

**DESIGN OF COST-EFFECTIVE AND ACCURATE LASER CUTTER THAT SERVES
A MARKET NICHE**

A Research Paper submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Mechanical Engineering

By

Cole Lloyd

May 9, 2022

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISOR

Sarah Sun, Department of Mechanical Engineering

Abstract - Laser cutters are devices that play an important role in effective machining of manufacturing processes. With their high cutting speed and precision, laser cutters can efficiently machine various materials, including and not limited to wood, paper, certain plastics and metals. This paper focuses on a specific CO₂ laser cutter custom built by the writers of this paper. The aim of the team was to design an inexpensive CO₂ laser cutter capable of working with woods and plastics for rapid prototyping and fabrication of parts for pre-production models. The innovation that was strived for was minimizing cost given a bed size of two by four feet and a laser tube power of one hundred watts. In doing so, the laser cutter will serve its own niche to consumers in comparison to widely-available market counterparts.

I. INTRODUCTION

A. Motivations

The motivations for this capstone research project are the following: UVA's mechanical engineering department has invested little in laser cutters comparably to other manufacturing machines, the typical laser cutting needs are usually outsourced to third party service providers, or siloed within a specific "working group" within UVA, the high cost of a laser cutter provides a barrier of entry to the low end of the market, the goal of the project is to discover what design parameters should be prioritized in order to create a high performance laser cutter optimized for a \$4000 budget.

B. Laser Mechanism and Types of Lasers

LASER is short for Light Amplification by Stimulated Emission of Radiation. As stated by Sattel et al. [5], a stimulated emission is triggered when a lasing medium gains energy from intense flashes of light or electrical discharges. This energy forces a large collection of electrons to an excited state, which brings them to move from a lower-level energy orbit to a higher-level energy orbit of an atom's nucleus. During the emission stage, excited electrons release the energy that they have absorbed and fall back down to their original position at the ground level. At the same time, photons at specific wavelengths are released. Any other stored photons are also released as excited electrons stimulate other electrons to amplify the process. With greater energy difference in the two levels, the more energy there exists to be transformed into light energy to create a light beam. M. Madic et al. [7] stated that "the high power density of the focused laser beam in the spot melts or evaporates material in a fraction of a second, and coaxial jet of an assist gas removes the evaporated and molten material from the affected zone".

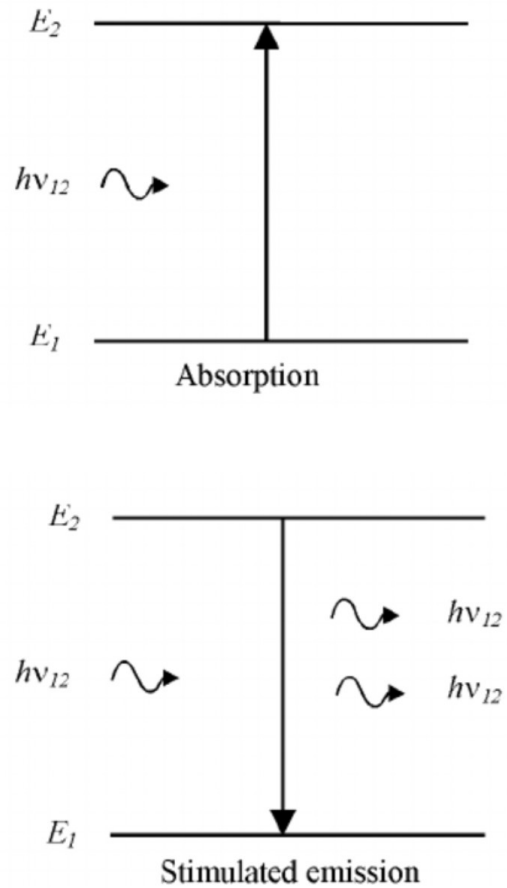


Figure 1. Laser Mechanism in Atomic Level (Kitching et al. [10])

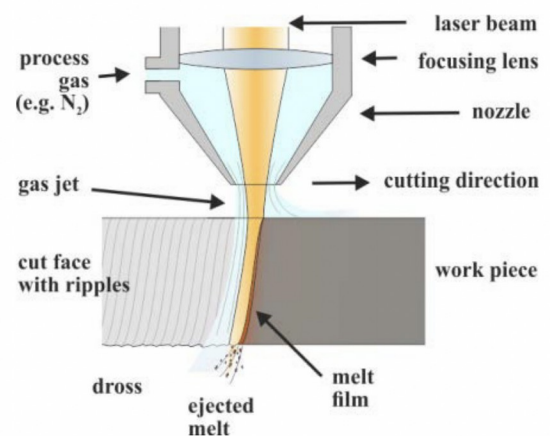


Figure 2. Diagram of Laser Mechanism (Thombansen et al. [8])

According to Patel et al. [6], lasers can be categorized into solid, liquid, gas, or semiconductor lasers

based on the medium that they employ. CO₂ lasers, which is the laser of choice for investigation, are gas lasers which use electrically stimulated carbon dioxide gasses to emit energy to cut through materials. They are most effective on non-metallic materials, such as wood, paper, acrylic, and most plastics. CO₂ lasers are widely used in industrial and medical practices because of their relatively high efficiency, high output power, and high laser beam quality.

C. Marketing Survey

Due to the team having a single semester to work on the project instead of a typical entire school year, a standard market survey with multiple iterations of surveying and interviewing professionals or people in the industry could not be conducted. Consequently, a marketing survey was performed in which various popular laser cutters on the market were compared. Multiple criteria such as cost, bed area, resolution, focal length, tube power, and whether the machine had an aiming laser or air assist, which were important “parameters to be considered for laser cutting” as stated by Vasiga et al. [9] were observed on each laser cutter. Based on these criteria, specific design parameters for the laser cutter were decided upon as displayed in the rightmost column of Table I.

The laser types that were sampled were a K40 laser [4], two Omtech lasers with a tube power of 80W [2] and 100W [3], respectively, and the Lasersaur laser [1]. These four types were chosen as they varied in cost, accuracy, and power - allowing for an observation of the advantages and disadvantages of each model and applying them to the design considerations of the desired laser cutter for the project.

Laser Type	K40	Omtech 80 W	Omtech 100 W	Lasersaur	Desired Laser
Cost	\$500	\$3,200.00	\$3,900.00	\$7,300.00	\$4,000.00
Bed Area	200x300 mm	500x700 mm	500x700 mm	1220x610 mm	610x1219 mm
Resolution	300 dpi	335 dpi	335 dpi	840 dpi	700-850 dpi
Focal Length	50 mm	63.5 mm	50 mm	100 mm	50-100 mm
Tube Power	40 W	80 W	100 W	120 W	100 W
Aiming Laser	No	No	No	No	Yes
Air Assist	No	Yes	Yes	Yes	Yes

Table I. Laser Cutter Marketing Survey

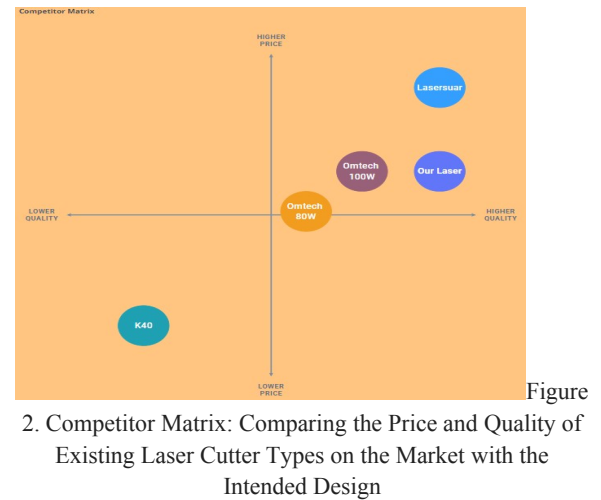
The resolution and focal length correspond to the accuracy of the laser. Resolution measurements are in dpi, defined as dots per inch or how many dots can be lined up

in an inch without overlapping. In simple terms, the larger the value, the more accurate the laser cutter will be as it can engrave and cut very small shapes. Furthermore, focal length refers to the cutting performance of the laser. A larger focal length allows the laser to cut through thicker material, thus allowing for higher efficiency. For example, a high focal length could cut through a thick material in less trials than a low focal length laser would.

The K40 laser is by far the cheapest out of the options at only five hundred dollars; however, it lacks tube power and accuracy. On the other hand, the Lasersaur laser has very high accuracy and tube power yet is ultimately much too expensive. The Omtech lasers find a good balance between cost and power but are not quite as accurate as desired. Therefore, the intended laser cutter model for this project seeks to meet the high resolution and focal length of the Lasersaur laser, while achieving a budget similar to that of the Omtech one-hundred-watt laser.

D. Analysis of the State of the Art

Based on the findings from Table 1, the project intends to answer the question: how can the laser resolution and power be optimized to ensure accuracy while staying within the budget? Data from the marketing survey was compiled into a competitor matrix in Figure 2 that highlights the emphasis on designing a high-quality laser cutter that is low in cost, as this combination is not seen in the current laser market.



2. Competitor Matrix: Comparing the Price and Quality of Existing Laser Cutter Types on the Market with the Intended Design

E. Framed Goal of the Intended Design

The primary goal of this project is to design a high-power, low-cost, and accurate CO₂ laser cutter capable of working with woods and plastics for rapid prototyping and fabrication of parts for pre-production models. The project is met with five main design objectives to ensure a model that is not currently seen on the market.

First, the cost must be within a budget of \$4000. Second, the laser must have a high resolution within the range of 700-800 dpi to allow for precise engraving. Next, the focal length should be between 50-100 mm to ensure efficiency when cutting material. Fourth, the tube power will be 100 W to achieve high performance. Lastly, a large bed cutting area of 2 feet by 4 feet will be built to allow for the cutting and engraving of large pieces. By meeting these criteria, the design will provide an innovative laser cutter rarely seen in the current market.

II. DESIGN

A. Design Questions

With main design objectives framed for the study, the laser cutter has been detailed with a \$4000 budget, a resolution of 700-850 dpi with a focal length between 50-100 mm, a tube power of 100 W, and a bed size of 2' by 4'. Concerning these main design objectives, five design questions have been formulated.

The first question is: Where is the desired balance between cost and tube power? This question is especially important when considering the fact that the highest tube power, hence the most powerful laser cutter, is not something the project is looking to optimize for. A tube power that is sufficient enough to carry out the fabrication of pre-production models would be enough, but only when taken into account with respect to the cost of the entire system.

The second question is: Where is the desired balance between cost and resiliency of the frame? A similar interpretation can be taken as done with the balance between cost and tube power. While a resilient frame with the right dimensions and the right material are optimized for, the cost should not be sacrificed to the point that the system becomes an ineffective attempt at making a high-end model, which does not align with the objectives of this capstone design.

The third question is: How low of an XY resolution should be aimed for? This question is more important in the context of the expected usage of the intended design of the laser cutter. Depending on the type of models that are cut out, striving for better XY resolutions may suffer the problem of diminishing returns as far as the price to performance ratio is concerned. Considering the budget, 0.1 mm is a good compromise between speed of cutting (i.e. how fast head can travel (mm/sec)) and the repeatability of moving off of and back to the same point (dial indicator test). This must be taken into account in the design of the system.

The fourth question is: What is the desired focal length of the laser cutter's focal lens? Typically, the focal lengths range from 1.5" to 4", with 2", 2.5" and 3" being common intermediates. This question is an important guiding point in the research because the lens choice for the

intended design is crucial for determining the compromise between engraving performance and cutting performance. The higher the focal length, the more emphasis the system will have on cutting performance. The beam waist equation for gaussian distribution explains how small of a "spot size" one can obtain for a given beam diameter and focal length of the lens. If the beam diameter is kept constant (approximately ½ in), then one can see that the smaller the focal length, the smaller the spot size is and the longer the rayleigh range is (i.e. the 'length' of the beam waist)).

The fifth and final question is: What are the upper and lower bounds to the mass of the laser cutter, is portability a key factor? The heavier the machine, the less likely it is that the forces generated by the rapidly accelerating machine head will overcome the friction force keeping the workpiece in place, preventing the workpiece from shifting while in the process of cutting. On the other hand, a heavy enough machine will make it an ordeal to transport the laser cutter from shop to shop or anywhere else. A trade-off between the two factors is necessary for a functional laser cutter.

B. Design Overview

End goals for this design project are divided into five subareas: mechanical, electrical, optical software, and supply chain.

Mechanical is responsible for the following deliverables:

- Full CAD Model in SolidWorks

Electrical is responsible for the following deliverables:

- Full Block Diagram with all of the components and traces labeled

Optics is responsible for the following deliverables:

- Full Block Diagram with all of the components, traces and beam paths labeled

Software is responsible for the following deliverables:

- State Diagram describing the implementation of motion control in GRBL
- UI flowchart describing how to go from CAD to part

Supply Chain is responsible for the following deliverables:

- Full Bill of Materials with quantities, prices and sources for each component

B.1. Mechanical Design

The team examined a few different kinds of XY motion systems to determine which might work best for the intended application of the laser cutter, keeping in mind the various requirements given (\$4k budget, cutting area of 2' x 4', and the approximately 1.5 m long laser tube).

From the list, debates as a team occurred, and the list was narrowed further. Some positioning systems would take a large amount of additional work to control, such as the Stewart platform, Scara, Delta and Maslow designs.

Some would make the beam path for the laser overly complicated, such as the stacked Linear Positioners, and some would have made the footprint of the design too large, such as the Split 1D Drives.

Based on the above decisions, the team narrowed the feasible designs down to 4 different styles, which are summarized in the table below.

Motion Platform	Moving Mass	Mechanical Complexity	Control Complexity	Cost to Implement	Time to Implement
CoreXY	1 beam	Very Complex	Very Complex	Expensive	8 Hours
Gantry w/ Shaft	1 beam, 1 motor	Straight-forward	Simple	Cheap 1 shaft	2 Hours
Gantry w/ 2 Motors	1 beam, 1 motor	Simple	Straight-forward	Extra motor & control slot	4 Hours
Ultimaker	2 beams	Complex	Dead Simple	Extra beam	4 Hours

Figure 3. Design Matrix for Motion Platform

Of the four options, the gantry with shaft design was selected, as it was the least mechanically complex option, worked with the existing control scheme, and was the least expensive system to implement that would bring satisfactory results, namely the minimization of the accelerated mass as much as was reasonably possible within the \$4000 budget.

Once the 2D motion platform design was designed, the safety requirements necessary for the laser cutter to meet the specifications for Class 1 Laser products in the US were examined. This evaluation necessitated the design of an enclosure which could mount various safety interlocks such as limit switches, a door open switch, a keyed interlock switch to prevent unintended operation, and an emergency stop switch to kill power to the machine should an unanticipated problem arise. There were also provisions for evacuating smoke and vapors generated when laser cutting, as well as a method of temporarily keeping the laser tube cool, and a method of suppressing a fire in the cabinet, should one break out.

After all of the individual parts were designed on CAD and built, the laser cutter was assembled. The starting point of the mechanical assembly was the frame and the kinematics, and upon completion, progress was made to remaining parts until prept for testing.

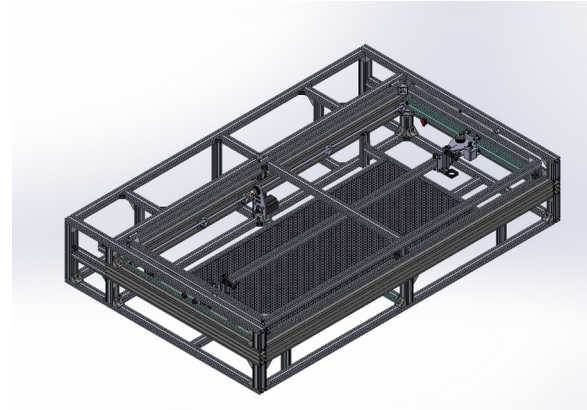


Figure 4. Final CAD Model of Intended Laser Cutter

B.2. Electrical Design

Once the specifications for the laser tube, the number of motors to be used, and the required positioning accuracy were gathered, work began on the electrical design for the laser cutter.

The first order of business involved listing the requirements for a laser cutter controller (the list is included in Appendix B). The laser cutter controller is typically a motherboard-like device with an integrated processor and motor drivers that can take a line of g-code and turn it into a specific set of commands that the motor drivers can use to drive the motors that move the laser head around in the machine.

The team chose to use stepper motors for their high torque, low cost, and ease of implementation. While a stepper motor's open loop control system is not ideal, cost was a limiting factor. Since the Y-Axis needed to drive 2 different belts, the decision was made to use a NEMA 23, which can output more torque than the standard NEMA 17 used for the X-Axis. This means that the Y-Axis would have a similar acceleration profile as the NEMA 17 used on the X-Axis. For the X axis, the NEMA 17 was chosen due to weight considerations, owing to the fact that the X-Axis should have very little to no load applied to it due to the lack of contact between the laser head and the workpiece.

Once the decision was made on the types of motors to use, the team then looked for a control board that could drive these motors. Through this process, the smoothie board, which is an open-source 3D printer controller board, was discovered. Upon further digging through forum posts and build logs, a supplier by the name of Cohesion3D who manufactures a derivative of the smoothie board that is set up to control a CO2 laser cutter natively was identified. After checking the board's features against the requirements, the team decided that the Laser board V1 from Cohesion 3D would meet the project needs, and so a purchase was made of the item along with a larger stepper driver for the NEMA 23 that would drive the Y-

Axis. Figure 8 is a picture of the control board that the team chose to use.

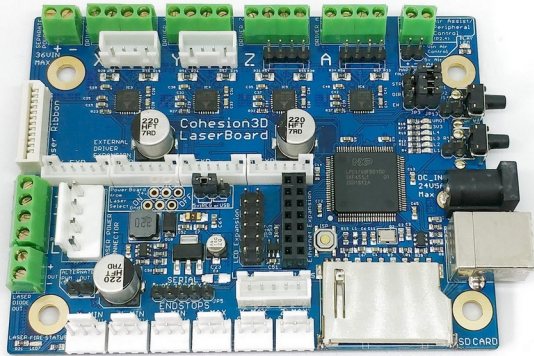


Figure 5. Cohesion 3D Laser Board (Cohesion3D [13])

This board is designed to run laser cutters. It has built in drivers for up to 4 NEMA 17 stepper motors (59 oz/in versions), pinouts to pass a control signal to a larger driver (such as that required for a NEMA 23), and a 32-bit processor. It is also capable of headless operation. The control architecture is based on GRBL, which makes troubleshooting easier due to the common protocol grbl uses to send movement commands in g-code.

The electrical diagram is included below in Figure 9.

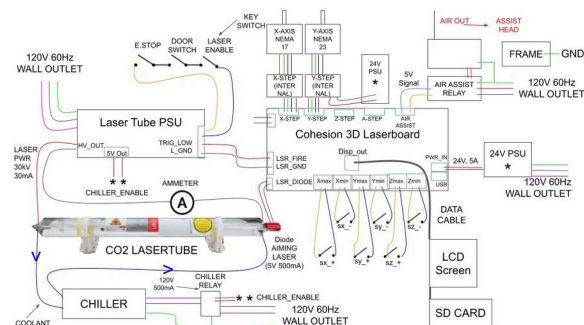


Figure 6 . Electrical Wiring Diagram

This diagram includes all of the additional components required to safely operate the laser and shows how each piece is connected. Once the main electrical components were ordered and the mechanical parts had been assembled, the layout of electronics followed. The device was powered up to test the motion control and the laser independently. Following both of their integration, the laser cutter was ready.

B.3. Optical Design

The most difficult piece of the design process was selecting a laser tube suitable for the planned laser cutter. Approximately a week was spent browsing through Ebay, Amazon, Aliexpress and other websites to determine

where the local minima was in price and performance for different ‘classes’ of laser tube. Based on the results from the decision process for the laser tube, a tube suitable for the design was identified. However, there were issues with importing the tube into the country from China, so a decision had been made to order the identical tube from a US supplier. The specifications for the tube has been listed below:

Wavelength: 10.6 μm (Infrared Range)
Output Power: 100 W continuous, 130 W in full-power mode
Cooling: 5 kW continuous chiller recommended; 3 kW Minimum
Dimensions: 1480 mm (Length) x 80 mm (Diameter)
Beam Diameter: 12 mm approximately



Figure 7 . Selected Laser Tube: SPT 100W Laser Tube (SPT Laser [12])

Once the decision has been made on the laser tube, components necessary to finish the optical subassembly were identified. These included mirrors, lenses, a power supply for the laser, mirror aiming stages, and lens holders.

All of these components were either sourced by examining other laser cutters or by searching for and selecting the best price/performance part. The pieces were then assembled into an Optical Layout Diagram (figure 8) was established to confirm that all parts would work in unison.

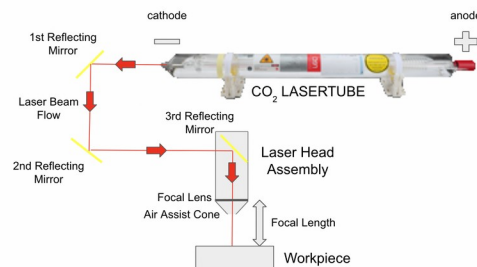


Figure 8 . Optical Layout Diagram

B.4. Software Design

Software design of the laser cutter did not present too much complication. A day was spent looking at possible software programs to control a laser cutter, results of which set forth three main options: self-building a new software, running an open source software package, or using a pre-made software package specifically designed for laser cutters.

Most large companies that manufacture and sell laser cutters (BOSS, Epilog, etc.) include default software that allows the machine to run. Some of these include features capable of multiple layers, variable cut power, raster engraving, and the like. However, considering the timeline and budget that were given, and the team's level of experience in software development, which was little to no experience, the first option was eliminated.

The second option was to run an open-source program or a combination of open-source programs. This could be accomplished using a program, namely inkscape, to layout the parts in space, then using a plug-in within inkscape to convert the 2D shapes into g-code, and then streaming the g-code to the control board. While acceptable in theory, the process of going through several different software platforms to cut out a shape is excessive.

The third option was to use the student license of a software designed to perform vector editing and layout for laser cutters. This was the chosen option for testing the laser following the completion of assembly.

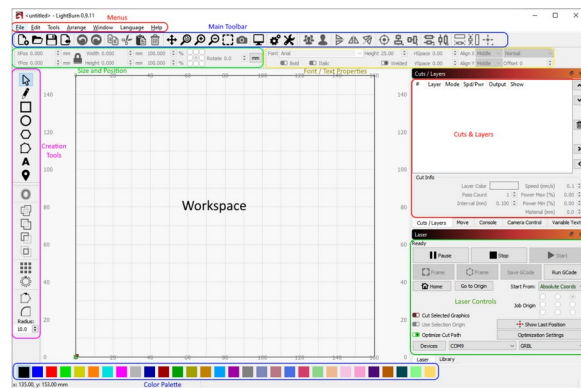


Figure 9 . Main Window of LightBurn Software (Dorie [11])

C. Design Iterations

In the interest of time and money, design iterations were focused on during the conceptual and simulated modeling phases of the project. Other important factors for design included the consideration of Class 1 laser specifications and the compatibility of parts in relation to the intended performance of the laser cutter. Once the design plan was solidified, no radical changes were made in the construction and assembly phase as adjustments during full-scale prototyping can be considerably more costly and time-consuming.

III. METHODS

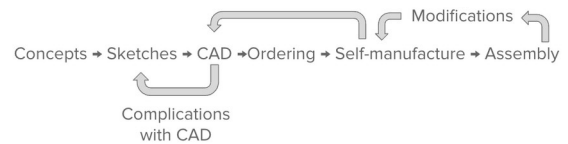


Figure 10. Design Process

The design process began with a team meeting and whiteboard sketches. The team took a look at the accuracy of several 3D printers, CNC machines, and laser cutters to generate a desired list of design requirements, which were found to be a 2' by 4' bed, a 100 W laser tube (subject to budgetary constraints) and a \$4000 budget.

The next step after deciding on the initial design and laying out broad requirements was to start building the CAD model. The process was a long and iterative process, as complications and subsequent remodeling occurred. The Bill of Materials was formulated in unison with the CAD model, as new parts had to be researched and ordered as complications with the model arose. Since the components necessary for the mechanical design were expensive and time-consuming in terms of delivery time, the CAD model was perfected as much as possible before ordering parts in order to stay within the desired budget.

Once the CAD model was finished, all of the necessary parts and tools to build the machine were gathered. Several parts, such as the cover panels, various brackets, and the nozzle for the laser cutter had to be self-manufactured by means of water jetting at Lacy Hall or by machining at one of the machine shops around UVA grounds.

D. Design Validation Tests

With design questions laid out, it is critical to come up with validation tests to ensure that the laser cutter meets planned objectives. The tentative test plans are outlined below.

1) Repeatability of X & Y Axes → conduct a dial indicator

This test verifies that the XY resolution reliably reaches a certain target number across repeated runs of the machine.

2) Bed Size → cut a 2' by 4' piece of plywood, fit in bed

This test verifies that the laser cutter is not using more materials than it needs and is not encroaching over a certain amount of volume in order to limit the mass of the final system.

3) Laser Tube Power → check the power of tube using the EHS power meter

This test verifies that the laser tube is not outputting a lower tube power than expected due to various

reasons, ranging from faulty product to insufficient power supply.

- 4) Engraving Accuracy → Etch a raster image into a piece of plywood

This test is a quality measure for how well an image can be etched into a piece of plywood.

- 5) Useability → go from CAD to Cut Part in less than 30 minutes

This test will be used to fine tune the entire system as a whole. If the CAD to cut model takes more than 30 minutes, then parts may need to be rearranged or switched out to optimize for such a completion time.

IV. RESULTS

The laser tube optics were set up as shown in Figures 11-13. The laser beam was directed out of the laser tube as seen in Figure 11 then off of three angled mirrors before exiting the laser head as shown in Figure 13. For safety reasons, this aiming laser was used for alignment of the beam.



Figure 11: Head of the Laser Tube and Air Compressor

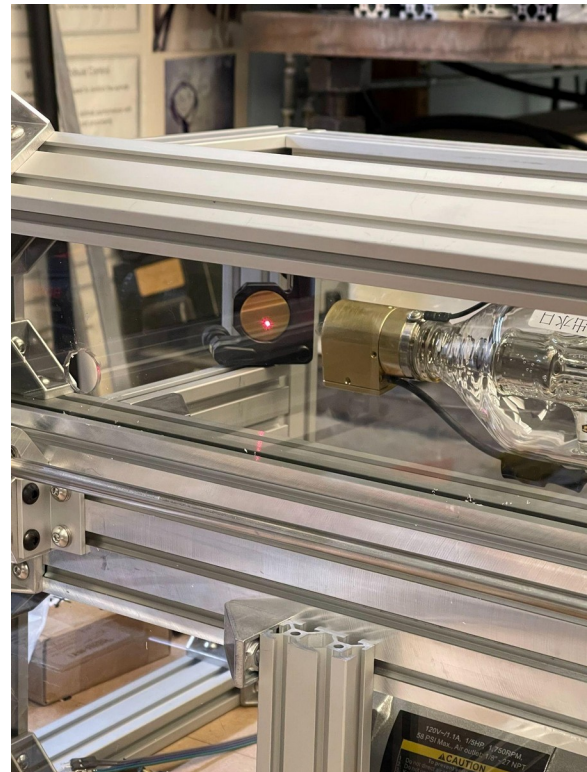


Figure 12: Laser Beam Hitting First Mirror



Figure 13: Laser Beam Exiting Laser Head Assembly

The XY motion system successfully worked and could navigate the laser head to any point within the two by four foot bed frame. Both the X-axis belt mount and the Y-axis belt mount were equipped with limit switches to detect when the laser head has reached the outermost portion of the bed area as seen in Figures 16 and 17. These limit switches successfully worked and would stop the mechanism from traveling any further. The electrical

wiring of the limit switches and stepper motors for the X and Y-axis mounts is seen in Figure 15.

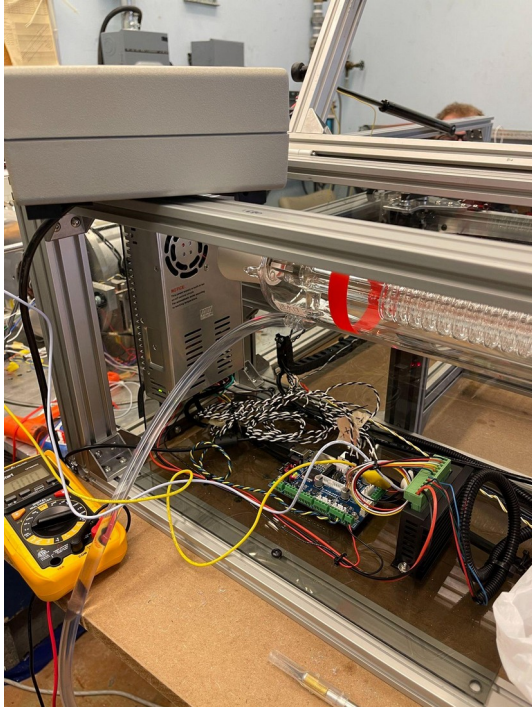


Figure 15. Wiring of Electrical Components



Figure 17. Y-axis Belt Mount

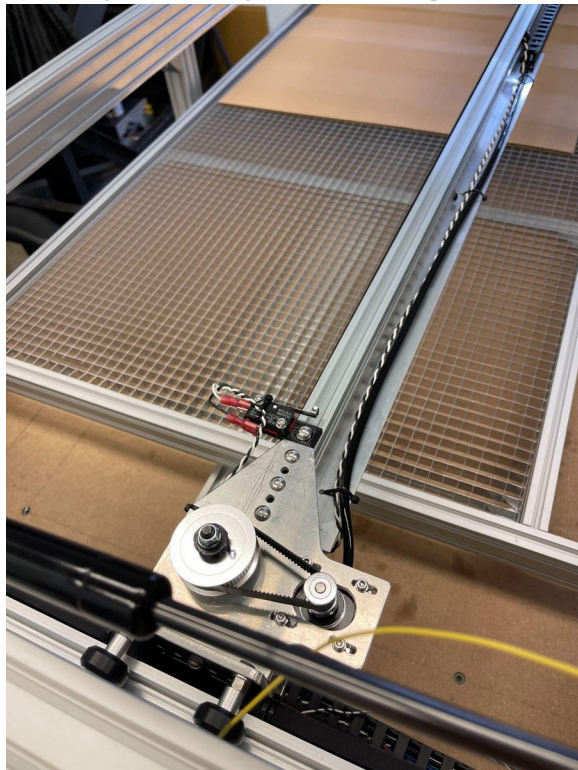


Figure 16. X-Axis Belt Mount

Demonstration of the operating system was as follows: powering up all of the components, putting the laser cutter in full operation mode, and cutting out a rectangle with cardboard as the target object.

While the laser beam could be powered on and the XY traversal system operated properly, the two of these could not perform in unison to make a definitive cut. The error is likely due to an optical issue and unfortunately could not be solved due to lack of time. The full assembly apart from enclosing panels is shown in Figure 18.



Figure 18. Full Assembly

V. CONCLUSION

A. Discussion

Further configuration must be done to make sure that the laser is properly powered on and will fire a beam of hot, melting light through the material to be cut. During the demonstration, it became apparent that the laser cutter would not cut the material, and no light was detected despite the aiming laser assist being properly guided through the mirrors in the test run prior. This could be due to a number of factors, ranging from faulty wiring, newly misaligned mirrors, and software-specific issues.

B. Conclusion

Once the optics, software, and electronics are troubleshooted, the laser should be ready to cut out materials like paper and cardboard to start and then tougher materials after.

C. Future work

The main future work that needs to be done with respect to the laser cutter is to contribute to the open-source Lasersaur project, which provided a basis for our project. The update will include five major components: refining the overall CAD model of the laser cutter and its associated components, reviewing the bill of materials, organizing the code, creating documentation for assembly and testing, and packaging and publishing all updates. There were inconsistencies with the CAD model that were not accounted for which contributed to improper fabrication of parts (wrong dimensions), improper assembly of them, and

last-minute adjustments needed to make certain inconsistencies align. In addition, the bill of material has to be updated accordingly. There were a significant number of parts that needed not be ordered and were also missing that needed to be shipped. Additionally, there were instances of over-ordering. The code should be organized as well, with sufficiently detailed documentation on assembly and testing. Finally, the updates will be packaged and published onto Lasersaur for the public to follow along with the project.

ACKNOWLEDGEMENTS

The team of Borah Choe, Chris Dauber, Dong Wook Kim, Cole Lloyd would like to thank Professor Sarah Sun for her tremendous support towards the project.

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