Control Architecture of Cranial Implant Laser Cutting System

Final Project Report: Group 18
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The goal of this project is to develop a portable, 5 DOF laser cutting system. This robot-assisted system aims to help surgeons to quickly and accurately resize custom cranial implants (CCIs) in single-stage cranioplasty.

Cranioplasty is a procedure to treat and repair cranial defects using CCIs. The implants are usually made in oversized profiles, and require numerous iterations of manual modification to become suitable for patients. This process can take up to 80 minutes depending on the size of the implant and the complexity of the modification. Furthermore, the modification is based on the surgeon's visual analysis, and therefore is prone to errors in precision and accuracy. The goal of our project is to enable faster and more accurate modification of the implant profile with robot-assisted technology.

Previous work related to our project is the computer-assisted technique using intraoperative navigation and projection to perform single-stage cranioplasty, in which regions of resected defects are detected using a digitizer to trace the outline of the defect on the skull. After the optical tracker captured all the points of the edge, the contour of the defect is projected onto the preoperatively-designed CCI for the surgeon to mark the desired shape and resize the implant manually. This technique provides a good closure fit with less gaps between the implant and remaining skull, and reduced the time needed for the manual modification.

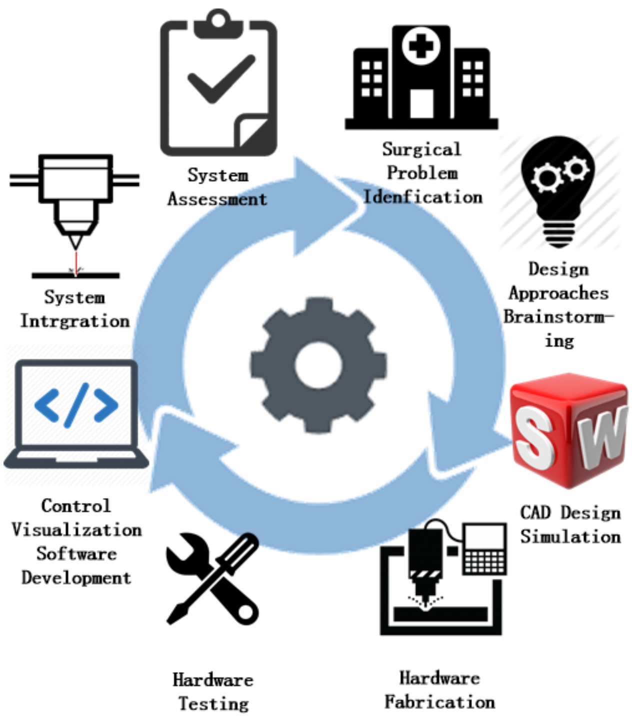
Technical Approach

Design requirement

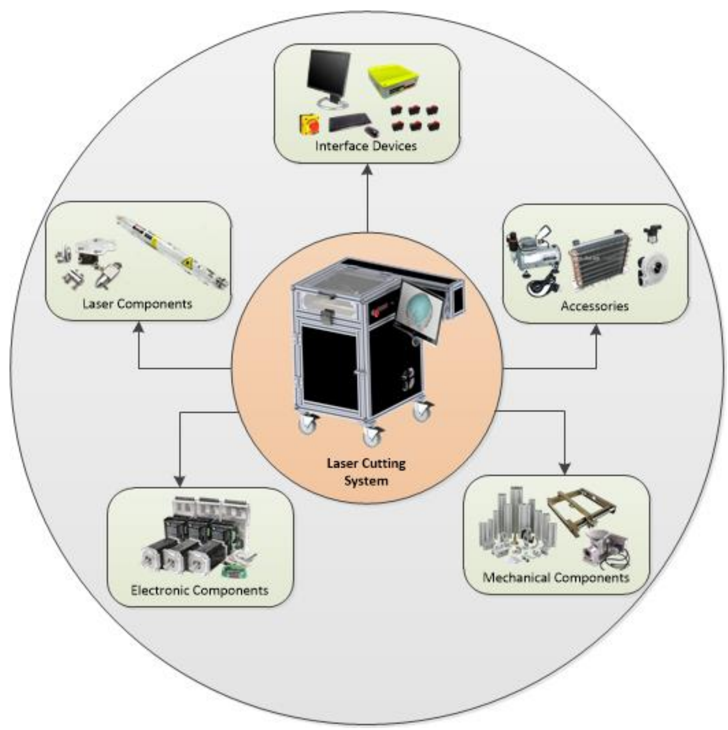
The entire surgical procedure is to be performed under sterile environment. Therefore, the robot-based system is designed to cut the CCIs with laser instead of other methods (i.e. contact, stress, or pressure) in order to preserve sterility of the implant. The system is also designed to be compact so that the machine can be easily transported from one operation room to another. The CCIs are composed of biocompatible materials such as animal bone, autologous bone graft, acrylic resin known as bone cement (PMMA), or Polyether ether ketone (PEEK). It is important to note that different material requires different laser power setting. Preliminary test on a PMMA implant had shown a promising cutting effect with the laser system, so we will perform test trials on PMMA implants.

Technical Overview

This project consists of eight steps (figure 1): 1) Surgical problem identification; 2) design approach of the laser cutting system; 3) CAD modeling and simulation of the system and hardware components; 4) fabrication and assembly of the hardware; 5) functionality testing and calibration of the hardware; 6) software development on motion controls and visualization; 7) system integration; 8) system assessment through experimental trials.



(Figure 1: 8-step project approach)



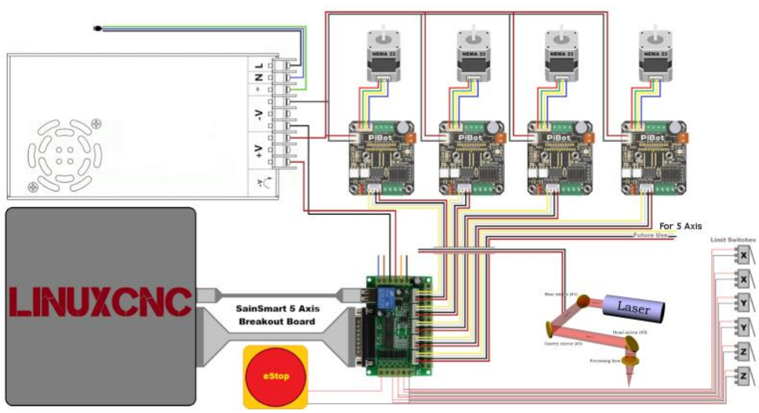
(Figure 2: system overview)

System Overview

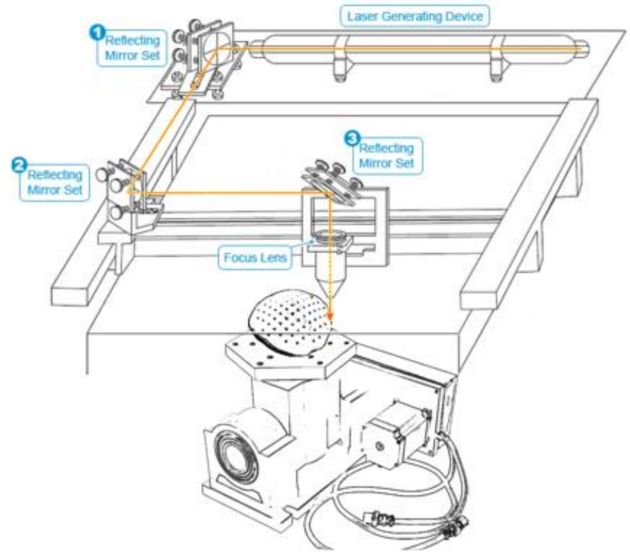
This robot-assisted laser system consists of five units: mechanical hardware, electronic components, laser components, interface devices, and accessories (figure 2.) The system provides up to 5-axis of simultaneous motion to trim continuous edges on the implant with any desired angles. It is composed of three Cartesian linear stage (XYZ) and a rotary table (AB) with one *nema* series stepper motor. The stepper motor is controlled by its motor driver board, which in turn is controlled by a 5-axis breakout board (figure 3). The laser source is a 35W CO_2 sealed laser tube. Through three reflecting mirrors, the laser beam will be directed to shoot downward onto a rotary table, which is situated on top of a horizontal platform that controls the movement in the z-axis (figure 4).

<u>Software Overview</u>

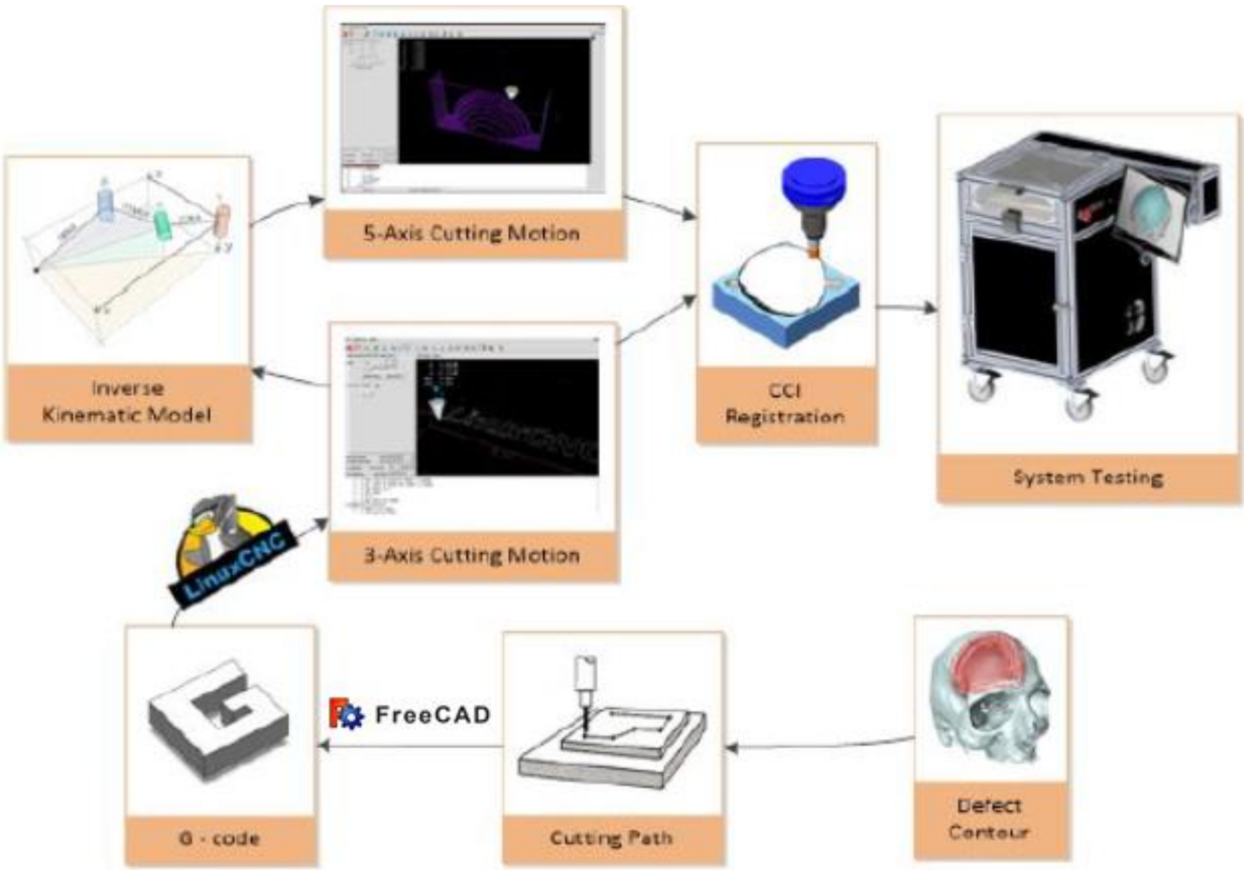
The software development of this laser cutting system falls under two categories: machine control and cutting path generation (figure 5). For machine control, the existing version of LinuxCNC, which is an open source software that controls CNC machines, to operate the laser cutting system. This system reads the G-code and instructs the machine to move accordingly by sending control signals from NC-box to the controller board and eventually to drive the motors. In the preoperative interval, the system requires the calibration of the implant holder in order to minimize the time spent on implant registration during the surgery. In regard to the motion control of the machine, we will first develop a 3-axis control interface in LinuxCNC environment and further extend the development to a 5-axis control interface. For path generation, we will take the cranial defect model as the input to generate a cutting path. This cutting path will be converted to G-Code through our modified version of the open source software FreeCAD, and the G-Code will then be be executed by LinuxCNC.



(Figure 3: circuit diagram of electronic components)



(Figure 4: configuration of linear stage & rotary table)



(Figure 5: project technical approach)

Deliverables

Minimum

1. Hardware troubleshooting (Completed May 4)
2. Laser components alignment (Completed March 15)
3. Linear stage and rotary table motor calibration (Completed March 25)
4. 3-axis controlled cutting motion implementation (Completed March 28)

Expected

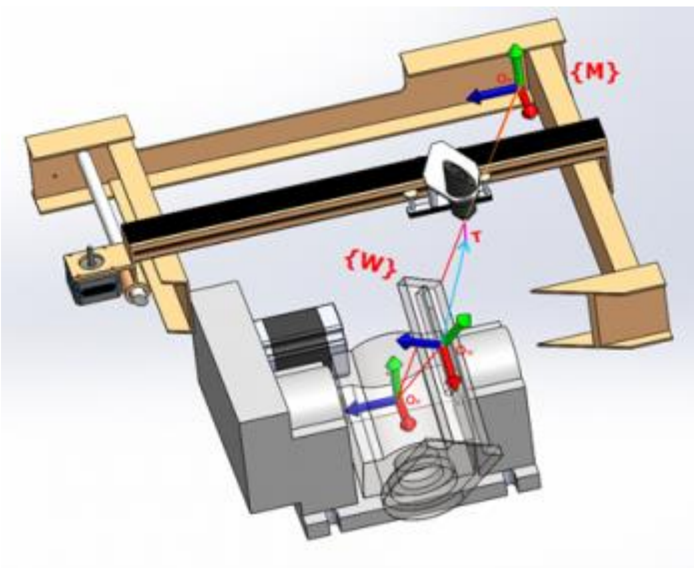
1. Fabrication of workspace platform for raw implant material (Completed March 17)
2. Inverse kinematic model for the rotary table (Completed April 6)
3. 5-axis controlled cutting control implementation (Completed April 8)

Maximum

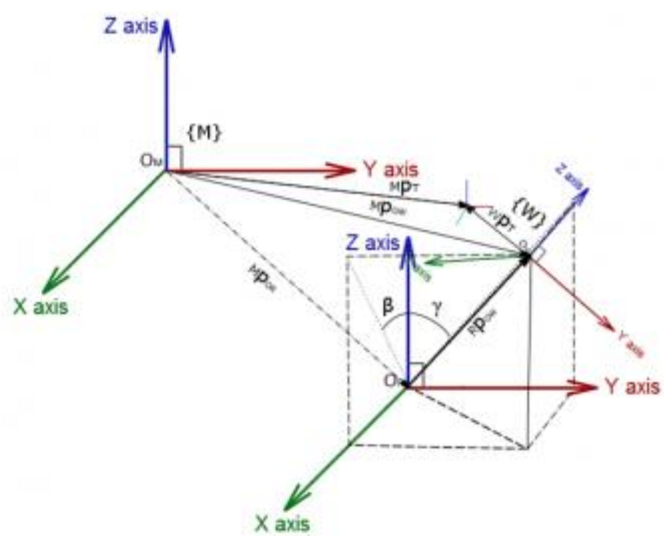
1. Mechanism for implant registration (Completed April 11)
2. Cutting path to G-Code conversion algorithm (Incomplete)
3. User interface with visualization and cut path simulation (Incomplete)
4. Test the laser cutting system on real implants (Completed May 4)

Kinematics Modeling

There are four frames to consider: the machine frame {M}, rotary table intermediate frame {O}, the workpiece frame {W}, and the tool frame {T}. The origin of {M}, {W}, and {T} is defined to be the home position of the system, the point on the mounting plate and above the point at which the two rotary axes coincide, and the tip of the laser head, respectively (figure 6). Because the implant is to be mounted on {W}, it is necessary to perform frame transformation from {M} to {W} (figure 7.). This is because for CAD/CAM system, a tool path defined by a set of successive tool positions and orientations (G-code) expressed in {W}.



(Fig.6 System frames)



(Fig.7 Frame transformation)

<u>Forward Kinematics</u>

The following is the derivation of the forward kinematics from the above kinematics model. First there are few parameters to be defined:

Angle γ and β are defined as $tan\gamma = \frac{y}{z}$ and $tan\beta = \frac{x}{z}$.

The link L is the fixed distance between the {W} and {O} and is given by $L^2 = x^2 + y^2 + z^2$

From the above relation, the coordinates (x,y,z) can be represented as L, γ and β.

$$z = \frac{L}{\sqrt{\tan^2\gamma + \tan^2\beta + 1}} \quad x = z * tan\beta = \frac{L * tan\beta}{\sqrt{\tan^2\gamma + \tan^2\beta + 1}} \quad y = z * tan\gamma = \frac{L * tan\gamma}{\sqrt{\tan^2\gamma + \tan^2\beta + 1}}$$

Frame transformation from {M} to {W} involves two transformations: {M} to {O} and {O} to {W}. {M} to {O} has only the translation component and is denoted as vector${}^{M}P_{OR}$. {O} to {W} requires both rotation and translation components and are denoted as ${}^{M}_{R}R$ and ${}^{R}P_{OW}$, respectively. Since the rotation angle is embedded in the translational component, ${}^{M}_{R}R$ is simply an identity matrix.

$$
{}^{M}P_{OR} = \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix}
$$

$$
{}^{R}P_{OW} = \begin{bmatrix} \dfrac{L * tan\beta}{\sqrt{\tan^2\gamma + \tan^2\beta + 1}} \\ \dfrac{L * tan\gamma}{\sqrt{\tan^2\gamma + \tan^2\beta + 1}} \\ \dfrac{L}{\sqrt{\tan^2\gamma + \tan^2\beta + 1}} \end{bmatrix}
$$

$$
{}^{M}P_{OW} = {}^{M}P_{OR} + {}^{M}_{R}R * {}^{R}P_{OW}
$$

A tool position is given by the position vector of the tool tip T in {W} as ${}^{W}P_{T} = \begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix}$ and the tool orientation is given by unit vector associated to the tool axis direction as${}^{W}K_{T} = \begin{bmatrix} k_{tx} \\ k_{ty} \\ k_{ty} \end{bmatrix}$.

The tool tip position vector and unit vector of tool axis direction in the frame {M} can be represented as

${}^{M}P_{T} = \begin{bmatrix} x_M \\ y_M \\ z_M \end{bmatrix} = {}^{M}P_{OW} + {}^{M}_{W}R * {}^{W}P_{T}$, where ${}^{M}P_{OW} = \begin{bmatrix} x_{OW} \\ y_{OW} \\ z_{OW} \end{bmatrix}$ is the position vector of {W} with respect to {M}

$$
{}^{M}k_{T} = \begin{bmatrix} k_{Tx} \\ k_{Ty} \\ k_{Ty} \end{bmatrix} = {}^{M}_{W}R * {}^{W}k_{T}
$$

To bring {T} to a desirable angular position with respect to the {M}, {T} must be rotated first about the x_M axis by an angle A, and then about the y_M axis by an angle B. The rotation matrix ${}^{M}_{T}R$ is as followed, where R_B and R_A are basic rotation matrices.

$R_A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\gamma & -sin\gamma \\ 0 & sin\gamma & cos\gamma \end{bmatrix}$ and $R_B = \begin{bmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{bmatrix}$

$$
{}^{M}_{T}R = R_B R_A = \begin{bmatrix} cos\beta & sin\gamma sin\beta & cos\gamma sin\beta \\ 0 & cos\gamma & -sin\gamma \\ -sin\beta & sin\gamma cos\beta & cos\gamma cos\beta \end{bmatrix} = \begin{bmatrix} i_{Tx} & j_{Tx} & k_{Tx} \\ i_{Ty} & j_{Ty} & k_{Ty} \\ i_{Tz} & j_{Tz} & k_{Tz} \end{bmatrix}
$$

Inverse Kinematics

Using the above rotation matrix, the angles can be computed:

$$A = \gamma = atan2\left(-k_{Ty}, \sqrt{1-k_{Ty}^2}\right) = atan2(sin\gamma, \sqrt{1-\sin^2\gamma})$$

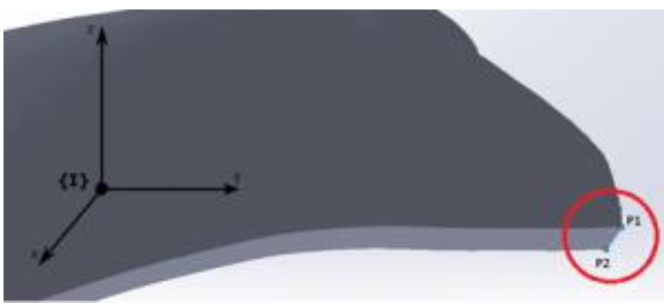
$$B = \beta = atan2(\frac{k_{Tx}}{cos\alpha}, \frac{k_{Tz}}{cos\alpha}) = atan2(sin\beta, cos\beta)$$

And the world coordinate (in {M}) can be represented as $x = [x_M \; y_M \; z_M \; A \; B]^T$

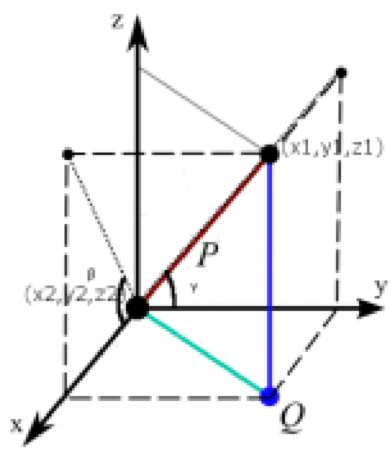
Contour Path to G-code

Two contours are considered in creating the cut path: upper contour (P_1) and lower contour (P_2) (figure 8). The entire contour path is discretized into frames, and each frame contains one point from the upper contour and its corresponding point from the lower contour (figure 9).

$P_1 = (x_1, y_1, z_1)$ and $P_2 = (x_2, y_2, z_2)$



(Fig. 8 Sample pair of points in {I})



(Fig. 9 Frame representation with angle)

The angles can be calculated as followed:

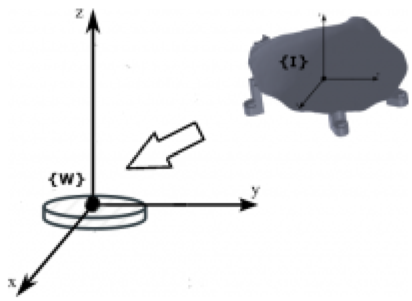
$A = 90 - \gamma = 90 - atan2(\Delta z, \Delta y)$

$B = 90 - \beta = 90 - atan2(\Delta z, \Delta x)$

And the world coordinate (in {M}) can be represented as $x = [x_1 \; y_1 \; z_1 \; A \; B]^T$

Implant Registration

There are two goals for the implant registration: Mapping the implant frame {I} to Workpiece frame {W}, and eliminating rotational offset (figure 10).



(Fig. 10 Frames of implant registration)

The planned approach is to use point cloud to point cloud rigid transformation.

1. Design a mount to secure implant on the work-piece
2. Drill two holes for screw placement as fixture
3. Register hole axes to the workspace {W}
4. Repeat step 2 on the implant
5. Register implant {I} to implant hole axes

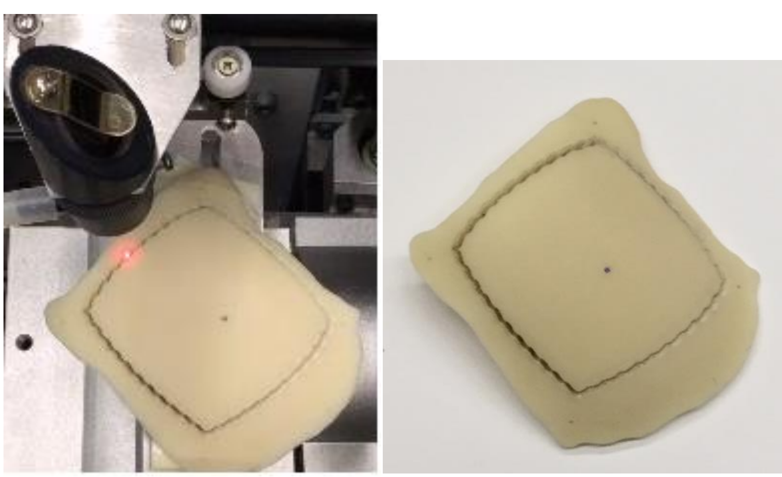
This procedure requires the manufacture of the oversized implant to attach two screw holes on the implant, place a fiducial point on the implant surface, and provide us the coordinates of those three points. We will then control the linear stage to physically determine where those points are with respect to the machine frame {M}, which can then be transformed to {W}.

Result

All the hardware components have been assembled. The machine (figure 11) is fully functional and calibrated. The laser has the capability to cut the implant (figure 12, 13). The laser is not powerful enough to cut through the implant in one loop. Instead, it requires two (or possibly three) loops, with each loop at a different height, in order to cut out the implant.

(Figure 11. Assembled laser system)

(Figure 12. Implant cutting: one loop)



(Figure 13. Implant cutting: three loops)

Quantitative analysis of the cutting has yet to be performed due to time constraint. Based on the image, one problem with the result is that the laser does not cut in a smooth line. This is attributed to the nature of the stepper motor. This may be resolved by increasing the motor speed or replacing the stepper motors with servo motors. In addition, the implant material generates repugnant smell during the cut. It is strongly advised to connect the system to a fume hood.

Future Work

Future work includes implant registration, cutting path to G-Code conversion algorithm, FreeCAD cranioplasty module, and laser power reference table.

The mechanism and procedure to register the implant is described in the previous section, but the current setup of the system is unable to physically determine the height (z-axis) position of the implant. The plan is to fabricate a device consisted of a slide ruler with a laser diode attached. The height can then be determined by adjusting the laser diode.

The algorithm to convert the cutting path to G-Code is also described in the previous section, but the method to process mesh model to useable input is not yet developed. An open source software FreeCAD has the capability to convert a path to G-Code, but only support up to three axis. The plan is to develop a module in FreeCAD to extend the feature to five axis.

It is important to note that different laser power setting is required to cut different material. However, due to the time constraint, the setting has yet to be determined. Each material will be cut extensively to determine the optimal laser power parameters.

Dependency & Resolution

1. Hardware
   - Class IV laser usage: we have completed the laser safety training. **Status: resolved**
   - Computer system: current computer (NCbox189) does not have the necessary compiler to compile the kinematics model, and the system cannot be updated. We're currently using the lab computer and looking into a viable computer system to replace the current one. **Status: pending**

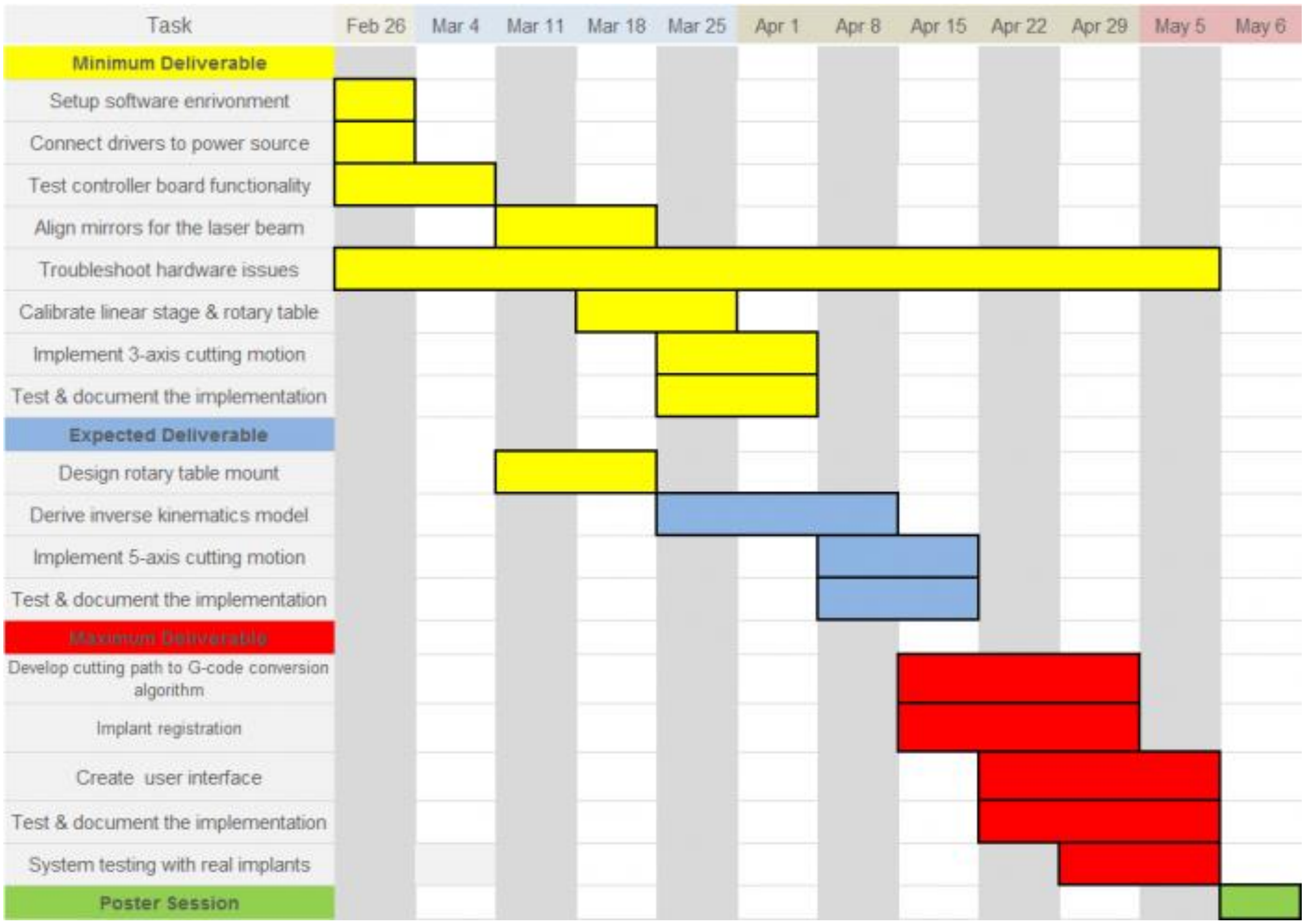
2. Software: we need the following software/library to assist us in this project. We have completed the installation. **Status: resolved**
   - SolidWorks – CAD modeling software. It will be used to design mechanical components.
   - LinuxCNC – open source software that interprets G-code to CNC machines. It will be used to develop cutting control software.
   - CAMotics – open source simulator of 3-axis CNC engraving. It will be used to simulate the cutting path and generate the corresponding G-code.
   - Open CASCADE– open source 3D modeling library. It will also be used to generate cutting path from the defect model.
   - QT – cross-platform application development framework that will be used to build the GUI.
   - Visualization ToolKit (VTK) – open-source software for 3D computer graphics, image processing and visualization. It will be used to visualize the system, implant, and the work procedure.
   - FreeCAD – open source CAD modeling software that has the ability to generate 3-axis G-Code from user-defined path.
3. Material: we need the data file of the raw implant material to complete the registration process. We will contact the cranioplasty surgeon, Dr. Gordon, for the materials**. Status: resolved**
4. Accessibility to laboratory: the laser cutting system is at the lab in Johns Hopkins Bayview Medical Center. We have acquired access to the lab. **Status: resolved**
5. Accessibility to machine shop: we need access to the machine shop to work on the design. We have completed the training and acquired access to all machines. **Status: resolved**

Management Plan & Responsibility

All project-related files and materials are stored on Google drive. We met with our mentors once every other week to discuss the progress of the project. We usually went to Bayview to work on the project three times a week.

Joshua focused on implementing algorithms for cutting motion and tool path generation, and developing user interface. Jerry focused on assembling hardware, aligning laser components, path to G-Code conversion, and mesh modeling. Both contributed to configuring and debugging the system.

Timeline



Reading List

[1] R. J. Murphy, K. C. Wolfe, P. C. Liacouras, G. T. Grant, C. R. Gordon, and M. Armand. Computer-assisted single-stage cranioplasty. 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015.

[2] Milutinovic, D., Glavonjic, M., Slavkovic, N., Dimic, Z., Zivanovic, S., Kokotovic, B., & Tanovic, L.. Reconfigurable robotic machining system controlled and programmed in a machine tool manner. The International Journal of Advanced Manufacturing Technology Int J Adv Manuf Technol, 53(9-12), 2010, pp. 1217-1229.

[3] D. Winder. Computer Assisted Cranioplasty. Virtual Prototyping & Bio Manufacturing in Medical Applications, 2008, pp. 1-19.

[4] J. U. Berli, L. Thomaier, S. Zhong, J. Huang, A. Quinones-Hinojosa, M. Lim, J. Weingart, H. Brem, and C. R. Gordon. Immediate Single-Stage Cranioplasty Following Calvarial Resection for Benign and Malignant Skull Neoplasms Using Customized Craniofacial Implants. Journal of Craniofacial

Surgery, 26(5), 2015, pp. 1456-1462.
[5] R. Zavala-Yoé, R. Ramírez-Mendoza, J. Ruiz-García. Mechanical and Computational Design for Control of a 6-PUS Parallel Robot-based Laser Cutting Machine. Advances in Military Technology, 10(1), 2015, pp. 31-46.
[6] P. J. Besl and N. D. McKay, “Method for registration of 3-d shapes,” in Robotics-DL tentative. International Society for Optics and Photonics, 1992, pp. 586–606.
[7] R. J. Murphy, C. R. Gordon, E. Basafa, P. Liacouras, G. T. Grant, and M. Armand, “Computer-assisted, le fort-based, face–jaw–teeth transplantation: a pilot study on system feasibility and translational assessment,” International journal of computer assisted radiology and surgery, 2014, pp. 1–10.
[8] Giorgia Willits, Shahriar Sefati, Russell Taylor, Mehran Armand, “Robotics Drilling for Single-Stage Cranioplasty.” JHU Internal paper.