Design and Testing of Components for a Low Cost Laser Cutter

by

Joshua D. Ramos

Submitted to the department of Mechanical Engineering in
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ABSTRACT

The main goal of this thesis is to document the design and testing of various components for use in a low cost laser cutting mechanism for hobbyists and recreational designers. Different electronics were used to assess the cutting potential of a laser diode, a small silicon chip based laser light producing unit. A test rig was constructed to evaluate the cutting potential of the laser diode, and several tests were conducted on different materials. In addition, a low cost positioning machine design was also explored, which used servo motor actuators to drive the system and was used to evaluate the potential of using a potentiometer for position feedback.

Tests with the laser diode using different cutting strategies revealed that the cutting potential of the diode is limited and not likely well suited for cutting through materials of useful structural thickness (0.125 inch to 0.25 inch thick materials). The tests of the potentiometer feedback were positive, indicating that potentiometer feedback is a good method for low cost position control. However, the mechanical designs tested proved insufficient for positioning the system to within 0.01 inches of the commanded coordinates so further improvement is necessary.

Thesis Supervisor: Daniel D. Frey

Title: Associate Professor of Mechanical Engineering and Engineering Systems

Acknowledgements

I would like to thank my parents for always supporting me and letting me find my own path through life. I would also like to thanks Carmen Graves, and all of my other friends who had to deal with the constant smell of burnt plastic. A special thanks to Professor Frey, who allowed me to explore a project in which I had personal interest, and guided me along the way.

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1 Introduction:

The concept of using lasers to cut material has been around since the invention of the first devices that were able to produce laser light. Often pictured in science fiction, the ability to use lasers to cut many different types of material is a reality today and is an exciting sector of manufacturing processes that is constantly changing and evolving. Recently, laser cutting machines have reached the point where there is a market for them not only in manufacturing facilities, but also universities and various design firms, especially those that focus on architecture, graphic design, and product design.

While manufacturing facilities utilize laser cutting machines as ways to quickly fabricate parts made of various plastic and metallic materials, institutions like universities and design firms have laser cutters that take the role of prototyping machines. Because of the high precision offered by a commercial laser cutter and the relative ease of designing parts in solid modeling software and transferring that data to the laser cutting machine, using a laser cutter greatly reduces the time between designing a prototype and having the fabricated parts in hand. This reduction in time assists the prototyping process by being able to make multiple prototypes with various improvements at each step of the way. Educators in the field of mechanical design and engineering students have come to realize the potential of having laser cutting machines during the prototyping stage of the design process.

Increasingly, hobbyist designers have become interested in the uses of laser cutting machines for fabricating personal prototypes in their own home laboratories and workshops. However, because of the high cost of commercial laser cutting machines, which can be tens of thousands of dollars per unit, buying a commercial machine is not an option for most hobbyists and recreational designers. For this reason, some hobbyists have resorted to fabricating their own laser cutting machines for their personal use, even reducing the cost to close to one thousand dollars.

This thesis was inspired by a recreational designer who was attempting to construct a laser sintering 3D printing mechanism, another type of machine that has become increasingly popular in the hobbyist world. Using the relatively inexpensive, and likewise relatively weaker, laser diode in the 3D printing design, he decided as a side project to evaluate the promise of the laser diode as a cutting tool. Upon successfully cutting the thickness of a CD cover using a reciprocating laser design, he eventually concluded that with more adjustments the laser may be able to cut materials with thicknesses useful for mechanical construction. The main goal of this thesis is to document steps taken by the author to further characterize the power of the available laser diodes on the market as cutting tools, and steps towards designing a machine with sufficient precision for household prototyping while keeping the total cost of the machine under two hundred dollars. As a secondary goal, this thesis is an exploration of the design process and a documentation of the design choices made throughout the project.

2 Background on Laser Cutting

2.1 Laser Cutting History and Presence in Manufacturing

The first commercial laser cutting machine was introduced into the manufacturing market in 1978 by Strippet, Inc., of Buffalo, New York [1]. By no coincidence, this commercial laser cutter was released within a year of the first Star Wars film, which did a great deal to popularize the idea of using powerful beams of laser light to cut through rigid material. Since the introduction of the laser cutter into industry, laser tooling has been used on commercial machines to do various machining processes, including boring, drilling, punching, and other machining tasks. In more recent developments, the precise control over the depth of cut for laser tooling has made it possible to create three dimensional features in the work piece, and laser tool heads with increased degrees of freedom and large workspaces have been able to create these features on parts the size of an automobile. In fact, laser usage in manufacturing has been growing the fastest in the automobile industry.

The two most common types of lasers used in manufacturing are CO_2 lasers and yttrium-aluminum garnet (YAG) lasers. While the two laser types can differ in many parameters, including thermal efficiency and power output, the main difference is the types of materials that will absorb the specific laser light.[2] YAG laser light has a wavelength of 1.064 microns, while CO_2 lasers have a wavelength ten times longer, or 10.64 microns. The shorter wavelength of the YAG laser allows the beam to be more readily absorbed by metals, although the wavelength does not allow for suitable absorption into non-metals. For this reason, CO_2 lasers are used more commonly when the material being manufactured is not metallic. Common examples of laser cut materials that are not metallic include plastics, wood, and fabrics.

Laser light absorption properties are essential for the proper cutting of materials because laser cutting is primarily a thermal process [1]. The laser light that is emitted by the tool head is normally focused to a small region on the material being cut and absorbed into the material, with a portion of the light being reflected off the surface of the work piece. Locally, the material near the focal point is raised in temperature to the point where the material melts or is vaporized. Usually an assist gas is used to remove the vaporized material, and when the assist gas is oxygen, the resulting exothermic oxidation reaction that occurs when cutting metals adds to the thermal efficiency of the cut. Figure 1 shows a diagram of the laser tool head, along with typical parameters that govern the laser cutting process.

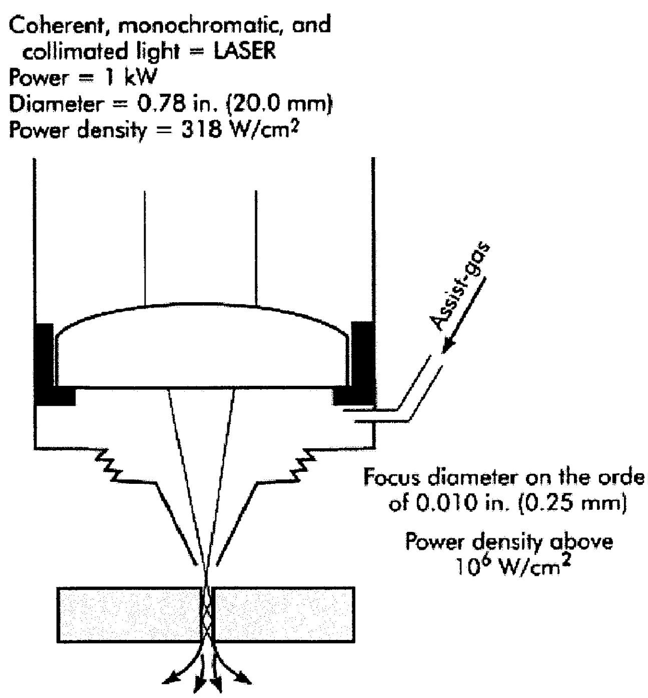

Figure 1: A common laser cutting tool head. [1]

Usually, the metric used to describe the potential strength of a laser is the power output. In industry, a laser will have a power output that varies depending on the task, but will typically have power output values on the order of a few kilowatts. These lasers are then focused to the point where the power density of the cutting beam will be around 10^6 W/cm^3, as compared to the power density of sunlight in Earth's atmosphere, 0.1 W/cm^3. In contexts that are not manufacturing, much less powerful lasers will suffice for cutting thinner materials in smaller volumes. Common lasers in commercial laser cutters marketed towards uses outside of manufacturing will have lasers with power outputs around 20 W. The laser diodes used in the design project of this thesis had a power output of 1 W, and common devices using laser diodes are measurement tools and sensors can be successful with power outputs on the order of milliwatts.

2.2 Laser Cutters as Prototyping Tools

In settings that are not manufacturing facilities, but rather areas of engineering learning or design practice, laser cutters are becoming popular tools for building prototypes. Common building materials that can be cut with laser cutters include acrylic, ABS plastic, wood, corrugated cardboard, and in some instances, rubber. Acrylic is the most common building material used because it is an ideal material to be cut with the CO_2 lasers found in commercial laser cutters.

Because laser cutters can only cut relatively thin materials, with 0.5 inch thick sheets of material being the largest typically cut well, many of the designs used with laser cutters as the cutting tool are made up of sheets of material either fixed with hardware such as bolts, or glued together. Figure 2 shows a group of laser cut parts that were later assembled to form the bulk structure shown in Figure 3.

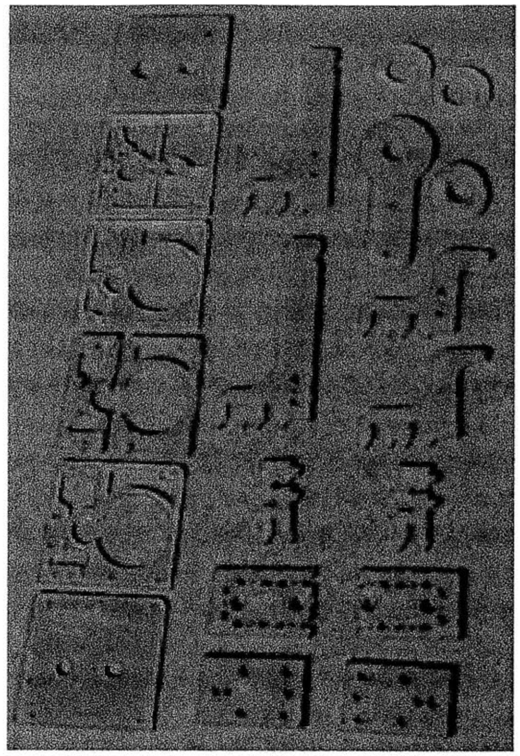

Figure 2: Laser cut acrylic parts, with protective covering still in place, being prepared for assembly. [3]

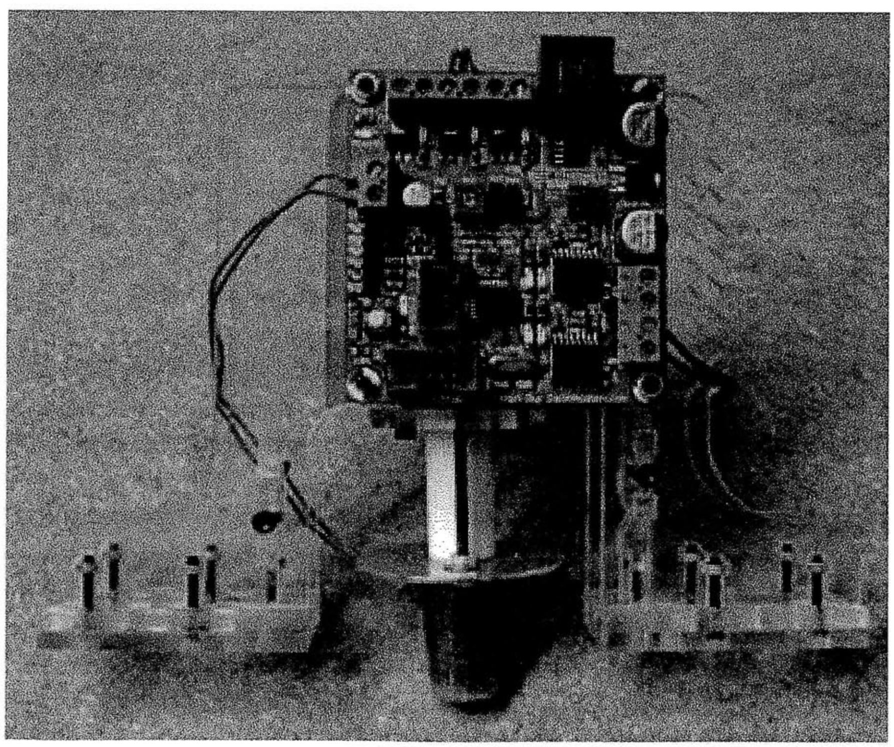

Figure 3: The assembly formed from the parts depicted in Figure 2. [3]

Both of these images relate to an essential mechanism in the Makerbot open source 3D printer, a common project for hobbyist builders. Advantages of using a laser cutter as a prototyping tool are simple design and fabrication of high precision parts, reduction of time between design and physical structure in hand, reduction of effort in manufacturing multiple parts with difficult-to-machine features such as tight corners, and much more. Figure 4 shows another assembled component of the Makerbot printer fabricated out of wood.

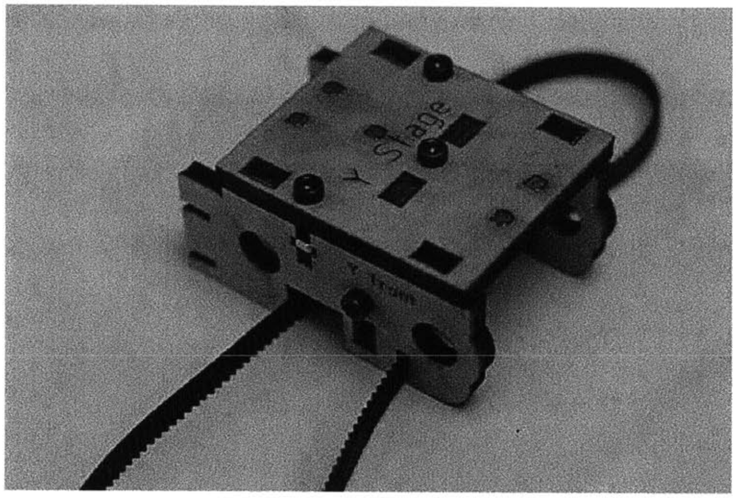

Figure 4: A component of the Makerbot 3D Printer fabricated from laser cut wood. [3]

2.3 Laser Cutting Machines in the DIY World: Inspiration for this Project

The various advantages of using laser cutters have led hobbyists around the world to desire laser cutting machines for their own personal use. However, laser cutting machines are incredibly expensive when considering the low budget of a recreational designer. Commercial laser cutters, like the ones commonly found in a university setting, cost on the order of ten thousand dollars. Even just the CO_2 laser tool head with a 20W laser will cost around two hundred dollars. A search of various websites that host designs for do-it-yourself (DIY) laser cutters will show that they rarely come to a cost less than one thousand dollars for the materials alone.

One designer, who at the time was working on a project that involved using a 1W diode laser to create a 3D printer based on laser sintering, decided to test out the laser diode as a cutting tool. [4] The test rig used to examine the lasers potential as a cutting tool was assembled out of parts from old CD and DVD drives. This test rig is shown in Figure 5. Besides just testing out the cutting potential of the laser diode, a theory about the cutting strategy was also being evaluated. Using one axis of the test rig to move the laser up and down vertically, the test rig was used to evaluate if the laser would be able to cut material by moving the focal point of the laser beam vertically through the thickness of the material. An illustration of this concept is shown as Figure 6.

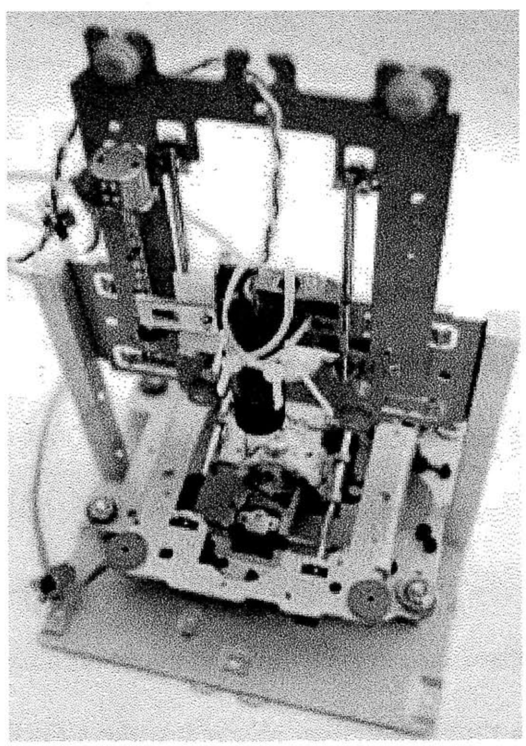

Figure 5: Test rig assembled from CD drive components. [4]

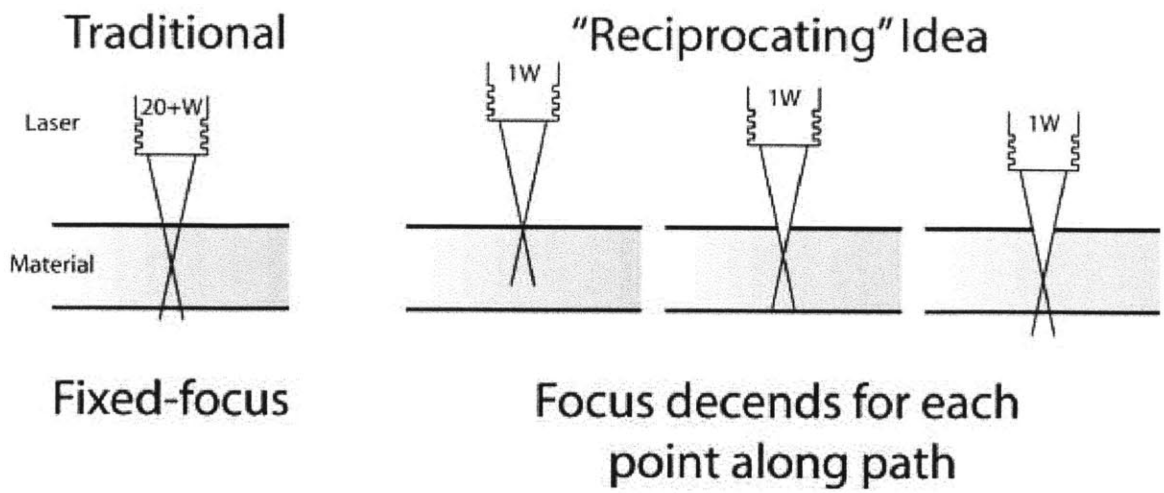

Figure 6: The reciprocating focal length idea. [4]

The results of the testing showed that the laser was able to cut through the thickness of a CD case, which is approximately 0.040 inches in thickness, as shown in Figure 7. The positive result was exciting for multiple reasons. First off, the laser diode used in the experiment was approximately an order of magnitude less expensive than the CO_2 lasers used in typical commercial cutters. Although the diode is significantly less powerful than a CO_2 laser, the possibility of having an available laser cutter for home use was sensational. In addition, with proper adjustment settings, a laser could also be used as an analog to a milling machine, making surface features that do not cut completely through the material. Combined with the original project, a laser sintering 3D printer, having the laser successfully cut material opened up the possibility of having a machine capable of 3D printing and laser cutting all in one.

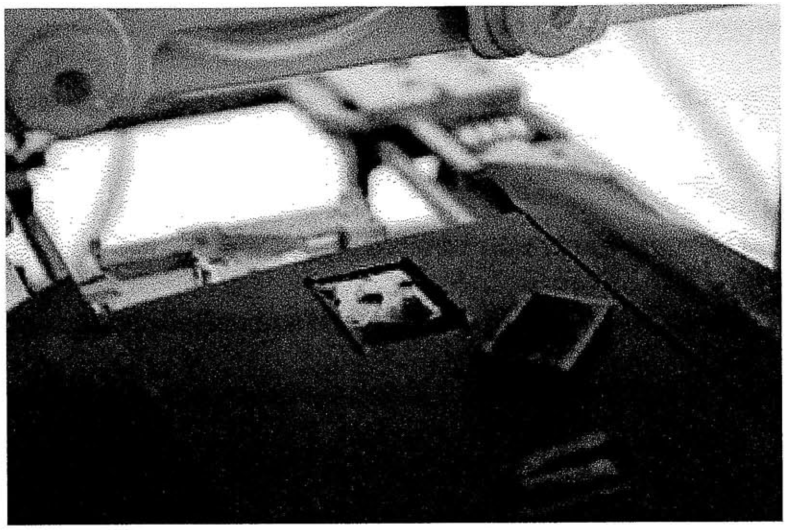

Figure 7: Cutting results using a 1W laser diode. [4]

Although further testing was necessary, the creator of the project did not have a chance to finish testing the laser's capabilities. With a few suggestions from collaborators on the project, who communicated through comments on the host website where the project was published, other cutting processes could have been tested. For instance, instead of using a reciprocating motion, the laser cutter could make a full pass outlining the figure to be cut, move to a lower height, and then make another pass, continuing until the material was completely cut through. In addition, perhaps the low power output of the laser diode could be mediated by using multiple laser diodes that all focused onto the same spot. Testing out these possibilities, as well as designing an inexpensive three axis machine to control the motion of the laser diode tool head, is the main focus of this thesis.

3 Electronic Components

3.1 Laser Diodes: Background and Design Choice

The laser light producers in common industrial laser cutting machines normally use mechanisms that create laser light by exciting a gas such as CO_2. These lasers have high power outputs and hence can cut through relatively thick layers of materials, but likewise have higher costs associated with them. Laser diodes are different in several respects. Fundamentally, a laser diode uses a doped silicon chip to produce the photons that make up the laser light. The physics involved in the theory of light production in a silicon chip is advanced and will not be reproduced in this paper [5]. Using silicon chip technology allows the laser mechanism to be much smaller than lasers found in commercial laser cutters, and the cost is also reduced greatly. A chip that forms the core mechanism for light production can be seen in Figure 8, with the eye of a needle used for scaling.

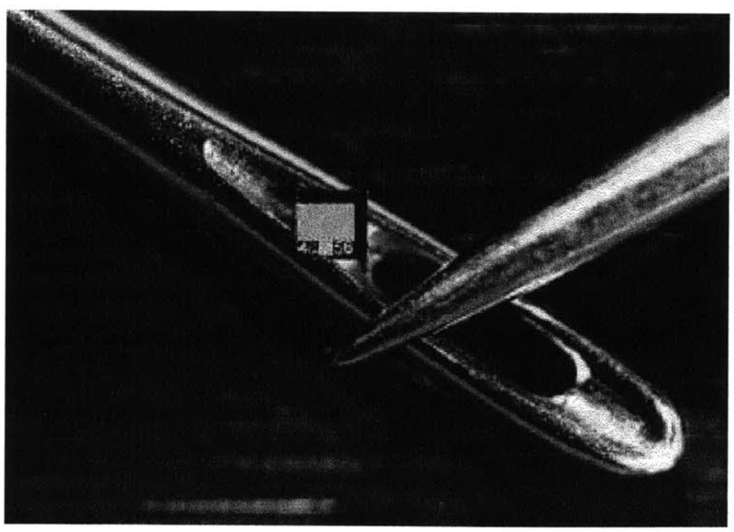

Figure 8: A sample diode chip. [6]

Because of their small size and cost, laser diodes are a perfect fit for a variety of uses. As measurement mechanisms, laser diodes can be used as sensors for temperature, distance, spectroscopy, and various other sensing devices. Lasers are also very common in CD and DVD readers and burners, scanning devices, and printers. Lasers used in instrumentation devices typical only require output ratings on the order of milliwatts, and once lasers reach power outputs of a few hundred milliwatts, they gain the ability to make burns for imparting the information capturing features on disks. These same diodes have enough power to ignite paper.

The diode used in the project documented in this thesis has a power output rating of 1 W. These diodes are from an independent seller who most likely has access to parts manufactured for scanning or printing devices. Although the diode is rated for 1 W, the actual power output is dependent on the applied voltage across the diode. Figure 9 shows the size of the laser diode used in this project, and Figure 10 shows the pins where connections are made to provide a voltage to the diode. Figure 11 and Figure 12 show operating specifications for the diode, and were produced by the seller of the diodes. These diodes were used because of their high power output and low cost.

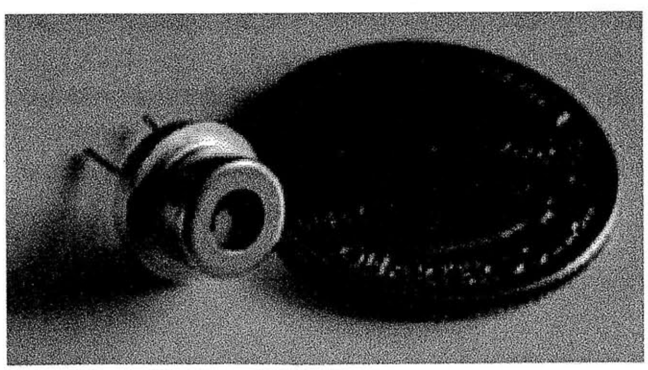

Figure 9: Laser diode used in this project with a quarter for scale.

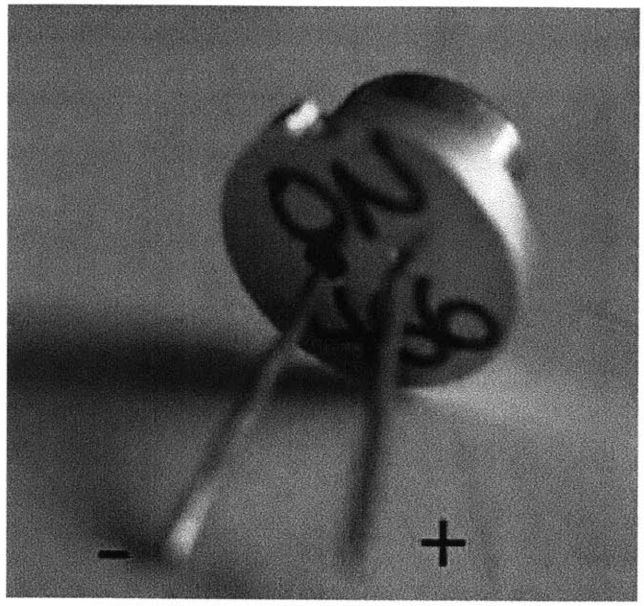

Figure 10: Backside of the diode, showing the leads.

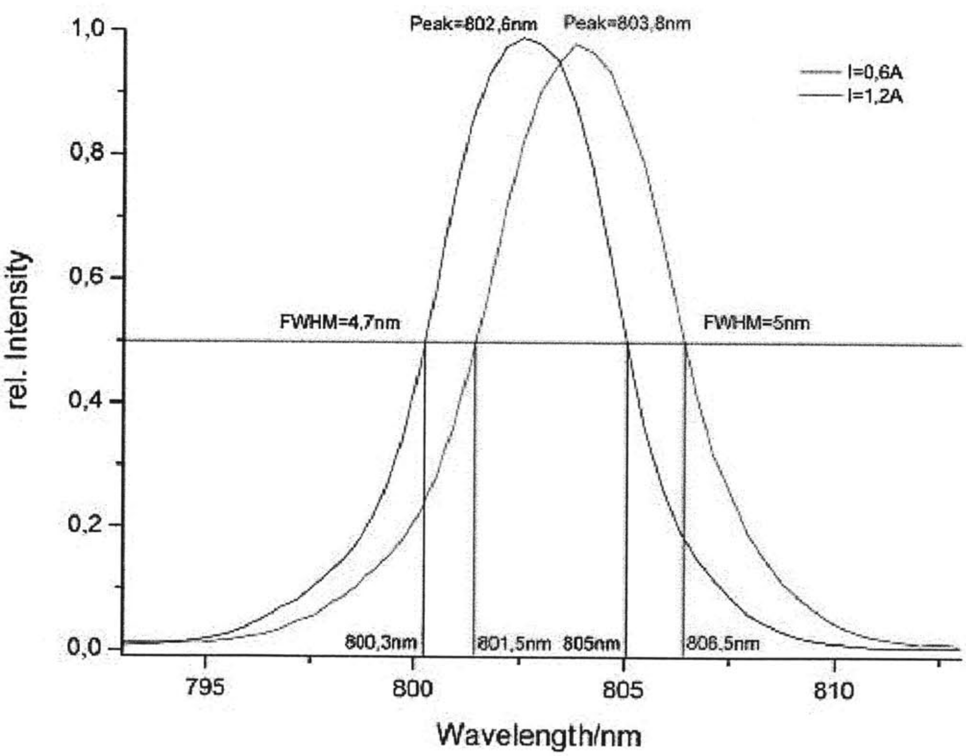

Figure 11: Intensity curves describing the output of the laser diode.

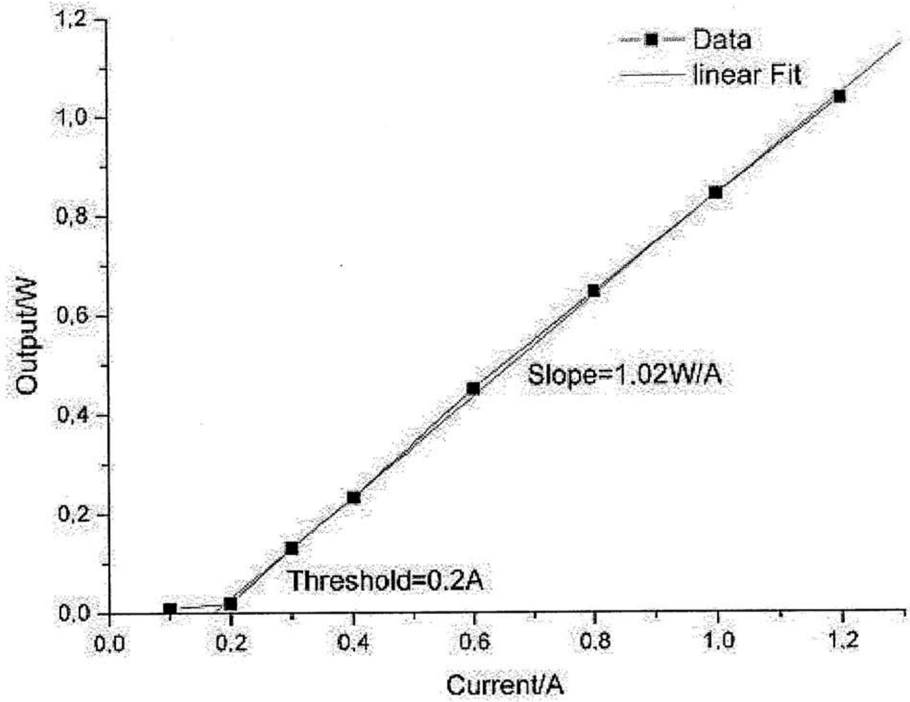

Figure 12: Curve describing the power output of the diode for a given current flow.

The laser diode by itself, if operated properly, will provide laser light that will be able to burn and bore holes through plastic. However, because the wavelength of the resultant laser light, which in this case is 808 nanometers, falls just upon the edge of the visible spectrum and the infrared spectrum, the laser light will only be completely absorbed by materials which appear to have darker colors. For this reason, black opaque ABS plastic has ideal optical properties for cutting, and was used in many tests conducted with the laser diode. Common clear plastics used in commercial laser cutting machines, such as acrylic, will not retain heat from the laser light coming from this specific laser diode.

Improvements on the cutting quality of the laser diode come from installing the diode in a proper housing module. An exploded view of the diode in the housing module assembly is presented in Figure 13. The housing module contains a lens that can be screwed into the head of the module, providing a mechanism to focus the beam, thereby increasing the power density of the laser light. A small spring provides a force between the laser diode, which has to be press fit into the head of the housing module, and the lens in order to prevent any movement of the lens during laser operation. Figure 14 illustrates the process of press fitting the diode into the housing. Other advantages of a proper housing module include protection of the diode leads, which need to be soldered to wires that run current to the diode, and assisted heat sinking as the housing module draws excess heat away from the laser diode via conduction.

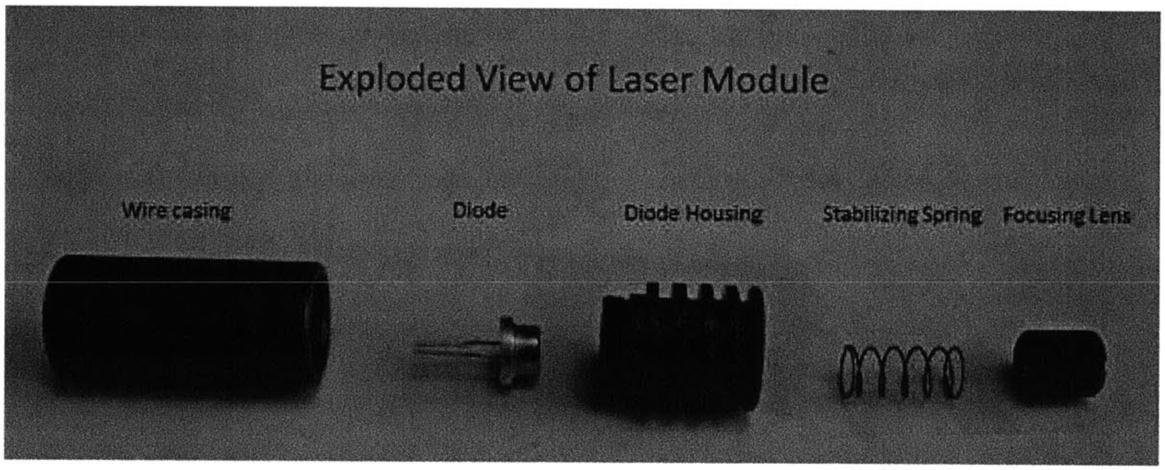

Figure 13: Components of the housing module.

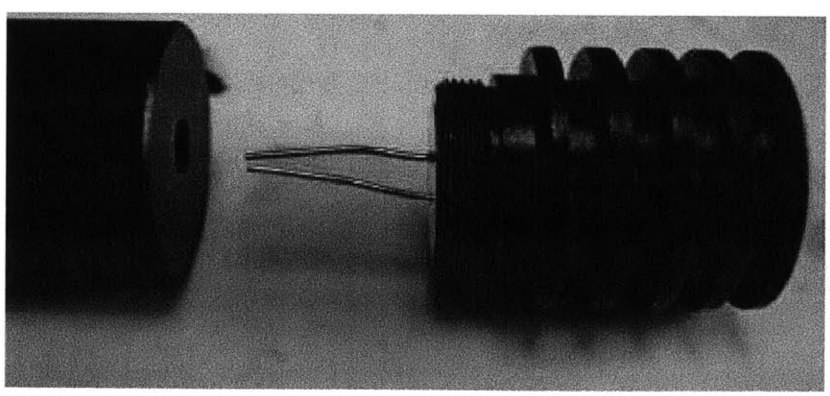

Figure 14: For press fitting, the diode is placed into the housing and the wire casing is flipped to show the wire outlet. The laser diode leads can be placed in the wire outlets, allowing the diode to be press fit into place.

3.2 Laser Safety

Any laser light that is shined directly into the eyes, no matter what the laser diode output power, should be considered dangerous and proper safety precautions should be taken. Any laser that is capable of burning constitutes an even greater danger and the safety measures are more important still. The lasers used in this thesis project are capable of burning through plastic, and have no problem burning skin and damaging eyesight. Proper laser safety goggles should be worn at all times when handling a laser that has the capacity to produce light. For the most part, besides where the laser is focused into a point, the laser light should not be strong enough to burn the skin, but skin contact should never occur and accidental exposure of laser to the skin should be prevented at all times. Never let reflected laser light reach unprotected eyes, although residual laser light has a low chance of harming skin. Protect yourself from reflected laser light by making sure the laser light path ends in material that will absorb the laser light.

These particular diodes are especially dangerous because they emit light on edge of the visible spectrum, and the laser beam itself is completely invisible. Because laser light damage to the eyes is rarely painful and takes time to show symptoms, unprotected eyes can be damaged without the user realizing the damage is occurring. Because they can burn skin and eye exposure can result in blindness, these laser diodes are considered Class IV lasers, the highest danger level assigned to laser mechanisms. They are powerful and should be treated as dangerous. Once again, never operate the laser diodes without the proper safety equipment, and be sure your laser goggles protect against the wavelength emitted by the diodes, in this case 808nm wavelength light. Figure 15 shows an example of proper safety ware.

Figure 15: Proper safety goggles for laser light protection.

3.3 Laser Driver Circuit

The minimum requirements for operating the laser diodes are a voltage source and a resistor to help inhibit current flow. However, operating the laser diode under these conditions is extremely risky. Laser diodes are very sensitive to voltage spikes, and applying a voltage that even slightly exceeds the maximum operating specification of the laser diode will result in permanent damage to the diode. Diodes are also very aggressive as a current draw, so proper precautions are necessary in order to prevent damage to the diode.

A proper operating circuit was already tested during a previous project involving the same laser diodes. The circuit used included the National Semiconductor Corporation's LM317 Integrated Circuit 3-terminal adjustable regulator. The LM317 is a linear regulator, and the circuit uses a potentiometer to adjust the voltage supplied to the load, which in this case is the laser diode. Figure 16 shows a circuit diagram for the laser driver, and Figure 17 shows a diagram of one of the circuits used to control the laser diode tested in this thesis. For ease of testing and rearranging, the circuit was constructed on a breadboard.

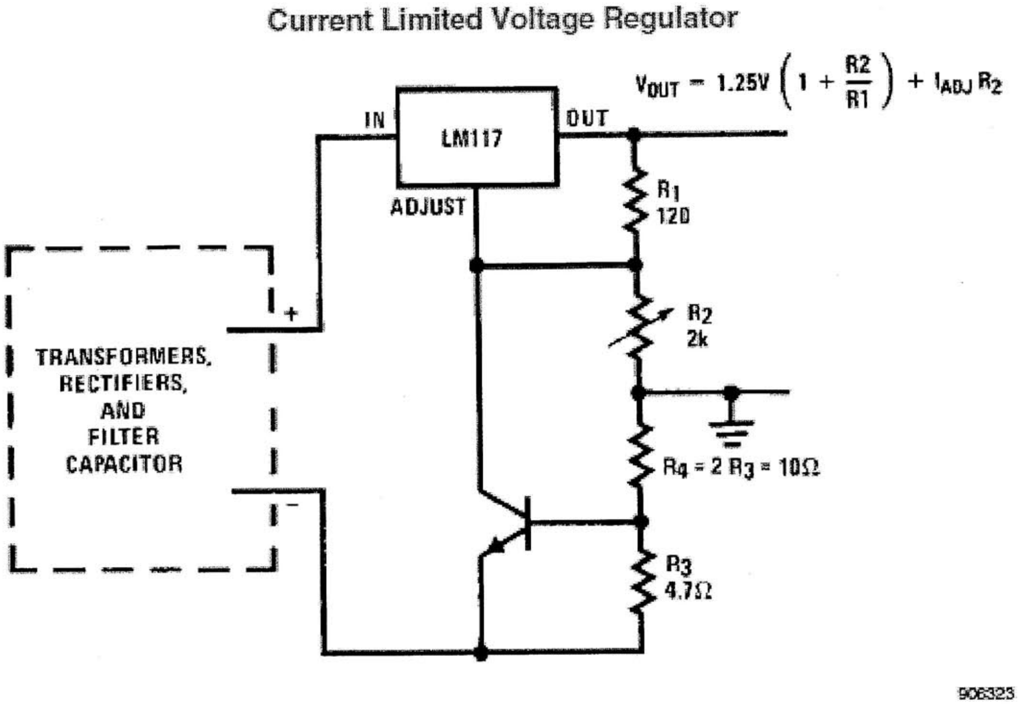

Figure 16: Circuit diagram showing the laser driver [7]

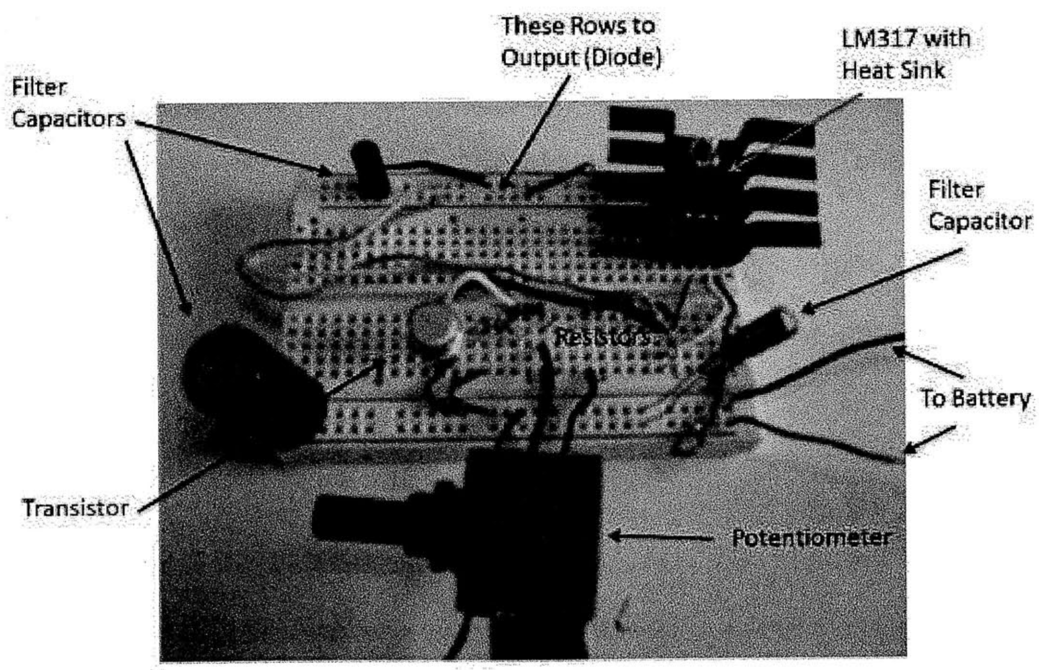

Figure 17: Diagram of an actual circuit driver used.

The LM317 in the laser driver circuits act as a current limited voltage regulator. This means that no matter what load is placed on the circuit, the LM317 unit will maintain the preset voltage across that load and adjust the current as needed. However, a maximum current will be set by the LM317 unit, and this preset current is governed by the resistor values in the circuit. The LM317 can be purchased for a small cost, typically under a single dollar per unit.

Most of the other components of the circuit can be found in circuit kits used in introductory courses on circuit design. The standard resistors used in the circuits are common. In order to finely tune the circuit, and to properly control the voltage placed across the diode, a high precision ten turn potentiometer was used as the variable resistor labeled R_2. As recommended by the data LM317 data sheet, filter capacitors were placed along the input and output wires in order to protect the diode from random voltage spikes coming from the power source. A 100 μF capacitor was used across the input and the output, and a 2200 μF capacitor was used across the input for the purpose of protecting the diode from voltage spikes.

The power source for the circuit was a 7.4 V high discharge lithium polymer battery with 500 mAh of charge. Under normal operating conditions for cutting material, the laser can draw 1 A of current, which will normally reduce the battery to an unusable voltage in slightly under a half hour of operation. When the LM317 senses insufficient input voltage, it automatically switches the circuit off.

One important factor in implementing this specific circuit as a laser driver is that the linear regular dissipates a large amount of waste heat, especially considering the high current draw from the laser diode. Therefore proper heat sinking is a necessity to keep the temperature of the LM317 down to within operating ranges. If the temperature of the LM317 unit rises above the specified maximum temperature, the laser driver will automatically switch off. Upon testing, with proper heat sinking the laser was able to run for more than five minutes continuously without reaching the maximum temperature specification.

3.4 A Second Laser Driver Option

Although not utilized during the tests conducted with the laser diodes, a second option for driving the diode was explored. Because the LM317 is a linear regulator, it wastes a great deal of power by producing excess heat, especially when the output current to the laser diode is around 1A. Switching regulators, which control the voltage output by quickly switching on and off and outputting the time average voltage across the output terminals, are much more efficient due to less waste heat. One commercially available switching laser driver is the Micro FlexDrive laser driver, which normally has a cost around $30 [8] and comes with a preset current rating specified during purchase. While the FlexDrive has the potential to improve the performance of the electronics components of the laser cutter, the driver circuit itself is extremely sensitive. A small potentiometer located on the chip, shown in Figure 18, is the means of adjusting the voltage provided to the output terminals. Over-adjusting the potentiometer even slightly permanently damages the driver. Because of the relatively poor documentation provided with the driver, as well as some external circuitry that is not often found in typical electronics kits, use of the FlexDrive was not implemented in this design project. However, with proper use, the benefits of eliminating waste heat, as well as being able to purchase an assembled laser driver as opposed to constructing one may be potential improvements for the future of this project.

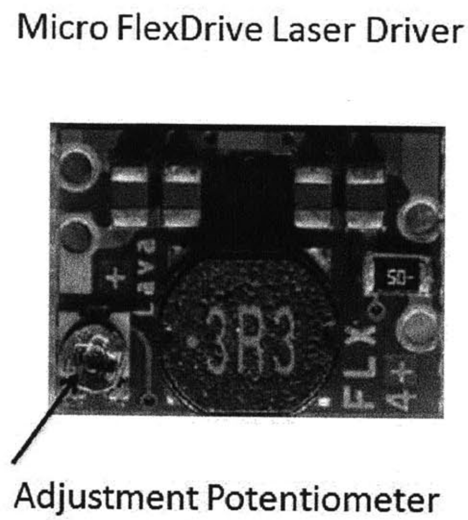

Figure 18: Micro FlexDrive switching laser driver. [7]

4 The Laser Test Rig

4.1 Design of the Test Rig

In order to begin testing to determine the cutting potential of the laser diode a test rig was constructed consisting primarily out of LEGO parts. The LEGO parts used in the design came mostly from the LEGO Mindstorm series, a set of LEGO parts created for the purpose of making robotic constructs. Besides the structural portion of the rig, including the supports and sliding rail systems, LEGO power transmission units, specifically two rack and pinion sets, were used in the test rig construction. The servos remained stationary, fixed to the structure of the test rig, and smooth surfaced LEGO pieces were placed under the racks of the test rig in order to create sliding bearings. To operate the rig, two position control servo motors were used to move the laser in a straight line while having the freedom to independently adjust the height of the laser above the material. These servos were driven using an Arduino Nano microcontroller fitted with a carrier board that was used in MIT 2.007 Design and Manufacturing I. Figure 19 shows a photograph of the LEGO test rig used during testing. Figure 20 shows the top view of the system, and the connections to the microcontroller. In Figure 21, the connections between the laser drivers and the test rig can be seen.

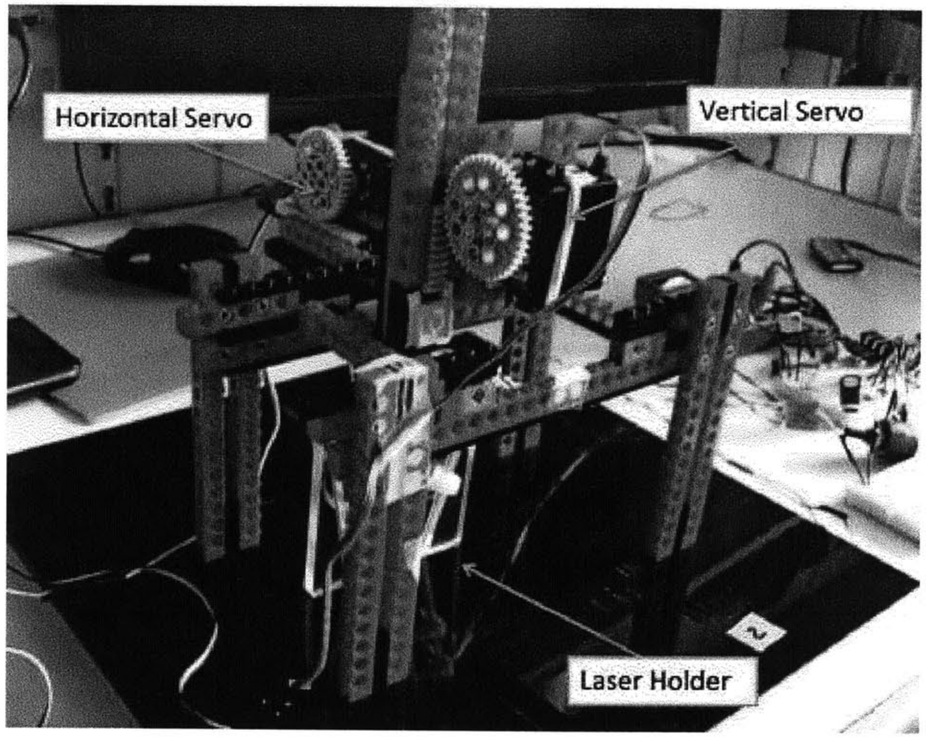

Figure 19: LEGO test rig.

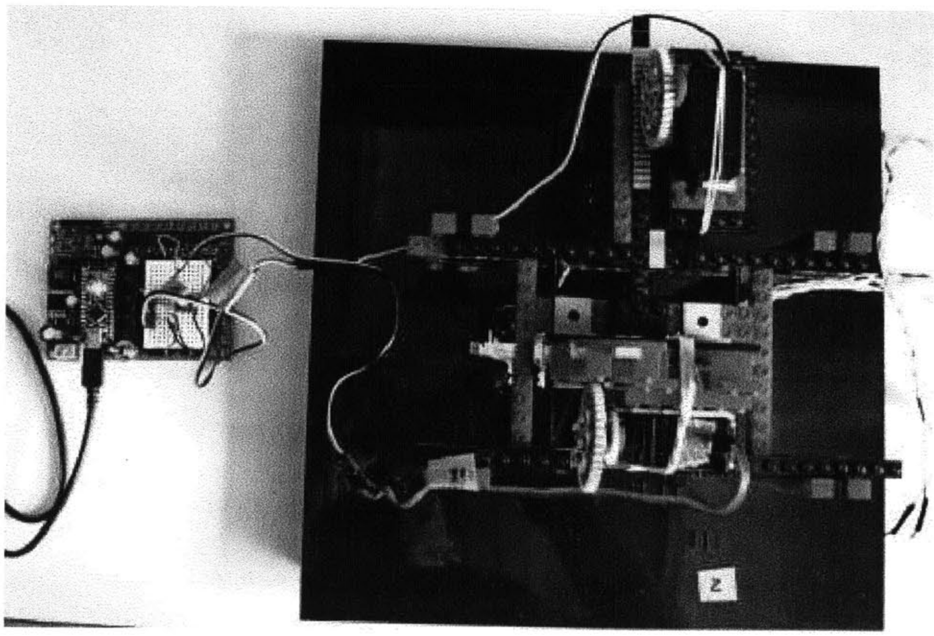

Figure 20: Top view of LEGO test rig showing connections to the microcontroller.

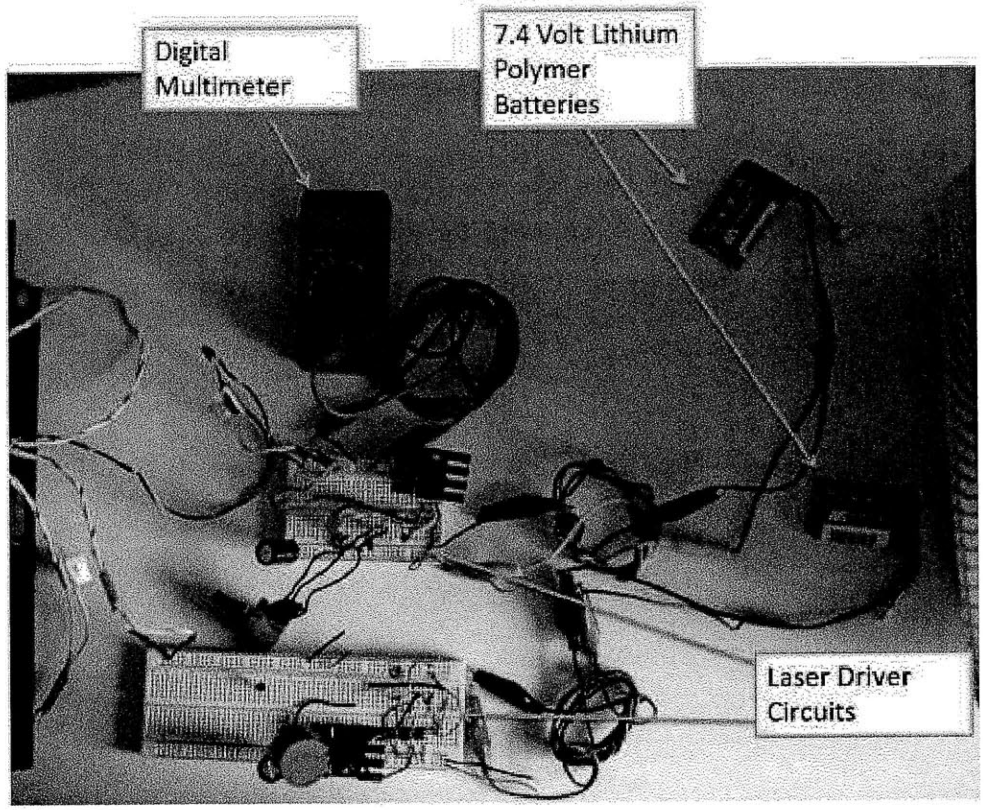

Figure 21: Laser driver circuits.

Using LEGO parts in constructing the test rigs had advantages and disadvantages for testing. Advantages included quick assembly and relatively easy on-the-spot adjustment in order to obtain an optimized design. As test design requirements changed, such as height needed above the cutting surface, adjustments could be made with ease. One of the disadvantages to using LEGO parts was the precision in the motion of the laser head. Although the play in the system was reduced to an acceptable level for testing the laser diode, improvement would have come from designing a custom machine that did not utilize LEGO pieces.

One component of the rig that was not constructed using LEGO pieces was the laser holder plate, which was cut out of clear acrylic using a commercial laser cutter. A solid model of the laser holder plate constructed in SolidWorks appears in Figure 22. The holder was designed to allow for variations on two different laser set ups. First, a laser would be able to shine straight down onto the work piece from a vertically oriented laser. Second, two lasers, each at an angle, could be adjusted to have the same focal point, aligning their beams into a single region on the work piece, effectively doubling the power output of the laser tool head. The lasers were fixed to the plate with double-sided tape to prevent twisting and cable ties were used to press them against the plate.

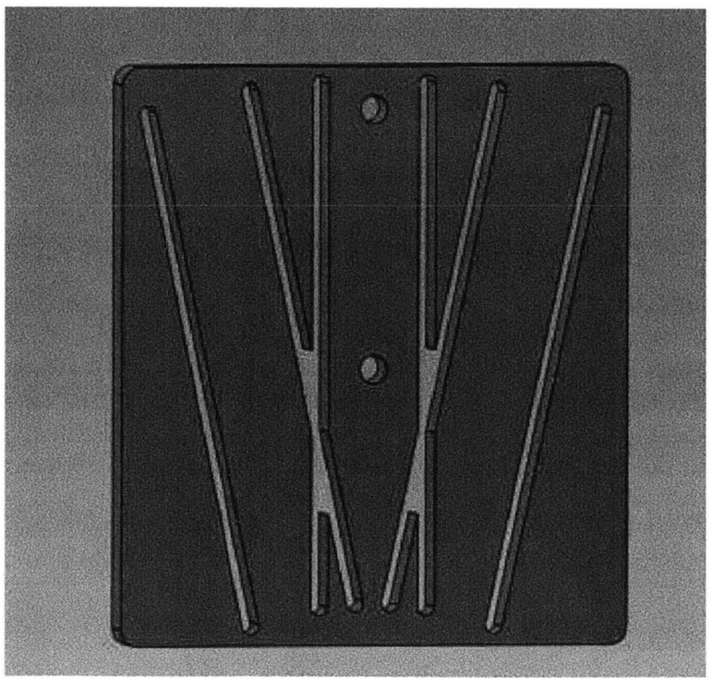

Figure 22: SolidWorks model of the laser holder

4.2 Test Design

Four different cutting strategies were tested on different materials. The four test settings conducted were straight laser cutting, variable height laser cutting, reciprocating, and double laser cutting. In each case, a cut nearly 0.25 inches in length was cut over duration of 22 seconds, chosen to be the slowest possible cutting speed for making a practical laser cutting machine. For each cutting strategy tested, three cuts were made. The first cut consisted of one pass, the second cut consisted of two passes, and the third cut consisted of three passes. Straight laser cutting consisted of passing the laser over the material at a single height. During variable height laser cutting, after each pass the laser height was lowered in order to place the focal point deeper into the thickness of the material. For reciprocating cutting, the laser was moved up and down vertically, passing the focal point through the entire thickness of the material before shifting to the next spot to cut. Finally, for the double laser test setting, two lasers with the same focal point were active at the same time during cutting. The different materials tested were 0.040 inch black plastic, 0.065 inch black opaque ABS plastic, and 0.25 inch wood.

For most the double laser setting tests, the laser orientation was perpendicular to the cutting direction. In order to investigate the effect of a perpendicular setup versus a setup where the laser orientation was parallel to the direction of cutting, referred to here as "in-line" cutting, an extra test setting was conducted with parallel cutting. The difference between these two cutting orientations is described in Figure 23.

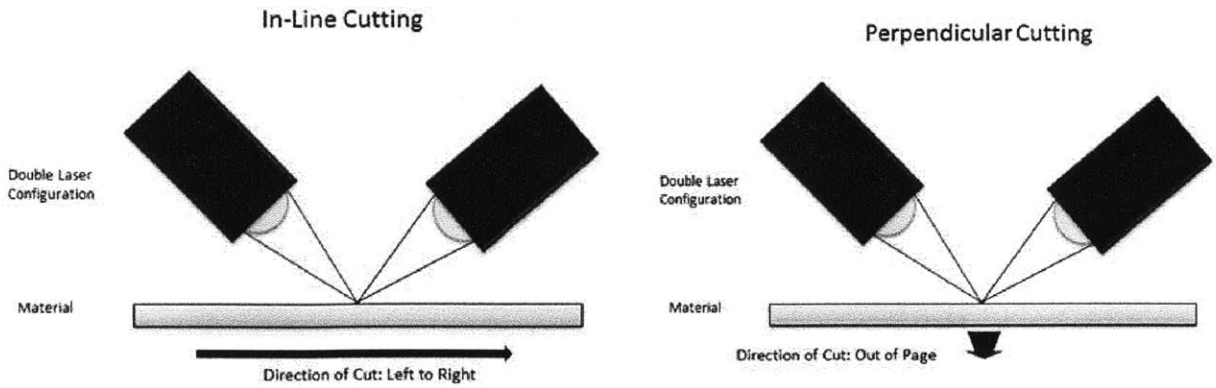

Figure 23: The cutting strategy referred to here as "in-line cutting" means the two lasers modules exist in a plane that is parallel to the cutting direction. In "perpendicular cutting" the plane that contains the laser modules is perpendicular to the cutting direction.

4.3 Test Results

Typical results for each material tested are shown in Figure 24, Figure 25, and Figure 26. The only thickness the laser was able to cut completely through with a clean cut during the test period, regardless of cutting strategy, was the 0.040 inch black plastic. Straight line cutting produced the smallest depth of cut, which was evaluated simply by observing the depth of cut visually after the test was conducted. Variable height trials and reciprocating trials yielded results that were indistinguishable by eye.

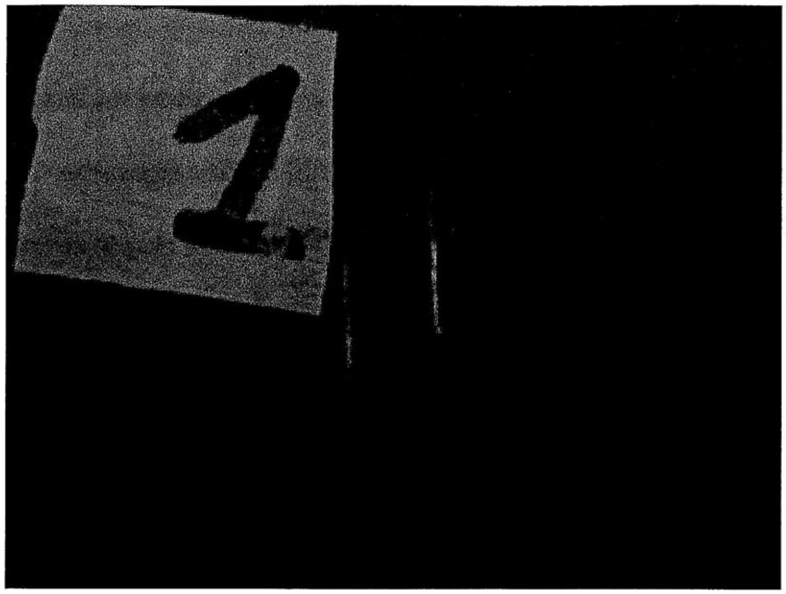

Figure 24: Cuts made by the laser diode in 0.040 inch thick material.

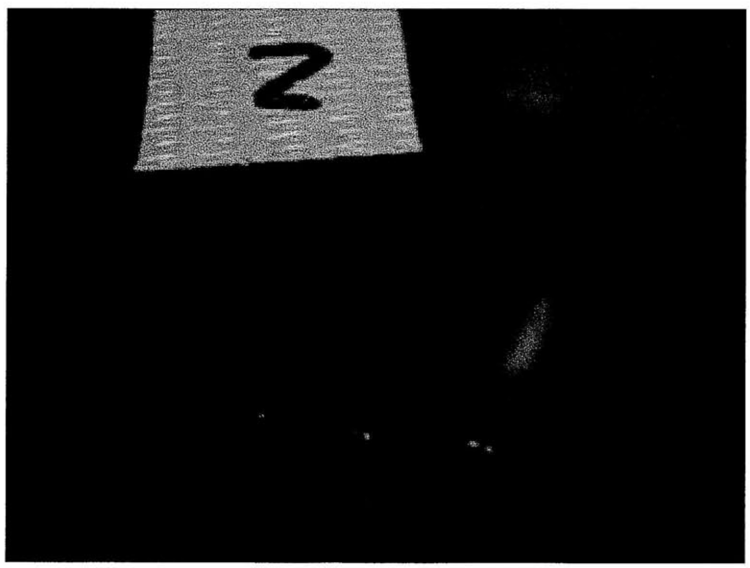

Figure 25: Typical cuts into 0.065 inch material.

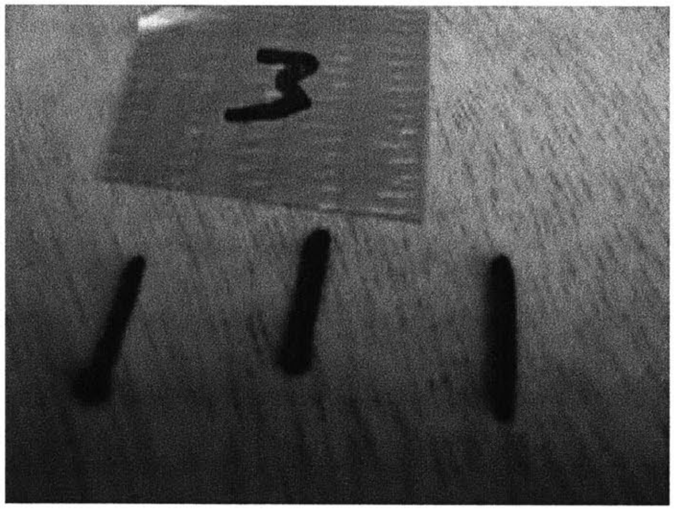

Figure 26: Cuts into wood material.

Double laser cutting had the deepest cuts, but this cutting strategy was not without its limitations. Double laser cutting was only able to just cut through the 0.065 thickness ABS plastic. Further tests were conducted in order to assess if some changes in cutting parameters could yield acceptable cuts through the material. Parallel versus perpendicular cutting orientations showed almost no difference in quality of cut. A test condition with six passes instead of three passes with two active lasers was not enough to pass through the thicker material. Adjusting the height of the double laser configuration was also tested, but problems with laser focusing prevented an improvement in cutting quality. This issue is explained in detail in Figure 27. Under no circumstances was an acceptable quality cut made out of the 0.065 inch material in the cutting time of the trials.

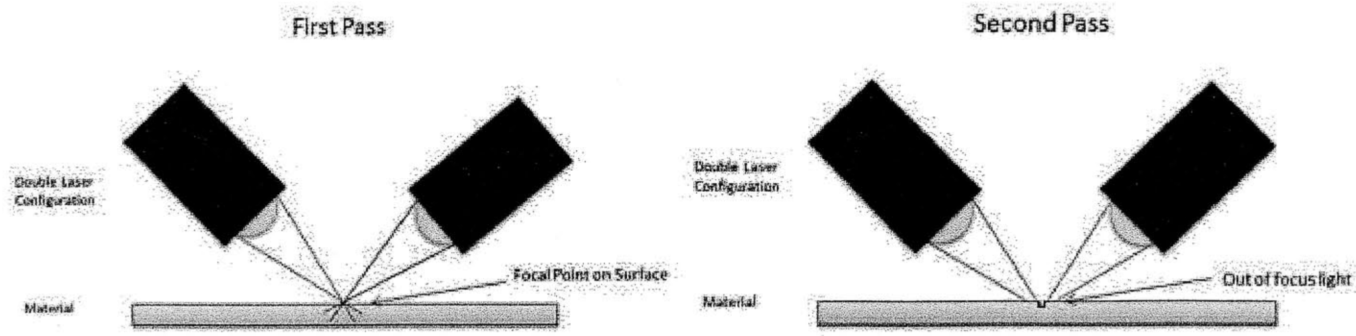

Figure 27: Changing the height by lowering the double laser configuration in between passes is problematic because the light does not reach the desired depth in focus. Even during in-line cutting melted material inhibits the focusing of the light.

There are several possible reasons for the failure of the laser to cut through thickness of materials that are structurally usable. The main reason for insufficient cutting is that the diode simply has a power output that is too low. Commercial laser cutters have enough power output to completely vaporize material near their focal point, even when the laser light is not completely focused to a point. The laser diodes used in this project did not completely vaporize material, but rather left some smoldering material that inhibited further cutting. In addition, whenever the laser was even slightly out of focus on the cutting surface the laser would be rendered ineffective. Because of the different failure modes of the laser diode, the cutting potential of the laser diode is too limited for the cutting the original goal thicknesses of this project.

5 Mechanical Design

Two prototype iterations were constructed as designs for a positioning machine for the laser tool head. The goal was to design a low cost machine capable of positioning the laser module in three axes, achieving planar positioning and actuating the laser up and down vertically. Low cost was a design constraint that was constantly held in mind. The parts used in fabricating the prototypes were purposely chosen to be inexpensive and readily available to hobbyists. For convenience, most of the structure was constructed out of laser cut clear acrylic parts made using a commercial laser cutter, but all of the structural components could be readily made with a hack saw or jigsaw and a hand drill with common drill bit sizes and common engineering materials. Using a commercial laser cutter to fabricate a final design would also have the added benefit of creating a "self-replicating" machine, a machine that is capable of creating the majority of its own parts. Other design constraints involved in the mechanical design portion of this project included reducing the number of actuators to only one per axis, and paying attention to instances of over-constraint and methods to alleviate any jamming.

Several possibilities were assessed in how to actuate the motion of the positioning machine. The most common approach to positioning machine actuation is the use of stepper motors. Another option was the use of standard motors or servo motors along with ten-turn potentiometers, which were also present in the laser driver circuit design, as a means of position feedback. Although the prices of servo motors and stepper motors are comparable, the extra cost of the controller used to operate the stepper motor made the stepper motor control less desirable. With the extra advantage of using the potentiometers in the laser driver circuit and in the positioning control, potentiometers made a better choice for driving the system.

Power transmission from the actuators to the moving components of the machine could also have been implemented in various ways. The design choices evaluated included rack and pinion, belt and pulley, and lead screw methods of controlling the linear motion of the system. Lead screw actuation would not be possible without extra gearing attached to the potentiometer for position feedback, which would in turn reduce the resolution of the position measurements. Lead screws are also somewhat expensive and need more maintenance in terms of cleaning and lubricating. Using a belt and pulley system made eliminating the redundant actuators a simpler task. Considering that belts only need to attach to the component they are guiding in only one spot, whereas a rack needs to be able to contact the guided component at various points, a belt and pulley system would also help save space.

5.1 Prototype 1

Figure 28 shows a solid model of the first prototype constructed.

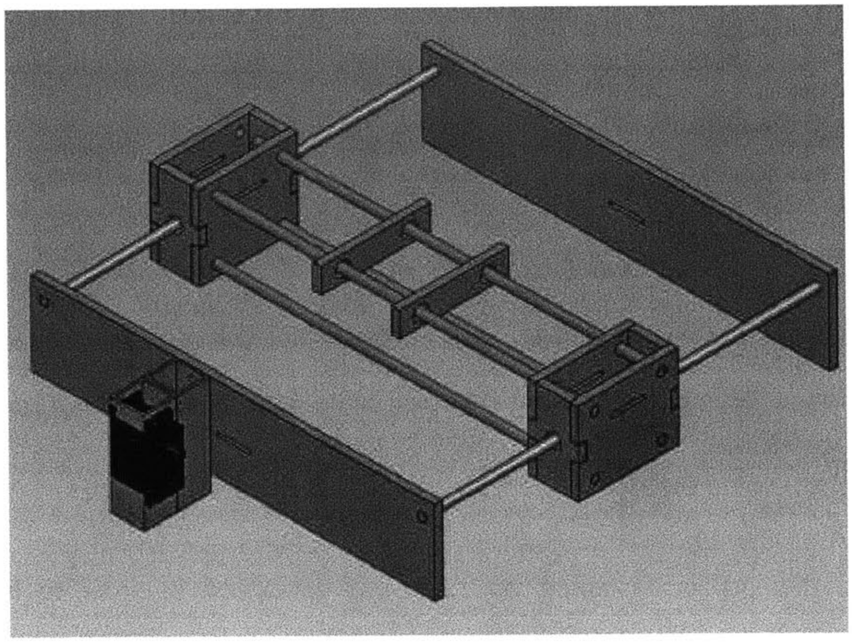

Figure 28: Prototype 1 solid model constructed in SolidWorks.

The first constructed prototype was designed to be as simple as possible. Fundamentally, Prototype 1 consists of an axis of motion that is able to move along the rails of a second axis. The details of the belt connections are described in Figure 29. The main advantage of connecting the belts in a non-continuous loop was to keep the belt out of the way of the laser beam placed at the center of the machine. The belts connecting to the actuating servos are always connected to the center point of the component that they are responsible for moving in order to prevent unnecessary torques placed on the system, which would in turn increase the friction of the sliding components.

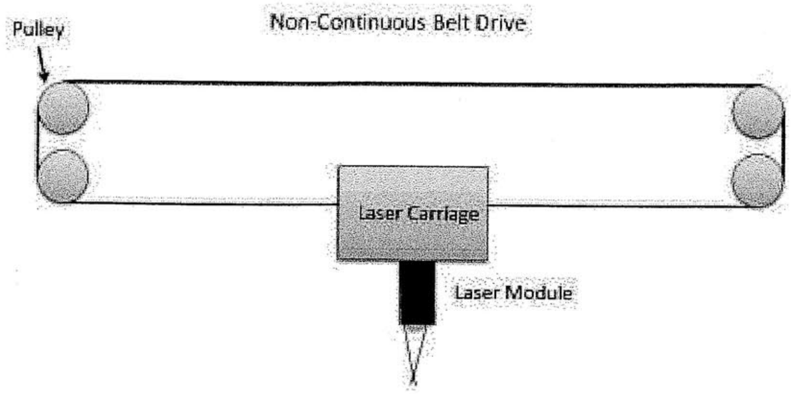

Figure 29: The concept of a non-continuous belt drive was implemented in Prototype 1 in order to keep the drive belt out of the way of the cutting laser. In the next prototype iteration, the belt orientation was changed, eliminating the need for a non-continuous belt.

The method for fastening the rails was developed in order to have a simple interface where machine screws with the proper nut would be able to hold the rails in place. Two slots were cut into the sides of the plates responsible for holding the rail in place. The lower slot provided a position for a 4-40 nut to fit in between the plastic surfaces exposed by the cut. The top slot provided a section for the plastic to deform in order to fix the rods in place. This method of rail fastening is pictured in Figure 30. The major flaw with this type of fastening design is that acrylic plastic turned out to be far too brittle to support the deflection, and even minor over-tightening caused the part to fracture. A close up of the fracture appears in Figure 31.

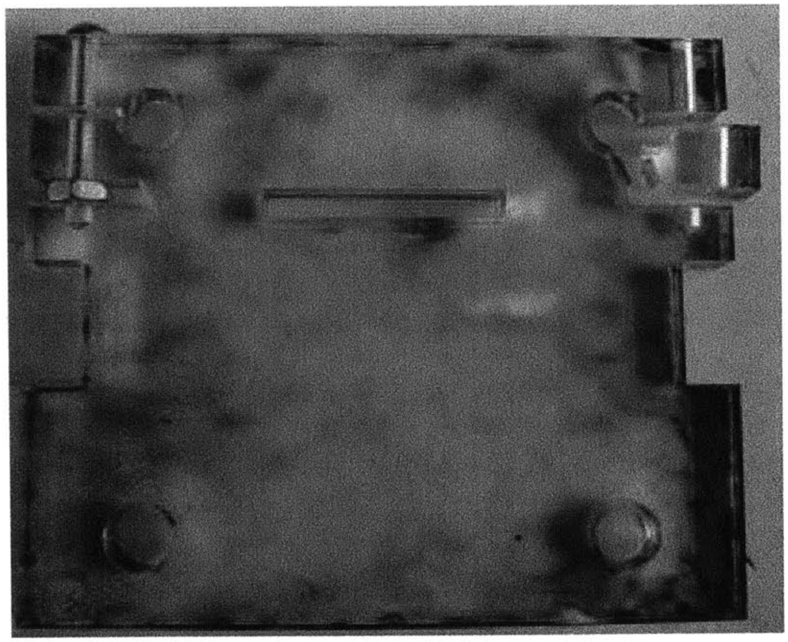

Figure 30: Rail fastening method used in Prototype 1.

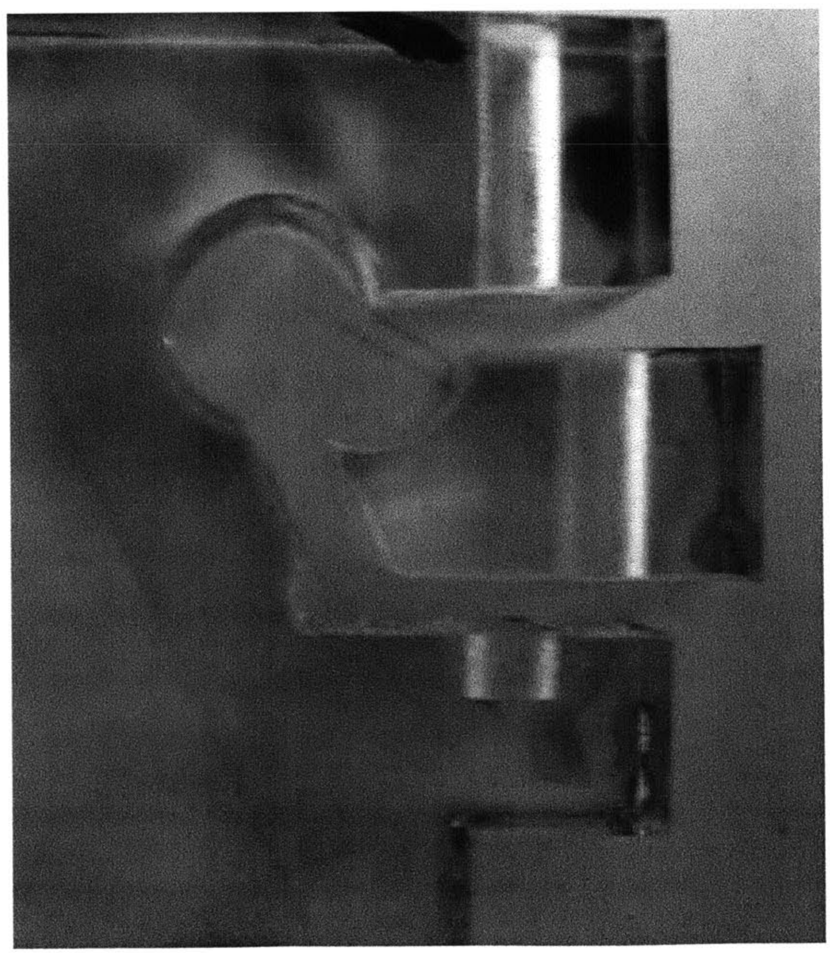

Figure 31: Close-up of the fracture caused by over tightening the fastener.

The main method of fixing the plastic plates together utilized in Prototype 1 was by using glue specialized for joining acrylic parts commonly referred to as acrylic cement. Figure 32 shows the sliding Z axis design for Prototype 1, which consisted of two separate parts that were each fastened together using acrylic cement. Two major issues exist with this type of fastening. The first is that the fastening is not reversible. Once the parts are fixed together with the glue, separating them usually involves structural damage to one or both of the parts. The second issue is that this fastening type is sensitive to gaps between the joined surfaces.

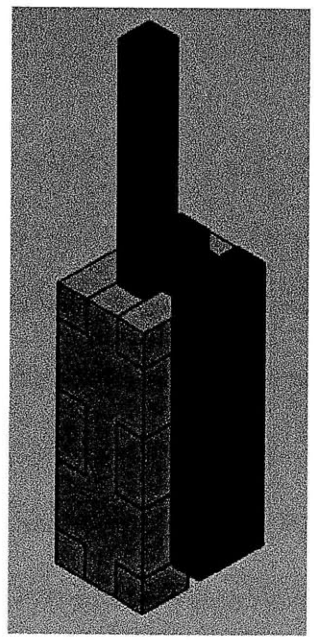

Figure 32: For controlling the laser height in Prototype 1, the darker part would slide relative to the lighter part via a rack attached to the protrusion from the top. Each parts was fastened together using acrylic cement.

A second design mistake for Prototype 1 involved not taking into consideration the width of the laser cut for parts that needed to be joined with acrylic cement. As demonstrated in Figure 33, the gaps that were not accounted for in the design of the laser cut parts were both noticeable, interfering with the aesthetic aspect of the design, and caused various alignments in the assembly to be off. Due to these issues, Prototype 1 was determined to be insufficient for improvement and a new design needed to be constructed.

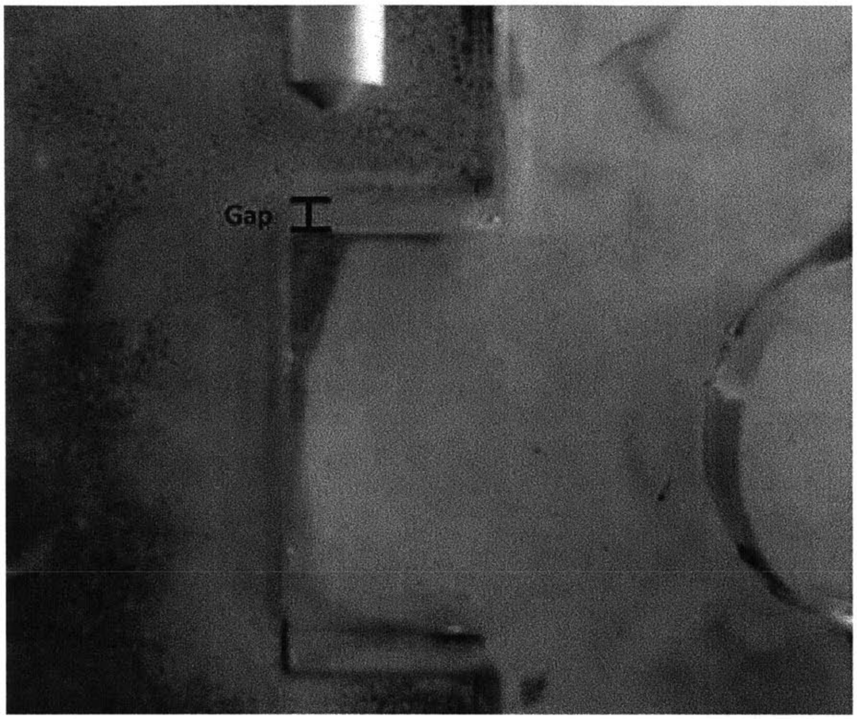

Figure 33: Gaps in the parts as a result of not taking the laser cutting width into account.

5.2 Prototype 2

Figure 34 and Figure 35 show the solid model of Prototype 2 and the physical constructed machine.

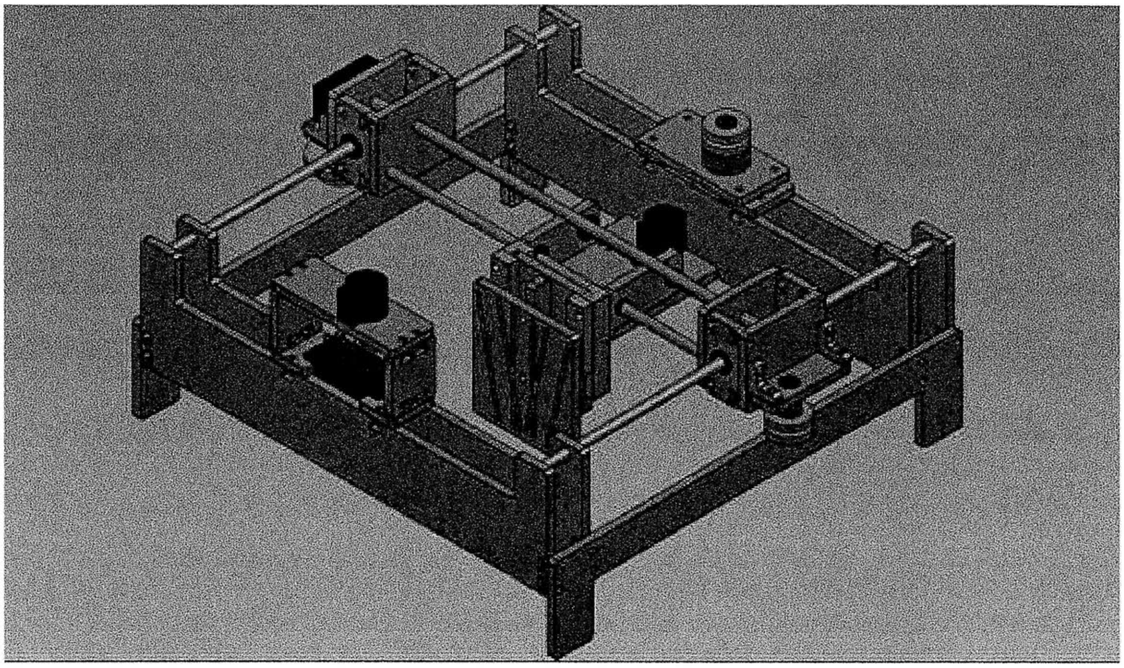

Figure 34: Solid model of Prototype 2

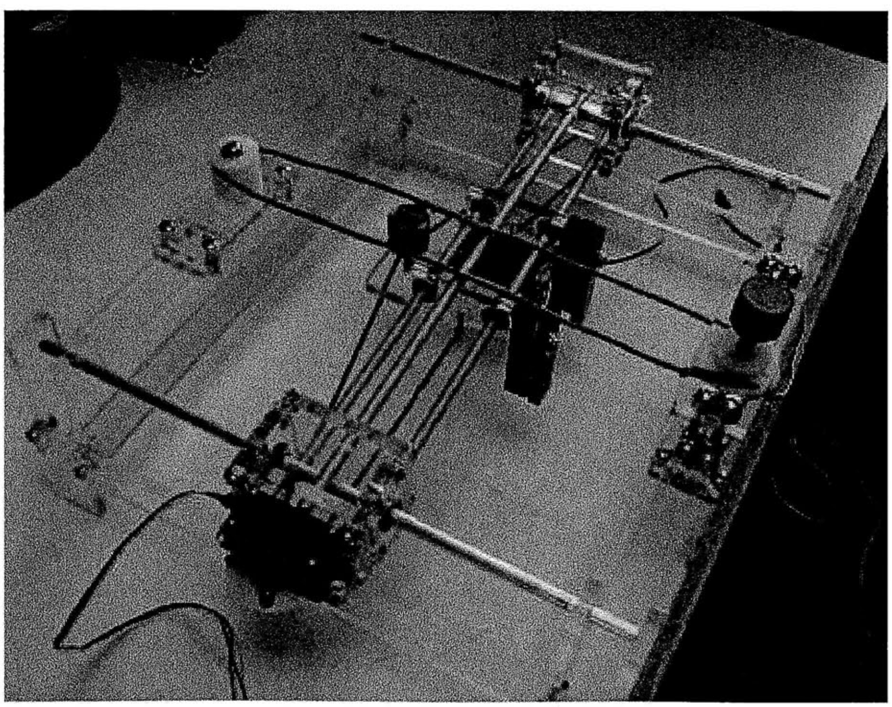

Figure 35: Prototype 2

The main goal for Prototype 2 was to use the lessons learned from Prototype 1 and improve upon them while still trying to maintain consistency with the design constraints. Prototype 2 is far more complex than Prototype 1, and several design choices lend themselves to laser cutting the structure as opposed to constructing the structure by hand. However, by replacing some of the features in the prototype the structure could still be made without the use of a laser cutter.

The main difference in the two designs, besides the further attention to detail, is the fastening method used to fix the surfaces together. As shown in Figure 36, the main fastening method comes from the spaces cut into the acrylic sheets for holding a machine screw nut. There are several advantages of this type of connection over fastening with acrylic cement. First, the connection is reversible, allowing for adjustments to be made while disassembling and reassembling the machine. Second, the fastening method allows for spacing dimensions to be slightly off and the fastening method will still be successful, as the nut has room to move inside the slot and can be fastened with a varying amount of contact between itself and the acrylic surface. Contact between the nut and the acrylic pressed into place by tightening the machine screw allowed for a great deal friction between the two plates being connected, forming a very rigid connection with little tightening of the screw.

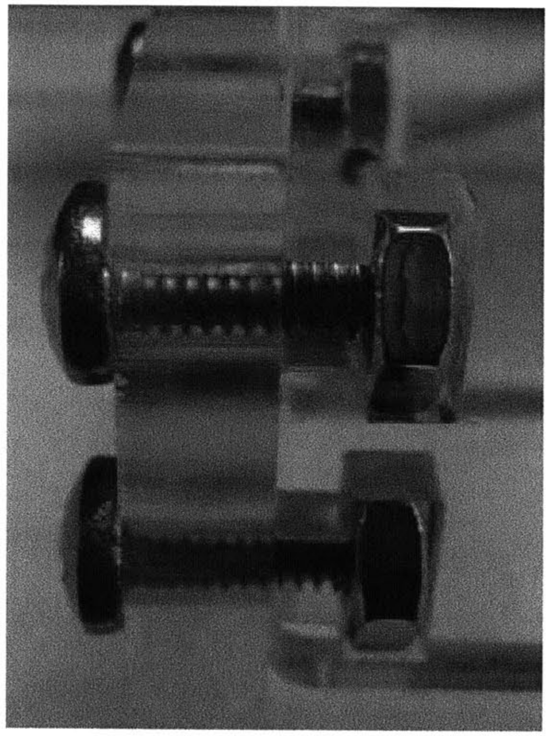

Figure 36: Fastening method used in Prototype 2

Pulleys were designed and fabricated for Prototype 2 out of Delrin rod stock using a lathe. Delrin stock was readily available as scrap. Alternatively, suitable pulleys for the round belt implemented in Prototype 2 can be bought for relatively low costs rarely more than two dollars each. One pulley assembly can be seen in the solid model in Figure 37. The L-brackets holding the pulley plate in place, which are also used to fix the servos into place, proved to be problematic. At first, the design dictates that holes for an 8-32 close-fit be drilled through the 0.25 inch side of the L-brackets. During fabrication, the L-brackets broke from the large size of the holes. In order to combat this design error without refabricating the L-brackets, smaller holes were introduced. Figure 38 shows the adjustments made to accommodate the new size screws.

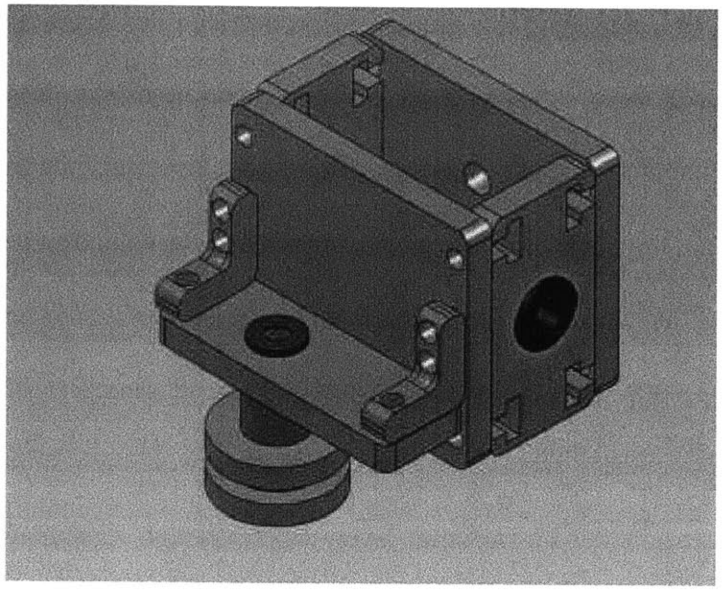

Figure 37: Pulley used in the drive system.

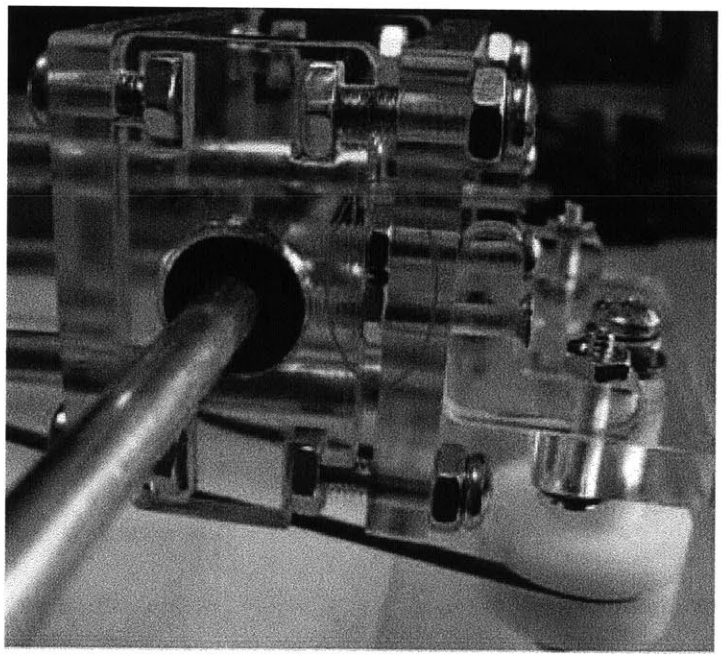

Figure 38: Extra nuts sandwiched in between two acrylic plates in order to allow for a change in screw size.

The belt system implemented in Prototype 2 proved to be unsuccessful in positioning the system, but did provide an accurate test setup for evaluating servo-potentiometer feedback control. Using the potentiometers attached to the continuous rotation servos to determine the angle of rotation of the servo, the servo could be adequately controlled to stop with as much resolution as the microcontroller could measure with an analog reading. The belt drive itself, however, had several issues. First, the pulleys did not have a proper design for creating enough friction between the belt and the pulley; consequently the pulleys attached to the servos would occasionally slip. In addition, a large rotation was required when switching direction of motion. The belt would need to completely remove the tension in one direction and build up direction in the opposite direction before moving. Even when enough tension was reached in the belts, the axis being moved would jump due do switching between static and kinetic friction. Even with lubricated rails, the belt system proved to be insufficient.

A disadvantage to using laser cut parts was evident in the parts that fixed the rails in place. During assembly it was evident that the rails were not being fixed perpendicularly to the surface of the acrylic sheets, but rather there was some minor angle at which the rails would extend from the acrylic surface. The most plausible reason for this issue was that warping occurs when laser cutting parts. Warping can occur by two mechanisms: either the material being melted around the laser beam shifts before it solidifies, or the entire plastic sheet is heated via convection during cutting, causing the sheet to bend and flex. In the second case, the laser continues to cut vertically into the plastic sheet, and any holes bored into the material end up at an angle to the surface of the plastic. The extent of the warping is shown in Figure 39.

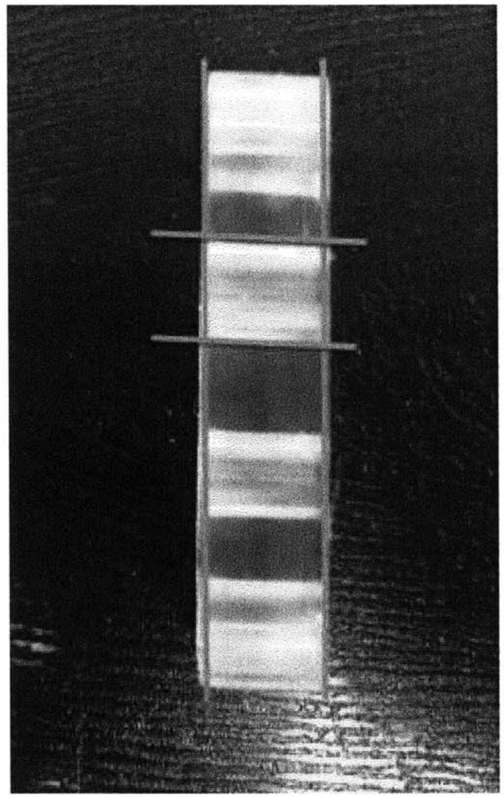

Figure 39: Warping in the acrylic parts

Overall, the design of Prototype 2 was far superior to the design of Prototype 1. Using Prototype 2 as a test rig for potentiometer control revealed that potentiometer feedback is a viable option for an inexpensive position control mechanism. However, several improvements need to be made before a working machine can be produced. The main issue is that the belt drive system needs to be improved. Several possibilities exist as options for an improved drive mechanism. Pulleys with tighter tolerances could provide better frictional forces and less slipping. A better method for adjusting the tensioning could help improve performance. The most viable option for improved performance is switching from a round belt to a timing belt, which would most likely improve friction issues and reduce any backlash effects.

6 Conclusions and Future Work

Great strides were made toward developing the components necessary for a low cost laser cutting mechanism, but the ability of the machine would be limited beyond the initial intentions of the machine. Using the laser diodes explored in this thesis, the machine would be limited to cutting thin (0.040 inch thicknesses and thinner) material completely through. The low power outputs of the laser diode is the main limiting factor of the cutting potential of the laser. Although additional lasers focused to the same point improve performance, this method is not without its limits.

The mechanical structures tested in this thesis are a good start for designing a low cost machine capable of providing accurate positioning, but improvements are necessary before the machine will reach the design goals. A better method of power transmission is the major issue preventing successful operation of the mechanical design. Perhaps testing a timing belt instead of round belts will improve the performance of the machine without increasing cost. The potential of using potentiometer feedback for positioning is a promising low cost method of position control.

Were the mechanical design of the machine improved and the laser parameters optimized to provide adequate burning power from the laser, the machine would most likely serve prototyping purposes as a method of layout planning better than actual cutting. Perhaps the machine would be better off used for marking material with layouts prior to traditional machining. In addition, boring holes may be an adequate way of creating guide holes for later drilling. Other uses for a well-positioned laser diode exist, and merely need a creative mind for implementing them. Using the components documented in this thesis, several useful mechanisms can be designed utilizing the laser diode and a low cost positioning system.

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