Freeform Optics Fabrication and Post Processing

by

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Dedication

To my LORD and Savior,

Jesus Christ

To God Be the Glory!

To my extraordinary wife,

Joy Palmer

To my lovely daughter,

Julia Palmer

To my loving parents,

Debbie Palmer and Patrick Palmer

To my grandparents,

Jim and Sarah Huckaby

D. Arvalee Palmer

To the memory of my grandfather,

R. Dale Palmer

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1. Introduction

The process of fabricating freeform optics in the past and present has been extremely expensive, time consuming, and technologically challenging. New methods of optical surfacing have made great strides in fabricating precision freeform optics. These methods include: Diamond Turning, Magnetorheological Finishing (MRF), sub-aperture grinding, and polishing. However, these methods are not without consequences when optical designers, engineers, and opticians desire to achieve a surface micro-roughness to within less than 2 nm Root Mean Square (RMS). A Diamond Turned Aluminum mirror was measured to have a surface micro-roughness of 10 nanometers RMS. The measured surface showed a periodic like circular ring pattern showing the tool marks left from the machining process. Thus mid to high spatial frequencies are present in the optical surface. These effects may be easily seen by pointing a laser pointer at such an optical surface and seeing what appears to be various diffraction orders because these mid to high spatial frequencies act like a diffraction grating and cause additional scattering of light. In addition, using a metrology equipment such as: an interferometer and profilometer it is possible to measure the surface roughness to see the mid to high spatial frequencies on the surface of the optic. The long term goal for freeform optics fabrication is to achieve a remarkable surface quality as fast as possible and as cheap as possible while maintaining the desired freeform shape within a given tolerance.

1.1. Freeform Optics Challenges

The problem facing freeform optics fabrication methods is that they are extremely expensive and often proprietary. Numerous optical fabrication companies indicate that their machines are able to post process aspheric surfaces but there is very little documentation showing the methods of post processing the freeform optics. Freeform surfaces are the most innovative and novel aspects of optical fabrication. Great strides are being made in academia and industry alike to understand the fabrication challenges and to overcome them. The first method in freeform optics fabrication is to use a Computer Numerically Controlled (CNC) machine to generate a freeform surface. Next, conventional polishing may be used in combination with metrology to determine the correct figure. The conventional polishing process takes an extremely long time to reduce a surfaces micro-roughness to within the visible specification of less than 2 nm RMS. The motivation for freeform optics fabrication and post processing is to determine an efficient method for reducing the micro-roughness to within the visible specification such that research groups may be able to use this process and make further improvements upon it for a variety of work pieces. In the next section, two methods for freeform optics fabrication and post processing are discussed in great detail.

1.2. Optimax VIBE™ Process

One such method, VIBE™, works extremely fast at reducing the mid to high spatial frequencies of an optic surface. The VIBE™ process was developed by Mike Mandina, the President of Optimax and is therefore proprietary. VIBE™ has been claimed to work extremely well on plano and spherical shapes. However, freeform surfaces are the next target for the VIBE™ process. The VIBE™ process has reduced an initial 9T alumina ground surface from 756.1 nm RMS to a 0.7 nm RMS in 10 minutes of VIBE polishing [1]. For this specific result, the Radius of Curvature of the spherical surface was specified to be 22.9 mm. The deviation from the Radius of Curvature was measured before the VIBE™ process and after running the VIBE™ process for 10 minutes [1]. The profiles were measured showing much less deviation from the ideal surface after post processing with the VIBE™ process. In addition, an interferometric measurement was made of the surface before and after showing convergence to 0.7 nm RMS. The problem presented herein expands to the fact that there is little to no academic research that can make the same claims for reaching the desired surface roughness in as little time as the VIBE™ process.

1.3. Iterative Stroking Process

The Iterative Stroking Process was developed at the University of Arizona, College of Optical Sciences, Large Optics Fabrication and Testing (LOFT) group. This method has been developed as an independent counterpart to the VIBE^{TM} process. Researchers at the University of Arizona are developing freeform optics and desire an in-house method to post process these surfaces. The Iterative Stroking Process has demonstrated good performance in reducing an optics micro-roughness from 120 nm to 8.683 nm in an hour. The primary benefit of using the Iterative Stroking Process is that research groups familiar with optical fabrication and metrology may use this method to post process their plano, spherical, or freeform optic. The second benefit is that the fabrication process is well documented and may be repeated for a variety of freeform shapes/materials. Currently, this method has been tested on Pyrex blanks, 3D printed photopolymer resin, and Diamond Turned Aluminum. The notoriety for in-house development allows for research groups to independently use the process and to make further developments in the hardware, software, or tooling. This report includes great detail in understanding the Iterative Stroke Process development as a whole and may serve as a reference for freeform optics fabrication and post processing using CNC machines.

2. CCPM Development

The Computer Controlled Polishing Machine (CCPM) was developed at the College of Optical Sciences, University of Arizona. The CCPM and associated research was funded by the Korea Basic Science Institute (KBSI) located in Daejon, South Korea. KBSI is a world class research institution interested in developing new methods of optical fabrication and instrumentation. The KBSI research project funded the purchase of the CCPM, various parts and upgrades, and three years of research funding for graduate students in the LOFT group.

The CCPM used for optical smoothing is a 4-Axis CNC Router that is run using the "Mach 3 CNC Software" for running the G-Code produced by the stroking software. The CCPM has been retrofitted to hold a polishing tool as opposed to a cutting tool that a Router would use. This chapter details the hardware design, tooling, and software utilized in stroking runs.

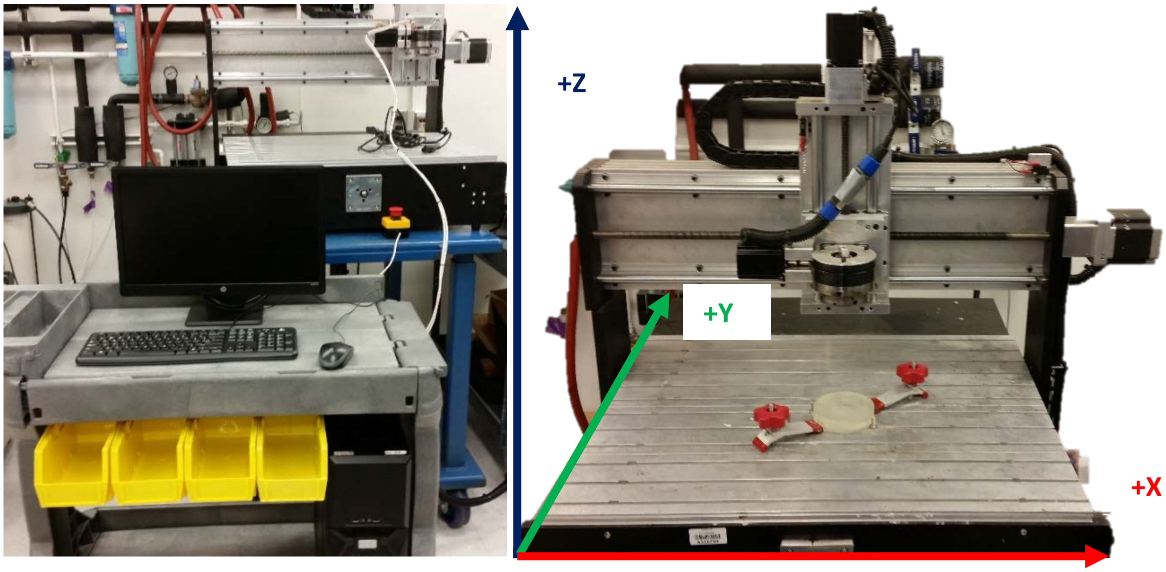


Figure 1 Control Computer and 4-AxisCCPM used for smoothing optical surfaces.

2.1 Hardware Development

The CCPM Hardware was purchased from Velox CNC as an upgraded CNC Router. The product name is "24W-ACE" and is priced starting at $5200.00. The product upgrades requested by the LOFT group increased the purchase price to $9395.00 which include a complete machine, aluminum T-Slot Table Top, Mach 3 CNC software, and computer workstation.

2.1.1 Stroking Machine

The CCPM operating as a Stroking Machine in concept produces very small amount of movement on the work piece while maintaining an accurate fit between the tool and the work piece. In order to perform these operations an orbital motion is required. The X and Y axes allow for a fast and repeatable orbital motion. The additional Z axes is required for aligning the tool to the work piece safely. The Z motion allows for various work pieces and tools to be attached to the CCPM giving the User more freedom in choosing experiments. The A axis also known as the Spin axis contains a 4 tooth chuck which enables a quick attachment of tools. The Spin axis is controllable via G-Code which allows for more smooth motion and may be used in the future for stroking operations on aspheric surfaces. This level of control would be of particular interest for an off-axis optic like the Daniel K. Inouye Solar Telescope (DKIST) primary mirror for which the spin axis of the polishing machine could follow the parent vertex to keep the lap shape as close to the shape of the optic as possible.

The Machine Travel specifications is extremely generous for optical surfacing allowing the CCPM to perform experiments on small to medium sized surfaces. The largest optical surface diameter that has been run on the CCPM is 3 inches in diameter. The workspace of this machine would modestly allow a work piece of up to 8 inches in diameter to be included in the experiments. The larger the diameter of the work piece the larger the lap becomes which also influences the available Z axis height and motion. The Velox CNC Stroking machine specifications are described below in **Table 1**.

Specifications	X	Y	Z	Units
Machine Travel	24	24	8	in
Leadscrew Diameter	5/8	5/8	1/2	in
Travel Per Turn	1/4	1/4	1/5	in
Max Travel Per Turn	200	200	150	in/min
Stepper Motor Torque	400	600	300	oz/in
Rapid Speeds	100	100	100	in/min
Resolution	0.00035	0.00035	0.00025	in
Repeatability (+/-)	0.001	0.001	0.001	in

Table 1 Upgraded Velox CNC (Stroking Machine) 24W-ACE specifications [2].

The Leadscrew Diameters are small allowing for a smaller pitch that yield a travel per turn of ¼ inch for X and Y axes and 1/5 inch for the Z axis. The max travel per turn for the X and Y axes allow for an extremely fast orbital motion or spindle motion up to a Feed Rate of 200 in/min or

5080 mm/min. The tool positioning requirement and repeatability on the work piece is 100 microns or 0.1 mm. The resolution of the stepper motors on the CCPM are on the order of 8.89 microns. The repeatability of the stepper motors on the CCPM are on the order of 25.4 microns. Thus the CCPM is more than adequate for performing optical smoothing runs.

Additional Specifications	
Overall Foot Print	42” x 42” x 34”
Drive Mechanism	Acme Leadscrew and Anti-Backlash Nut
Weight	Est. 175 lbs
Control Box	Smooth Step Ethernet Control Box
Control Software	Mach 3 Control Software
Home Switches	Installed on All Axes

Table 2 Upgraded Velox CNC 24W-ACE additional specifications [2].

The additional specifications highlighted above in **Table 2** are included for completeness. The Drive Mechanism specified is optimal for backlash correction by providing a mechanical backlash compensation with the leadscrew and an anti-backlash nut. The Mach 3 Control Software has been pre-installed and configured on the CCPM. Home switches are installed on all axes which enable the CCPM User to ensure the safe operation of the machine during a smoothing run.

The Control Box contains all of the input/output for the stepper motors, limit switches, status indicators, and parallel interface to the Control Computer as seen below in **Figure 2**. The control box also has two outputs to control mist coolant and flood coolant (for milling operations) which may be configured to use two peristaltic pumps (for polishing operations) as an automated slurry dispenser system. The automated slurry dispenser system is further discussed in Section 5.

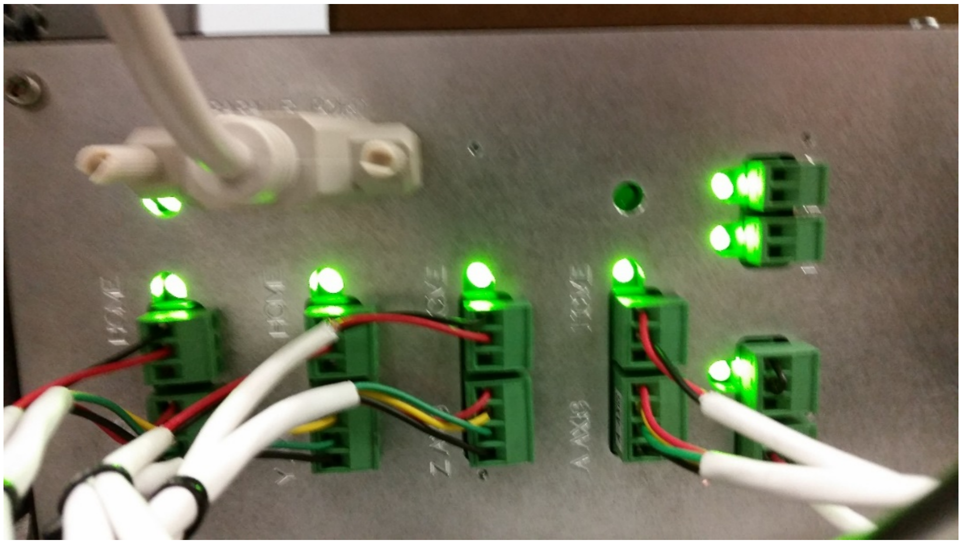


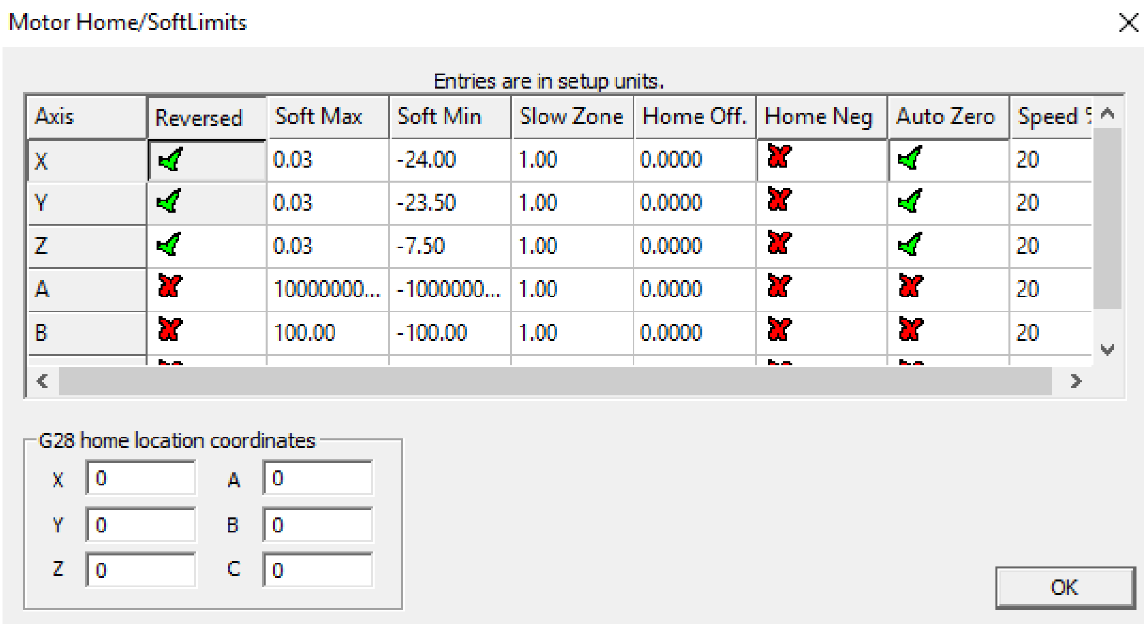
Figure 2 CCPM electrical connections for motors, limit switches, and communications cable.

2.1.2 Machine Safety

The CCPM should be treated like any other machine in the shop. It will perform exactly how it is programmed. It will also perform on par with the materials that require upkeep. Regular scheduled maintenance and machine inspection is recommended for continued safe operation of the CCPM. The next item in CCPM safety is the proper setup of the Soft Limits to ensure that the CCPM does not move outside of its travel range. The soft limits may be specified through the Mach 3 software by clicking the Config menu and the Homing/Limits submenu as shown below in **Figure 3**. The CCPM travel limits may be defined by the Soft Min, Soft Max, and Home Offset. The most widely used SoftLimits setup ensures the full motion of the CCPM over its working area. The SoftLimits are recommended to be adjusted in the following scenarios: setup of multiple work pieces on the table, changing the tooling that requires more Z axis motion than currently allotted, when

Figure 3 Mach 3 Homing/Limits Configuration [3].

restricting motion on specific axes, or any other possible obstruction on the CCPM is observable. In the event the SoftLimits are not to be changed removing possible obstructions from the work table is always recommended. In addition to visual inspection, machine maintenance is also important for the CCPM to maintain consistent operation.



2.1.3 Machine Maintenance

The CCPM like all machines requires regularly scheduled maintenance in order for the machine to function properly and for the polishing experiments to be repeatable. The first measure of maintenance is to keep the work area clean. Next, the individual machine hardware needs to be visually inspected to determine when maintenance shall be scheduled. The machine may be cleaned thoroughly through the use of a rag or Air Gun to blow away the dust and debris. The Velox CNC manual recommends an air gun from their website store with part number 1363VELOX7 [2]. It is important to use the Air Gun to clear the rails and leadscrews of dust and debris. The CCPM consists of three axes with leadscrews that should be greased at regularly scheduled intervals. The Velox CNC manual uses grease from www.mcmaster.com with part number 1378K33 [2]. The recommended schedule of maintenance is at least once a month.

The CCPM may be run without a tool on the work piece to verify if the CCPM needs to be greased. Such a procedure may be referred to as an “Air Run” where the machine is running in full motion without a lap contacting the work piece. The Operator may listen to the lead screws while the CCPM is performing an Air Run to check if the axes need to be greased. The Operator is looking for a grinding like sound that would indicate that the lead screws need to be lubricated. The CCPM in fast motion should sound smooth when lubricated properly during an Air Run. Before adding grease, the CCPM motors shall be in their home position and the Emergency Stop button pressed to verify that no motion will occur. Once the grease is applied, the Emergency Stop button shall be pulled out and cleared. The Operator may then move the axes to their end of travel and then press in the Emergency Stop button. Now, the remaining part of the leadscrews and rails may be greased. Upon finishing all three axes, the Operator may pull out the Emergency Stop button, clear the error, and rehome the Axis. Upon re-homing the Operator shall select a stroking run to perform an Air Run to visually inspect the machine performance and to listen for any grinding-like sounds. The manual is also clear when it lists a warning to not use oil for machine maintenance.

The operator may choose to query the Maintenance Statistics by clicking the Operator menu and clicking on the Maintenance Hours submenu. This dialog box reports the total distance travelled by each axes as well as the total operating time. The total operating time may be misleading as it appears to populate when the Mach3 CNC software is running which is less important than actual machine run time. The total distance travelled of the X and Y axes shall be the most important metric for performing machine maintenance. Upon finishing maintenance, the "Reset All" button may be pressed to reset the total distance and operating time.

2.1.4 Tooling

The mechanical tooling for the CCPM involves the use of smooth motion and a rigid interface between the CCPM, the lap or grinding tool, and the work piece. Multiple tools were used in performing polishing experiments ranging from 3D printed tools, flexures, and rigid rods with spherical balls and pins. The CCPM axes primarily involved in removal of material requires a smooth orbital motion. In this discussion the experiments were performed using the X and Y axes to perform motion in the XY plane. The Z axis was used primarily for alignment and providing secure contact between the tool and the work piece. The machine configuration using the 4 tooth chuck requires using two allen wrenches to tighten the chuck to secure the tool. More details about the specific procedures will be addressed later in Chapter 3.1.6. A trade off of the Polishing Heads is presented to clarify the scenarios in which each type is beneficial for various grinding and polishing operations.

2.1.5 Polishing Head

The Polishing Head supplied with the Velox CNC is a 4 tooth chuck, shown below in **Figure 4**, which is driven by a Stepper motor controllable through G-Code. In order to drive a grinding tool or lap, a cylindrical rod with a spherical tip/pin may be used to sit inside the chuck and protrude in a spherical hole in the lap. It is not required for the spherical tip to mate with excess pressure contacting the lap. The spherical tip should protrude enough so that the edge of the spherical ball is able to drive the lap without the pin coming loose from vibration, excess moments on the lap, too much wedge in the lap, or any other reason. The desired pressure to be used on the lap is determined by selecting the right amount of weight to put on the lap. Once the weight is secured, the spherical ball can make light contact with the hole in the lap and the Z axis may be lowered. Upon lowering, visual inspection is needed to check that the chuck doesn't smash the rod onto the tool while in contact with the work piece.

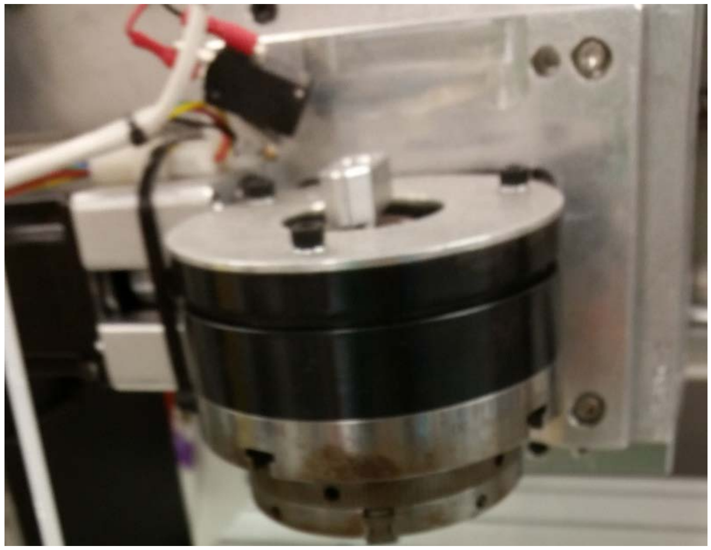


Figure 4 Four Tooth Chuck on rotary spindle (A axis).

2.1.6 Tools utilizing 3D Printing and Flexures

The CCPM served as a good testbed for experimenting with 3D printed tools and flexures in the polishing experiments. Several designs were developed with the primary interest of decoupling the Tip, Tilt, and Z motion. The various types of 3D printed tools and flexures will be discussed in detail for completeness. The 3D printed tools were printed using the Form Labs Form 1+ employing a technology called stereolithography (SLA). This technology consists of a computer controlled laser that is pointed at the point cloud of the 3D object with mirrors that point the laser beam into a tank filled with liquid resin that hardens when the laser comes in contact with the resin. Stereolithography allows for the printer to produce accurate 3D parts with a thickness layer resolution ranging from 25 to 200 microns. The build volume of the Form 1+ is 125 x 125 x 165 mm. This volume was more than adequate for the tools of interest in the polishing experiments.

The first concept of the 3D printed tool, shown below in **Figure 5**, consisted of a small diameter lap with relatively small thickness that had a circular extrusion allowing for a hex like pocket. A matching hex like shaft was designed to contact the lap with a small allowance of movement in tip and tilt rotation and z displacement. These tools were small and not well adapted to hold enough weight to achieve the desired pressure for the polishing experiments.

The next series of tooling, shown below in **Figure 5**, used a cylindrical flexure with certain slices through the cylinder allowing for tip and tilt rotations. This flexure was used to attach aluminum tools to the interface of a cylindrical rod to the 4 tooth chuck. The flexure was used once or twice before it was apparent that the forces of the tool were not compliant enough for the tool to follow the CCPM toolpath without tipping or tilting to a high angle. The experiment was aborted once it was obvious the lap wasn't making good contact with the work piece due to a moment on the flexure that prevented the pressure from being uniformly distributed on the lap.

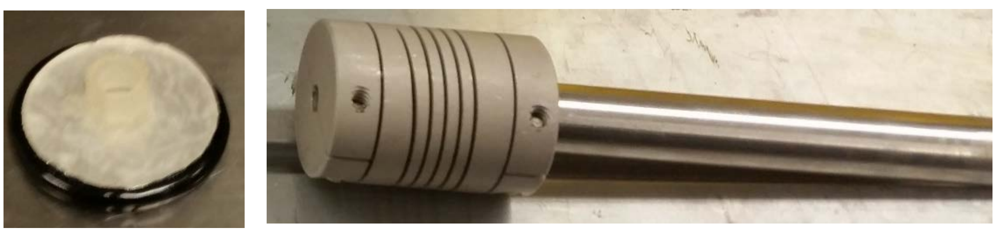


Figure 5 3D printed photopolymer tool (left). Cylindrical flexure (right).

Figure 6 Aluminum flexures mounted between rigid 3D printed part.

The next concept of the 3D printed tool was developed for a larger work piece. The lap consisted of a smooth photopolymer resin surface with a small circular ring extruding with a hollow inside. On top of the lap, shown above in **Figure 6**, there was an aluminum flexure that was the same diameter and consisted of mounting holes on the center and also at the edge of the flexure. The lap would be affixed to the flexure on the holes near the edge. A smaller 3D printed part would be bolted on top of the flexure while another ring was affixed to the flexure. Next, a second identical flexure would be mounted on top of the small circular piece concentric to the center and the outer ring. Finally, a 3D printed rod with bolt holes would be affixed to the topmost flexure and the end of the rod would be inserted into the 4 tooth chuck to secure the tool on the work piece. The tool had reasonable success in achieving the decoupling of the tip and tilt rotations and z translation. However, the photopolymer resin that contacted the 4 tooth chuck was brittle and started cracking upon running the machine at a higher feed rate.

2.2 Mach3 CNC Software

The Velox CNC Stroking Machine's Control Computer came preinstalled with Mach3 CNC Version R3.043.066 [3]. This software interfaces to the Velox CNC Electronics Chassis through the use of the computer's parallel port. The Mach3 software is preconfigured to function as a CNC Mill. The Mach3 software interfaces with the Windows Kernel to ensure that the CNC is performing at a specified update rate. The Mach3 software has multiple tabs or displays that display useful information when performing stroking runs. The first screenshot displays the complete interface and is the home screen for the Control Computer.

The Program Run Tab as described below in **Figure 7** shows most of the important information for an operator to perform Stroking runs. The olive green panel with a vertical scroll bar indicates the lines of G-Code that are presently loaded into the software. The controls below allow the operator to Load G-Code, Edit G-Code, Cycle Start, Stop, and Reset.

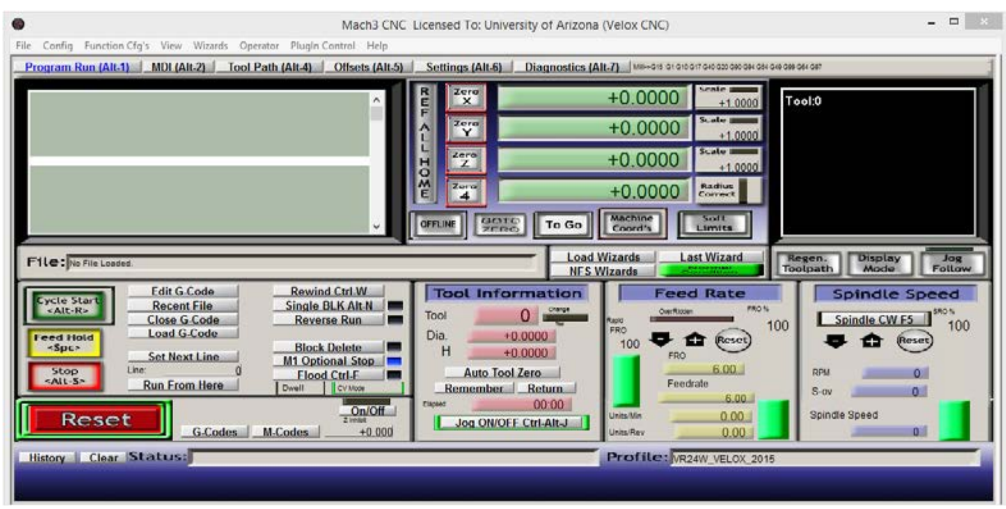


Figure 7 Mach3 CNC Program Run (Home Screen) for Stroking Machine [3].

These are the primary controls needed to interface with the G-code. The next set of controls is in the top center region of the screen. These controls control the motion of the 4-Axes and the ability to zero their respective Digital Read Out (DRO). First, the operator should click the "REF ALL HOME" button which will move all the Axes to their respective HOME positions by traveling to one of their limit switches. Next, the machine may be positioned by using the keyboard arrow keys for X and Y axes movement while the Page Up/Page Down keys control the Z axis movement. The “GOTO ZERO” button may be pressed to use the Machines Rapid Move to position the X, Y, Z, and Spin axes to their zero positions. Please take caution and to only use the “GOTO ZERO” button when the four tooth chuck does not contain any additional tooling. This button causes a rapid movement that does not accelerate or decelerate smoothly which may damage the surface of a work piece. Alternatively, when the machine is used remotely, the tab key may be pressed to bring up the Manual Pulse Generator (MPG) control which is essentially a “virtual” pendant control for the Stroking Machine as seen below in **Figure 8**.

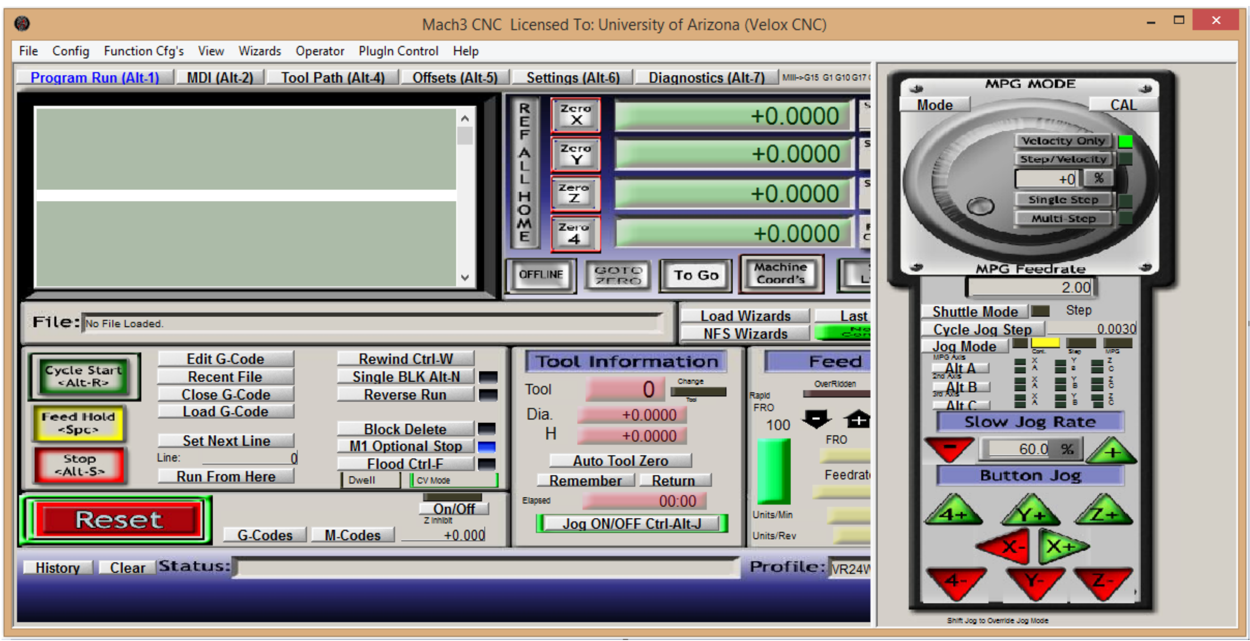


Figure 8 Mach3 CNC Manual Pulse Generator (MPG) or Pendant Control [3].

The second tab in the Mach3 Software is the MDI (Manual Data Input) tab. This tab contains many of the same motion commands as in the previous tab. It also contains an Input label and an elongated text box to enter a manual command. The command references for both G-Code and M-Code are presented as buttons. The operator may click these buttons to learn more about specific G-Code and M-Code used in CNC programming. The **Figure 9** below shows the MDI tab which is essential for learning the G-Code programming language and how to control the machine's multiple axes positioning.

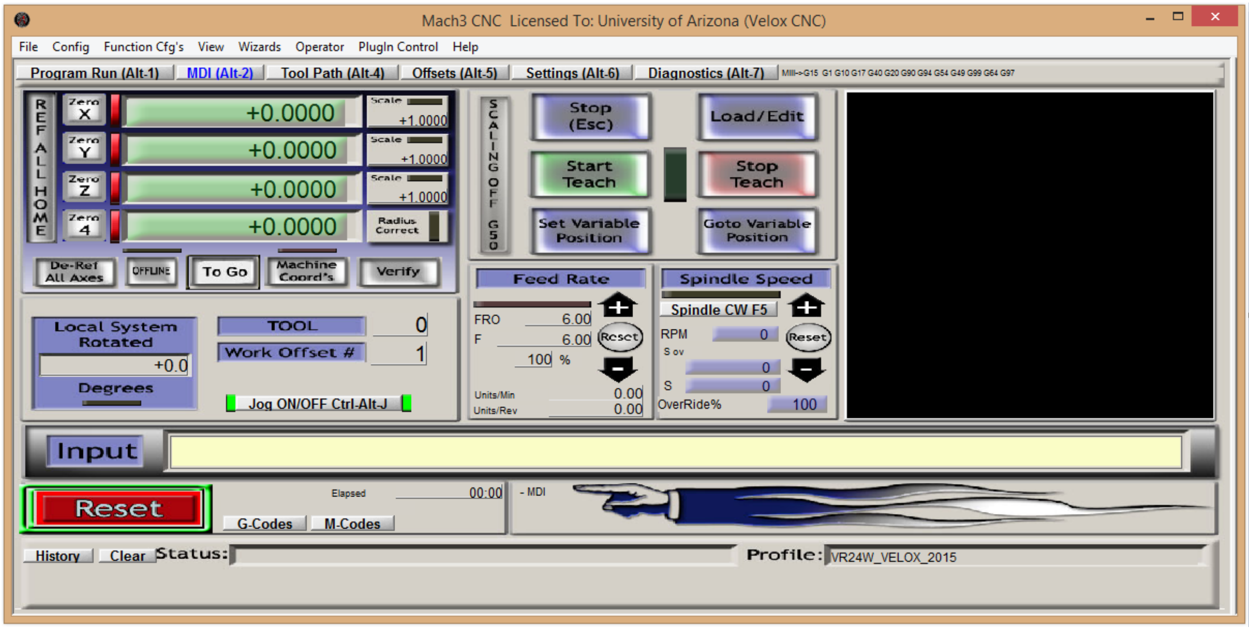


Figure 9 Mach3 CNC Manual Data Input (MDI) Tab for Stroking Machine [3].

For complex Stroking runs the "Tool Path" tab may be used to simulate the program run. The operator may load the Stroking Run by clicking the "Load G-Code" button in **Figure 7**. Next, the operator may be able to estimate the program run time by clicking the "Tool Path" tab and pressing the "Simulate Program Run" button in **Figure 10** below. The Mach3 CNC software then simulates the run by iteratively running each line of G-Code without moving any of the motors. This simulation is an approximation and may not accurately represent the time it takes to complete a Stroking Run. However, this is the best method that the Stroking Machine has for determining the length of a given run. Upon completion of a run, the operator is recommended to keep track of the run time and to save it in the header of the Stroking Run for future operations. The Tool Path tab also shows a larger view of the tool path while keeping essential controls such as: Cycle Start, Rewind, Stop, and Reset.

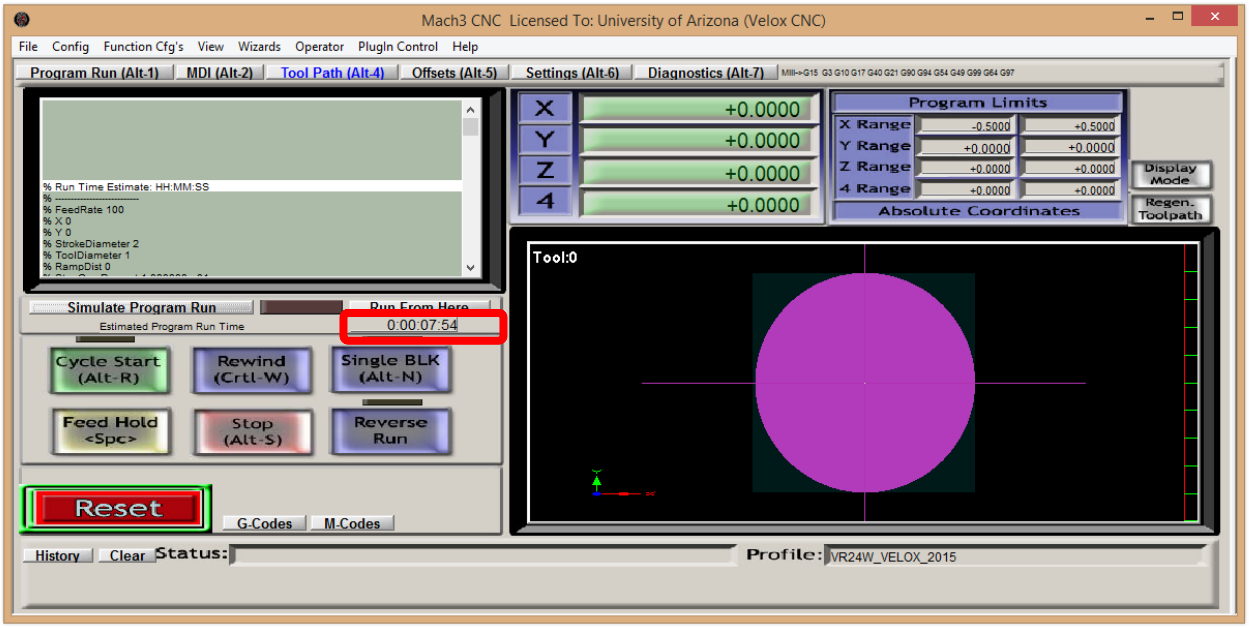


Figure 10 Mach3 CNC Tool Path Tab with Estimated Stroking run time [3].

The Settings Tab is displayed below in **Figure 11**. This tab shows the Encoder Positions and DROs for their respective axes. The Manual Pulse Generator is displayed in Absolute Coordinates and can be viewed in both Velocity and Counts. There is a "Set Steps per Unit" button which initializes an Axis Calibration which may be useful for Machine Configuration. This Axis Calibration may have similar properties to the "Motor Tuning" submenu in the Config menu. The Axis Calibration has not been performed since the Stroking Machine has arrived in the Optics Shop. The Stroking Machine's axes may need to be calibrated upon hitting a hard stop or changing motor configuration parameters.

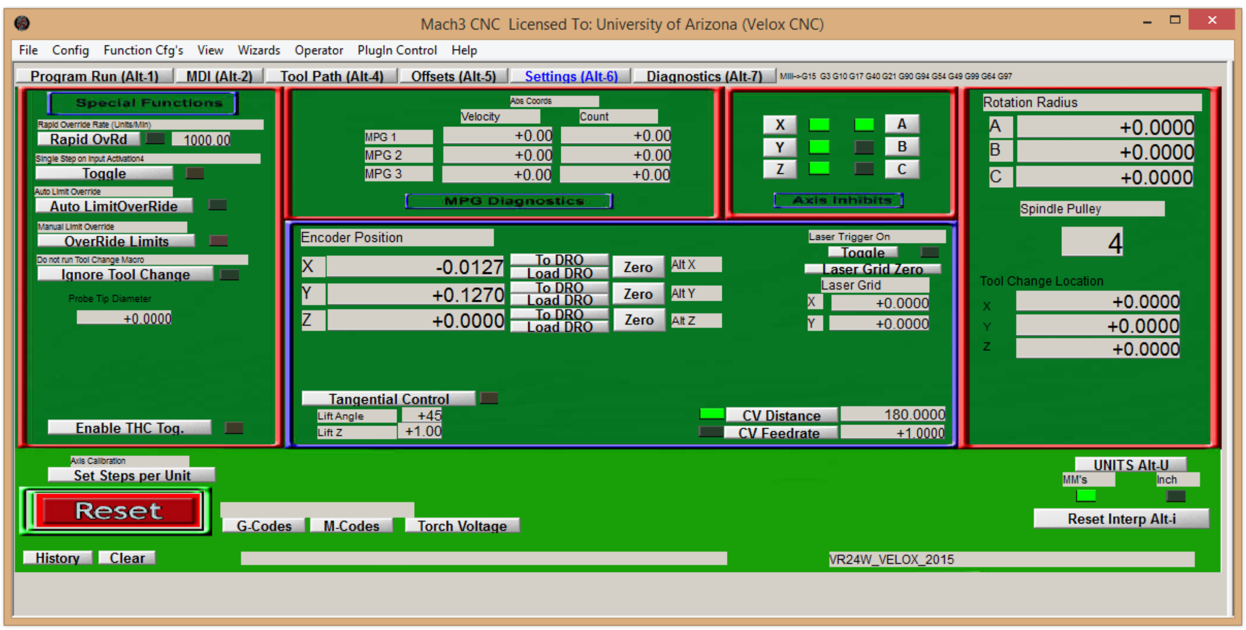


Figure 11 Mach3 CNC Settings Tab for Stroking Machine [3].

The Diagnostics tab is displayed below in **Figure 12**. This is an engineering interface and has a plethora of information that may confuse the operator. It is extremely useful in trying to debug machine performance. The Position information for all axes are readily displayed in multiple formats: Current Position, Machine Coordinates, Work Offset, G92 Offset, and Tool Offset. The absolute maximum and minimum of the X, Y, and Z axes are also displayed. The Port 1 Pins current state shows the communication over parallel port to the stepper motor driver board.

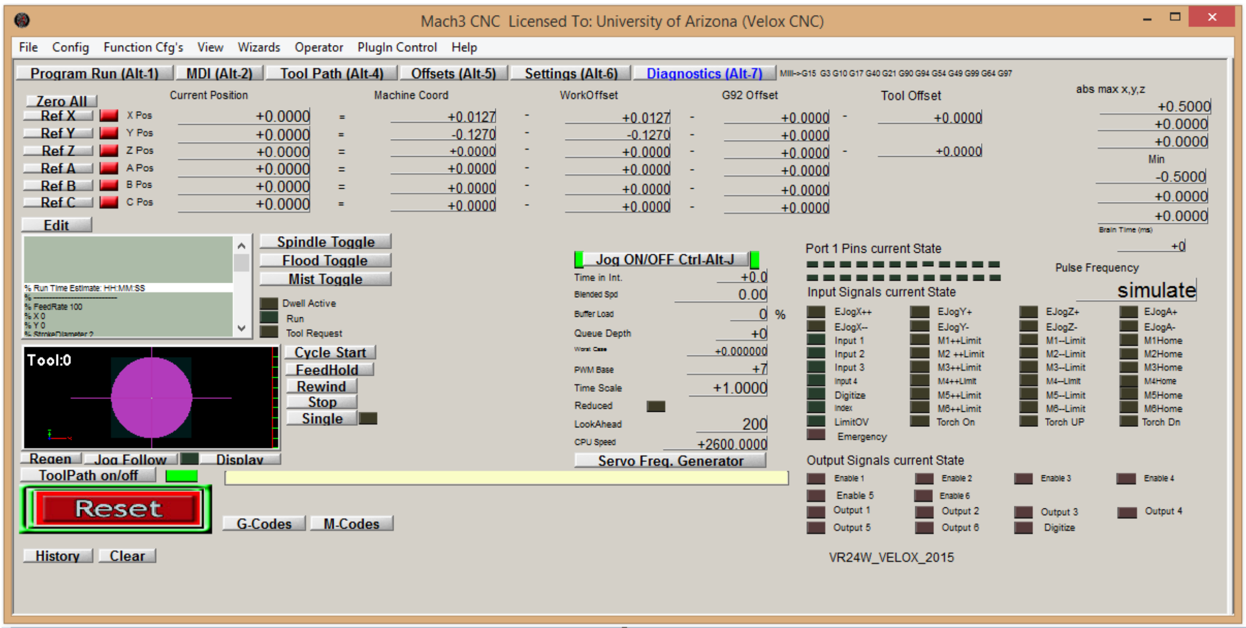


Figure 12 Mach3 CNC Diagnostics Tab for Stroking Machine [3].

The Mach3 CNC software also contains a VB Scripter Window for use with the Stroking Machine. This is perhaps the most hidden yet most valuable component in developing software for the Stroking Machine. The Visual Basic Script files are saved as a *.m1s file type. Once these scripts are run through the Mach3 CNC software they become compiled upon a successful run and may be saved as a *.mcc file. The Mach3 CNC software is essentially a black box requiring the Operator to use various G-Code and M-code commands to perform machine operations. The VB Scripter Window as shown in **Figure 13** below has the ability to interface with custom Dynamically Linked Libraries (DLL) which allow the Stroking Machine to query the Windows Kernel for system time, perform serial communications with external devices, and virtually can interface with any external libraries where the DLL Application Programming Interface (API) or Software Development Kit (SDK) are well known. These compiled codes can be run from within a G-Code and are recommended to be saved as M####.m1s where the user defined M-Codes start at 1000. The M-

Codes can increment up to M9999. The VB Scripter Window is quite powerful for looking similar to a notepad++ like interface. The VB Scripter includes debugging features such as Run Script, Step Into Script, Step Over Subroutine in Script, Stop Script, Toggle Breakpoint, and Clear Breakpoints.

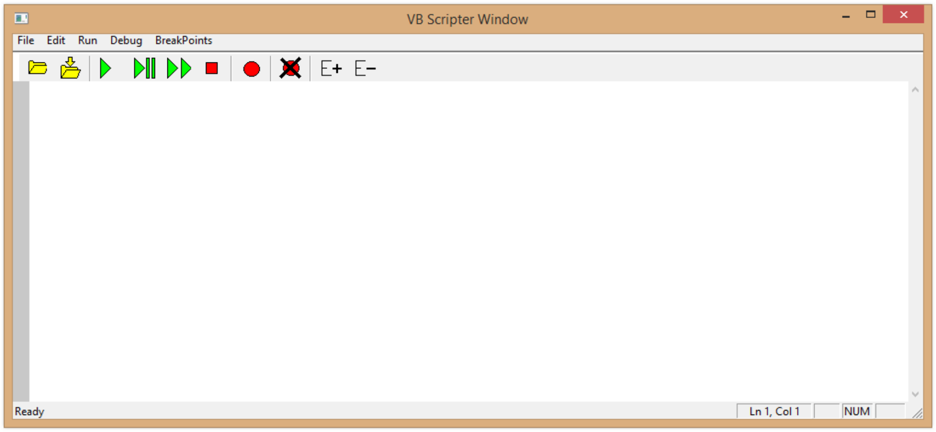


Figure 13 Mach3 CNC VB Scripter Window [3].

The VBScript editor enables the operator to build custom screens with various Inputs also known as DROs. The VBScript utility can read and write to the value of both DROs and LEDs. The Button control is also available to provide a VBScript function call to be assigned via the button callback. Through the use of these controls and indicators the Operator may create a custom machine interface that is specific to an operation.

2.3 G-Code Construction

The G-Code language created by Gerber Scientific during the early 1960s for use in the original mechanical photoplotters which used an optical exposure head [4]. The early G-Code format used a block format [4]:

Nnumber G-Code Xxxxx Yyyyy D-Code M-Code *

Where:

Nnumber is an optional sequence number. G-Code is an optional preparatory code. Xxxxx is the X axis coordinate. Yyyyy is the Y axis coordinate. D-Code is a Draft code. M-Code is a miscellaneous code. The Asterisk, *, is the End of data block character. The Gerber format was based on the RS-274 data standard for controlling CNC machine tools [4]. The G-Code language has had additional modifications for the adaptation of controlling CNC mills, lathes, and polishing machines. The G-Code language in use today has been modified to include additional axes. For this specific discussion all four axes of the CCPM may be controlled via the G-Code. The language itself consists of a one letter command, “G”, followed by a numeric command code. This distinction is similar to M-Codes which are numeric codes prefixed with an “M.” It is through many codes and sequences that define machine parameters: units (mm or inches), feedrate (mm/min, inches/min, revolutions/min), absolute position mode or incremental position mode, plane select, etc. It is necessary to include a header line with all of the necessary G-Code used to setup the run. An example header is included below in **Table 3**. This is called a “safe start block” because its nature is to protect the tool and work piece by cancelling any unsafe actions: cancel any tool diameter, cancel length offsets, and cancel any active canned cycles.

G-Code	Command
G90	Absolute Position Mode
G54	Fixture Offset 1
G17	XY Plane Select
G40	Cutter compensation (tool diameter) cancel
G49	Length offset cancel
G80	Canned cycle cancel
G94	Feed per Minute
G21	Unit Selection: Millimeter

Table 3 G-Code safe start block commands used in CCPM [3].

The next series of commands describe the motion of the tool on the work piece that the machine is to follow. These motion commands can be linear, arc, semi-circle, circle, or helical and specified in either Cartesian coordinates or polar coordinates. The most common G-Code used for issuing motion commands is presented below in **Table 4**. There are also multiple positioning modes that the CNC operator may specify: absolute position or incremental position. For extremely complex shapes the Distance Mode should be set to Absolute while the IJ Mode should be set to Incremental. The IJ Mode is similar to the standard G-Code language but instead of using X, Y, and Z to indicate the next position to move to the G-Code uses the I, J, and K prefixes before the next position. The Incremental IJ Mode allows for much smaller incremental moves from one position to the next which is extremely useful for complex curves. The G-Code language is largely standardized language in the machining industry, however, some commands are interpreted by machines differently.

G-Code	Command
G00	Rapid Move (feed rate ignored uses max velocity of machine)
G01	Linear Feed Move
G02	Clockwise Arc Feed Move
G03	Counter Clockwise Arc Feed Move
G04	Dwell – pause specified by P in number of seconds
G12	Clockwise Circle Interpolation
G13	Counter Clockwise Circle Interpolation

Table 4 G-Code movement commands available for CCPM [3].

The initial learning curve of the G-Code was a little steep but Velox CNC provided a getting started document and manual that proved to be very helpful with learning G-Code. The second tab on the Mach3 CNC software is for Manual Device Input (MDI). This view has an "Input" label next to a textbox for command entry. First time G-Code users are recommended to use the MDI interface to understand the G-Code programming to control machine motion and perform various subroutines. The operator needs to be alert when performing MDI commands due to the abrupt machine movement that may occur after entering the command. The risk of accidentally inputting the incorrect geometry or feed rate can have extreme consequences. Please refer to the machine safety discussion in chapter 2.2.1 for a more in depth discussion of safely operating the machine. The third tab on the Mach3 CNC software is used for analysis of the Tool Path. Due to the complex elliptical and arc like motions in the software it is recommended to load the G-Code file in the Mach 3 CNC software, click the Tool Path tab, and click the Simulate Program Run button to perform a run simulation.

2.4 Freeform Optics Software Development

The software requirements for the CCPM included that the G-Code input file would be processed and output by a scientific data processing software written in Matlab™ [5] called SAGUARO [6] which was developed by the LOFT group at the University of Arizona. SAGUARO [6] includes two types of modules: Standard Modules and User Modules. The Standard Modules have been written for general purpose use while User Modules are more specific to the development of the research purpose. The Freeform Optics Software have been categorized under the User Modules because it is run directly on the CCPM control computer. In the future, with more research projects utilizing the CCPM it may be appropriate to include the SAGUARO [6] module in the package of

Standard Modules which would allow anyone having access to SAGUARO [6] the ability to perform polishing experiments on the CCPM.

2.4.1 SAGUARO Modules

There were multiple iterations of the stroking software used on the CCPM. The first iteration of SAGUARO [6] module was used to create a circular orbital stroking motion around a series of points. The orbit along each pass brought the tool through the center of the origin through every pass which did not accomplish the stroking method of primary interest. Instead, the module was accepted to be generally good at the figuring process and is called the "FiguringStroke" module. The FiguringStroke module served as a verification that the CCPM was successful at performing general grinding and polishing runs on the machine.

The next iteration was called "GenerateStroke" which included more random point to point motion with smaller orbital motions at every point. This module was much more successful in the stroking process because the motion was truly random in that the tool wasn't forced to return to the origin after every circular pass. The stroke diameter was still able to be constrained by the Operator and if defined to be very small then good stroking experiments were performed. If the stroke diameter was defined to be as large as the diameter of the work piece than it would have similar performance to the FiguringRun module described previously.

The final iteration is called "SpiralStroke" which uses the CCPMs resolution at around 50 microns of machine motion to move the tool in extremely small movements very slowly across the surface. These modules require user input to generate the stroke, post process the coordinate information, and output the G-Code to perform the stroking run. In addition to post processing the stroke input parameters the data processing involved the use of some SAUGARO modules and other MATLAB™ [5] software. This section aims to provide the user with a detailed understanding of how to use the SAGUARO [6] modules: FiguringRun, GenerateStroke, and IterativeStroke to generate G-Code that can be loaded and run on the CCPM.

2.4.2 Common Run Parameters

Many of the SAGUARO [6] Modules discussed in this section use similar Run Parameters. The Run Parameters that are similar will be discussed in depth in this section. Additional Run Parameters will be discussed in each Modules section titled “Run Parameters.” The FiguringStroke and RandomStroke SAGUARO [6] Modules both use an elliptical envelope to generate the tool path.

The user is asked for the following run parameters as input: Feed Rate [mm/min], Number of Points, X Offset [mm], Y Offset [mm], Radius A [mm], Radius B [mm], Rotation Angle [deg]. The Feed Rate for the CCPM is specified in millimeters per minute and defines the overall speed at which the tool will be run on the work piece. A small feed rate allows the machine to run extremely slow enabling the polishing tool to contact the work piece more intimately due to allowing pitch to flow and adapt to the shape changes of the tool moving across the work piece. A fast feed rate allows the machine to run with increased speed across the tool which is required for removing more material from the work piece The X Offset and Y Offset parameters are defined as the X and Y offsets of an Ellipse to enable the ability of stroking to exist in a specific region of the work piece. The Radius A and Radius B parameters are the major axis and minor axis of an ellipse. The magnitudes of these radii are checked and the largest radii is the major axis and the smaller is the minor axis. The elliptical mask equation generates an elliptical mask with the inside values being True:

$$ellipse = \frac{(X - xOffset)^2}{Radius\ A} + \frac{(Y - yOffset)^2}{Radius\ B} \leq 1.$$

The elliptical mask is then rotated by the rotation angle input parameter to allow further positioning control over the stroking region. The area outside of the region defined by the ellipse equation is converted to NaN (Not a Number) to restrict motion from occurring at any point outside this boundary. This elliptical boundary defines the maximum travel path of the tool on the work piece.

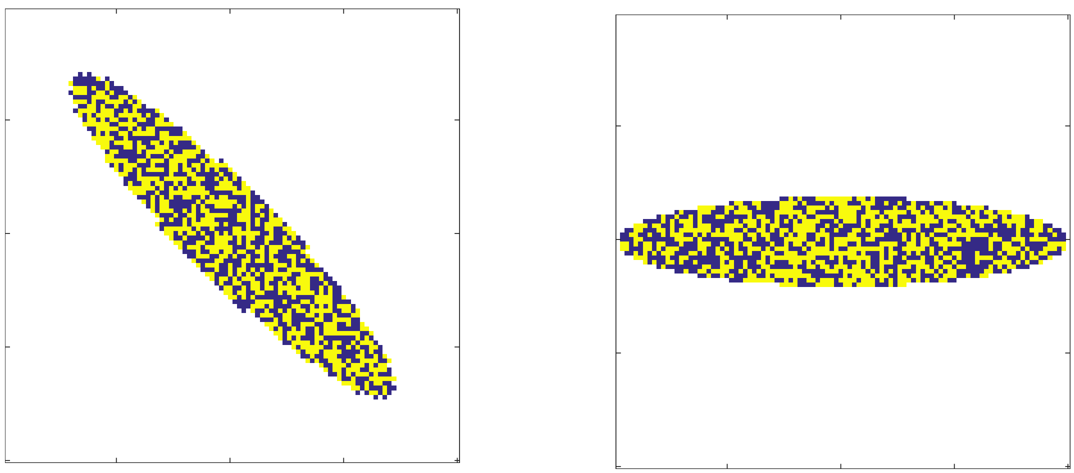


Figure 14 SAGUARO [6] MapPlot Module used to plot binary plot of elliptical boundaries with major axis of 5 mm, minor axis of 1 mm, rotation of 135 degrees (left) and 180 degrees (right).

2.4.3 Figuring Stroke

The Figuring Stroke SAGUARO [6] Module was developed primarily to determine the capabilities of the CCPM. The first requirement was to accomplish smooth orbital motion across the work piece. The second requirement was that the motion would be randomly generated. Originally, it was meant to perform the Stroking Process but was removing too much material toward the center of the optic that it was declared not usable for the Stroking Process. The module is not to be used when performing freeform optics smoothing but may instead be used for figuring. The module is included in this discussion for completeness and for verification that the 4-Axis CCPM is successful at performing grinding and polishing operations on a variety of work pieces.

2.4.3.1 Run Parameters

The Figuring Stroke SAGUARO [6] Module, as shown below in **Figure 15**, requires input from the user to determine what the tool path will look like. The first parameter is the Run Time specified in hours. This module uses circles to move between point to point so the total distance and run time are easily calculated. This module is able to estimate the time it takes to complete a run and will include as many circular motions as possible until the Run Time is reached. The second parameter is the number of points which refers to how many circles the Tool Path may contain. These circles are generated at random with the radius being the distance between the point and the origin. The random nature of the motion is defined inside an elliptical envelope where the X offset and Y offset may be specified. The ellipse has two axes a Major Axis and Minor Axis. The software chooses between Radius A and Radius B to determine which is larger for the Major Axis and the smaller radius is used for the Minor Axis. A rotation of the elliptical envelope may be specified to create an angular elliptical tool path. The last parameter is the feedrate in mm/min.

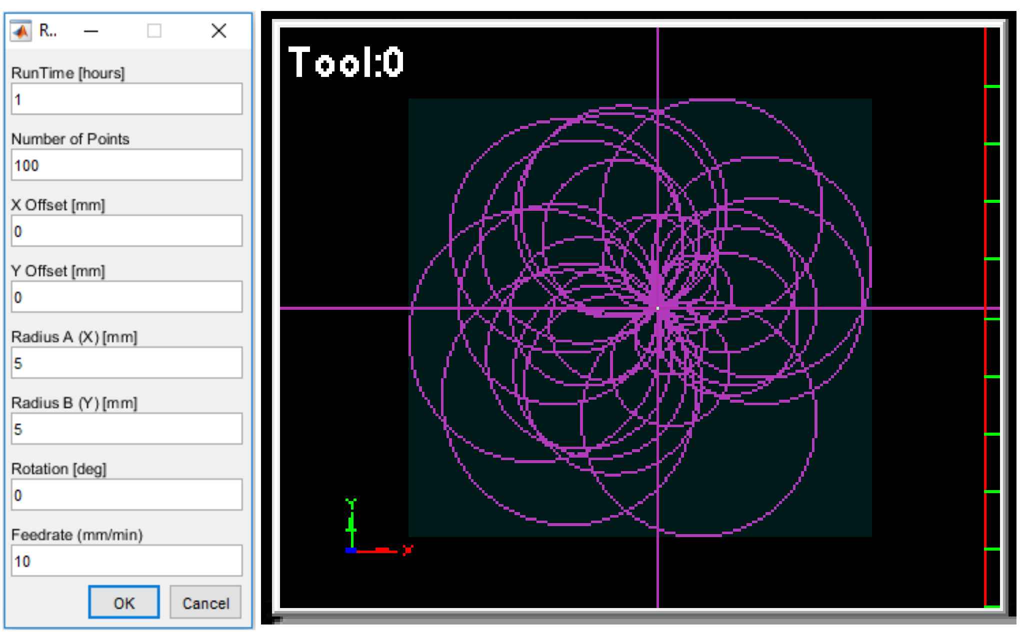


Figure 15 Figuring Stroke 5mm circular radius 1 hour run at 10 mm/min.

2.4.3.2 Module Description

The Figuring Stroke SAGUARO [6] Module first determines that the User has entered valid inputs for all run parameters. All run parameters shall be specified as numeric data types for the module to be able to correctly process the data. Next, the random number generator is initiated. The software checks for which Axis is the Major Axis and creates a meshgrid of points as a square matrix to represent the shape defined by the run parameters. Next, an elliptical mask is generated from the run parameters. A square matrix the size of the number of points is generated with random values of binary data points referred to as zero or one. These points that contain ones are then shuffled and their indices are recorded. The module then writes the G-Code to move from the origin to a circle the Radius of the distance to the random point as specified by its indices and then to move back to the origin. This step repeats until the number of points has been exceeded or the run time has elapsed.

2.4.3.3 Module Results

The Figuring Stroke module was successful in demonstrating CCPM performance in the figuring phase. The recommended stroke was approximately 5 mm to 3 cm to perform slight figuring operations. The goal of performing Stroking was realized when the stroke was continually reduced to close to 2 mm. The circular strokes generated behaved similar to the Strausbaugh machine used in grinding and polishing experiments [7]. It was determined that this module was moving to the center twice for every random point which indicated the possibility of nearly 200X removal rate at the center for a 100 point run while the average point had a 1X removal rate. Several improvements were made upon this module to include more random motion with a much smaller stroking motion and is covered in the next subsection.

2.4.4 Generate Stroke

The Generate Stroke SAGUARO [6] Module is responsible for taking user input, processing that input into a sequence of randomized stroking patterns, creating smaller strokes around the randomized point, and outputting the file as a G-Code text file. The module is run by clicking on the "GenerateStroke" from the User Module list. Next, a small input dialog box is displayed asking the user to input several run parameters that define a stroking run. The parameters are checked and verified to be of the correct data type: numeric for entries requiring numbers and string for the directory location to store the output G-Code. The SAUGARO module saves these input parameters in the module configuration file to ensure these parameters are remembered upon the next stroking run.

2.4.4.1 Run Parameters

The Run Parameters not common to the other modules include: Radius C [mm], Arc Radius [mm], and Directory. The third radius specified, Radius C, defines the radius of a small circular motion performed by the CCPM. The Arc Radius parameter defines the subtend of the arc required to arc between the randomly generated points. This parameter also defines how the CCPM moves smoothly. A small Arc Radius generates a nice smooth circular arc. A larger Arc Radius generates a more linear looking arc which may not offer the ideal smooth motion that the stroking experiment requires. The Directory is the location on the CCPM computer where the G-Code files are saved for a specific work piece. The number of points is an input parameter that most effectively determines how long the run will last. It defines the square matrix of randomly assigned boolean numbers to determine the indices or locations of the CCPM to move to in a stroking run. Due to the complex nature of the arc and elliptical motions the total run time is hard to estimate. The User may notice that the "Run Time" is not a Run Parameter for this module because of the complex nature of these randomly generated arcs. The User is recommended to run the generated G-Code file in the Mach 3 Simulation mode to know the estimated run time before starting the run.

2.4.4.2 Module Description

The random stroking path simulation software is a selection of routines that generates a smooth path for the CCPM to follow. This smooth path must remain in the elliptical boundary defined by the elliptical mask equation in section 2.4.2. To randomize the data, the rng(‘shuffle’) function is called with arguments of ‘shuffle’ to seed the random number generator based on the current time [5]. Next, the RANDI function is used to generate a square matrix of random integers between 0 and 1 thus creating a Boolean N by N matrix. The size of this matrix is specified by the variable number of points. The square matrix is then multiplied by the Boolean elliptical mask. The multiplication performed results in an elliptically shaped 2D plot with Boolean values occupying the inside of the ellipse while the outside of the ellipse is specified as NaN. The True boolean values are used in the stroking path while the False values are ignored. Next, the X, Y, Z locations of this boolean map are converted into a Coordinates data type for further data processing.

The Coordinates SAGUARO [6] data type is created with X, Y, Z variables as columns and the number of rows is defined as the Area of the Map or by the xDim * yDim. The X variable defines the x location at a given index. The Y variable defines the y location at a given index. The Z variable defines the boolean value if it is to be included in the run or not. The Z variable is checked that it isn’t assigned a value of NaN or 0. If it contains these values then the current X, Y, Z coordinate is not added to the list of coordinates. The software further randomizes the path by shuffling the rows of the coordinates file. The X and Y variables describe the indices that are valid within the masked ellipse. The software uses a nested for loop to read in the data points from the boolean map. The outer loop is cycling through the X values while the inner loop is cycling through the Y values. The problem with this approach is that a predetermined path could always be generated over how the looping variables loop through the X and Y indices. To further randomize the stroking coordinates, the rows of the X Y Z data type are passed through the randperm function to shuffle the rows of data. Shuffling the rows guarantees that the machine motion will move to points at random locations while preserving the good indices that are within the elliptical mask. The Coordinates data type is output to show the points along the smooth path that the CCPM will follow.

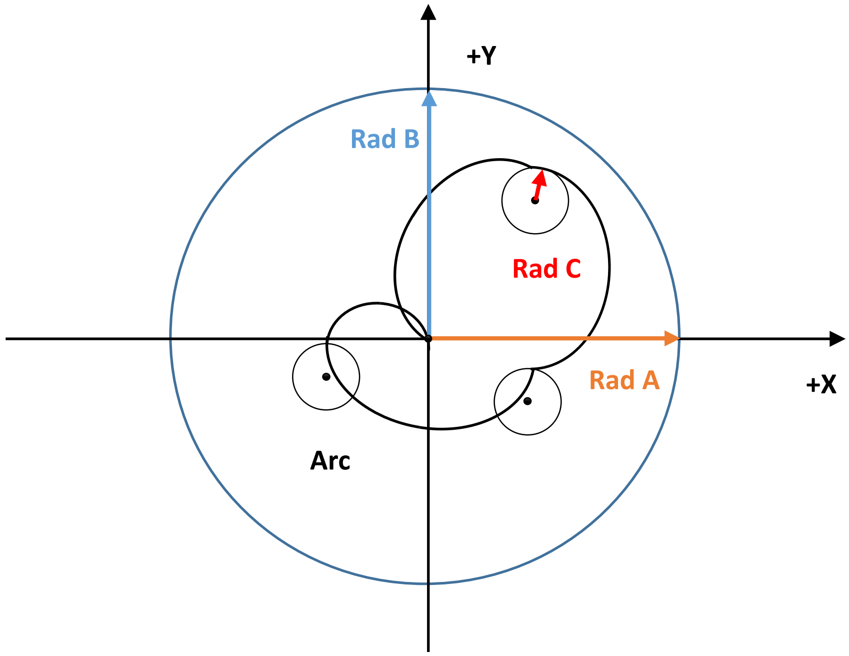


Figure 16 Random Stroke geometry shown for 3 Random Points.

The constraints in the software recommend:

$$Radius\ C < Radius\ A$$
$$Radius\ C < Radius\ B$$
$$Arc\ Length \sim Radius\ A$$

```
% Arc to a point Radius C above Point (X, Y)
fprintf(fid, 'G3 X%d Y%d R%d F%d\r\n', ...
 Coords(ii, 1), Coords(ii,2)+RadiusC, ArcRadius, feedRate);

% Arc to a point Radius C below Point (X, Y) completing Semicircle
fprintf(fid, 'G3 X%d Y%d R%d F%d\r\n', ...
 Coords(ii, 1), Coords(ii,2)-RadiusC, RadiusC, feedRate);

% Complete full circle with Radius C
fprintf(fid, 'G3 X%d Y%d R%d F%d\r\n', ...
 Coords(ii, 1), Coords(ii,2)+RadiusC, RadiusC, feedRate);

% Return Home, Program End, G-Code Rewind
fprintf(fid, 'G3 X0.0 Y0.0 R%d F%d\r\nM30\r\n', ArcRadius, feedRate);
```

Table 5 Matlab™ [5] code showing G-Code programming relevant to CCPM stroking motion.

```
G0 G90 G54 G17 G40 G49 G80 G94 G21
G3 X0 Y1 R3 F100
G3 X0 Y-1 R1 F100
G3 X0 Y1 R1 F100
G3 X2.5 Y3.5 R3 F100
G3 X2.5 Y1.5 R1 F100
G3 X2.5 Y3.5 R1 F100
G3 X2.5 Y1 R3 F100
G3 X2.5 Y-1 R1 F100
G3 X2.5 Y1 R1 F100
G3 X0 Y-4 R3 F100
G3 X0 Y-6 R1 F100
G3 X0 Y-4 R1 F100
G3 X2.5 Y-1.5 R3 F100
G3 X2.5 Y-3.5 R1 F100
G3 X2.5 Y-1.5 R1 F100
G3 X-5 Y1 R3 F100
G3 X-5 Y-1 R1 F100
G3 X-5 Y1 R1 F100
G3 X0 Y3.5 R3 F100
G3 X0 Y1.5 R1 F100
G3 X0 Y3.5 R1 F100
G3 X-2.5 Y1 R3 F100
G3 X-2.5 Y-1 R1 F100
G3 X-2.5 Y1 R1 F100
G3 X0.0 Y0.0 R3 F100
M30
```

Figure 17 Example G-Code output (left)

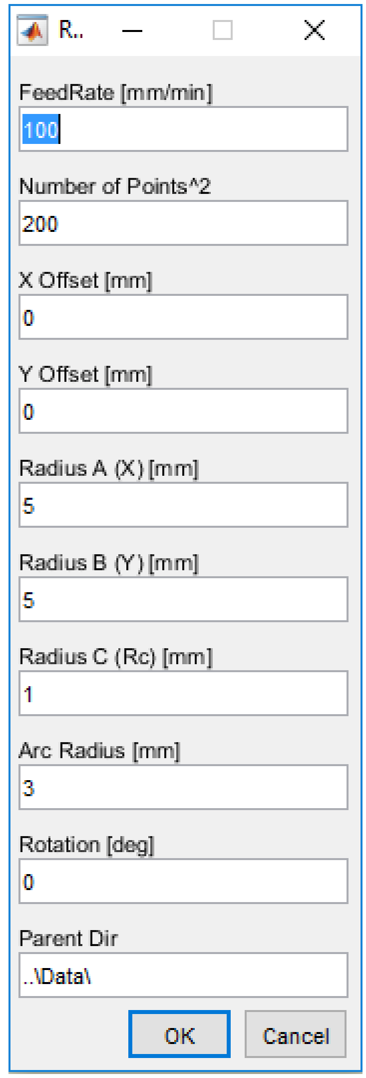


Figure 17 Example G-Code output (left) GenerateStroke module input parameters (right).

2.4.4.3 Module Results

The Generate Stroke SAGUARO [6] Module has worked well in performing Stroking Runs when the Run Parameters are specified with small radii. Typically, the radius defining the x and y axes has been kept same to indicate a circular stroke for most smoothing runs. Since most of the work pieces available to test are rotationally symmetric it is better to use a circular stroke. The Run Parameters listed above in **Figure 17** have shown to be effective. A small excerpt of the G-Code output from this run is also listed above showing the circular stroke commands and the X and Y positions, Radius of the circular interpolation, and feedrate.

2.4.5 Iterative Stroking Run

The Iterative Stroking Run SAGUARO [6] Module is the most recent development of the Stroking modules. Its origin comes from a CNC code similar to that of cutting a circular pocket for a CNC Mill. The most obvious change to the instruction set is that the CCPM is not drilling a hole and so no Z motion is commanded. The software process works by commanding very small incremental moves by arcing a semi-circle at a time with an incremental radius after each iteration. This module was also written to take into account the machine parameters: Resolution and Repeatability listed in **Table 1**. The following subsections will describe the Run Parameters of the Iterative Stroking Run, a detailed module description, and the most recent module results.

2.4.5.1 Run Parameters

The Iterative Stroking Run Parameters include the feedrate specified in mm/min, the X [mm] and Y [mm] position offset from the origin, the minimum stroke radius, maximum stroke radius, stroke increment, and parent directory. The input parameters are checked for their proper data types all run parameters are numeric with the exception of the parent directory which is a string. Upon completing the dialog below in **Figure 18** the G-Code run file is generated and the tool path is plotted in Matlab™ [5].

2.4.5.2 Module Description

The Iterative Stroke SAGUARO [6] Module takes the User input Run Parameters and starts by creating small semi-circular arc movements with the G03 G-Code command. Upon each successful iteration the Radius of the Circle is Incremented along with its final Y position. The X position is held fixed to keep the proper symmetry. The primary improvement of this module is the fact that the minimum stroke radius may be set very low along with the incremental stroke radius to ensure that the tool moves in very fine circular motions. The motion presented in this module is not random. It is a well-defined range of circular paths that increase radially in one axial direction until the radius of the current stroke reaches the maximum stroke radius. The Number of Iterations may be specified which allows the tool to start motion at the origin, complete one full stroke, and to move back to the origin by moving in the opposite radial direction.

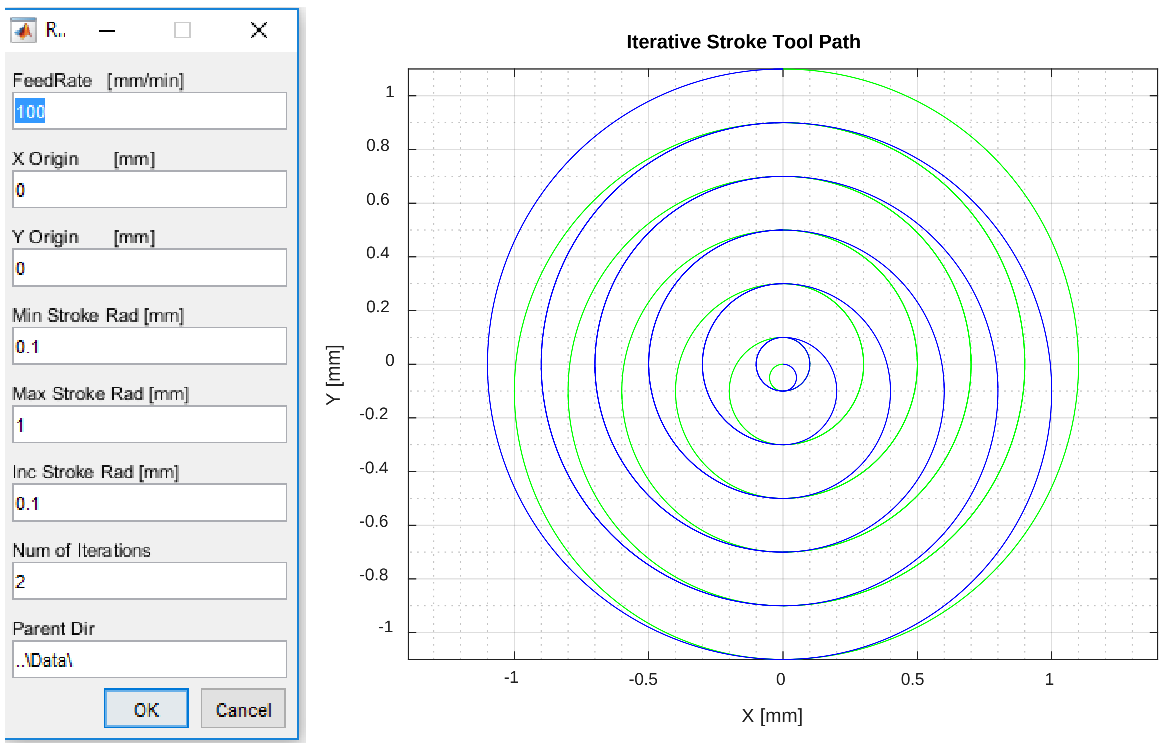


Figure 18 Iterative Stroke Run Parameters and Tool Path.

2.4.5.3 Module Results

The Iterative Stroke Module has had some exceptional success when using a slow Feedrate of ~ 10 mm/min and small numbers for the minimum stroke radius and incremental stroke radius of 0.01 mm. The maximum stroke radius is recommended to be no more than 5 mm for optimal smoothing. Using the Iterative Stroking Run Module on a BK7 glass optic with an average micro-roughness from 120 nm to 8.683 nm in an hour. Running on the same BK7 work piece with an additional time reduced the average micro-roughness from 8.683 nm to 4 nm in an hour. These measurements were performed on the center region of the work piece spanning an area of approximately 127 mm^2 with a radius of 6.35 mm.

3. CCPM Optical Fabrication Experiments

The optical fabrication experiments are run in the Small Optics Shop in the basement of the College of Optical Sciences. A variety of experiments have been conducted with different work pieces to verify the performance of the CCPM and its smoothing capability. The goal of performing the experiments is to rapidly converge on a desired surface micro-roughness without changing the figure of the optical surface. The efficiency of the experiments largely consists upon the method of tooling used and the care taken in performing experiments.

First, to verify that the CCPM was capable of smoothing optical surfaces the CCPM and tooling was put to the test. Initially, the experiments were performed upon a Diamond Turned piece of Aluminum. The surface was shiny and the initial measurement was approximately 10 nm RMS. Upon performing a few experiments, the surface measurement increased to over 15 nm RMS. It was clear that the CCPM was not working very well on metallic work pieces.

The focus was then switched to performing the same type of experiment on various types of glass and photopolymer resin work pieces. These photopolymer resin work pieces were designed in Solid Works ™ and created using the Form Labs Form 1+ 3D printer.

3.1 Fabrication

The primary goals of the experiments conducted with the CCPM are composed of two types of fabrication: grinding and polishing. Grinding focuses on coarse surfaces and is performed on the work piece until the surface roughness is measured to approximately 1.5 microns RMS. Polishing focuses on smoother surfaces to further reduce the surface roughness (measured in RMS) to less than 10 nanometers. For optical applications, the polished surface is required to have a specification of less than 2 nm RMS. The two fabrication methods can often times use the same tools or similar tools with slight variations. The primary difference between grinding and polishing is the type of polishing compound or polishing slurry that is used between the tool and the work piece. A common grinding compound is 220 Mesh Silicon Carbide (SiC) which 40% of the mixture has an average particle size greater than or equal to 46 microns. The smaller the mesh size the larger the particle size. This mesh specification is applied to polishing pads as well. Polishing compound particle sizes are much smaller than that of grinding compounds. For example, Rhodite 906 also known as Cerium Oxide has an average particle size of 1.15 microns with a maximum particle size of 7.7 microns. The success of optical fabrication, which is achieving the desired surface smoothness, largely depends upon the intricate care of the tool and the choices of tools, grinding compounds, and polishing compounds, as well as planning the correct sequence of tooling in the fabrication process.

3.1.1 Tool Fabrication Choices

Tool design is extremely important to the fabrication of optical components because it ultimately determines how well the optical surface can be polished. For this report, the primary tool design discussed involves the use of pitch and polishing pads. The first step in designing a tool is to choose an appropriate size that matches the work piece. For smoothing purposes, the tool is desired to match the size of the work piece to minimize the edge effect of the work piece. The next step is to determine the stiffness or compliance of the tool. The pitch type can be selected to be harder or softer dependent upon the viscosity. In some applications, two pitch types can be mixed. The primary benefit to using pitch is that after pressing the pitch on the work piece the pitch conforms to the opposite shape of the work piece. The smoothing experiment relies on intimate contact between the tool and the work piece. When the tool doesn't come into correct contact with the work piece, an additional surface error called misfit is likely to alter the surface figure which is detrimental to the smoothing experiments.

3.1.2 Pitch Tools

Pitch tools are created with an aluminum plate as a base with a spherical hole that doesn't protrude the entire surface. The surface with the hole is used to interface to the CCPM by a spherical ball at the end of a long rod. The other side of the aluminum plate needs to be cleaned before applying a new batch of pitch. Generally, the surface can be cleaned with the sharp edge of a clean razor blade, however, depending upon the quality of cleanliness on the surface and what residual compounds are on the surface, additional chemicals may be necessary to provide the desired level of cleanliness. The recommended list of cleaners in order of use is: soapy water, glue gone, isopropyl alcohol, paint thinner, and finally lacquer thinner. It is important to remember to safely clean the tool in the fume hood to minimize the outgassing of these dangerous chemicals. It is also recommended to use gloves when cleaning with the last four chemicals to keep the contents off of the skin to prevent irritation. Once the tool surface is cleaned it is ready for a fresh batch of pitch.

The pitch used in these polishing experiments is a mixture of Gugolz pitch numbers 64 and 73 purchased from Meller Optics, Inc. The mixture allows the pitch to be soft with more viscosity due to the added hardness. The pitch is heated up in a Stansport Campers Cook Ware 9-Cup Percolator Coffee Pot. The Coffee Pot is ideally sized because each tool requires a small amount of pitch. The Coffee Pot sits on the stove top and the oven burner is turned on to a warm setting. It takes nearly fifteen to thirty minutes for the entire batch of pitch to heat up. It is recommended to open the lid and stir often pushing down the pitch that hasn't melted yet. Once there is a uniform liquid consistency the pitch is ready to be poured on the tool.

The plate without the hole must be facing upwards. Next, a thin layer of masking tape is applied to the radial edge of the tool. The tape needs to be visually inspected that there are no noticeable gaps that the pitch could flow through. Once the tape has been firmly pressed and the tool is laid facing upward gently pour the pitch onto the tool and provide equal coverage to the whole surface of the tool as the pitch may not flow fast enough and settle in one spot. Once the pitch has been poured it is helpful to gently move the pitch to a flat leveled surface to minimize the amount of tip and tilt in the pitch lap. Now the pitch has to cool down to near room temperature before the lap can be trimmed and cut. The full procedure for creating a pitch lap is detailed below in an ordered list.

1. Open the pitch can with a razor blade.
2. Dump the hard pitch into a pot or kettle.
3. Heat the stove to low.
4. Check the pitch in 15 to 30 minutes and stir.
5. Push hard pitch down with the stir stick.
6. Turn heat off when pitch has good consistency.
7. Prepare tool interface (aluminum plate) with masking tape around the edges forming an open hollow cylinder above the plate.
8. Pour a thin layer of pitch across the entire surface of the aluminum plate.
9. Be careful not to pour too much pitch that it overflows the tape.
10. Be careful also to pour fast enough that the pitch flows to the edge of the circle.

The next step in preparing the pitch lap is to cut or press channels into the lap and to also trim the edge to remove any sharp points that may have been formed. The pitch lap needs deep channels in order for the grinding compounds or polishing compounds to flow freely. It is natural for these channels to disappear as the lap is pressed or as the lap is ran on the work piece. The lap must be inspected upon each run to verify that the fit is still good and that the channels are deep enough. The pitch lap channels may be cut in with a razor blade or pressed in by the use of a razor blade or by the use of a 3D printed tool. The demonstration of these methods may be observed below in **Figure 19**.

Figure 19 Pressing pitch (left), pressed pitch with 3D printed tool (center) and tool (right).

To cut the channels in the pitch the lap must be at or near room temperature. When using a razor blade, the process for cutting pitch tools is to score the pitch tool in one direction with the razor blade at a 45 degree angle and to repeatedly cut in the same direction multiple times. Next, in the process of the same cut the razor blade can then be rotated to -45 degrees from the normal to extend the channel on the other side. Once the cuts are made in one direction the lap may be rotated by 90 degrees and the same procedure is used. Once the straight channels are cut into the lap, the edge of the pitch tool should also be cut along the periphery with a razor blade at an angle of 45 degrees to eliminate any sharp points along the edge. The details for cutting channels in the pitch lap is below in an ordered list.

1. Orient the lap with the pitch facing upwards
2. Take a razor blade at a 45 degree angle to score the pitch lap in straight lines.
3. Cut deep channels by striking the previous score at -45 degrees.
4. Cut as many channels as desired across the X direction of the Lap.
5. Rotate the Lap 90 degrees and perform the previous steps.
6. Cut the edge of the pitch tool along the periphery at an angle of 45 degrees.

For more rapid and somewhat more predictable patterns the pitch lap may be pressed by using a 3D printed tool or by quick and steady use of a razor blade. To press the channels into the pitch lap, the pitch must be warm and must be able to flow quickly. Achieving the desired temperature requires the use of the oven and to set the temperature to 120 degrees Fahrenheit. Once the oven has reached the desired temperature the lap must be put in the oven for approximately 2 minutes. Now, the pitch lap is removed, and the razor blade is quickly pressed into the pitch with no angle. Once the razor is deep enough it is rocked back and forth in angles of +/- 45 degrees. Upon rocking a few times, the razor blade is then lifted straight up. This process is repeated in the x direction until the desired channels have been pressed in. Next, the lap is rotated 90 degrees and the same process is repeated to produce the channels in the Y direction. Once it is finished, the edge of the tool should also be cut by a razor blade to eliminate the edge effect. The details for pressing channels into pitch using a razor blade are listed below in an ordered list.

1. Heat the pitch lap for roughly 2 minutes at 120 degrees F heat.
2. Pull the pitch lap out and firmly push a clean razor blade into the pitch.
3. Tilt the razor back and forth to keep the pitch from attaching to the blade.
4. Continue the process until the desired channels are pressed in the X direction.
5. Rotate the lap 90 degrees and perform the previous steps.
6. Cut the edge of the pitch tool along the periphery at an angle of 45 degrees.

To finish the pitch tool, for a plano surface the optician must press the pitch lap against a Flat surface. First, a clean sheet of paper should be placed above the reference flat, while the lap is placed on top of the paper with the pitch facing down. Secondly, applying a lead weight, as shown below in **Figure 20**, to the top surface of the tool will decrease the overall pressing time. The lap may be checked in 15 to 30 minutes to inspect the quality of the fit of the pitch tiles against the paper. The lap is now flat, pressed, and ready to be used as a polishing tool on the CCPM for running against a flat work piece. For curved surfaces the lap will have to be pressed against the work piece for an intimate fit to the work piece.

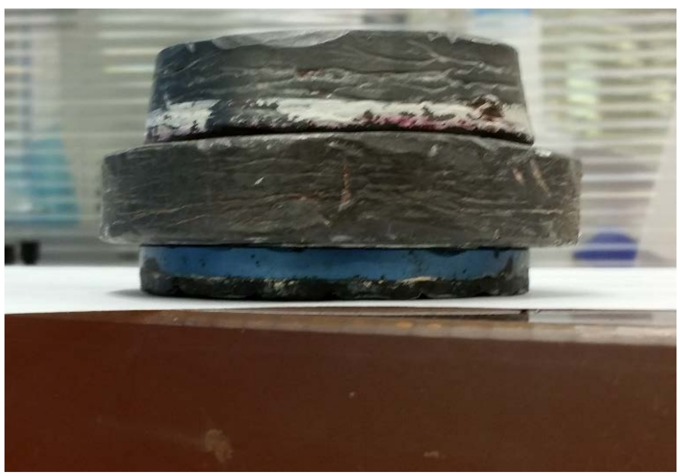


Figure 20 Pitch lap pressed on optical flat with paper interface and lead weights on top.

There are two methods of pressing the tool against a work piece: wet press and a warm press. The wet press assumes that the shape of the lap is close to the curvature of the work piece. Liquid slurry is poured onto the work piece, the pitch tool is placed on top of the work piece, and apply lead weight to press the pitch against the work piece. The warm press is used when the pitch needs to flow farther or faster to make better contact with the curved surface. The lap may be placed in a beaker with hot water for a few minutes to allow the pitch to flow better. A similar method, the lap may be placed in the oven at 120 degrees F for two to five minutes. Once the lap has been warmed, pour polishing compound onto the surface of the work piece, place the lap on top of the work piece, and apply lead weight to accelerate the pressing out of the lap. The lead weights must be centered as best as possible on the surface of the lap to reduce the amount of tip or tilt that may be induced in the pitch. The next topic in the fabrication of pitch tools is to choose which grinding compounds to use during the grinding phase.

3.1.3 Grinding Phase

The polishing experiment requires the use of various grinding compounds depending upon the surface roughness. Before performing a run, the work piece is measured through the use of the interferometer. If the surface is too coarse to be measured with the interferometer than the grinding phase begins. The type of work piece determines the grinding tools used during the grinding phase. For softer materials like photopolymer resin a pitch grinding tool may be acceptable. For harder materials like glass a rigid iron grinding tool may be needed to achieve the desired material removal. The iron grinding tool is included in this report for completeness. In the interest of Stroking experiments, it is not recommended to use an iron grinding tool on contact with a work piece that has an optical surface as it is a rigid interface that doesn't conform to the shape of the work piece.

3.1.4 Grinding Tools

During the grinding phase it is important to select the proper grinding tool for the right application. Many grinding and polishing experiments were performed with Pyrex, BK7, and 3D printed photopolymer resin. For the Pyrex glass the iron grinding tools, shown below in **Figure 21** and **Figure 22**, were used to achieve a finer coarse grind. The measurement of the grinding tools radius of curvature via a spherometer is recommended for selecting the correct tool to achieving the desired level of flatness. If the grinding tool radius does not meet the required flatness specification it may be ground upon by a grinding tool that meets or exceeds the flatness specification. These grinding tools may be used on the CCPM for grinding experiments if CNC is required for a specific work piece. However, these grinding tools are likely to completely refigure the work piece. This is not a desirable outcome for Stroking experiments and the smoothing of Freeform Optics.

Figure 21 Grinding tools available for use on the CCPM for grinding experiments.

Figure 22 Grinding tool with Radius of Curvature of 1000 m used for conditioning other grinding tools.

3.1.5 Grinding Compounds

The grinding phase includes the use of loose abrasives for the use of grinding. The grit starts out coarse and decreases in coarseness as the grinding continues to produce a better surface roughness (measured in RMS). Grinding compounds are selected depending upon the material of the work piece and the measured profile of the surface of the work piece. For glasses, photopolymer resins, and metals the grinding compounds may have different effects upon the materials. For instance, grinding on a glass work piece the loose abrasive selected may be more hard than that for grinding on a photopolymer resin work piece. Alternatively, grinding on a metal work piece with a water based grinding compound may cause quick oxidation of the metal resulting in a chemical process that damages the surface of the work piece. For metals, it is imperative to use an oil based grinding compound or slurry to ensure that the grinding tool is able to move smoothly over the work piece while not causing any oxidizing of the work piece. This chapter highlights the most successful grinding compounds used in performing these experiments: Silicon Carbide, Aluminum Oxide, and 1200 mesh diamond compound followed by a discussion of their results.

The primary loose abrasive in the beginning of the grinding experiments are varying grades of Silicon Carbide. The Universal Photonics Unasil Black Silicon Carbide ranks third in hardness. The hardest material being Diamond and the second hardest being boron carbide [10]. The Silicon Carbide is found to be nearly 7.5 times stronger than Aluminum oxide [10]. The hardness on the Knoop Scale is 2850 and ranges in size from a mesh size of 8 (coarse) to a mesh size of 1600 (extremely fine). Silicon Carbide has been used extensively for the grinding of glass Pyrex blanks and 3D printed photopolymer resin.

The secondary grinding compound used after the Silicon Carbide in this discussion is Aluminum Oxide. It is also known as Rhodes Alumina or Alumina. Aluminum Oxide is available in size from 50 microns down to the size of 0.05 micron, however, in grinding the minimum particle size used is approximately 5.6 microns. MICROGRIT WCA is an aluminum oxide powder developed by Micro Abrasives Corporation. The WCA number specifies the particle size of the Alumina. The designation on the packaging of the Alumina may have a “T” for suspension treatment designed for water based slurries. For glass and photopolymer resin, it is recommended to use the Alumina with a “T” designation mixed with water. The Grinding recipe, shown below, in **Table 6** indicates that the work piece started at 4 microns before switching to Alumina and down to 1.5 microns after varying grades of Alumina.

Grinding			
Tool	**Average Particle Size [micron]**	**Run Time [hours]**	**Final RMS [micron]**
SiC 220 Mesh with Pitch 64/73	74	2	4.6
SiC 80 Mesh with Pitch 64/73	233	2	4
Al_2O_3 WCA 15 with Pitch 64/73	9.06 – 11.13	1.75	1.83
Al_2O_3 WCA 9 with Pitch 64/73	5.60 – 6.75	2	1.5

Table 6 Grinding recipe for 3D printed photopolymer resin performed on Strausbaugh.

For the grinding of metals, the olive oil based slurry was mixed with a hard loose abrasive for optimal removal rates. Two grinding compounds performed extremely well in grinding Aluminum: 1200 mesh diamond compound and aluminum oxide. The 1200 mesh diamond compound from the Crystalite Corporation was found to perform very well. The hardness of the diamond ensured good material removal while the particle size remained relatively small at around 15 microns. The diamond compound was applied to a felt pad. The diamond compound was suspended in olive oil for proper use [11]. The coarsest diamond powder sold by Crystalite is 100 mesh which has a particle size of 150 microns. The finest diamond powder sold by Crystalite is 100,000 mesh which has a particle size of ¼ micron. The Aluminum Oxide also performed well with an Aluminum work piece. The Alumina with a "TO" designation indicates suspension treatment designed for oil based slurries [11]. Alumina's "TO" designation is essential when grinding metals to prevent oxidation which is a chemical process that damages the surface of the work piece.

The initial surface of the 3D printed optic used in the grinding experiment was 5.947 microns RMS. The use of the harder Silicon Carbide with varying mesh sizes reduced the surface roughness down to 4.6 microns RMS and then eventually 4 microns RMS. The Grinding recipe, shown above, in **Table 6** shows a higher average particle size for the 80 Mesh Silicon Carbide. The results in this table are predicted to be decreasing in Average Particle Size (in microns) while the Final RMS (in microns) is also decreased. This result may have been the product of a contaminated bottle of

220 Mesh Silicon Carbide because this mesh is finer than the 80 Mesh but did not yield superior results. As the grinding phase elapses, finer particle sizes (decreasing WCA/higher mesh) are used on the work piece.

Toward the end of the grinding phase the Alumina WCA #15 with average particle sizes of 9.06 to 11.13 microns are used. Finally, wrapping up the grinding phase the WCA #9 with average particle sizes of 5.6 to 6.75 microns are used. It may be appropriate to continue with decreasing WCA numbers but upon a work piece convergence of less than or equal to 1.5 microns the polishing phase now begins.

3.1.6 Polishing Phase

Upon completion of the grinding phase the polishing phase begins. Polishing is the start of using finer grit sizes on the order of 1 micron or less. The polishing tool almost always uses pitch as the interface between the rigid plate and the polishing compound. There are exceptions to this rule but in general a lap using pitch outperforms most other polishing tools due to its unique properties of conforming to the shape of the work piece [7]. The polishing phase also requires extreme care in the setup of polishing tools to avoid contamination. The possibility of contamination in an Optics Shop can be the result of an unclean workspace, mislabeled squirt bottles, and unfortunately in rare cases unknown contaminants in the preferred polishing compound. The risk of contamination must be present in the Opticians mind when preparing experiments. Any failure to address the risk of contamination may prove to set back an experiment in excess of twelve days or more depending upon the size of the contaminant and the stage of polishing. For smoothing experiments, the risk is elevated due to the fact that the goal of smoothing is to not change the surface figure of a work piece. It is almost impossible to maintain the surface figure of a work piece to exact specifications when a careless experiment yields a contaminant that causes a series of scratches. It is imperative that the Optician performing smoothing experiments is understanding of the risks and also seeks out the right expertise in setting up polishing experiments, keeping workspace and work pieces clean, and mindful of the cleaning and handling of optics.

3.1.7 Polishing Tools

The primary polishing tools used for smoothing experiments includes the use of Pitch. Specifically, all smoothing experiments to date have used a mixture of Gugolz Pitch numbers 64 and 73. This mixture creates a Medium Soft pitch by mixing the two varieties of pitch. The pitch lap must be inspected before performing polishing experiments to verify that the pitch lap has deep channels for the movement of slurry and the ability for the pitch to flow. The pitch lap needs to be checked for any sharp edges or any brittle areas that may contain sharp fragments of pitch that may break off during the polishing run. Upon performing polishing runs without seeing any noticeable improvements to the surface RMS it is recommended to make a new lap. Pitch may not respond properly if it is heated up too fast. It may also not conform properly to the work piece if it is not pressed out with the correct weight and time. All of these items must be taken into consideration during the polishing experiments to ensure that valuable time is not wasted. The back plate of the lap most commonly has a spherical hole allowing for a good contact between a spherical ball mounted at the end of a rod. This tooling as described previously allows the Strausbaugh Machine or the CCPM to move the lap smoothly over the work piece. The desired amount of pressure applied to the polishing tool is generally in the range of 0.2 to 0.3 Pounds per Square Inch (PSI) for most experiments.

The secondary type of polishing tools involved the use of polishing pads. The disadvantage of using the polishing pads in the experiments is that the pads are often missing labels and specifications. It is extremely difficult to look up the type of polishing pad with certain details such as the part number and lot number without knowing the manufacturer. At least four different types of polishing pads have been used in the experiments but their technical specifications are unknown and therefore the results have not been discussed. It is recommended for future experiments to contact known vendors and to purchase a set of soft polishing pads and to increase in hardness to determine which pad will meet the desired smoothing specifications.

3.1.8 Polishing Compounds

The polishing phase includes the use of extremely fine loose abrasives for the use of polishing. The polishing compound grit size used in the polishing experiments ranges from 9 microns down to approximately 0.05 microns. The polishing process is an iterative process that requires finer and finer grit sizes to be used to achieve the desired optical surface roughness (measured in RMS). The polishing compounds are selected based on their average particle size, their hardness, and their ability to be used with various polishing tools. The polishing compounds may be used with a pitch tool or with a polishing pad. There were four different types of polishing compounds used in the stroking experiments on the 3D printed photopolymer resin. The process of converging to a smooth surface often relies upon varying the type of polishing compound and polishing technique. This chapter highlights the most successful polishing compounds used in performing these experiments: Cerium Oxide, Rouge, Diamond Powder, and Alumina.

Once the polishing phase has begun the common choice of polishing compound for use on glass and photopolymer resin is to use Cerium Oxide with Rare Earth Metals also known as Rhodite 906. The Universal Photonics Rhodite 906 polishing compound has an average particle size of 1.15 micron while the maximum particle size is 7.7 micron [10]. Cerium Oxide is known to be one of the best polishing compounds due to its softness and small particle size. The polishing recipe, shown below, in **Table 7** indicates that at two separate polishing phases Cerium Oxide was used and each time had very successful polishing results. The first result shows that in an hour the surface RMS was reduced from 1.5 microns to 680 nm. The second result shows that in seven hours the surface RMS was reduced from 77.5 nm to 29.9 nm. These two results show exceptional polishing performance when in the range of tens to hundreds of nanometers. Another popular polishing compound amongst opticians and lens makers include Iron Oxide also known as Rouge.

Polishing Tool	**Average Particle Size [micron]**	**Run Time [hours]**	**Final RMS**
Rhodite 906 Pitch 64/73	1.15	1	680 nm
3M™ Trizact™ Diamond Tile 677XA	9	2	166 nm
W1.5 Diamond Powder with Pad	1.5	0.75	77.5 nm
Rhodite 906 with Pad	1.15	7	29.9 nm
Alumina A	0.3	3	8 nm
Alumina B	0.05	2.5	6 nm

Table 7 Polishing recipe for 3D printed photopolymer resin performed on Strausbaugh.

Ball milled rouge has a small particle size on the order of 1 micron and is typically suspended in water. For long periods of time, the rouge may begin to settle and the squirt bottle may start to look somewhat transparent. A quick shake of the bottle will produce a dark red or dark brown color almost instantaneously. For some super polishing, rouge has been used to settle in the pitch tiles [7]. Upon the particles pressing into the pitch, the slurry may be varied to use reverse osmosis water to further smooth the surface.

A novel polishing material that is self-contained is the Trizact™ Diamond Tile by 3M™ [12]. This innovative material functions as "a structured, fixed abrasive composite pad consisting of an inorganic abrasive (vitreous diamond agglomerates) in an organic binder (cross-linked polymer)" (3M™ Trizact™ Diamond Tile 677XA) [12]. The Trizact™ doesn't require a slurry while maintaining extremely high potential for lapping on a variety of surfaces [12]. The Trizact™ was extremely successful in reducing the surface RMS of the work piece from 680 nm down to 166 nm in two hours. For this experiment, there was only one grade of Trizact^{TM} that was used. Due to the clean properties of the Trizact^{TM} not requiring messy slurries is an attractive solution.

Diamond powder is a great polishing compound due to its fine particle size and extreme hardness. The 1.5 micron diamond powder used in the stroking experiment in **Table 7** indicates that it was able to reduce the surface RMS by over 50% from 166 nm to 77.5 nm. The Diamond powder may be combined with olive oil as the slurry.

Finally, there exist at least two super fine grades of Aluminum Oxide. The two types of Alumina polishing compound used: Alumina A has a grit size of 0.3 micron while the Alumina B has a grit size of 0.05 micron, mixed with olive oil provides a good polishing slurry with good hardness and small particle size. The discussion of Alumina was covered in section 2.4.5 and likewise needs a similar mention as a polishing slurry when using finer grades of Alumina. The Alumina A was used to reduce from 29.9 nm down to 8 nm. The next finest grade, Alumina B, was used to further reduce the surface from 8 nm down to 6 nm. The final results of both the grinding and polishing of the 3D printed work piece are discussed in the next chapter.

3.1.9 Optimal recipe for stroking surface

The recipe for polishing a 3D printed photopolymer resin optic was found by using the Strausbough machine with a 30 RPM eccentric speed and a 50 RPM spindle speed. The Strausbough is excellent at grinding and polishing optics due to its smooth motion and predictable stroking pattern. This machine is generally used for figuring as the stroke is setup to cover at least half the diameter of the optic. It is common to set the center of the tool to be at the center of the work piece and adjust the stroke so that the tool reaches to the edge of the optic. For this experiment the stroke was set to under half the diameter of the optic such that the center region of the optic would become nicely polished and the edge of the optic would remain close to the original reference surface.

The primary purpose for using the Strausbaugh was to develop a method of comparison against the CCPM. Even though the Strausbaugh is primarily used for Figuring it was still helpful to determine a recipe for grinding, polishing, and stroking the 3D printed photopolymer resin optic. The recipe includes the necessary steps to move from the grinding phase to the polishing phase with the machine run time to produce the desired results. This is insightful to the User because it allows more focus to be applied in the development of a stroke instead of tooling and grinding/polishing compounds and/or pads.

The grinding recipe mentioned previously in Section 3.1.5 in **Table 6** shows that a 3D printed photopolymer surface may need up to approximately 8 hours before the surface is ready for polishing. The polishing recipe mentioned above in **Table 7** shows the same work piece may need up to 11 hours of polishing time with various laps in order to have a good surface finish. The total time required to converge on 6 nm RMS surface roughness was 24 hours. The initial surface RMS was measured by the Profilometer to be 5.947 microns. The desired final target of a micro-roughness of 2 nm RMS may be achievable with slight variations to the polishing recipe and more polishing time. This result is possible of yielding a surface capable of operating in the visible spectrum.

3.1.10 Machine setup procedures

For successful optimal smoothing experiments, paying attention to details when setting up the machine to perform experiments is crucial. The polishing head and tool must be aligned by using a laser pointer to make the chuck concentric to the work piece. The work piece may be adjusted while keeping the chuck in the same spot. When the work piece and chuck are aligned well, a minimum of three support points are recommended to hold the optic in place. The CCPM table is constructed of T-slotted aluminum which allows for ¼ inch hardware to be used to clamp the work piece. In addition, there are two large red clamps that may also be used for securing the work piece. The work piece is recommended to be secured to a plate through the use of double sided tape, hot glue, or wax. Different methods may be applied depending upon the geometry of the work piece. The use of a plate or interface holding the optic may allow for quicker and easier cleanup.

The tool must be inspected to verify that sufficient channel depth has been cut or pressed into the pitch and that no sharp edges are on the lap that would potentially scratch the surface.

The tool may be pressed on the work piece with slurry applied and lead weights to accelerate the press. Upon waiting fifteen minutes, the weights may be removed and the tool may be moved around by hand to check that the pitch is in good contact with the work piece.

The sphere at the end of the rod must be held in good contact within the tool to ensure that excessive pressure and moments from the orbital movement of the chuck does not contribute to the force and pressure applied by the lead weights used for constant pressure.

The four tooth chuck polishing head can be hand tightened when aligning the tool to the machine. When the work piece has been placed on the optic and the run is ready to go it is highly recommended to further tighten the chuck. There are two small allen wrenches near the table that can be used for tightening the chuck. The application of more torque will cause the chuck to hold a much firmer grip on the tool.

Before changing to a new, untested, polishing compound it is essential to test that the pitch and the chemical makeup of the polishing compound do not have a reaction that degrades or alters the chemical properties of the pitch.

4. CCPM Optical Fabrication Experiment Results

The CCPM was used in numerous experiments with varying types of materials as work pieces, various slurries were used, varying machine configurations, varying software parameters, and varying software algorithms. The overall CCPM performance will be evaluated in this discussion. The work pieces included in this discussion include: Pyrex blanks, aluminum mirror, Red IR material, Yellow material, and 3D printed photopolymer resin. In the previous section, the interferometry and profilometry metrology techniques were discussed in great length. In the Data Analysis section these techniques are used to determine the overall machine performance on the work pieces used in the grinding and polishing experiments.

4.1 Metrology

The definition of metrology is the scientific study of measurement. In the field of Optics, the art of fabrication rises and falls on metrology. An optician cannot fabricate a part better than the current technical ability to measure that part. The saying goes, “You can only make what you can measure.” The metrology used in these experiments, shown below in **Figure 23**, included multiple instruments: Zygo White Light Interferometer [8] and KLA Tencore Alpha Step Profilometer [9]. The metrology devices will be discussed in detail: the basic theory of operation, setup of the machines, taking measurements, and post processing of the data. The integration of the metrology into the fabrication experiments is essential to efficiently converging upon a good result. This process involves taking meticulous care in measuring the same regions of the work piece for each metrology device. The work piece is measured after two to four hours of a stroking run to verify the performance. The measurement of the work piece is essential in determining to keep using the same slurry or to move on to a finer grit to achieve a smoother surface finish. The decision making process for selecting a different grinding/polishing tool and slurry is detailed in **Figure 24** below.

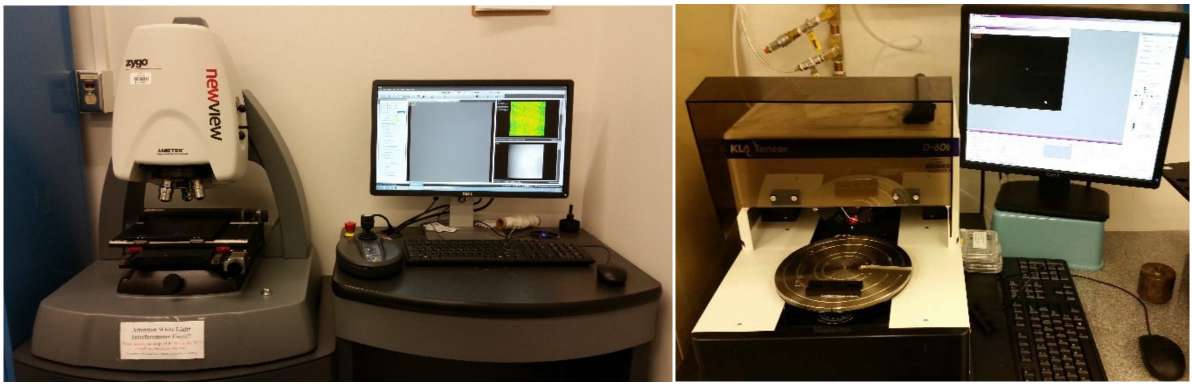


Figure 22 ZYGO New View White Light Interferometer (left) [8].
KLA Tencore D-600 Alpha Step Profilometer (right) [9].

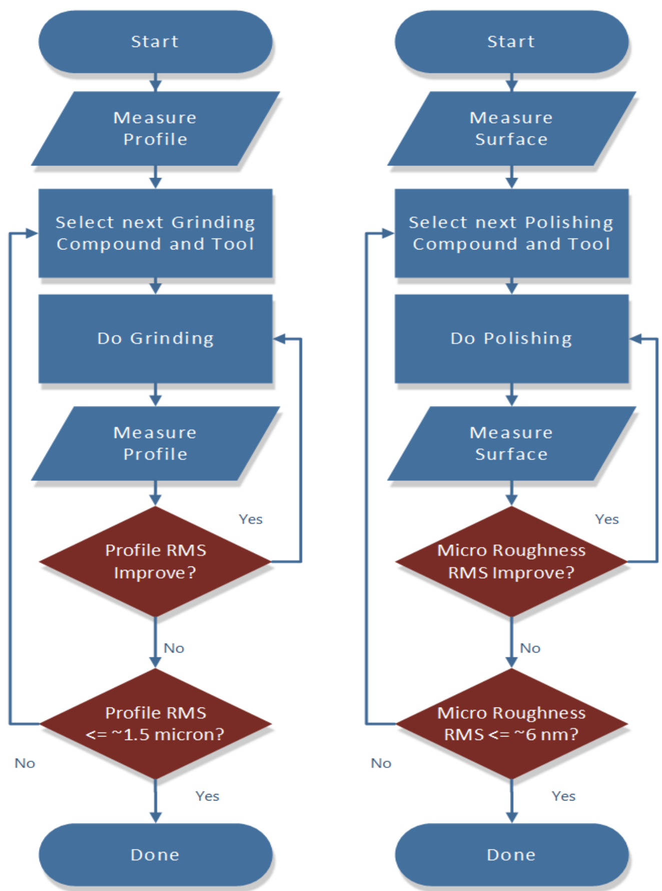


Figure 23 Grinding process flow chart (left). Polishing process flow chart (right).

The primary difference between the grinding process and the polishing process is the level of smoothness of the profile whether it be around 1.5 microns or 6 nanometers RMS. During the grinding process the surface is too coarse for the interferometer to record a good surface measurement. During the polishing process the profilometer and interferometer are used to assess the RMS of the surface quality.

4.1.1 White Light Interferometer

The ZYGO New View White Light Interferometer is the premier metrology device for measuring the surface micro-roughness of optical components. ZYGO's workstation comes complete with the White Light Interferometer, three stepper motors for XYZ stage motion, two manual tip and tilt adjustment knobs for leveling the stage, and a software interface for controlling the motion of the stage and interferometer. The Interferometer Specifications are listed below in **Table 8**. The specifications for the 10X Objective used in the measurements are listed below in **Table 9**. These specifications show that the Zygo New View 8300 White Light Interferometer is the premier instrument for measuring the surface micro-roughness of a work piece. The User is recommended to average at least three total measurements to greatly reduce errors in the measurement.

Interferometer Specifications	**Zygo New View 8300 White Light Interferometer**
Vertical Scan Range	150 microns with precision Piezo drive 20 mm with extended scan
Surface Topography Repeatability	0.2 nm
Repeatability of RMS	0.01 nm
Optical Lateral Resolution	0.34 micron (100X objective)
Spatial Sampling	0.04 micron (100X objective 2X zoom)
Maximum Data Scan Speed	96 micron/sec
Step Height Repeatability	0.1%
Height Response Linearity	<= 30 nm
Step Height Accuracy for Extended Scans	0.8%

Table 8 Zygo New View 8300 White Light Interferometer Specifications [8].

10X Objective				
Power	**FOV (mm)**	**Optical Res (micron) Sparrow Criterion**	**Spatial Sampling (micron)**	**NA**
0.5X	1.68 x 1.68	0.95	1.64	0.3
1.0X	0.83 x 0.83	0.95	0.82	0.3
2.0X	0.42 x 0.42	0.95	0.41	0.3

Table 9 Zygo New View 8300 Typical Objective Chart [8].

4.1.2 Alpha Step Profilometer

The profilometer was used before any experiments were performed on the work piece to establish a reference surface. Upon completing an experiment, a new profile is measured with the profilometer and its profile is compared to the reference surface. The profile is expected to stay the same near the outer radial edge where stroking wasn't applied to the work piece and it is expected to decrease in magnitude with the same shape in the region where stroking was applied to the work piece. The particulars of the results obtained with the profilometer will be discussed in Section 4.2 titled Data Analysis.

The KLA Tencore D-600 Alpha Step Profilometer is a form of contact metrology that involves using a diamond tip to gently press against the optics surface. As the probe tip moves in one axis direction the deflection on the tip is measured and the height of the surface is calculated from this deflection. The profilometer has a limited scan range at the specified resolution so multiple scans may be necessary to cover the entire surface of the optic. The profilometer specifications are listed below in **Table 10**. The software includes a method of stitching and data leveling, as shown below in **Figure 25**, that ensure that the data taken in different profiles can be stitched together and the slopes of each profile can be preserved and converted into a single profile.

Profilometer Specifications	**AlphaStep D-120**
Sample Stage Diameter	200 mm
Scan Length Range	55 mm maximum
X-Y Stage Translation	150 mm x 178 mm
Sample Thickness	30 mm (~1.25 in)
Stage Positioning	<5 micron
Vacuum Chuck	Standard
Vertical Resolution	0.38 A Least Sig bit
Lateral Resolution	100 nm (Stylus dependent)
Vertical Range	1.2 micron
Step Height Repeatability	6 A or 0.1% (one-sigma), whichever is larger
Max Data points per scan:	120,000
Sample Viewing:	Black and White or Color Camera
Standard Magnification	40–160X motorized zoom
Field of View:	1.4mm
Stylus Tip Radius:	2.0 microns (standard)
Stylus Force Range:	003–10mg (programmable)
Software Leveling	Yes-cursor-controlled, or Auto-Leveled (for repeated scans)
Stress Option:	Yes

Table 10 D-Series AlphaStep Profilometer Specifications [9].

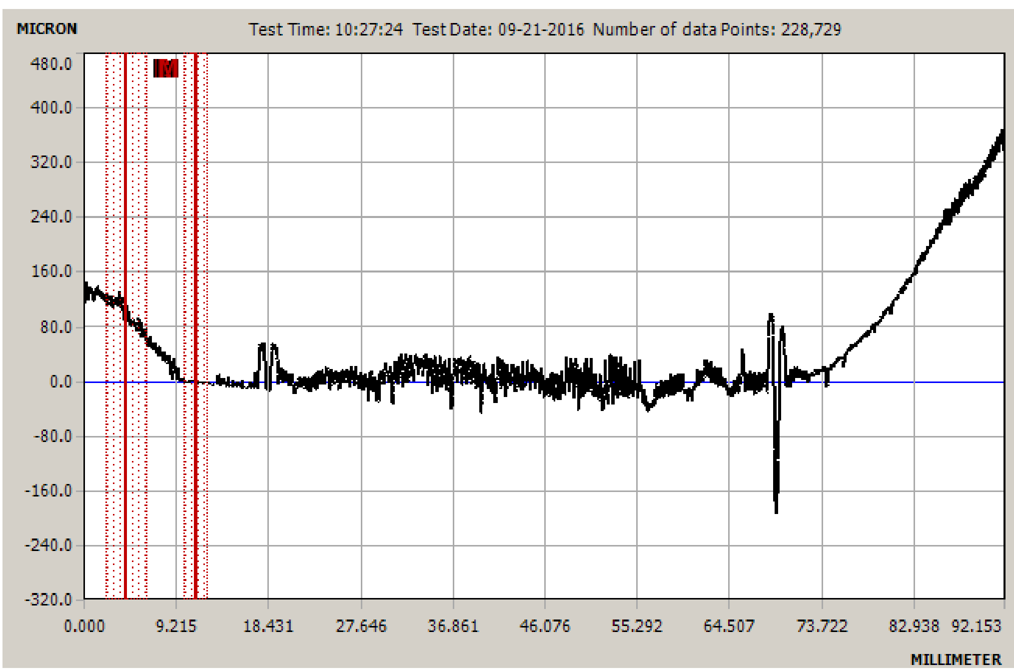


Figure 24 Profilometer data after performing stitching and leveling [9].

4.2 Data Analysis

The CCPM performance is measured primarily through the use of rigorous data analysis to check the surface of the work pieces used in the stroking experiments. This chapter further explores the results obtained in the polishing experiments by the interferometer and profilometer. The analysis of profilometry results are useful in determining how well the CCPM can perform in grinding experiments but may not prove to be an accurate enough method to determine the quality of the post processing of freeform optics. Using the profilometer before and after the grinding run and taking the difference and plotting the Z position verses the X position will yield one dimensional slice of the surface of the work piece. The work piece may also be setup in such a way that the reference surface begins at a farther radial distance than the clear aperture of the work piece. The work piece clear aperture is the most important region of the work piece that has to meet predetermined optical specifications.

The CCPM may be optimized to run close to the clear aperture leaving the outside reference surface untouched. The reference surface will then be accurately compared throughout the stages of the experiment. The graph below in **Figure 26** shows the reference surface, the surface after a nine hour run, and the surface after thirty hours of run time. It is easy to see that the reference surface matches the two other surfaces for nearly 2.5 mm in the x direction. This is a verification that the outer radial profile was not touched by the CCPM and is an accurate reference surface. The profile of the nine-hour surface shows that approximately ¼ of a micron was removed in the span of nine hours over the clear aperture of the work piece. The profile of the 34.65-hour surface shows that the CCPM has removed more than 2.5 microns over a distance of approximately 30 mm in the region of the work piece clear aperture.

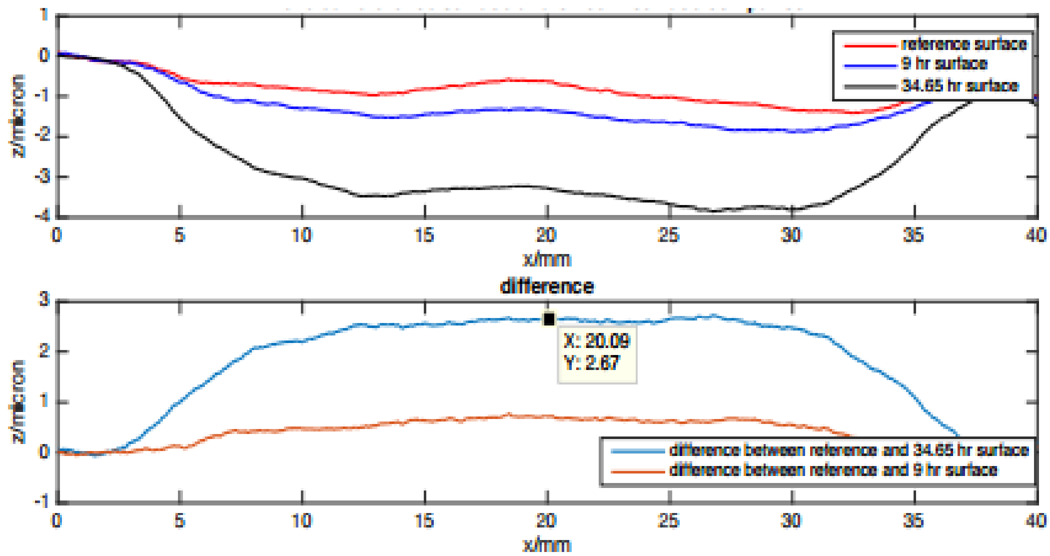


Figure 26 Profilometer of reference surface, nine hour surface, 34.65 hour surface (top), Material removal in the Z direction verses X position (bottom).

The next method for verifying the quality of the CCPM is to use a full aperture interferometer such as the Zygo Verifier. This instrument can measure the entire surface height and output the results in a binary format that can be read through the use of a SAGUARO [6] Module called "ReadMetroProDatX." The data is read in through SAGUARO [6] and then is converted to the MAP data type. It is imperative to take a measurement before performing the first smoothing run and after subsequent runs. While performing experiments, it is extremely important to keep track of the run time, the pressure on the surface, and the stroking run parameters. Upon converting the data into a MAP data type the data can be better analyzed through the use of Zernike terms. It is recommended to specify up to 300 to 500 Zernike terms by using the "Map2Zernike" SAGUARO [6] module to get an extremely accurate fit of the work piece surface. For determining the performance of the CCPM the operator may continue recording Before and After Maps and then converting these Maps into Zernike data types as described. Upon saving the data as a Zernike data type it is recommended to save a copy of the data and then to incrementally remove Zernike terms using the "ZernikeTermRemoval" module. Using an iterative Zernike term removal process characterizes the whole surface shape and how it changes after each run. The Zernike Term removals above may then be restored back to a MAP data type by using the “Zernike2Map” module. Next, the MAPS have to be subtracted in the order of After – Before through the use of the “MapCombine” module. Note: The “MapCombine” module requires that two SAGUARO [6] data types be selected before it appears in the list of modules. Next, “MapStatistics” module may be run on each of the maps to show the useful statistics such as Surface RMS and Surface P-V. Alternatively, the “MapPlot” can be updated to perform the same analysis functions and record the values of RMS and P-V in the title of the plot.

The next method for verifying the performance of the CCPM is through the use of the Zygo White Light Interferometer to analyze the micro-roughness of the work piece. The procedure includes aligning the work piece to the interferometer. Next the interferometer is focused on the surface of the work piece to locate the fringe pattern showing that the Optical Path Difference is approaching zero. Once fringes are visible the measurement may be made. It is highly recommended to always take averages of the data. It is highly likely to receive a low number of noisy measurements that may be significantly reduced through the use of averaging at least a minimum of three measurements. The results from the interferometer may be read in through the SAGUARO [6] module ReadZygoNewView. The Zernike terms: Piston, Tip, Tilt, Astigmatism in X, Astigmatism in Y, and Defocus may be removed to evaluate the surface micro-roughness. Due to the extremely small field of view of the White Light Interferometer it is not appropriate to analyze the full 300 – 500 Zernike terms as before because the data does not show the whole surface but only a very small percentage. Since the Zygo New View doesn’t render a full surface map of the work piece it is advantageous to set up a measurement plan that will take multiple measurements of the surface at varying locations. The higher the number of measurements made at varying locations will yield a better understanding of the overall surface micro-roughness. However, this is no simple task, as the measurement plan often requires the Operator to move to the correct focus location in the Z direction before the motion stages move to the next X and Y positions. These measurements as a whole may be grouped together and the RMS and P-V measurements recorded for each measurement. Next, these data points can be binned and plotted as a histogram showing the convergence to smaller and smaller RMS values. The ideal shape of the histogram at the finishing point looks like a narrow Gaussian function at low RMS values and smooths out in increasing values of RMS.

The final method for evaluating the CCPM performance is through the use of a Map to Map comparison. A similar method was described above, however, this method differs in that the surface of the work piece may be registered with a specific mark called a fiducial. The fiducials indicate specific X, Y locations on the surface of the work piece that are of primary interest when performing a measurement plan. These fiducials may be distributed with varying radial zones with a different pattern for each radial zone. The use of Fiducials will allow the Operator to take more comfort in knowing that the same point(s) are being measured for every measurement plan. This may be more appropriate than the use of taking random measurements without paying attention to specific radial zones. The measurement of many points along each radial zone will help to identify the performance of the CCPM at each region of the work piece. It may have better performance in the center.

5. Conclusion and Suggestions for Future Work

The present state of the CCPM used for smoothing experiments has proven its value in the polishing experiments. Multiple students in the LOFT group and other research groups have been able to successfully use the CCPM to perform various polishing and post processing experiments. The CCPM hardware was carefully specified to ensure a smooth orbital motion between the tool and the work piece. The accuracy of the CCPM exceeds the initial requirements. The discussion of the machine setup gave a strong introduction as to how the machine was to be used for stroking experiments. The hardware details were covered in depths ranging from the polishing heads, to the type of tooling used, and the various choices of laps and slurries available to be used on the CCPM. In this discussion it became clear that the success of post processing optical surfaces largely depends upon good optical shop practices and the repeated use of consistent tooling.

The critical features of the software design and development were covered in depth to show various toolpaths and their strengths and weaknesses. The conventional optical shop fabrication methods combined with the computer control is a strong combination when needing to perform freeform post processing. The two primary means of metrology were covered in great detail to give a better understanding of how the post processing of an optic converges to an extremely tight surface micro-roughness specification ranging from 2 nm to 6 nm RMS. The results section has demonstrated that for several different work pieces the CCPM has continued to show improvements upon the surface roughness and micro-roughness. Ultimately, the CCPM is now ready for its next set of challenges in freeform optics post processing.

The future work in Freeform Optics Post Processing with the CCPM includes carefully thought out developments to decrease the overall experiment time. The first challenge the Operators may address is the ability to leave the CCPM running overnight. A plan was put into place to allow for such operations but the hardware wasn't quite ready. The ability to run overnight without an operator present will aid tremendously in the convergence of the tight 2 nm specification. It is recommended that a slurry supply system be used to regulate the proper amount of grinding compound or polishing compound to the CCPM. Various sensors may be used to verify that the compound hasn't settled and that it can continue to be used on the work piece. With the addition of a slurry compensation system, the CCPM would be able to operate in near autonomy, with the operator primarily responsible for metrology.

There exist two mechanical Polishing Head configurations that are recommended to apply to the CCPM in the future development. First, the Polishing Head responsible for determining the stroking recipe would give a good interface for applying uniform pressure contacting the work piece. It is designed to hold the polishing weights above a pin that contacts the tool. This is a similar mechanical design used in many Strausbaugh grinding and polishing machines. The primary advantage to using this Polishing Head is that it has a better interface for securing the tool to the work piece. It consists of the A frame holding the same type of rod with spherical ball on the tip. At the other end of the rod the A-frame secures the rod and is able to hold varying amounts of weights to distribute the pressure evenly across the lap. The pivot allows for compliance in the Tip, Tilt, and Z axis which allows for the possibility to use the CCPM on curved work pieces. The second mechanical Polishing Head configuration would be to use a virtual pivot using a six arm bi-pod configuration which would mount into the 4 tooth chuck instead of using a rod with a spherical ball at the end. The six arms would be connected to two plates. The first plate would include a small rod end protruding to interface to the 4 tooth chuck. The second plate surface includes a small rod end protruding to secure the lead weight to the tool. The bottom of the second plate is the interface that would be used as the grinding tool or the lap. The six arms separating the two plates decouples the motion in the Tip, Tilt, and Z degrees of freedom while constraining the X motion, Y motion, and Rotation degrees of freedom. This design effectively allows for a rigid interface that allows the weight to be evenly distributed across the tool while being free to rotate and move up and down according to the sag of the work piece. The mechanical design of these two Polishing Head configurations would greatly improve upon the quality of experiments currently available with the 4 tooth chuck.

The next future development that would aid the post processing immensely would be a full aperture deflectometry measurement system that could work in both grinding and polishing. The Software Configurable Optical Test System (SCOTS) is a great measurement tool developed in the LOFT group. The addition of such a system with its own motion control and stages that could be controlled via the CCPMs Visual Basic Scripting Interface would allow for powerful in situ measurement capabilities. The SCOTS platform doesn't have a fine enough resolution to measure micro-roughness like the Zygo New View White Light Interferometer. However, SCOTS would better serve as an intermediary aide to give the operator helpful feedback for when the post processing is ready for the next phase.

A secondary measurement device that could provide useful profile information is through the use of a chromatic confocal probe. One such probe is developed by Precitec and has a serial communications interface that would allow for communication between the CCPM. This technology would allow for high resolution in measuring the distance in interferometric mode to accurately reconstruct a 3D surface map of the work piece. This form of non-contact metrology reduces the risk of damaging a work piece via operator error. The maximum data rate of the Precitec CHRocodile is 4 kHz which yields the ability to take a measurement every 250 microseconds. The fast data rate coupled with accurate machine motion over the work piece would likely reduce the metrology time by a factor of 2.

The next development that would greatly increase the performance of the CCPM is to perform an upgrade to the internal motion controller hardware. Currently, the CCPM utilizes the Smooth Stepper through a Parallel port interface. This interface is largely becoming obsolete due to much newer peripherals requiring faster data rates. An upgrade to the Ethernet Smooth Stepper (ESS) would allow for the software to be upgraded to 64 bit operating systems. In the current configuration, the Mach3 CNC software is running on a 32 bit operating system which has some limitations when it comes to the depth of recursive operations that the CCPM can perform. This consequence is limiting when the operator is trying to perform accurate movements that are difficult to program (without using approximations) via an arc, circle, or helical interpolation. When custom tool paths require fine resolution of shapes with varying conics (elliptical, hyperbolic, parabolas, and other aspheres) the 64 bit upgrade also unlocks more memory to be available to the operating system ensuring a finer G-Code depth and resolution available.

The Mach3 CNC software enables the operator to "train" the CCPM to follow a specific toolpath. An interesting idea proposed by Mr. Bryan Smith was for the operator to use a joystick to control the CCPM over specific high areas of the work piece. An interferometric test in the shop would yield the fringes to generate the 3D contours allowing the operator to "draw" or take an image of the interferogram and to trace a custom tool path on the work piece. The Mach3 CNC software MDI tab has two buttons called Start Teach and Stop Teach. Utilizing this interface would allow the operator to run in custom locations and could further reduce the post processing time. Two additional plugins may be needed to perform this optimization. The first plugin that is recommended is the JCode plugin available on the Mach support website. This plugin allows the operator to jog the machine to specific locations and the jog motions are converted into G-Code which the CCPM can perform through running a program. The second recommended plugin is to select one of the Joystick Jog Pendant Manual Pulse Generator (MPG) plugins to allow for smooth jogging control with an Xbox 360 controller. These two plugins coupled with an accurate surface map of the work piece may further reduce the post processing time. Another method to achieve similar results with far more accuracy is to use a G-Code generator. A G-Code generator is a program that takes an input file in various formats: STL, DXF, BMP, etc. and transforms the file into G-Code that can be run on the CCPM. Many open source solutions exist, however, the industry standard is Mastercam which has developed a plugin to generate G-Code from Solidworks. Through the ability to process a Solidworks design and output G-Code may provide even further freeform optics fabrication and post processing abilities.

In conclusion, the Freeform Optics Fabrication and Post Processing software and hardware have achieved success in the ability to perform smoothing of various optics efficiently. This chapter has wrapped up the context of this report and highlighted the crucial elements in the development of this application. The future work has also been discussed which may further improve the performance of the CCPM. The success of the polishing experiments is multi-faceted and results from a well thought out plan with meticulous care in preparing the tools, performing measurements, and observing when to switch tooling.

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