Control Architecture of Cranial Implant Laser Cutting System

Project Proposal: Group 18
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Goal

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.

Relevance/Importance

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

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

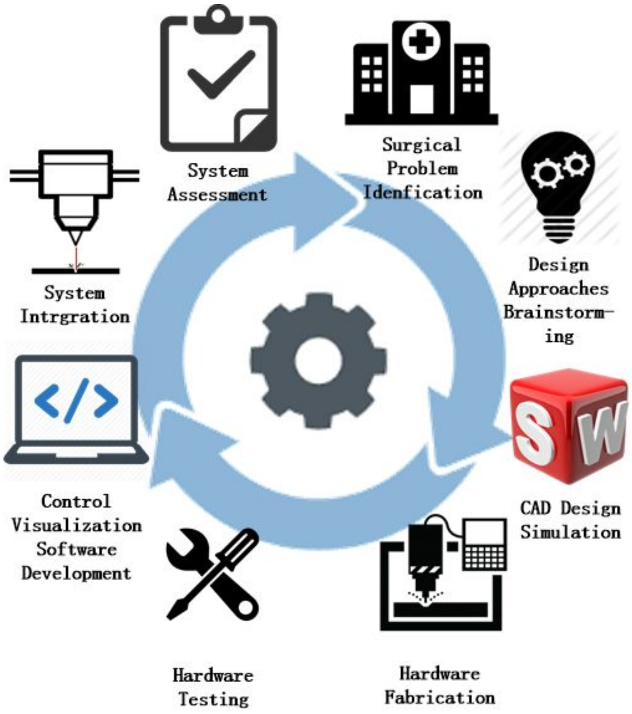
The entire surgical procedure is to be performed under sterile environment. Therefore, the robot-based system is designed to cut the CCIs with laser instead of other methods (i.e. contact, stress, or pressure) in order to preserve sterility of the implant. The system is also designed to be compact so 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

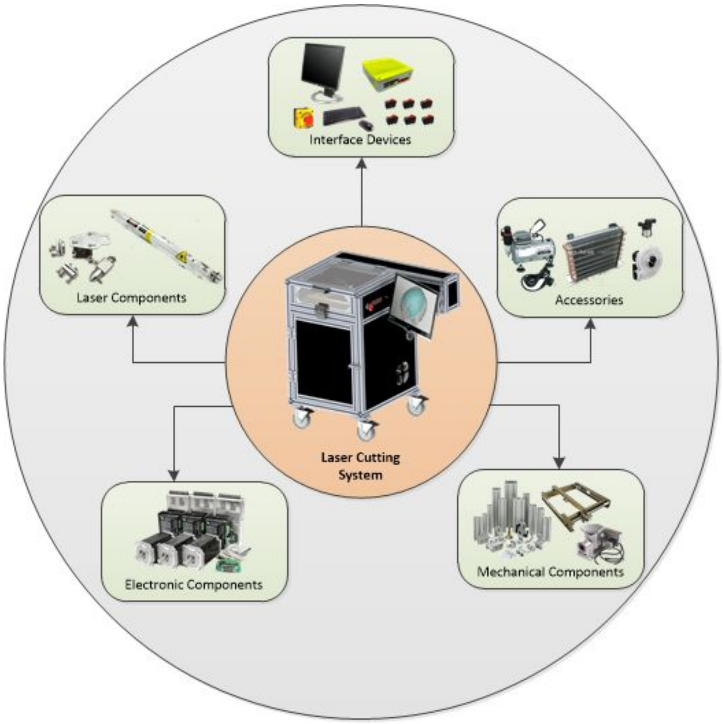
This project consists of eight steps (Figure 1).

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.

As of date, the process involving the design, CAD modeling, and fabrication is completed. Although the above diagram implies a dependency of software development and hardware testing, in reality these two processes will occur concurrently.



(Figure 1: 8-step project approach)



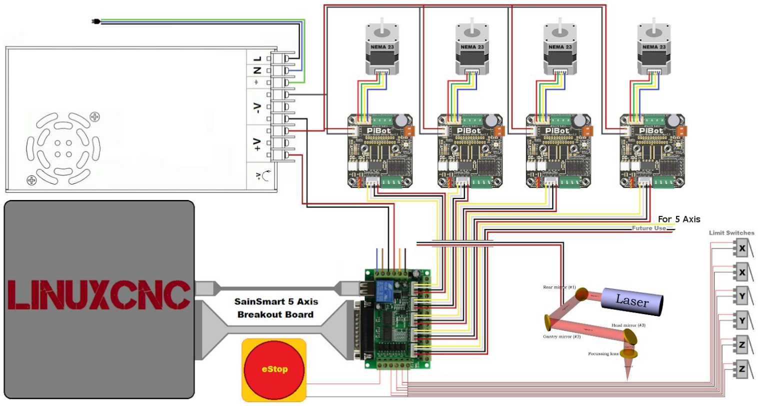
(Figure 2: system overview)

System Overview

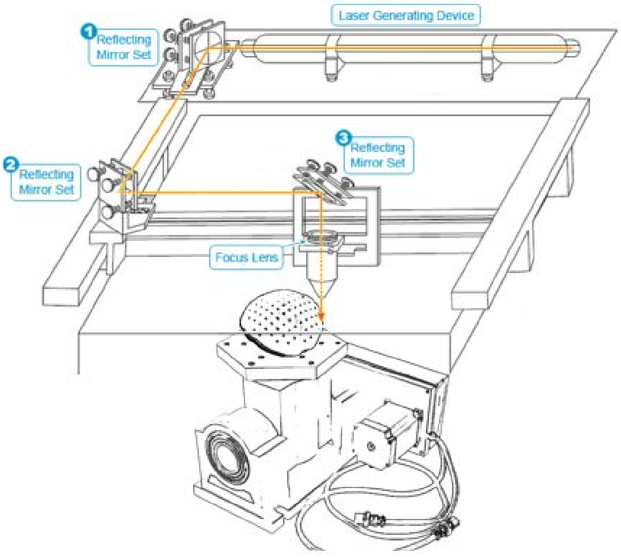
This robot-assisted laser system consists of five units: mechanical hardwares, electronic components, laser components, interface devices, and accessories (Figure 2.) The system provides up to 5-axis of simultaneous motion to trim continuous edges on the implant with any desired angles. It is composed 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 mirrors, the laser beam will be directed to shoot downward onto a horizontal platform that controls the movement in the z-axis (Figure 4).

Software Overview

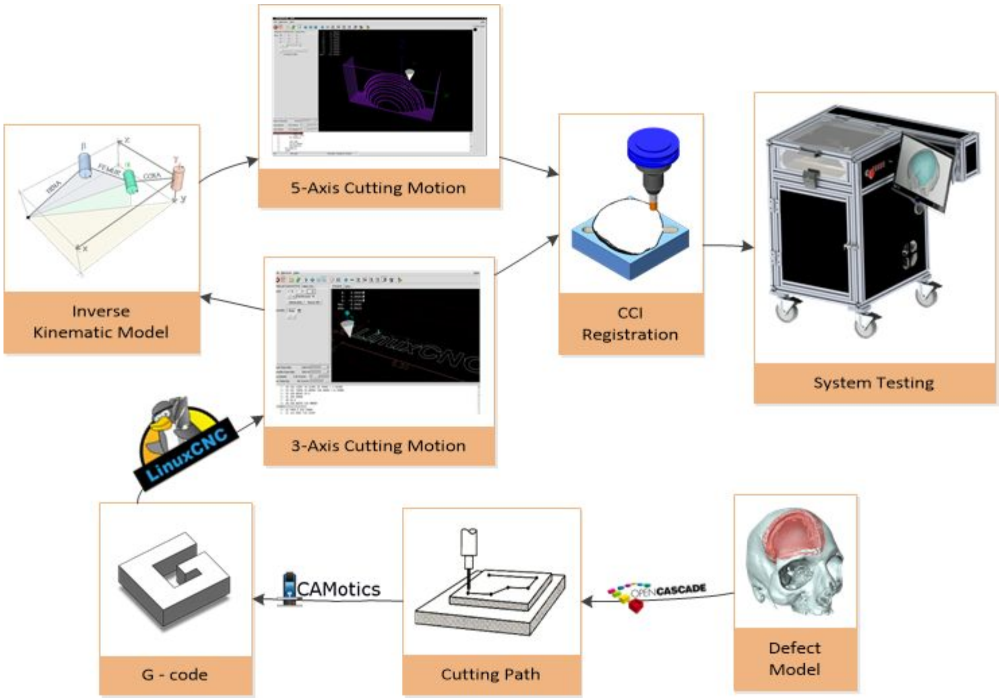
The software development of this laser cutting system falls under two categories: machine control and cutting path generation (Figure 5). For machine control, we will first develop an user interface for LinuxCNC to operate the laser cutting system. This system reads the G-code and instructs the machine 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 created by our modified version of the open source software, CAMotics. The current CAMotics The generated G-code will then 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. Troubleshoot all hardware issues to ensure that the mechanical components are functional
2. Calibrate the linear stage and the rotary table
3. Develop and implement 3-axis cutting control algorithm

Expected

1. Design a mechanism that holds and registers the raw implant material
2. Derive the inverse kinematic model for the rotary table

3. Develop and implement 5-axis cutting control algorithm

Maximum

1. Develop cutting path to G-code conversion algorithm
2. Create an user interface that loads the implant data file and simulate the cutting path
3. Test the laser cutting system with generated G-code on real implants

Dependency & Resolution

1. Hardware: this project involves the use of high power laser (class IV). We have completed the laser safety training. Resolution status: **resolved**
2. Software: we need the following software/library to assist us in this project. We have completed the installation. Resolution status: **resolved**
    a. SolidWorks - CAD modeling software. It will be used to design mechanical components.
    b. LinuxCNC - open source software that interprets G-code to CNC machines. It will be used to develop cutting control software.
    c. Camotics - open source simulator of 3-axis CNC engraving. It will be used to simulate the cutting path and generate the corresponding G-code.
    d. Open CASCADE- open source 3D modeling library. It will also be used to generate cutting path from the defect model.
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. Resolve status: **pending**
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. Resolution 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. Resolution status: **resolved**

Management Plan & Responsibility

All project-related files and materials will be stored on Google drive. We will have weekly meeting with our mentors to discuss the progress of the project. We will meet on Tuesday and Thursday work on the software, and will go to the Bayview campus on Monday and Friday to work on the hardware. Joshua will focus on developing the software and Jerry will focus on fixing and calibrating the hardware components. Both team members will work together to derive the mathematical model and develop the algorithms for the motion control.

Key Dates

Minimum deliverable

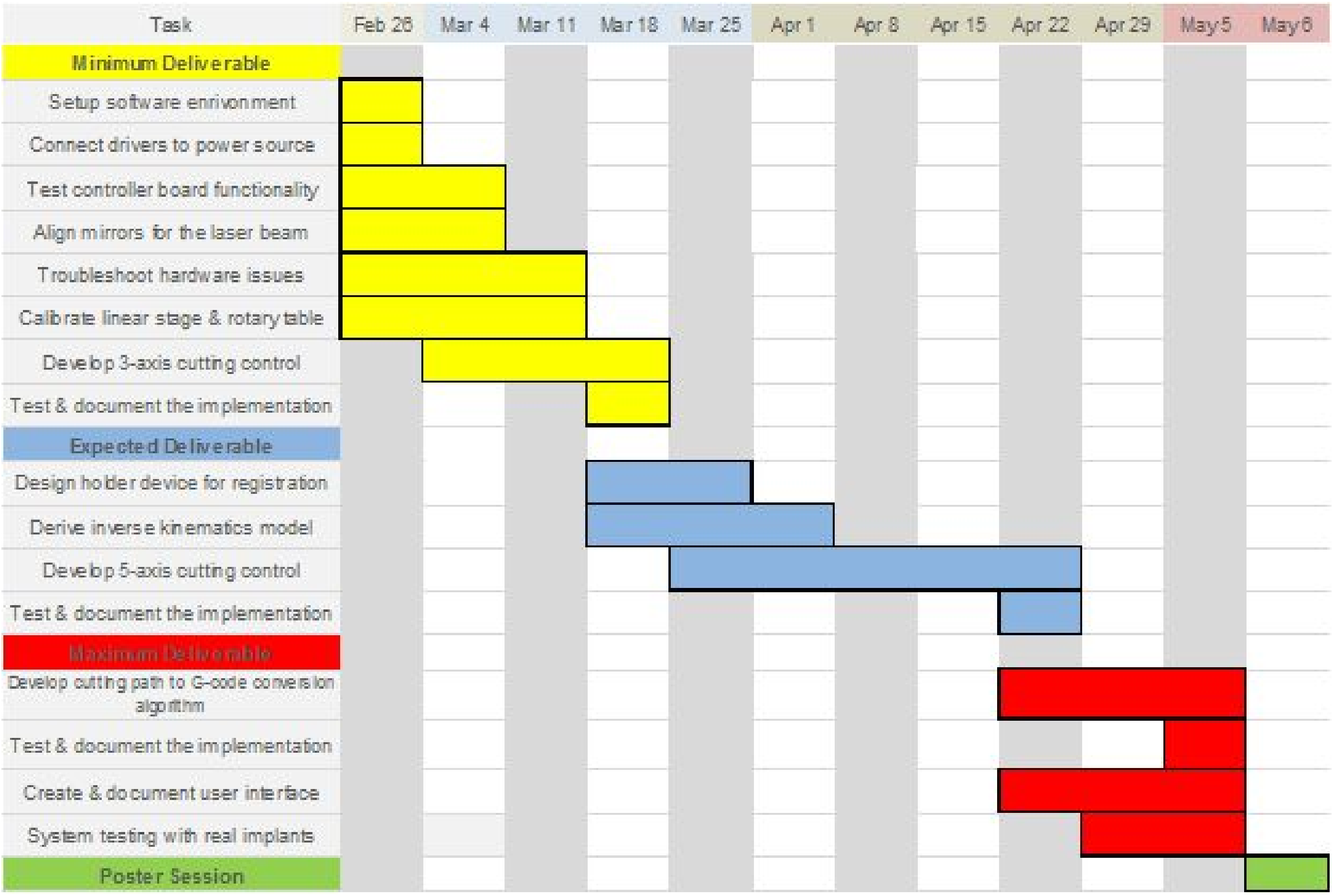
March 11: Troubleshoot all hardware issues
March 11: Calibrate the linear stage and rotary table
March 18: Develop, test, and document 3-axis cutting control algorithm

Expected deliverable

March 25: Design a holder device used to register raw implant material
April 1: Derive inverse kinematics model
April 22: Develop, test, and document 5-axis cutting control

Maximum deliverable

May 5: Develop, test, and document contour path to G-code conversion algorithm
May 5: Create and document user interface
May 5: Test the overall system



Task	Feb 26	Mar 4	Mar 11	Mar 18	Mar 25	Apr 1	Apr 8	Apr 15	Apr 22	Apr 29	May 5	May 6
Minimum Deliverable												
Setup software enrivonment	🟨											
Connect drivers to power source	🟨											
Test controller board functionality	🟨	🟨										
Align mirrors for the laser beam	🟨	🟨										
Troubleshoot hardware issues	🟨	🟨	🟨									
Calibrate linear stage & rotary table	🟨	🟨	🟨									
Develop 3-axis cutting control		🟨	🟨	🟨								
Test & document the implementation				🟨								
Expected Deliverable												
Design holder device for registration				🟦	🟦							
Derive inverse kinematics model				🟦	🟦	🟦						
Develop 5-axis cutting control					🟦	🟦	🟦	🟦	🟦			
Test & document the implementation									🟦			
Maximum Deliverable												
Develop cutting path to G-code conversion algorithm									🟥	🟥	🟥	
Test & document the implementation											🟥	
Create & document user interface									🟥	🟥	🟥	
System testing with real implants										🟥	🟥	
Poster Session												🟩

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

[3] 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.

[4] 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.

[5] 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.

[6] 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.

[7] Giorgia Willits, Shahriar Sefati, Russell Taylor, Mehran Armand, “Robotics Drilling for Single-Stage Cranioplasty”