 5-axis Milling for the Production of Dental e-models from Intra-oral Scanning, Yau et al.,* discusses the scope of orthodontic manufacturing.

Dentures, implants and orthodontic products are often unique to the individual and are quite complex in geometry. Additionally, they require a high degree of accuracy ~0.01-0.02 mm. For these reasons, orthodontic manufacturing is a challenging process that has been steadily improving over time. With the advancement of 3D-scanning and computer graphics technology, manufacturing of dental products has moved away from traditional impression models. CAD models from 3D-scanning can be produced quickly and with a high level of accuracy. From here CAM software can develop a manufacturing solution.

This study used 3D scans from a case study concerning an internal premolar rotation. Orthodontic planning software was used to generate 8 continuous steps in the correction process. These models were manufactured using both 5-axis milling and 3D-printing, another technology with increasing popularity in medical manufacturing. The results of working models were compared with the planned models for error analysis **Fig 3.** and **Fig 4.**

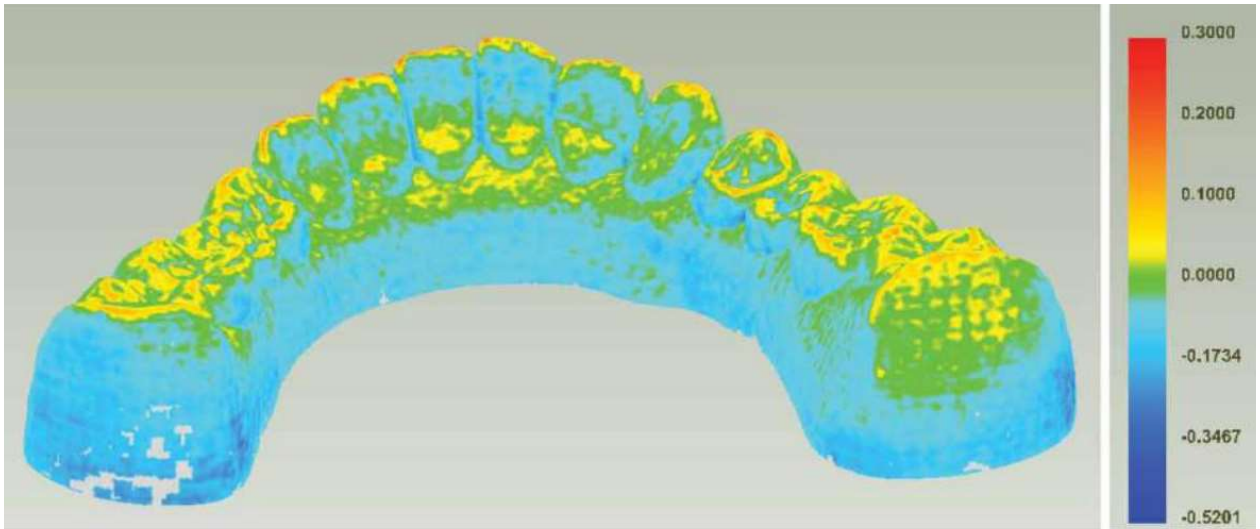

Fig 3. Error between 3D printed model and planned model [4]

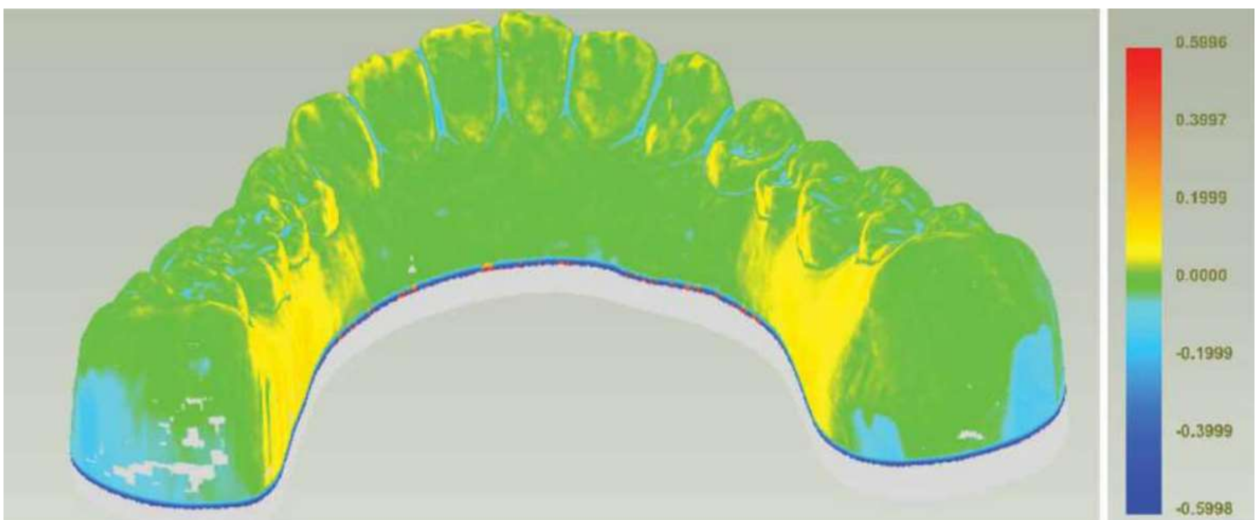

Fig 4. Error between 5 axis milled model and planned model [4]

As can be seen, the degree of error found in 5-axis machining models was significantly less that found in 3D printing models. 5-axis machining was shown to have smoother surface quality in the steep and curved areas of the crown portion. 3D printing on the other hand suffers from the formation of a stepped surface during fabrication.

This study provides further evidence towards the importance of 5-axis machining in medical manufacturing due to its high level of precision and accuracy when creating complex geometries [4].

Materials and Methods:

Materials and Methods 1.1: Custom 5-Axis Milling Machine

The goal of developing a 5-axis milling machine was to gain an understanding of how CAM software, control software, and the physics of motorized rotary axes interact to perform complex surface machining tasks.

The examination of 5-axis milling began with converting a standard 3-axis mill into a 5-axis machine as a proof of concept. This served as a method of testing how practical and perhaps how simple the addition of an axis is to a machine. Understanding the required steps to get these additional axes working with the rest of the machine is necessary to understanding 5-axis milling. These are important considerations when using a 5-axis milling machine as the manufacturing solution to complex scientific designs.

Additionally, the Hydrocephalus flow sensor discussed in the Introduction section was manufactured using a 3-axis Roland milling machine. Observations were made on the limitations of 3-axis milling for complex geometries and the potential for a 5-axis toolpath for this design was considered.

The standard 3-axis mill after assembly can be seen in **Fig 5.** As can be seen, it consists of the frame, a XZ-axis spindle, and Y-axis table. It came with a control board that had built in drivers for 3 axis and an on/off relay for the spindle. Obviously this board was too simplistic for 5 axis machining and a board with more flexibility was

needed. The PoKeys57CNC was chosen for this task **Fig 6.** The primary purpose of this device is to control up to 8 STEP/DIR signal-driven motors. It came equipped with 8 dedicated connectors for the motor drivers, pendants, a galvanically-isolated 0-10 V analog output and much more [5].

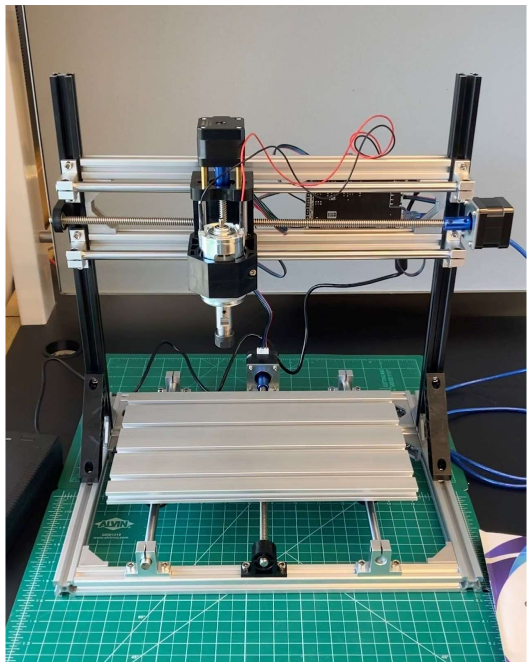

Fig 5. Generic 3 axis milling machine

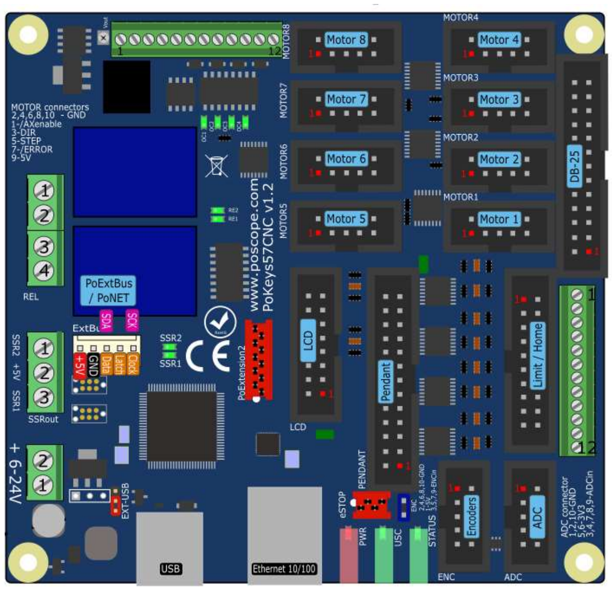

Fig 6. Pokeys 57CNC control board pinout

In order to control the PoKeys57CNC, a compatible CNC software package was needed. Mach3 was chosen due to its flexibility, popularity, and overall utility. Mach3 allows a typical computer to function as a 6-axis CNC machine controller with a fully customizable interface and G-code display. Its 2 primary functions are to communicate with the firmware controller and to process G-code [6]. In order to set up PoKeys57CNC with Mach3, there are a few configuration changes that need to be made. PoKeys has a software plugin specifically designed for compatibility with Mach3. This has to be downloaded and moved to Mach3's plugin folder. This will allow Mach3 to recognize the PoKeys57CNC through a USB connection during launch. Once Mach3 is connected to the Pokeys57CNC the plugin must be configured to jog the motors of the system. First, within Mach3 Ports & Pins, the Motor Outputs can be enabled for all required axes. This allows the external pulse generator ie. Pokeys57CNC to generate pulses on motor driver connections 1-6.

Next, the motors must be tuned to the correct steps/mm to ensure they are traveling the correct distance per rotation of the lead screw. This can be found manually or using Mach3's built in calibration setting. To find the correct steps/mm manually we need to know the specifications of the lead screw for that axis. Specifically we need to know the millimeters traveled along the length of the lead screw per revolution. This is known as the lead dimension of the lead screw, in the specifications. An important detail to keep in mind is that as the lead screw increases in threads the lead will become larger than the pitch or distance between threads. This can be seen in **Fig 7.**

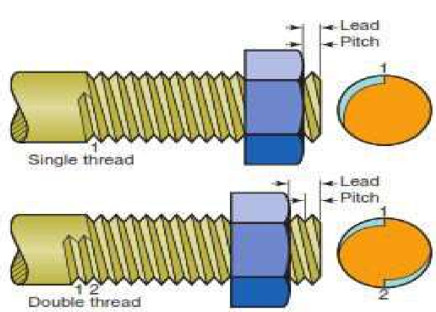

Fig 7. Lead and Pitch of Single and Double Threaded lead screws

Before calculating the correct motor tuning, some information on the motors themselves is needed. It is necessary to know the steps per revolution and microstep setting of the motor. Steps per revolution is determined by the number of rotor teeth which is typically 200. The full 360 degrees of rotation are divided evenly between these rotors by 1.8 degree full step angles. In this full step mode both coils are energized and current is reversed alternately. This leads to the rotation of one rotor to the next. For applications that require accurate positioning and smooth motion it may be necessary to further divide the number of steps per rotation. This can be achieved using a method that controls the current in the motor winding further subdividing the locations between poles. It should be noted that microstepping comes at the cost of reduced torque [7]. Our motor drivers, PoStep25, came with options for half-stepping, ¼ stepping, ⅛ stepping, and 1/16 stepping. With this information we can now calculate the correct motor tuning using **Eq 1.**

$$steps\ per\ mm\ =\ (steps\ per\ revolution \times microsteps)/\ lead\ of\ lead\ screw\ \ -\ (1)$$

Alternatively, the Mach3 calibration setting can be used. In this method, the desired distance or angle of an axis is entered and the actual distance/angle is measured. This value is reentered and Mach3 will calibrate accordingly. The last step in motor tuning is to adjust the acceleration and velocity. This process is done graphically as seen in **Fig 8.** and is a bit of a test and adjustment process. It is desirable to have the motor accelerate quickly to a desired feed rate while not losing torque and creating error.

Once the stepper motors are wired to the drivers, Pokeys57CNC must be switched from USB power to an external power supply to generate enough current. To use a power supply the red jumper must be moved from the USB pins to the external

power pins. From here the axes can be jogged and it is time to set a machine home. This step is vital in order to avoid crashes by ensuring all the axes are moving in conjunction with each other to the correct location in the work coordinate system. It will also provide a reliable method of resetting the machine if something goes wrong. In order to understand the positioning behavior of the mill it is important to understand the difference between the 2 coordinate systems.

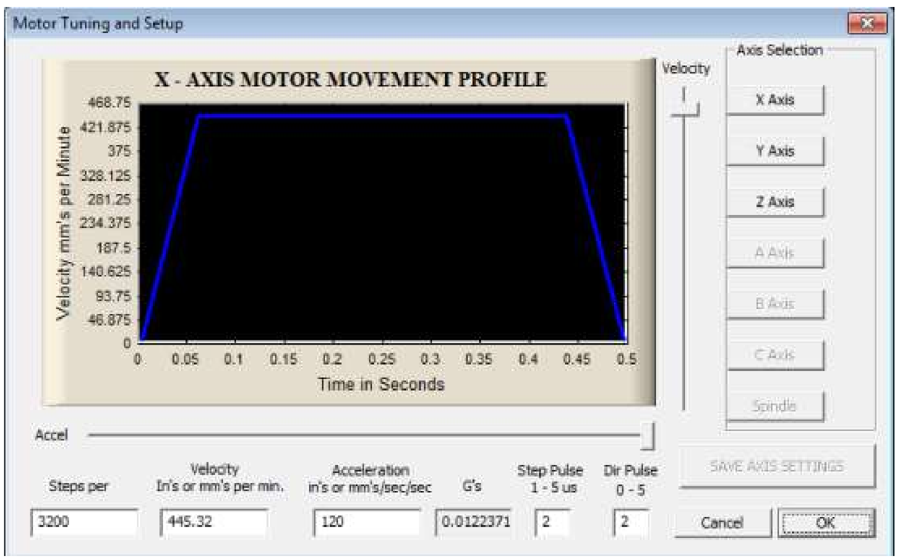

Fig 8. Motor Tuning User Interface Mach3

The 2 most important coordinate systems to consider when it comes to milling are the Work Coordinate System and the Machine Coordinate System. The Work Coordinate System defines a coordinate system relative to an origin which is offset from the Machine Coordinate System. In G-Code, these coordinate systems can be assigned to offset registers G54-G59. These registers will hold the value of the Work Coordinate Systems origin in relation to the origin of the Machine Coordinate System. The Work Coordinate System is assigned by jogging the machine to the zero position of the toolpath in relation to the stock. In this way the CNC can execute a toolpath and

accurately carry out the design by using the Work Coordinate System offset to the Machine Coordinate System. It is vital to find the exact offset origin for an accurate milling procedure. As previously mentioned, when designing a CNC it is vital to have a homing procedure. The Machine Coordinate System allows us to do just this. A zero origin is set for all the machine's axes, usually at the minimum distance for linear axes and the zero angle position for rotary ones. This position is the origin of the Machine Coordinate System. The machine will often move to this position when a homing switch is triggered [8]. It is important to not to run a toolpath in the Work Coordinate System after changing the Machine Coordinate System as it will not recognize the correct offset and the machine will crash.

In order to set homing/limit switches, for the CNC machine, physical sensors must be declared in the Pokeys plugin. In **Fig 9.**,

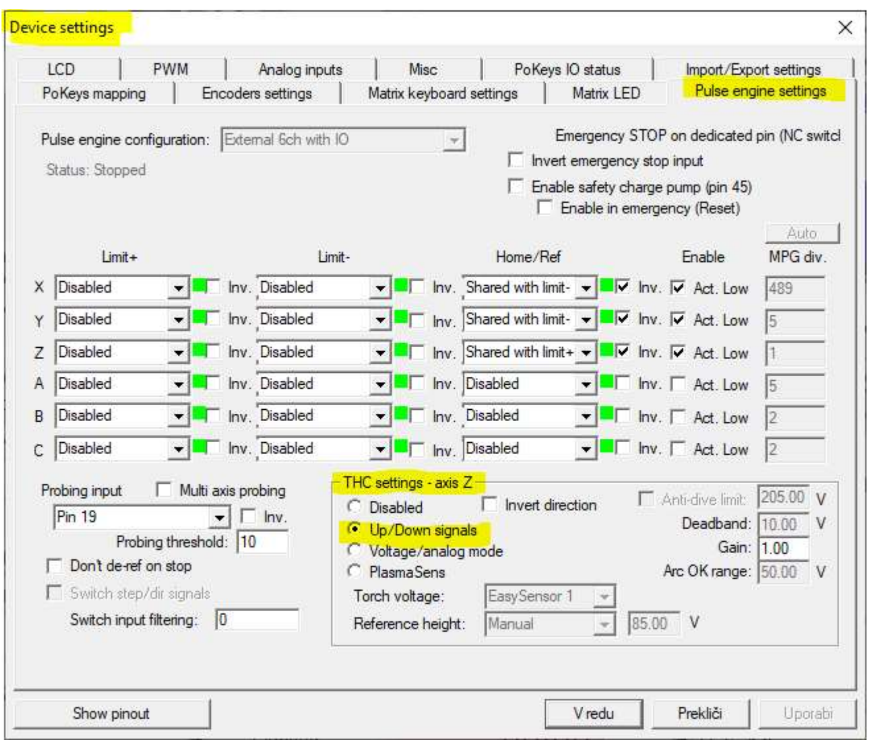

Fig 9. Pulse Engine Settings Mach3

the settings for homing/limits can be seen under Pulse engine settings of the Pokeys plugin. Pulse engine settings provides the option for an externally dedicated limit +/- as well as home for axes X, Y, Z, A, B, and C. It is important to notice the emphasis on inversion and active low in the Pulse engine settings tab. Stepper drivers can be either active high or active low. An active low stepper driver will enable the motor while it is receiving 0V and disconnect the motor while it is receiving the positive voltage step. An active high stepper driver works in vice versa. Pokeys plugin by default recognizes motor drivers as active high but allows them to be configured to active low. Switches can also be active high or active low and the inversion option allows flexibility in this domain. If a limit switch is tripped the green block will turn red and Mach3 will enter emergency mode. A switch can be returned to a non-tripped state through inversion [5]. This allows for complete flexibility between switches and motor drivers.

In the study, rotary stages using active high electromagnetic switches were tested. They were wired to the dedicated limit pins on the Pokeys57CNC **Fig 10.**

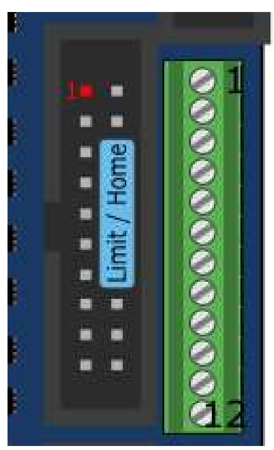

Fig 10. Limit/Home pins on the Pokeys57CNC

When the magnets in the rotary table become aligned during rotation the circuit is open and the Pokeys57CNC receives a high signal. The switch is triggered in Mach3. A further notable configuration in the Pulse Engine settings is the ability to share a

limit/home switch to the same external dedicated circuit. This means that the minimum or maximum limits can be shared with the Machine Coordinate home position. This is useful as it is typically conventional to set a machine's home position at the minimum end of linear axes and the 0 degree angle of rotary axes.

Another advantage of the Pokeys57CNC over the control board that the modified 3-axis milling machine originally came with is its isolated 0-10 V analog output that can be used to control spindle speed. Pin 17 on the Pokeys57CNC device is connected to a PWM to analog converter for controlling standard spindle drivers. The PWM tab of the Pokeys plugin allows for an adjustable multiplier based off of the maximum RPM of the machine’s spindle [5].

Now that the machine has its basics configured it can be tested with generated toolpaths. Fusion 360 was used to generate toolpaths for this study. Fusion 360 is a development tool with both CAD and CAM softwares. CAD allows for the creation of a design while CAM allows for the generation of G-Code for a manufacturing process. The requirements of the CAM software are quite extensive to ensure that the generated G-Code will function properly on the physical machine. First, a setup must be created that allows the selection or creation of a machine, the operation type, defining the Work Coordinate System, and the model. Once this is completed, a toolpath can be chosen. Several toolpaths are provided by Fusion 360 that are best suited for certain geometries and designs. They can be broadly categorized into 2D, 3D, and multi-axis toolpaths. A 2D toolpath will move in the XY plane during cutting and only change its position in the Z axis between cutting moves. A 3D toolpath allows for movement in all 3 linear axes during cutting moves. Multi-axis toolpaths include the addition of 1 or more rotary axes.

In some cases the rotary axis is used only to reposition the part between cutting moves while in true multi axis setups rotary axes are used in conjunction with linear axes during cutting moves [9]. This study will focus on the toolpaths which can enable simultaneous multi-axis functionality.

Once the toolpath has been developed, a process which will be covered in greater depth in Results and Discussion, a post processor can be used to generate G-code from the toolpath. For custom machines, a post processor must be configured to match the specifications of the machines. This process will also be covered further in the Results and Discussion section. It is important to use Fusion 360's simulation feature to make sure there are no errors in the G-Code.

Mach3 allows for G-Code to be directly opened in the console and a screen will provide a visual representation of the entire toolpath. Once the machine is zeroed in the Work Coordinate System the Cycle Start button can be pressed and the machining process will begin.

Materials and Methods 2.1: Implantable Flow Sensor

In contrast to the 5-axis machining, a Roland 3-axis milling machine was used to manufacture the Senior Design Team's Hydrocephalus flow sensor. The setup process for this commercial machine was far more simplistic. Roland provides a CAM software with very user friendly options at the expense of some more advanced and sometimes necessary milling customization. The stock is defined, the Work Coordinate System is set, and a tool is selected. The toolpath creation is simplified to allow the selection of a design with more flat or curved geometries. Once the CAM has generated a toolpath the

spindle is manually set to a marked zero coordinate of the defined Work Coordinate System. The cycle can then be started. The results of the milling of the flow sensor will be discussed in the following Results and Discussion 2.1 section.

The Implantable Flow Sensor transduces flow rate using a cantilever deflection system seen in **Fig 11.**

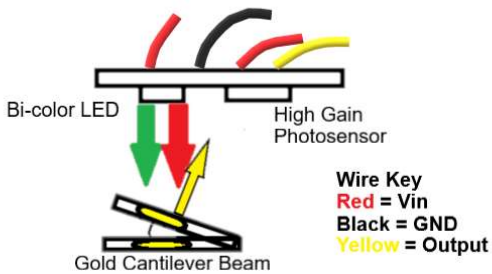

Fig 11. Cantilever beam inside sensor deflects to flow changing light intensity on the photosensor

Results and Discussion:

Results and Discussion 1.1: Custom 5-Axis Milling Machine

The generic 3-axis mill was modified to have additional rotary axes through the use of a trunnion table **Fig 12.**.

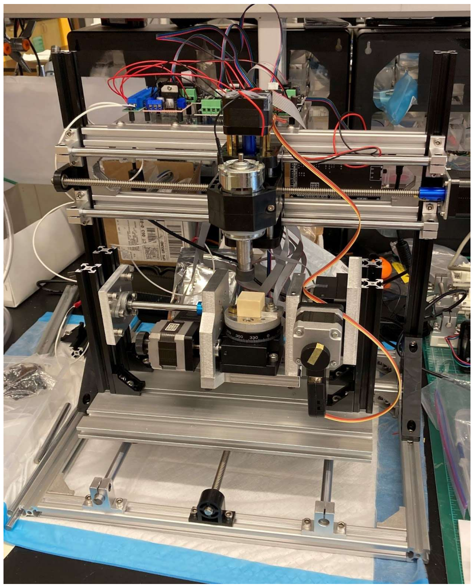

Fig 12. Modified generic 3-axis mill into 5 axis with a trunnion table

This table was mounted on the current mill's table. It rotated in the A and C axes. This table required the use of 2 additional stepper motors. Once the set up procedure described in Materials and Methods was completed, it was time to test the data flow of custom 5-axis milling. The first step was to create a simple design in Fusion 360 CAD and develop a toolpath for this design in Fusion 360 CAM.

Milling styrofoam was chosen as an appropriate material for testing the machine due to its soft structure. The stock was approximately 30 x 30 mm. A simple design was created in Fusion 360 CAM **Fig 13.**.

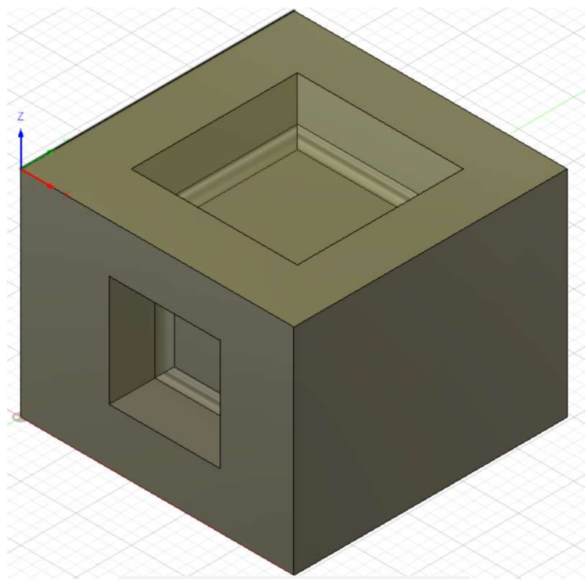

Fig 13. CAD model of test design

It had square pockets on the front and top faces, in the XZ and XY planes respectively. This design was intended to demonstrate the capabilities of the machine to read a toolpath requiring rotation on the A axis. On a typical 3 axis milling machine, a design like this would require 2 reclampings to mill these faces. Fusion 360 allows for the creation of tools and chucks from measurements. This option was used to replicate the 1/32" flat end mill and the chuck. 2D adaptive clearing was chosen as the toolpath for

both pockets with the Work Coordinate System being changed between each clearing to create the required rotation about the A axis **Fig 14.**

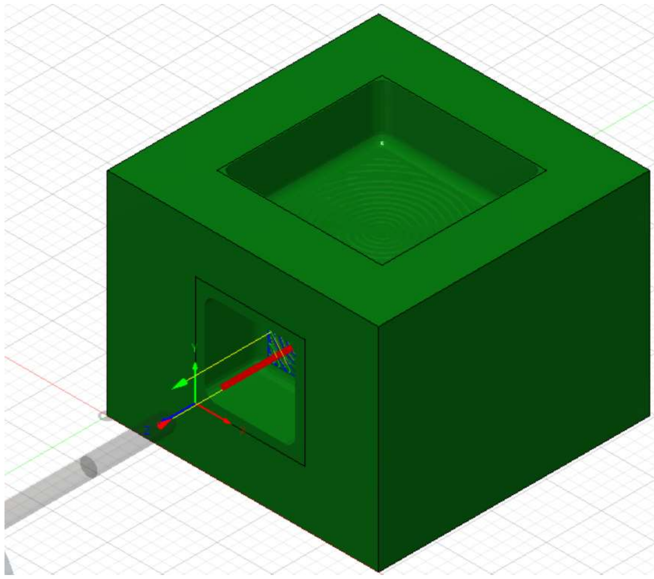

Fig 14. Simulation for 2D-adaptive clearing showing 90 degree rotation about the A axis

After simulating the process, a general 5-axis post processor from Fusion 360's libraries was used to generate G-Code. The G-Code was loaded in Mach3 and a preview was created **Fig 15.**

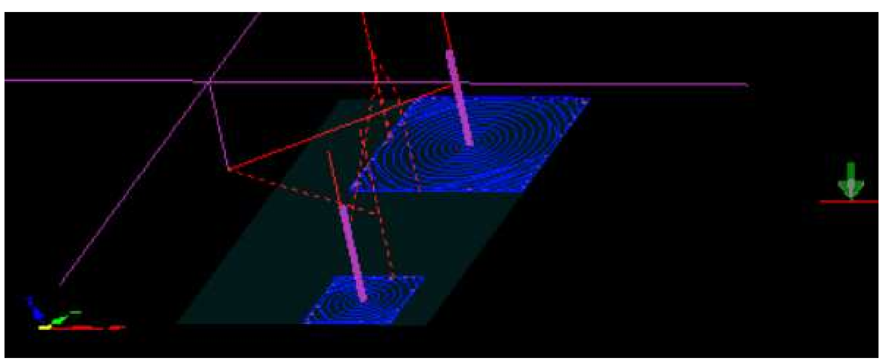

Fig 15. Mach3 preview of toolpath

The results of running the toolpath cycle can be seen in **Fig 16.** The rotation about the A axis was successful however some complications were encountered. Namely the G-Code did not account for the physical rotational limitations of the machine. Additionally, the second pocket was not centered in its face because after rotation the

machine was not able to set the new Work Coordinate System with the correct offset to the Machine Coordinate System. These challenges were a direct result

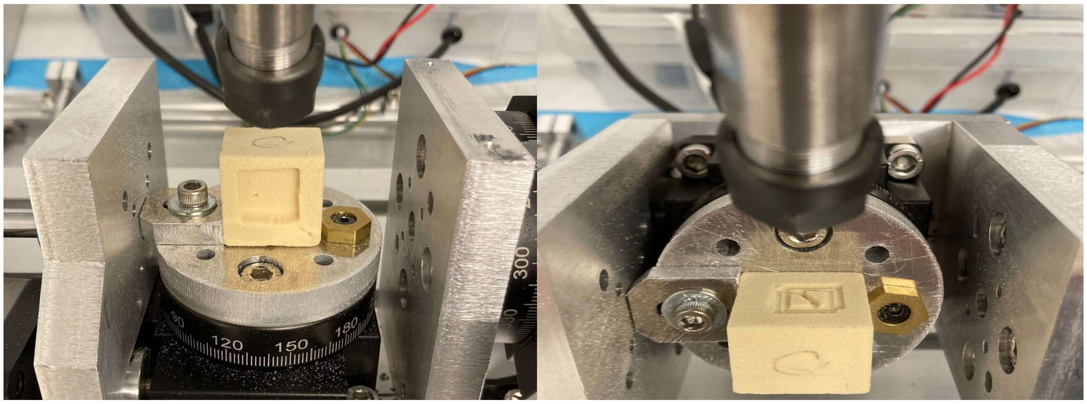

Fig 16. Results of the Fusion 360 generated 5-axis toolpath

of Fusion 360 not accounting for the limitations and mechanics of the 5-axis mill. The means of improving Fusion 360's understanding of a custom machine's geometry will be discussed further in the Conclusion and Future Work section.

Results and Discussion 2.1: Implantable Flow Sensor

The flow sensor was milled with a 3-axis Roland mill. The bottom component of the flow sensor is geometrically complex with cylindrical inlets and outlets. Since the Roland 3-axis mill can only move the tool in the X, Y, and Z axes, it is not capable of creating the curved surfaces unless it is behaving as a lathe. In order to achieve this the stock has to be repositioned twice to orient the inlet and outlets along the Z axis **Fig 17.**

Fig 17. Implantable flow sensor remounted on the table to mill cylindrical geometries

This is a time intensive process as the stock has to be clamped securely each time and the tool has to be reset to the zero position. It can also increase the chance of error or malfunction in the manufacturing process. In the creation of the first bottom component, an inlet was broken as the result of this repositioning error. Although the flow sensor was eventually successfully machined using the 3-axis Roland Mill, the repositioning and failed cycles greatly slowed the workflow of the design process. This supported the advantageous nature of 5-axis milling for complex geometries. The outcome of the implantable flow sensor milled by the Roland 3-axis mill can be seen in **Fig 18.**

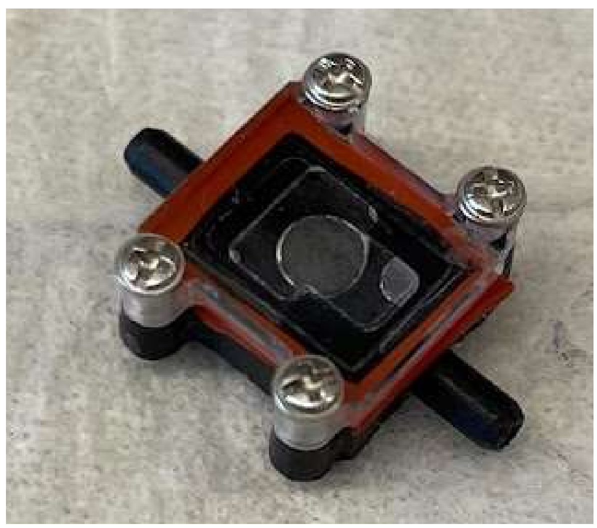

Fig 18. Hydrocephalus Implantable Flow Sensor

Conclusion and Future Work:

This study surveyed the use and practicality of 5-axis and 3-axis micro machining in several biomedical studies, including one being conducted in house. In addition, a generic 3-axis milling machine was converted into a 5 axis milling machine with the use of a Pokey57CNC control board and Mach3 control software. Fusion 360 was used for both CAD and CAM software. A simple design was created and tested on the custom 5-axis machine. The results showed success in automated rotary motion during a multiaxis toolpath. However, an unanticipated offset was created due to the machine code not properly understanding the machines geometries.

In the future, work will be done to import machine geometries into Fusion 360 for improved accuracy in toolpath cycles and to decrease the risk of crashing. Additionally, servo motors will be investigated as an improvement to the stepper motors. Servo motors have feedback encoders which can accurately control the motors position, speed, and torque.

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