PROCESS DESIGN FOR AERATION OF FACIAL PROSTHETIC

By

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Abstract

Facial prosthetics are becoming a necessary step for the recovery of injured veterans and civilians who have suffered severe facial burning. Current users of such prosthetics are not able to wear the prosthetic for an extended period of time due to uncomfortable conditions created by the silicone material. A solution for this problem was to develop a process for creating small holes similar to skin pores that will both ventilate and aid in the evaporation of accumulated sweat under the prosthetic. The main steps of this process were to create a flexible fixture capable of supporting and securing the prosthetic during processing, creating a process for using a computer measuring machine to scan the varying and unique contours of the human face, and a process for converting the data into code that can be read by a CNC laser to create the holes. The approach for this project was to first design and fabricate the flexible fixture. The fixture consists of a stainless steel base connected and supported with steel rods and various connecting hardware. The top portion of the fixture is a plaster of paris mold that will be unique to each prosthetic and allows the flimsy silicone to be secured without unnecessary damage. The next process was to use a computer measuring machine (CMM) to record all contours of the prosthetic. To accomplish this, linear scans across the surface of the face were completed using a ball-probe taking measurements of its position across 100 points. The ball-probe measured 60 degrees to each side from the middle of the face, incrementing 1 degree for each scan. After the data was collected, an Excel program was used to convert the data into G-code that allowed the CNC controller to process the information. With the fixture loaded into a 4th axis indexer, which allows access to all portions of the face, the final processing step using the CNC laser was completed. The CNC laser used the points measured

from the CMM to position itself for each individual cut. The completed prosthetic was successful in increasing the airflow and ventilation but still requires further research to fully solve the problem. The overall process is sound but will require additional equipment for a fully completed prosthetic. One of the recommended changes is to use a more accurate measuring system such as conoscopic holography or a structured light 3-D scanner which will increase both the accuracy and efficiency of the scanning process. Another recommendation is to incorporate a 5th axis into the head of the laser to reach areas of the prosthetic that are too steep to reach using just a 4th axis. The current cost of both producing the fixture and running the processes is $1,523.96. This cost is justified because it represents less than 10% of the total current cost for a completed prosthetic.

Introduction

The team of Robert Barron and Robert Pivetta has been fabricating large facial prostheses for patients with severe disfigurement (for example, burn victims). Such prostheses could provide significant social rehabilitation, such as avoidance of stares in public places. However, these appliances were found to be uncomfortable to wear for extended periods and thus were seen to have only very limited utility. A project was proposed to use a CO2 laser to drill small ventilation holes into the prostheses. These small pores would enable the prostheses to act very similar to how the pores in skin act by increasing the airflow through the prosthetic and therefore increasing the evaporation rate of any moisture build-up under the prostheses. Because of the complexities of the human face and the unique shape of each prosthesis, how can a practical system for increasing airflow be developed that can be applied to any custom made prosthesis?

Challenges

- Process for scanning the varying contours of the prosthetic into CAD
- Process for cutting small holes into the prosthetic
- Designing a fixture for holding the prosthetic during processing

The new process will be to scan the prosthetic using a CMM and cutting the small holes using a CO2 laser.

- CMM utilizing a ball-probe will use linear scans to create a point cloud mapping the surface of the prosthetic
- CNC CO2 laser will be used to cut small holes into the prosthetic at points generated by the CMM

- Flexible fixture will be developed to hold the prosthetic in the same position for both scanning and cutting

The first challenge is how to develop a process for scanning the varying contours of the prosthetic into a computer CAD program. The challenge with this step is the prosthesis is not a simple flat piece of silicone. The rounded surface and varying slopes associated with the human face presents a unique fixturing challenge and highlights the importance of choosing correct scanning paths. The next challenge is developing a process for drilling holes into the prosthesis. This step will employ the use of a CNC CO2 laser for which settings such as frequency, watts, and focal length will be determined with experimentation. The final challenge that determines the overall success of the project will be developing a method for securing the prosthesis during both laser processing and scanning of the contours. The prosthesis will need to be secured using non-destructive methods so as to not damage the silicone while still providing access to the entire surface of the prosthesis.

The method for solving the problems faced will employ knowledge acquired from various IME course work as well as methods researched for the project. The first challenge of developing a process for scanning the contours of the prosthesis will be solved using a CMM, or computer measuring machine that will utilize a ball-touch probe to scan the features and contours of the prosthesis. The scanning method used will be sequential linear scans across the surface of the prosthesis while indexing a 4^{th} axis of the fixture 1-2 degrees for each scan. The CMM controller will produce a series of points, a ‘point cloud’, which will be used to create a solid model of the prosthesis in CAD. A program will be developed using various algorithms that will compensate for the error created from scanning sloped surfaces with the ball-probe. These errors are created because the CMM records the position of the center of the ball-probe, not the actual surface the ball-probe contacts. This program will also be able to determine the normal vector for each point measured. This will be important because the optimal position for the laser is perpendicular to the surface being processed, i.e. the normal line associated with each point.

A Haas ZM100 CNC laser will be used to cut small 'pores' into the prosthesis. The points collected from the CMM scan will be the points put into the CNC laser controller. The fixture will be rotated using a 4^{th} axis indexer to allow the laser to be perpendicular to the surface of the prosthesis during cutting. For determining the proper settings for the laser an experiment will be employed to determine the optimal frequency, watts, and focal length. This is important in order to create the proper sized holes without causing excessive surface damage to the silicone. The experiment will also determine how close the holes can be drilled without interfering with each other. A material will also have to be researched that will be placed between the silicone and the fixture to absorb any excess laser energy passing through the silicone so as to not damage the fixture.

The challenge of creating a non-destructive method for securing the prosthesis will employ the use of a custom made vacuum fixture. The fixture will be fabricated from stainless steel sheet metal and will be a rectangular box with a half-dome attached to the top to properly fit the curved prosthesis. Holes will be cut into the top of the dome and a vacuum will be attached so the prosthesis can be held without using destructive methods such as clamps or screws. The vacuum will also allow for some of the fumes from cutting to be evacuated from the cutting surface. One end of the fixture will be fitted into a 4th axis indexer while the other end will be held using a live center that will negate any deflection effects caused by the overall weight of the fixture.

The project will be a multi-disciplinary approach with a BIO-MED student. This student will determine any destructive thermal effects the laser will have on the silicone as well as developing a method for measuring the airflow through the drilled holes to determine the change in the thermal properties of the processed prosthesis versus the original design. This step will be crucial in determining the success of the process in creating a more comfortable prosthesis.

The following sections of the report will outline the literature resources used, a more detailed explanation of the experimental methods and fixture design, and the results of the project. The appendix will include diagrams detailing the fixture, the algorithm developed for offsetting the measured points, as well details of the experimental process for determining the settings of the laser.

Background

A quick summary describing the mission statement and purpose of the principle sponsor, Quality of Life Plus (QL+):

Quality of Life Plus (QL+) was founded to generate research, development and innovations to aid and improve the quality of life for those injured in the line of duty for our country. QL+ has two principal focuses: identifying the challenges of those injured; and working with teams of university students and faculty to solve these challenges as part of their educational curriculum. QL+ serves disabled military veterans, first responders and those serving on the front lines. QL+ has two principal focuses: identifying the challenges of those who have been injured; and working with teams of university students and faculty to solve these challenges as part of their educational experience. Imagine performing the rudiments of daily life missing three, two, or even a single limb. One of the key elements the program will foster is independence. QL+ strives to help disabled individuals find solutions to their challenges in order to live, work, and play unassisted.

This project fits perfectly into the mission statement of QL+ because the main goal will be developing an innovative technique for improving a product that will improve the quality of life for injured veterans. This a very important project because of the extent of comfort the prosthetic will provide for the patient. It is very difficult for them to be comfortable in public and this causes tremendous emotional stress. By creating a process to allow them to wear the prosthesis for extended periods of time, their overall quality of life will be increased and they will finally feel comfortable to be out in public.

Literature Review

The literature regarding the process of aeration of a silicone prosthetic can be broken into 4 different sections. The first section regards the principles of fixture design to describe how the fixture used to hold the prosthetic will be designed. The next section is references for the fabrication of sheet metal which will be important for the manufacture of the fixture. The third section contains information for scanning the contours of the prosthetic into a CAD program using a CMM. The final section will cover details of using the CNC laser and the 4th axis indexer.

Principle of Fixture Design

The majority of the fixture will be designed using the CAD program Solidworks and the finite element analysis software Algor. The Solidworks Sheet Metal tutorial and accompanying sheet metal tools will be used to design the body of the fixture. In manufacturing, a fixture is "a work-holding or support device used in the manufacturing industry" (Fixture Design). When designing a fixture there are a couple key concepts that must be kept in mind. A fixture must locate a part, have a method for clamping (securing) the part, and be able to support the part to counteract any machining forces. For locating a part, the idea of a part having 6 degrees of freedom must be kept in mind; the X,Y,Z axis and then the 3 axis's associated with rotating around those axis's. Most of the surfaces must be located for accuracy. For example the primary axis will be identified and used as the surface opposite a clamping force and will be the surface to which crucial dimensions are based from. For a part to be constrained two other degrees must be secured. In the case of this project the Z axis will be secured and serve as the primary axis, and the rotational axis around the X, Y, and Z axis's will be secured. The other component of a fixture is the method used for clamping or securing a part. Methods for securing a part can range from using vises, clamps, set screws, or just plain old nuts and bolts. In this case I will use a non-destructive method for clamping to avoid damaging the silicone material. A series of holes will be drilled into the top surface of the fixture and a vacuum will be used to provide a clamping force that will both secure the part and aid in evacuating fumes created by the laser cutting process.

Sheet Metal Fabrication

Sheet metal fabrication methods will be critical for manufacturing the fixture used for this project. Sheet metal can be cut and bent to desired shape using various methods and machines. The primary methods for cutting sheet metal are shearing and punching processes. Shearing is a sheet-metal cutting operation along a straight line between two cutting edges. Punching involves cutting of the sheet metal along a closed outline in a single step to separate the piece from the surrounding stock (Groover, 2007). Once the outline of the part has been cut the sheet metal will be bent into shape using a process called V-bending. V-bending is a forming method where sheet metal is bent between a V-shaped punch and die on a press brake (Groover, 2007.). The angle of the bend can be varied but will mostly be 90 degrees for this project. Because of the thickness of the sheet metal, bend allowance calculations will need to be performed to ensure the desired angle as well as bending force calculations. Once the sheet metal is cut and bent to the desired shape the seams will be welded together. When deciding the welding type, TIG welding stood out as the best choice for this application. The advantages of TIG welding over other types is its ability to weld a wide variety of metals, a concentrated arc that leaves a small heat-affected zone, and no slag or sparks are created (TIG Handbook). The TIG Handbook will also allow the proper selection of filler rod to be used and procedures for preparing the metal for welding. Groover will also help for weld preparation by providing calculations and tables for the frequency and amperage settings. A special technique called cup-walking will be used because the material (Stainless Steel 304) has problems with carbide precipitation and distortion. Cup-walking is a technique that involves resting the TIG torch cup on the weld groove and gently rocking it back and forth (Cup-walking, 2007).

CMM

In order to scan the contours of the prosthetic into a CAD program, a CMM must be used to measure the exact position of the contours at predetermined points. One of the problems with using a CMM is the error associated with the ball-end scanning probe tip. An error occurs during the scanning of angled surfaces because the CMM records the position of the center of the probe tip rather than the actual surface of the part. The error is small however spread out over hundreds of measurements the error becomes increasingly problematic. To solve the problem an approach to connecting corresponding points between every two adjacent measuring trajectories is proposed to formulate triangular meshes directly from the massive data points, so as to determine the normal vector of each point for probe-radius compensation (Liang, Lin, 2002). From this approach we will be able to use algorisms to create triangular meshes out of the collection of data points and develop curves showing the contours of the prosthetic. Another important consideration when using a CMM is how many sample points are needed to create an accurate copy of the part being scanned into CAD. Sample size is affected by many factors such as the shape of the surface in terms of its complexity, the manufacturing process used to create the part, tolerance specifications, and confidence level of the measured results. As the accuracy increases, the sample size has to be increased (Suleiman, 2008). An algorithm as well as the equiparametric approach and the patch-sized-based sample method will be used to determine the efficient number of sampling points to create an accurate scan. The equiparametric sampling method distributes the sample points equally in the u-v space. The patch-sized-based sampling method is an algorithm that divides the surface into its patches and the points are distributed where a patch has a high number of points proportional to its size (Suleiman, 2008).

CNC Laser and 4th Axis Indexer

The last section of the project will be using a 4th axis indexer and a CO2 laser to create small holes in the prosthetic. When using the 4th axis indexer a new parameter will have to be used in conjunction with normal X, Y, Z coordinates. To index the rotary fourth axis in G codes, simple G0(rapid) moves are used with A or B denoting that the 4th axis will be the moving axis and the number of degrees to index (Leonard, 2008). The Haas Manual will also be used in connecting the 4th axis indexer to the CNC controller and for troubleshooting any problems that might arise.

Lasers in industry can be used for many different processes ranging from welding, spot heat treatment, measurement, and marking, cutting, or drilling. Laser is an acronym that stands for "*light amplification by stimulated emission of radiation*". The physical properties of a laser allow the light generated by a laser to be focused, using optical lenses, onto a very small spot with resulting high power densities (Groover). Laser machining uses this light energy to vaporize thin materials and has the capability of being applied to almost unlimited work materials. When choosing a material the ideal properties for being laser machined are high light energy absorption, poor reflectivity, good thermal conductivity, low specific heat, low heat of fusion, and low heat of vaporization (Groover). Of course it is very difficult to find a material with all of these characteristics so the ideal materials are ones that exhibit the majority of these factors.

There are many factors to consider when using the CNC laser. One of the most critical factors in using the laser is determining the proper focal point. Two factors determine focal length; thickness of the material to be cut and the vertical positional tolerances that will occur during the cutting process. The laser beam enters the lens and converges to a focus, after which it diverges. A small area right between the convergence and divergence of the beam is the optimal area for the surface to be located for cutting (Synrad-focal). For determining the proper focal point an equation from Parallax website that incorporates the diameter of the lens, wavelength of the laser, and the size of the focused area will be used. Another factor in cutting with a CO2 laser is whether or not to use assist gas during processing. Some of the functions of assist gas during processing are to aid in the removal of debris, shield the processing area from oxidizing, and a cooling effect to minimize the heat-affected zones. When processes plastics and organics the assist gas must cool the sides of the cuts to reduce melt-back, charring, and surface discoloration (Synrad-gas). The assist gas will also be beneficial for ejecting gases created from vaporizing the silicone into the vacuum from the fixture. When using the laser for drilling the focused spot from a single laser can produce a wide range of hole sizes in the material. The term 'tip processing' means that only the central part of the Gaussian beam is used for drilling. As the circular diameter of the beam decreases, the power density at the outer edge increases. This power density level corresponds to an effective beam diameter. The wavelength of the laser will limit how small a focused spot can be (Sinbad-tip processing). This is important for the project because the student can use this principle to create the smallest possible holes while still keeping a large enough power density to cut through the material without affecting the surrounding area.

Although all the sections are extremely integrated into modern manufacturing, the process have rarely been put together to solve the problem that the student is proposing.

Design

The design portion of the report will discuss the methods behind developing the fixture used to process the prosthetic. The main material used in the fixture is 0.030 inch type 304 stainless steel. This particular type of metal was chosen due to its excellent corrosion-resistance, weld-ability, and its high flexural strength (bend strength). The support and rotation bars are carbon steel, chosen for its low price and resistance to deflection. By using a solid modeling program and testing each design as it was being fabricated, time and money was saved in both material and labor costs. This process is also known as concurrent engineering where the design and manufacturing engineering teams are integrated to reduce the time-to-market for a product, while also ensuring design errors and manufacturing problems are eliminated early or entirely.

Fixture Design

First Fixture

The main focus for the initial portion of the project was to design the fixture that would be used to hold the prosthetic during processing. A unique approach had to be taken in order to hold the prosthetic due to the fragile material while being flexible because of each prosthetic's different and individual shape. The solution for this would be to create a vacuum fixture that would not damage the prosthetic while keeping it securely in place for processing. In Figure 1, the initial design for the fixture was a sheet metal cylinder with sheet metal circles welded to the ends that could be rotated around its central axis to allow access to all areas of the prosthetic. A series of holes set into the main body of the cylinder would allow for the prosthetic to be held by the vacuum force created in the interior of the cylinder. The metal bar going through the cylinder would be a single entity to ensure concentricity around the rotating axis. Rubber seals would both ensure the metal rod would be secured by friction to the cylinder while maintaining the vacuum inside of the cylinder.

First Fixture Problems

This initial fixture was designed before the prosthetic was examined and an error in the design was soon realized. The prosthetic encompassed more of the face than originally anticipated and would not be able to lay flat on the cylindrically shaped fixture. The first fixture design was scrapped but the vacuum and rotation aspects of the fixture were carried over to the second design.

Second Fixture

The second fixture was designed with the mindset of creating a more unique system for supporting the prosthetic on the fixture. Keeping the aspect of using a vacuum to hold the prosthetic, sheet metal would still be the main material used for the body of the fixture. In order to create a more unique holding surface, the prosthetic was measured and a dome was modeled that would be able to support the depth and length of the prosthetic. In Figure 2, a box was used instead of a cylinder in order to accommodate the dome. To create the box a rectangular piece of sheet metal was bent using a press brake to bend two of the sides up perpendicular to the body of the sheet metal. To finish the box, side pieces and a top piece was cut out using the Haas CNC laser. A hole was left in the top piece to allow for the attached dome to have a vacuum seal. The top dome was designed using two isosceles trapezoids that would be bent and welded around an oval top piece to create a dome. This dome would then be welded onto the top piece of the box to create a single fixture piece. As with the first design, a metal rod was used with rubber seals to maintain the vacuum. A balance issue was soon realized with using a rectangular fixture as opposed to a cylindrical one. To solve this problem another metal bar was incorporated into the design to pass through the middle of the original bar and go through the sides of the rectangle. This was used to help stabilize the fixture and allow it to be rotated without slipping around the middle bar.

Second Fixture Problems

The problem with the second fixture was soon realized during the testing of the CMM with the prosthetic. Since the second fixture was only half-way fabricated a substitute dome was used to test the CMM. During the testing it was shown that the ball-probe of the CMM was pushing down on the unsupported sections of the prosthetic causing extremely inaccurate readings. The stainless steel sheet metal was also proving difficult to work with when making the dome. Due to the high flexural strength of the stainless steel that was needed to create a rigid fixture, the bending and welding of the side pieces of the dome proved to be difficult, if not impossible for creating a smooth surface. The second fixture design was scrapped but the box, vacuum, and rotation aspects of the fixture were carried over to the third design which is described in the Methodology section following the Design section.

CMM

The CMM will be used to measure the changing contours of the prosthetic mold. To accomplish this the student will use the ball-probe of the CMM and take measurements of the surface every 0.010 inches. These measurements will record the position of the ball-probe in Cartesian coordinates (X, Y, Z). The machine will take measurements by slowly bringing the ball-probe close to the surface of the part until it senses any type of deflection in the tip of the ball-probe. At the instant it records any deflection it simultaneously records where the ball-probe is located in relation to a pre-determined origin. To completely scan the face the student will use the approximate middle of the face as their starting point and take linear scans from the forehead to the chin every 0.010 inches across the prosthetic. Once the entire prosthetic has been scanned the data will be imported into a solid modeling program and put together to create a digital copy of the surface of the prosthetic. Figure 4 illustrates how the scans look once imported into the solid modeling program.

CMM Testing

For using the CMM the student had to start from the basics. Having never taken a class using the CMM, the Help Guide Tutorials in the CMM program were used to learn how to setup the machine, setup the axis', and complete linear scans using the CMM. After reading all of the tutorials the student decided to test the linear scanning process with a flat angled piece of metal. During this test the student was able to determine the optimal distance between each registered point and learned that the best way to scan an incline was from the highest point to the lowest point. The reason for this is because the CMM is more likely to crash into the part moving over to the next point when blindly measuring up an incline rather than down. After testing on a simple block the student decided to conduct a single scan test on the prosthetic. During this time the second fixture was in the process of being developed so the student had to improvise and create a cardboard replica of the top of the fixture to mimic how it would be held during actual processing. During this test it was discovered that a simple dome shape would not be sufficient for holding the prosthetic because the ball-probe would not be deflected in the areas where the dome did not directly contact the prosthetic, this problem lead to scrapping the design of the second fixture and the creation of the third fixture. After developing the plaster of paris positive mold for the third fixture the student was able to again test to see if the CMM would be able to scan the prosthetic using this fixture. After the initial scans it was realized the CMM was having problems scanning the extremely steep contours around the nose and the lips of the prosthetic. It was decided that with the machinery available to the student the steep contours could not be drilled; therefore, the nostrils, mouth, and lip area were skipped during testing. After successful testing and data collection the student decided to settle with the design of the third fixture and proceeded to conduct scans on the entire surface of the prosthetic.

Ball-Probe Error

One of the problems with using a CMM is that an error is created when the ball-probe contacts the measured surface as can be seen in Figure 7. This is due to the CMM recording the position of the center of the ball-probe and not the point the ball-probe touches the surface. Unless the surface is completely horizontal or vertical the operator cannot add the radius of the ball-probe to either the X or Y coordinate. The CMM machine automatically compensates for the probe error as long as the correct setting for the radius of the ball-probe is recorded by the machine. In order to understand how the CMM compensates for the probe error it was decided to create a program using Excel (**Figure 8**) that would mimic the process the CMM uses. To do this the operator placed the recorded data points into the proper cells of the program. Using three sets of data points the slope of the line going through the middle point was calculated. From the slope the program was able to calculate the equation of the line normal to the point which will be useful if the 5th axis head is incorporated for the CNC laser. From the slope the angle of the line compared with the horizontal Y axis was determined. Using the radius of the ball probe and the angle of the line the program used trigonometry and similar triangles to determine the values to offset the measured Y and Z values. Adding or subtracting depending on if the slope was negative or positive the student was able to determine the coordinates of the surface of the part the ball-probe makes contact with. Because of the ease of use the student used the values given by the CMM and not from the Excel program. Using the program the student could understand how the values were calculated and will be able to calculate the line normal to each point if a 5th axis is incorporated.

CNC Laser

The final process step for the project is to use the data collected from the CMM and import it into the controller for the CNC laser to position the laser head, as can be seen in Figure 10, over the correct position on the prosthetic. The final design of the fixture was used in conjunction with a 4th axis indexer, as can be seen in Figure 12, to secure the prosthetic and rotate it into the proper positions. Using settings determined from a designed experiment the laser was set to create the optimal sized holes while not burning or creating unwanted markings on the prosthetic. The following will explain how these settings were determined as well as how the fixture and 4th axis was used on the table of the CNC.

Laser Testing

For testing the laser there were three different variables needed to be determined to ensure the laser was in the optimal position and would cleanly cut through the prosthetic without either burning the silicone or having a situation where the laser does not have enough power to cut completely through the silicone. For the test a sample piece was cut from one of the prosthetics and placed over a non-reflecting surface to ensure no energy was reflected back into the test piece. The three values that were tested were the frequency of the laser, the wattage of the laser, and the distance or offset value the laser was from the surface of the prosthetic. Referencing similar materials like balsa wood, the student was able to narrow down the testing values to three values for both frequency and wattage. For testing, a design of experiment table (**Figure 9**) was developed that would randomly select each of the three values to determine the optimal settings. Due to the nature of the test, the results are determined based on a visual inspection and not numerical values. After testing it was able to be determined that the optimal values for the laser are 4500 Hz, 25 Watts, and an offset of 50 thousandth from the surface of the test piece. With these values determined the next step was to develop a process for taking the measured points from the CMM and transforming them into G-code that would be read by the controller of the laser and would position both the laser head and the 4th axis into the proper positions for each hole.

Methodology

Finalized Fixture

The third and final design for the fixture needed to incorporate a more unique and distinctive way to hold the prosthetic in order to be able to scan the contours using the CMM. The solution for this became apparent when looking at the mold used for creating the prosthetic itself. As can be seen in Figure 11, using the mold and liquid plaster of paris, a positive mold was created that would be a perfect replica of the prosthetic. As can be seen in Figure 3, the plaster mold would be fastened to the top of the fixture using screws anchored into the body of the plaster mold. By using the plaster mold for holding the prosthetic the need for a vacuum force to hold the prosthetic was eliminated. This was beneficial because it saved both energy and time when setting up and using the fixture. This also meant the fixture itself did not need to be completely sealed and eliminated the need to weld. The side pieces were then cut down in size to 3 inches and used exclusively for support of the top piece and to prevent the fixture's main bar from rotating freely. The center where the two bars connected was also modified to make the fixture easier to assemble and disassemble for storage. An aluminum block was used to connect the two bars that were cut in half and secured into the block using set screws and a notch cut into the metal bars. To create easy access to the inside of the fixture, copper hooks were screwed into the sides of the box and the top piece and straps were used to tightly hold the pieces together. The rubber striping around the sides of the top piece and box piece were used to create a secure fit between the pieces and prevent injury to the operator from sharp metal edges. This design proved to be very effective when tested under the CMM and when testing using the 4^{th} axis to rotate the entire fixture. The choice for

304 type stainless steel was also warranted with the additional weight of the plaster mold that was not initially anticipated.

CMM Process

After completing the testing of the CMM and determining the proper settings and fixturing techniques, the measuring process was conducted. Using linear scans separated by 0.010 inch, we were able to complete 25 scans on each side of the prosthetic, as can be seen in Figure 4. Once the data has been collected with the CMM it has to be sorted out and edited in order to be accepted by the solid modeling program. To do this the text file (**Figure 5**) containing the data was opened using Excel and sorted according to where the commas and spaces in the text file were located. After deleting the extra data and coordinates the saved text file (**Figure 6**) consisted of three columns of data representing the X, Y, and Z axis's. This file can was then opened using the solid modeling program and put into an X, Y, and Z curve representing the contours of the prosthetic along a specific line. The data was then ready to be transformed into G-code that will be read by the CNC laser.

CMM Data to G-Code Conversion Process

After acquiring the data points from the CMM they need to be transformed into G-code that can be read by the CNC controller. To do this a series of Excel documents and text documents were created that contained equations which would both shift the data points into the correct orientation and create spaces between the data points to add in additional code. This process starts by opening the text file with Excel and selecting how Excel will read and interpret the data. With the proper selection the data is imported into individual cells and is ready for further processing. Next the cells are modified to align with the designated origin from the CMM and placed into a template which already includes the extra code needed for positioning the CNC and a pause is added for the laser over each data point. After all of the data is modified and imported into a text file the process is ready for the CNC.

Laser Process

After determining both the proper settings for the laser and creating the G-code from the CMM data the laser processing can be conducted. The first step was to secure the 4th axis indexer to the table of the CNC laser and connect the indexer to the controller of the CNC. After ensuring the 4th axis was properly working the fixture can be secured into the indexer. With the fixture secure in the 4th axis a quick test was conducted by rotating the fixture from the CNC controller back and forth, ensuring there are no obstructions to prevent the fixture from rotating. The G-code text file was then loaded into the controller and a virtual test of the G-code was done by the controller to see if any errors are in the code. The next step is to use a level to locate the flat plane of the top piece of the fixture with the horizontal plane of the CNC table. The X, Y, and Z axis of the laser head then needed to be “zero-ed” at the exact point the CMM used for an origin point. This is to ensure both the controller and the CMM are using the same coordinate system, without this step catastrophic errors are unavoidable and the prosthetic will be ruined or the damage can be inflicted to the laser head. With all axis’ set and the fixture secured, the G-code program was ready to be run to drill the holes into the prosthetic. The CNC machine is designed to run through all the code with no input from an operator, however an operator must be present in the event of a malfunction or errant code that would cause the machine to cause damage to itself or the prosthetic. After processing was completed a visual inspection of the prosthetic was conducted to ensure all holes were properly drilled. From this step the process was complete and the prosthetic was ready for further processing by the artist to apply skin tone and facial features such as facial hair or beauty marks.

Results

The results will be based on visual inspection and functionality of all processes and prototypes developed. Because of this all results are speculation and can be interpreted in many ways. There will be no numerical comparisons aside from an economic justification for the project. The main results will cover the functionality of the fixture prototype, the process for obtaining data from the CMM, and the results from creating the holes in the prosthetic with the CNC laser.

Fixture

The prototype for the fixture worked very well in the CMM and the CNC. Having the plaster of paris positive mold created a very stable platform to obtaining data with the CMM. The metal base was also very solid with the extra weight of the plaster which ensured correct data for every measurement and a reliable platform for performing the CNC process. The 4^{th} axis rotating ability of the fixture also worked very well when tested with the 4^{th} axis. One major problem with the fixture is the overall weight of both the metal base and the plaster mold. This extra weight lead to the fixture having a tendency to be slightly unstable when moved past 60 degrees from horizontal. An improved design for the fixture would be to determine a way to either hollow out the plaster mold or use a material less dense than plaster of paris. The metal base of the fixture and 4^{th} axis capabilities performed as expected and I do not foresee any changes to be made.

CMM Process

The CMM process worked well despite not being able to use the 4^{th} axis during the measuring process. To compensate for this the student made all the measurements from the horizontal Z plane and ignored some of the side features and facial features deemed non-critical for the CNC process. This created unexpected results and extra conversions had to be done in order to properly create code for the CNC. The actual process of using linear scans while incrementing in the Y-plane was a good theory on paper but did not hold well during testing. The problem was not in the actual data acquired but the overall method used for acquiring the data. Having to increment the scan for every 0.010" meant an operator had to be present during the entire process and while devoting all attention to the process. The scans also took a large amount of time to complete, almost 8-10 minutes per scan, which computed out for all planned 120 scans meant the entire process was estimated to take 16-20 hours with no problems or delays. Given better resources and equipment an improved method would have been to use conoscopic holography or a structured light 3-D scanner to complete the scanning process. Both of these processes work in relatively the same manner with either an emitted laser or pattern of light being projected and reflected off of the measured surface and acquired by a sensor to determine the features of the part. These processes are both faster and more accurate than the traditional ball-probe measuring system used in this project. Another benefit is they are also automated if placed in the proper rotating 4th axis or table indexer, which eliminates the need for an operator to be constantly supervising the process. Future work on the project should research into incorporating either of these scanning processes in order to improve the efficiency and accuracy of the measurement step.

CNC Laser Process

The CNC laser processing to create holes in the prosthetic did not work as initially anticipated. The main problem in this process was difficulties in getting the silicone prosthetic to sit flat with plaster of paris mold. There were certain areas around the nose and lips that either protruded out farther than anticipated or were impossible to get flat against the surface. This caused the head of the laser to either be too close to the surface of the prosthetic or in some causes actually crashing into the prosthetic. The main reason for this after reviewing the prosthetic is that while the contours are all correct, the thickness of the prosthetic greatly varies across the surface. This is due to how the prosthetic was created. The creator brushed layers of silicone into the negative mold until all of the features were covered. Then to fill in features such as the cheek and around the nose and lips he added extra material that was not initially realized or anticipated. This leads to a uniform surface on the inside of the prosthetic but not a perfect match when placed onto the plaster mold created from the negative mold. The alternative methods described in the CMM process for scanning the prosthetic into CAD would compensate for these errors by enabling the scanning of the flexible prosthetic that is not possible with contact measuring processes such as the ball-probe used.

Despite the problems with the process the positive aspects were the performance of the fixture as a solid base for processing and the plaster mold that supported the prosthetic. As anticipated the plaster both provided a platform for processing and a medium to absorb any laser energy passing through the prosthetic to prevent any of the laser energy from reflecting back into the prosthetic as a metal base would. It also provided support for the assist gas to blow away any loose particles or fumes created from the process.

An advanced approach for further investigation into the project would be to incorporate a 5^{th} axis during the CNC laser processing step. With a 5^{th} axis in place certain problems arising from the complex contours of the nose as well as some of the steeper portions of the prosthetic will be reached by the laser head. The most promising alternative would be to utilize a rotating head on the laser itself that would coordinate with the 4^{th} axis indexer to reach these areas. If available a 2 axis indexer that has the ability to rotate in both the 4^{th} and 5^{th} axis relative to the 3 axis's established by the CNC laser would be another alternative instead of a rotating laser head.

Economic Justification

As can be seen in Figure 13, the total cost of building the fixture and processing a single prosthetic is $1,523.96. Many assumptions had to be made in determining the cost of both fabricating the fixture and completing the scanning and hole creation processes. The first is a base cost for a machinist/operator of 25 dollars an hour. This was chosen due to the relative simplicity of the fabrication and further processing steps so an 'expert' machinist/operator is not necessarily needed. Also neglected from the economic summary is the cost of the machines and operating costs of each specific machine. This is intentionally left out because we can consider the fixture to both be produced and purchased from another vendor or if produced in house to be such a small percentage when distributed over all fabricated products that it is negligible. The time assumptions for fabrication are not based on the actual time spent by the student during the project, rather estimates an experienced machinist would take to complete each process. The time assumptions for the CMM, code generation, and CNC laser process are a reflection of the approximate time the student spent on each process because of the automated nature of each process. In the students opinion the cost for producing the fixture and the subsequent processes are justified when compared to the overall cost of creating the actual silicone prosthetic, with the estimated costs only constituting less than 10% of the overall cost of creating the fixture.

Conclusion

This report addresses the problem of creating a process for increasing the airflow for custom made silicone facial prosthetics. Because of the complex contours of the human face and the unique shape and material of each prosthetic a multi step process was created to address the challenges presented.

Challenges

- Process for scanning the contours of the prosthetic into CAD
- Process for cutting small holes into the prosthetic
- Method for fixturing the prosthetic during processing

After researching different fixturing methods and scanning processes the best solution given the machinery available was to create a flexible fixture from metal and plaster and to scan the prosthetic using a ball-probe CMM system. The final process designed intended to use a 4^{th} axis indexer and a CNC laser to create the holes in the silicone.

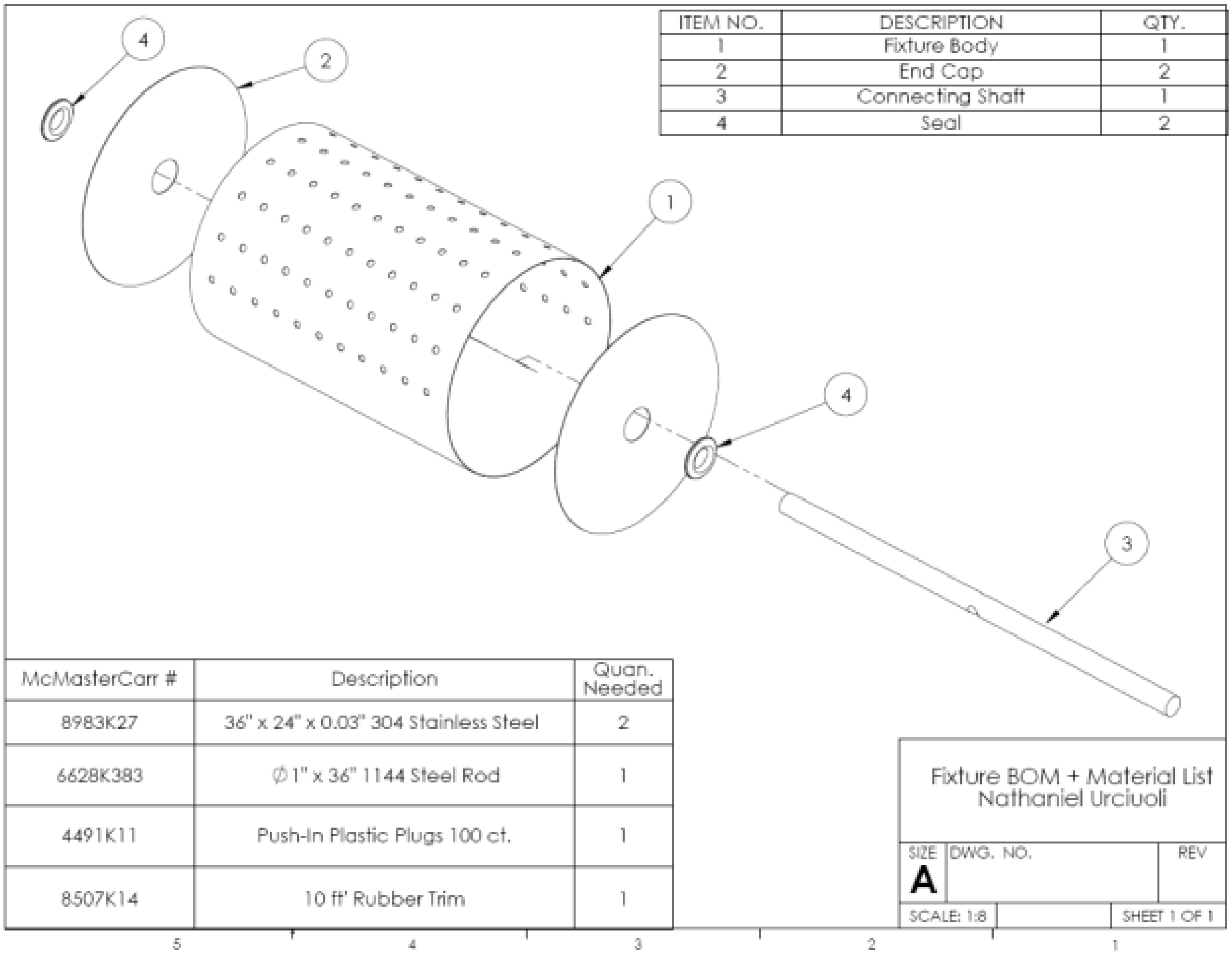
The most important results obtained from conducting experiments and creating a prototype are summarized below.

- Flexible fixture designed and fabricated using stainless steel and a plaster of paris base to both secure the prosthetic during processing and providing a solid base to rotate the prosthetic around the 4^{th} axis indexer
- Process for scanning the contours of the prosthetic using progressive linear scans with a ball-probe on a computer measuring machine

- Process for translating positional code obtained with the CMM to G-code that is capable of being read by the CNC controller
- Process for creating the holes using a CNC machine fitted with a laser head

The final product produced was very close to what was anticipated from the beginning. Problems encountered such as not having the ability to use a more accurate measuring system and not being able to incorporate a 5th axis into the last process prevented the project from reaching complete success. The overall process designed in the report is sufficient in finding a solution to the problem but with further exploration into the proposed changes will more than likely produce a fully functioning and successful prosthetic.

Appendix



ITEM NO.	DESCRIPTION	QTY.
1	Fixture Body	1
2	End Cap	2
3	Connecting Shaft	1
4	Seal	2

McMasterCarr #	Description	Quan. Needed
8983K27	36" x 24" x 0.03" 304 Stainless Steel	2
6628K383	∅ 1" x 36" 1144 Steel Rod	1
4491K11	Push-In Plastic Plugs 100 ct.	1
8507K14	10 ft' Rubber Trim	1

Figure 1 – Fixture One Exploded View and Bill of Materials

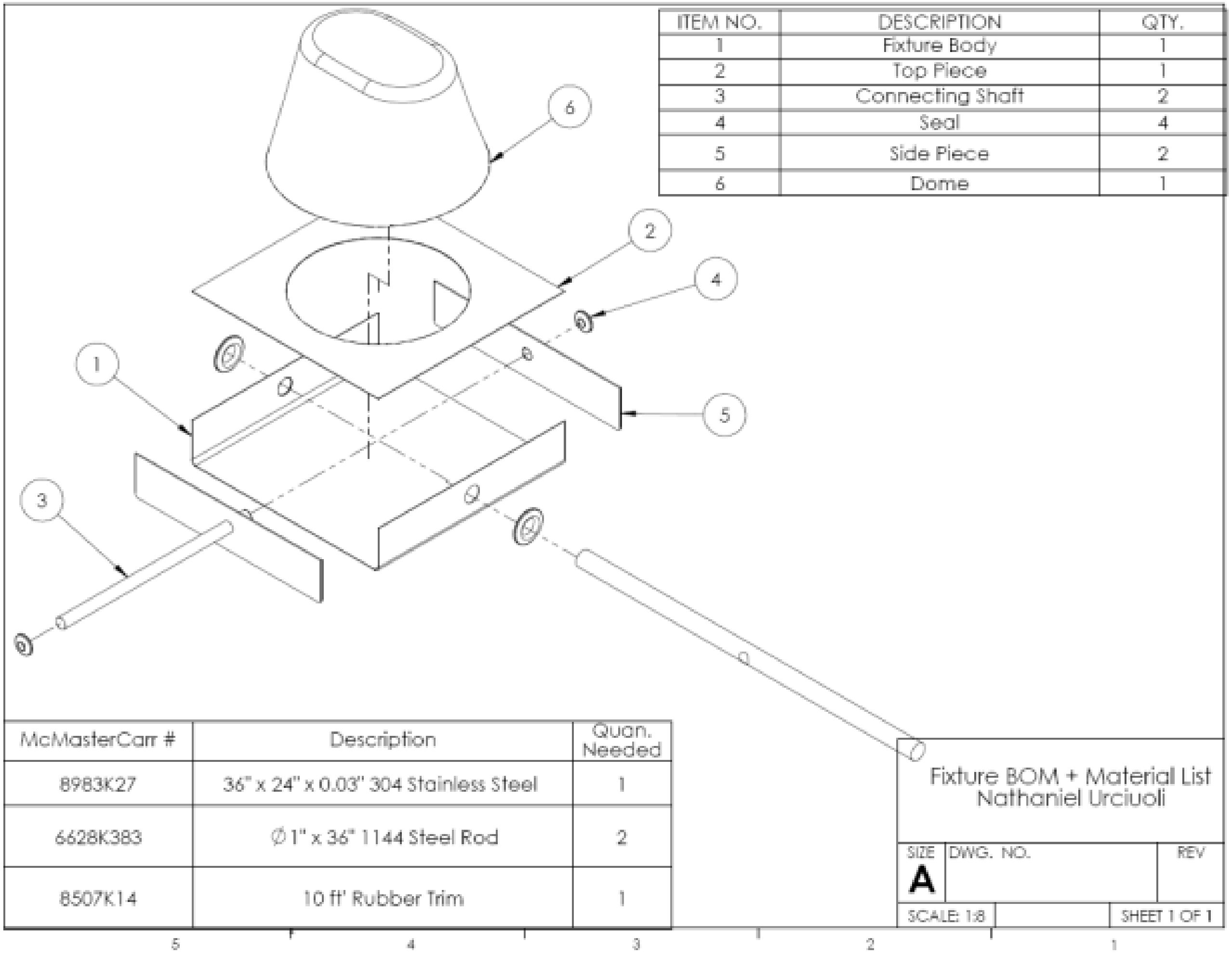
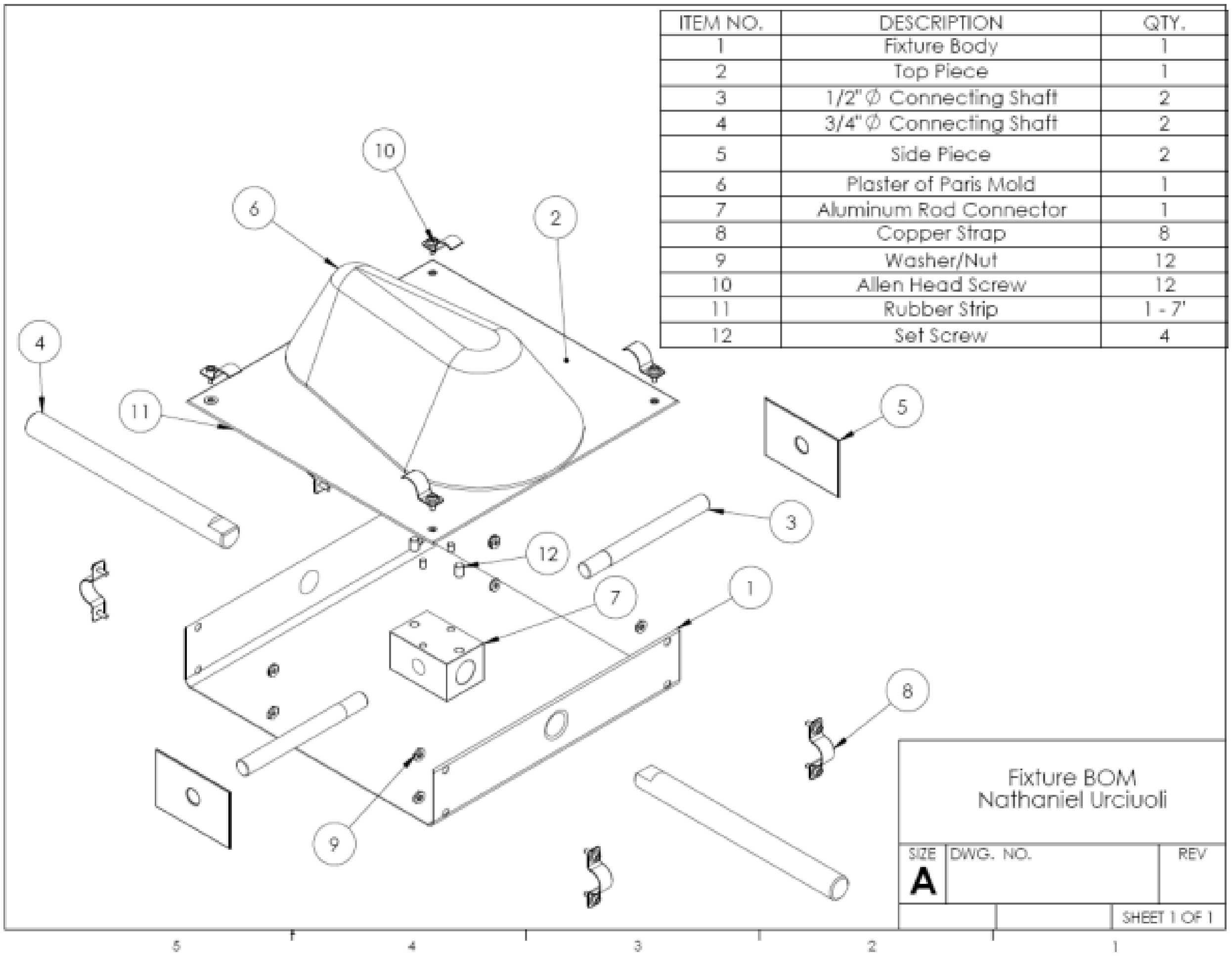


Figure 2 – Fixture Two Exploded View and Bill of Materials



ITEM NO.	DESCRIPTION	QTY.
1	Fixture Body	1
2	Top Piece	1
3	1/2" ∅ Connecting Shaft	2
4	3/4" ∅ Connecting Shaft	2
5	Side Piece	2
6	Plaster of Paris Mold	1
7	Aluminum Rod Connector	1
8	Copper Strap	8
9	Washer/Nut	12
10	Allen Head Screw	12
11	Rubber Strip	1 - 7'
12	Set Screw	4

Figure 3 – Fixture three Exploded View and Bill of Materials

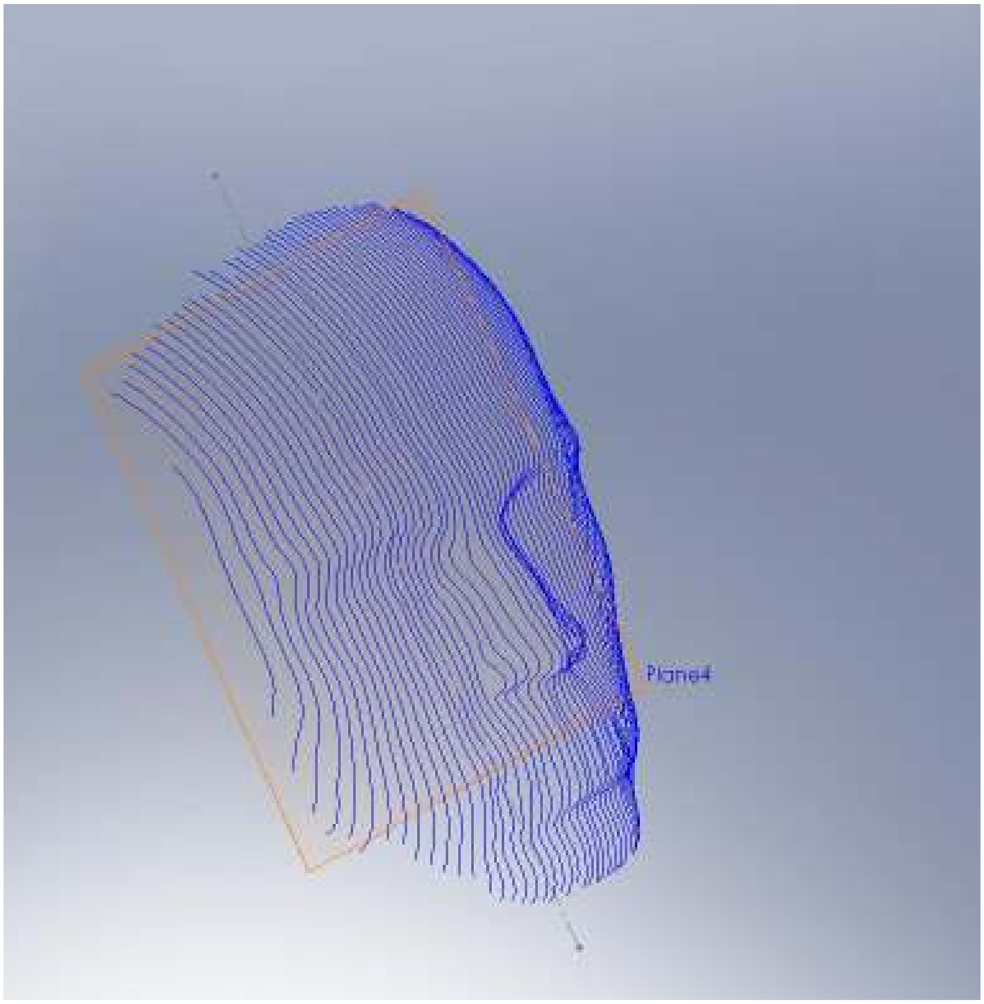


Figure 4 - Prosthetic CMM Scans

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Figure 5 – CMM Data Before Processing

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Figure 6 - CMM Data After Processing

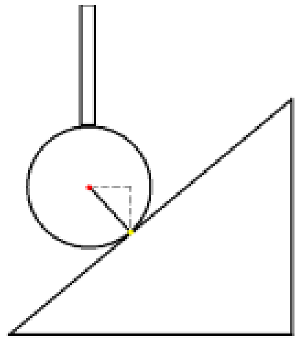

Figure 7 - Illustration of Ball Probe Error

Measured X	Measured Y	Slope	Angle	Radius	YN	H	Yoffset	X offset	**Y Actual**	**X Actual**
1.9375	2.8125									
2.25	3	0.611	31.430	0.125	0.076	0.146	0.065	0.107	2.935	2.357
3.0625	3.5	0.857	40.601	0.125	0.107	0.165	0.081	0.095	3.419	3.157
3.125	3.75	1.143	48.814	0.125	0.143	0.190	0.094	0.082	3.656	3.207
3.5	4									

Figure 8 - Excel Program for Ball Probe Error

Settings	Watt										
		15	15	20	20	25	25	30	30	35	35
	2000	1 -no	2 - no	1 -no	2 - no	1 - no	2 - no	1 -no	2 - no	1 -no	2 - no
	2000	3 - no	4 - no	3 - maybe	4 - no	3 - maybe	4 - maybe	3 - maybe	4 - no	3 - no	4 - no
	4500	1 - no	2 - no	1 - no	2 - maybe	1 - maybe	2 - yes	1 - no	2 - no	1 - no	2 - no
Hz	4500	3 - no	4 - no	3 - maybe	4 - no	3 - yes	4 - maybe	3 - maybe	4 - no	3 - no	4 - no
	7000	1 - no	2 - no	1 - no	2 - maybe	1 - maybe	2 - maybe	1 - no	2 - no	1 - no	2 - no
	7000	3 - no	4 - no	3 - no	4 - no	3 - maybe	4 - no	3 - no	4 - no	3 - no	4 - no
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	8500	3 - no	4 - no	3 - no	4 - no	3 - no	4 - no	3 - no	4 - no	3 - no	4 - no

Offset
1 = 10 thousandth
2 = 25 thousandth
3 = 50 thousandth
4 = 75 thousandth

Figure 9 - DOE for Determining Laser Settings

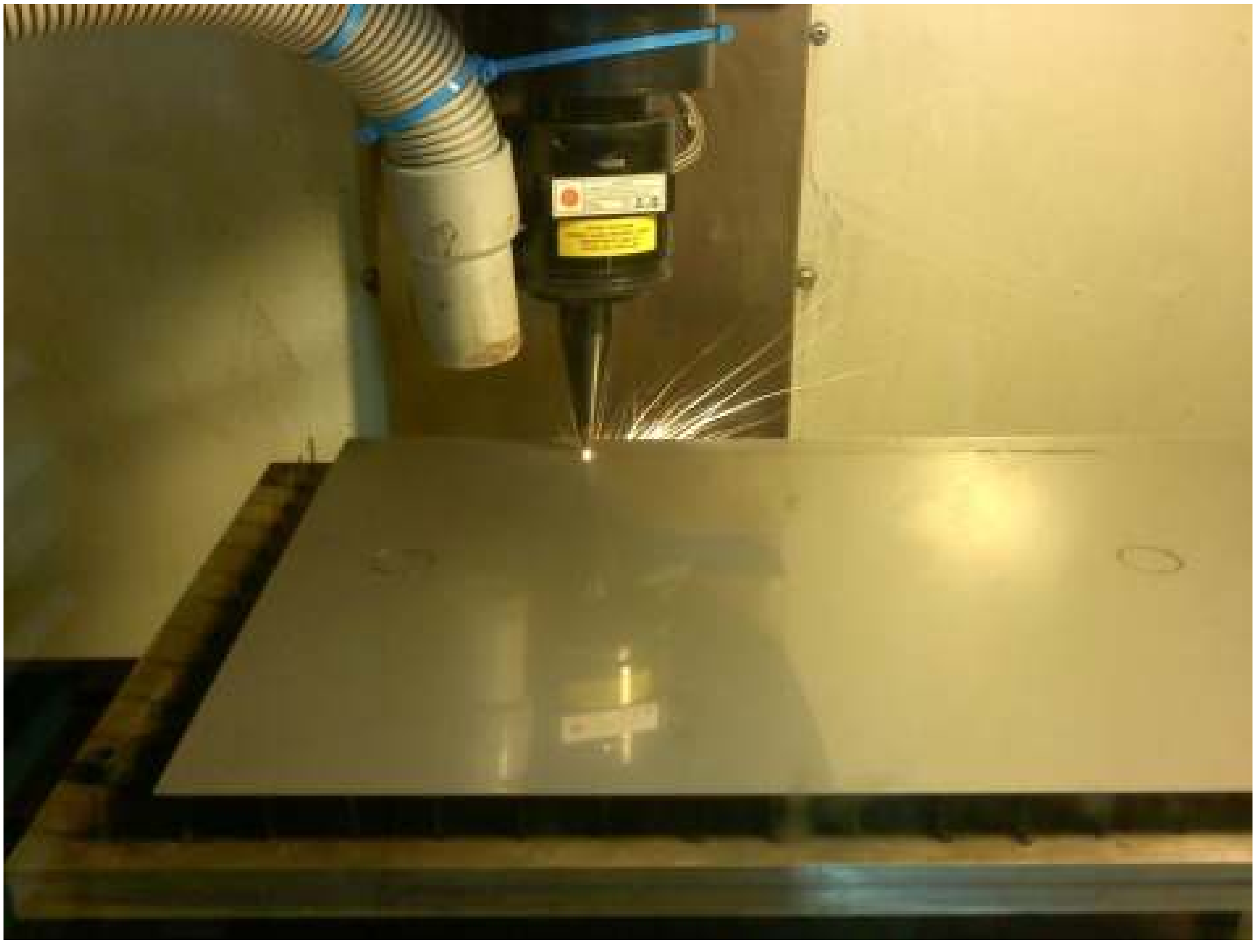

Figure 10 - CNC Laser Head Cutting Stainless Steel

Figure 11 - Plaster Setting in Mold

Figure 12 - Haas 4th Axis Indexer

Economic Justification — **Average Machinist Cost = $25/hour**

Material Cost

Fixture	Cost Per Unit	Cost Per Material Used
304 Stainless Steel	$38.61	$38.61
1/2 Dia. Tool Steel Rod	$2.48	$2.48
3/4 Dia. Tool Steel Rod	$12.60	$6.30
Rubber Striping	$8.50	$6.80
Copper Hooks	$6.75	$6.75
Al Connecting Block	$15.52	$15.52
Hardware	$10.00	$10.00
Plaster	$25.00	$6.25
		Total Material Cost $92.71

Machining Costs

Process	Time (hr)	Machining Cost
Stainless Steel Fabrication	4	$100.00
Rod Fabrication	1	$25.00
Molding Plaster	1	$25.00
Al Connecting Block Fabrication	1.5	$37.50
Assembly	1	$25.00
		Total Fabrication Costs $212.50

Costs for Operator

Process	Time (hr)	Operator Cost
CMM Process	13.75	$343.75
CMM Code to G-code Conversion	25	$625.00
CNC Laser Process	10	$250.00
		Total Operator Costs $1,218.75

Total Process Cost
$1,523.96

Figure 13 - Economic Analysis

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