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Design of an Ultrasonic Ribbon Bonder

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Design of an Ultrasonic Ribbon Bonder

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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Design of an Ultrasonic Ribbon Bonder

By

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SENIOR DESIGN PROJECT REPORT

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ABSTRACT

Ultrasonic Bonding is a solid-state bonding mechanism that can join two dissimilar materials. This report details work done to design, build, and analyze an ultrasonic ribbon bonder for research use at Santa Clara University. The bonder would allow researchers to view the bond site as the bond is being formed, which would be accomplished by bonding an aluminum ribbon to a silica substrate. Unfortunately, issues corresponding to COVID-19 led to difficulty in building the bonder during the final stages of construction. This led the team to focus on analysis rather than construction of the bonder. Specifically focusing on creating a plot of tool amplitude versus transverse force for different input powers, which showed a linear relationship between amplitude and force and also showed that input power has significantly more impact on amplitude than it does on force.

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Table of Contents

List of Figures

List of Tables

1. Introduction

The process of bonding different or similar materials utilizing ultrasonic frequencies has become increasingly popular due to the large number of benefits that the technique provides. Ultrasonic welding/bonding is capable of creating clean bonds that do not require the utilization of a melted substrate. Additionally, the bond is generally created at much faster rates and one can achieve high levels of precision. Nevertheless, when discussing metal-to-metal bonding, ultrasonic welding is generally capable of creating small bonds with limited surface areas. It is for this reason, that the technique has become popular in practices of electronic packaging where clean bonds are necessary, at high rates, and on small surfaces. Thus, to provide a greater understanding of ultrasonic bonding the process is explained in the following segments.

In creating a bond between metals using ultrasonic frequencies the procedure is separated into four different phases. In the first phase, the bonding tool pushes the substrate and ribbon together and ultrasonic vibrations begin. The normal force and vibrations cause the surface oxide layer to crack. The broken oxide layer is transported either to the peripheral regions of the contact area or not far from where it was broken. As a result of the oxide fracture and transport there is bare contact of the metals. This will lead to localized areas of metallic bonding, or microwelds. Microweld formation occurs throughout the contact area as the ultrasonic vibration ramps up. The next phase is the friction phase. There is an increase in relative amplitude between the ribbon and substrate, which will increase the friction experienced between the unbonded area. This friction energy and the strain energy of the formed microwelds contributes to bond growth. There may be high local maximum temperatures and heat that contributes to this growth. In addition, it is possible for microwelds to break and reform. However, once enough microwelds are formed, the relative amplitude between the ribbon and substrate begins to decrease, because the shear strength of the formed bond exceeds the force exerted by the ultrasonic vibration. This also leads to a reduced number of bonds breaking. Following friction, the third stage is the ultrasonic softening, where the stiffness of the ribbon and substrate are reduced. One theory behind this phenomenon is that stress superposition between the oscillating stresses and the metal dislocations will soften the two materials. The fourth and final stage that takes place in ultrasonic bonding is interdiffusion. Here, the energy created by the ultrasonic frequencies creates vacancies that allow for the diffusion of the materials. Throughout the bonding process, recrystallization and recovery of the metals occurs. The overall process will generally occur in milliseconds which speaks to the effectiveness and speed of the bond [1].

However, as many studies have expanded on how ultrasonic bonding works between metal surfaces, there are still a multitude of questions regarding the characteristics of the operation. As a result, researchers at the Santa Clara University Materials Lab have sought to expand in-situ analysis of ultrasonic bonding. To do so, they need a custom designed ultrasonic ribbon bonder to conduct thorough graduate level research and answer some of these questions.

1.1 Project Overview and Objectives

The scope of this project is to build an ultrasonic ribbon bonder for research at Santa Clara University. Ultrasonic bonding is a process that can join two similar or dissimilar materials through a solid-state configuration allowing for bonds to be formed without needing to melt either material. The main factor of bonding is the ultrasonic vibrations that are applied to the sample to achieve a bond. This parameter is unique to the type of materials that are being bonded and their geometrical features but is generally achieved with a vibration that ranges from 40 to 120 kHz and with amplitudes of 5 µm. Building an ultrasonic bonder at SCU will allow researchers to perform more research on the specifics of ultrasonic bonding, specifically on the exact process of bond propagation and how input parameters affect bond quality and propagation. Advanced research in this field can aid the process of ultrasonic bonding in markets like electronic packaging or additive/subtractive manufacturing. An example of ultrasonic bonding being used in electronic packaging is presented in Figure 1.

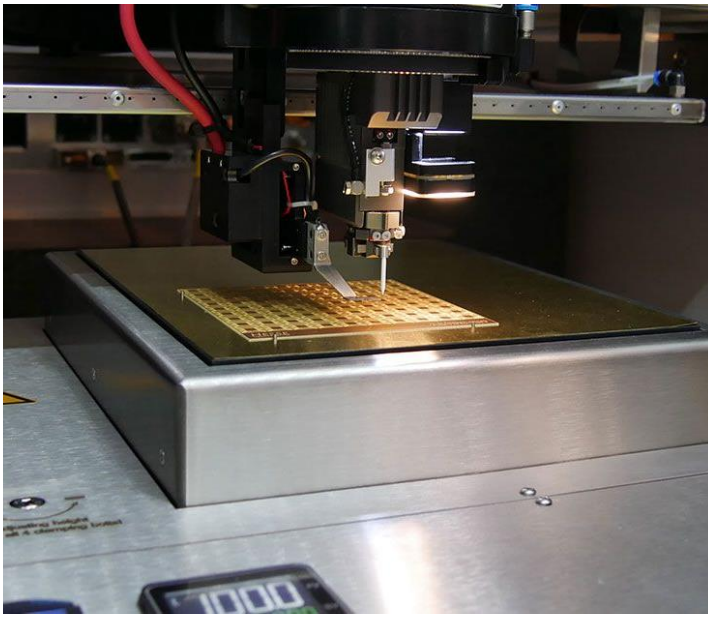


Figure 1: Example of ultrasonic bonding used in electronic packaging industry [3] (used with permission)

In this case, the project involves building a small-scale ultrasonic ribbon bonder that allows for in-situ observation of the bond as it is being formed, similar to the set up in the study by Takahashi et. al [2]. To do this, the system will bond transparent silica to aluminum ribbons of about 1 mm by 0.5 mm and uses a high speed camera to observe bonding. For this specific project, the bonder was designed to use frequencies of 60 kHz with a bonding force of 9.8N and a voltage of 100V corresponding to a power of 100W. Creating such a bonder would be of great value to students and professors involved in the ongoing ultrasonic bonding research projects at Santa Clara University. For instance, the observed bonding could be compared to simulations of bonding on the micro and macroscopic scale.

The research gained from use of the bonder will help increase the utility of this technology and should be quite useful. For example, combining ultrasonic bonding with CNC milling results in a manufacturing tool that allows creation of complex layered parts with less material waste than standard milling. A company called Fabrisonic has been able to produce a joint CNC mill and ultrasonic machine [4]. However, this application of ultrasonic bonding is not widespread due to the lack of understanding of how to achieve optimal bonding.

The final render of the ultrasonic bonder that was created is shown in Figure 2. In general, ultrasonic bonders consist of at least six main components [5]:

- Ultrasonic Transducer- converts high frequency electrical signal to mechanical vibration

- Booster - mechanical device between the horn and transducer that helps achieve desired amplitude of vibration
- Horn/Tool - transmits vibration to parts to be welded
- Frame and Bonding Stage- holds together components, holds parts to be welded, and brings horn in contact with the parts to be welded
- Power supply - converts input electrical signal to higher frequency signal. Should be at least a 900-watt power supply.
- Controller - takes in user input parameters for frequency, normal force, and time

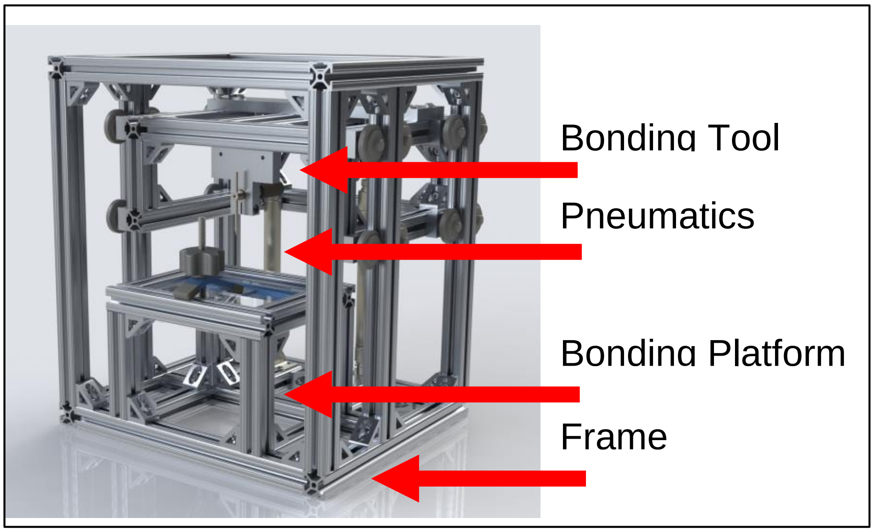


Figure 2: Render of Final Design

Our bonder is broken into the following subsystems: frame, bonding platform, bonding tool, normal force generator (pneumatics), and electronics. The main purpose of our device is to build an ultrasonic bonder that allows for future upgrades and scalability such as in-situ analysis. The following analysis gives insight into ultrasonic bonding and the strategy that was used in designing our ultrasonic bonder.

1.2 Technical background

1.2.1 Types of Ultrasonic Bonding Processes

There are two main types of ultrasonic bonding, ball bonding and wedge bonding. Ball bonding involves a wire that is sent through a tube to the tip of the ultrasonic bonder's arm. A spark is then used to melt the tip of the wire allowing for a larger area of bond and then ultrasonic vibrations are used to connect the wire with the desired substrate. This process is shown in Figure 3.

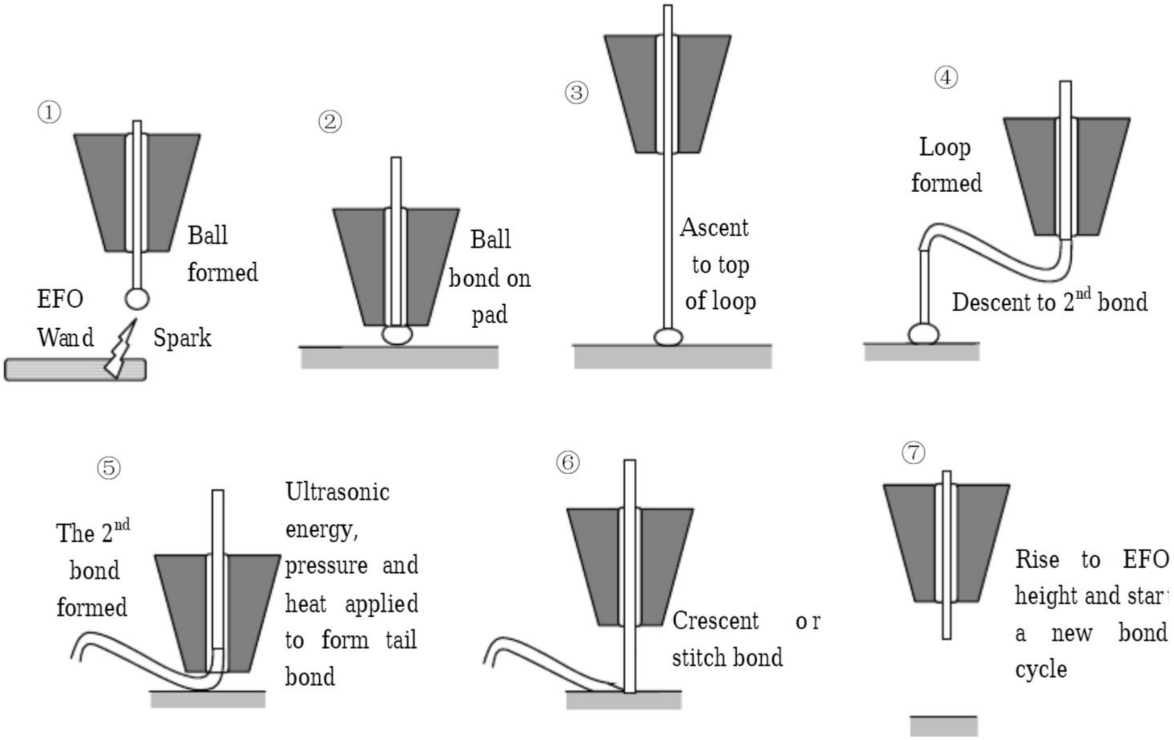


Figure 3: Diagram of Ball Bonding [6] (asked for permission, never received response)

The other main ultrasonic bonding process that is used, and the one that will be used for this project, is wedge-wedge bonding. In this process, the wire or ribbon is held onto a tooltip outside of the machine and the tip, or wedge in this case, is used to force the wire into the correct location and then provide ultrasonic vibrations to weld it in place. A diagram of this process is shown in Figure 4.

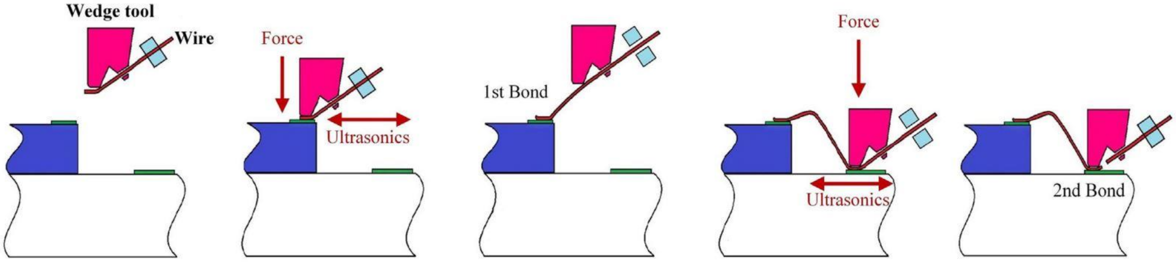


Figure 4: Diagram of wedge-wedge bonding [1] (used with permission)

1.2.2 Advantages and Disadvantages

Ultrasonic bonding has several advantages over traditional welding but two of the main advantages are that it can easily bond together two different materials and it can bond materials together without a melting stage. In most circumstances, ultrasonic bonding also utilizes less energy than traditional welding, mostly because it does not require a significant heat investment, instead relying on ultrasonic movement. This ability to weld materials without melting also allows ultrasonic bonding to bond aluminum materials together very easily, something that is difficult to do with traditional welding given aluminum's low melting point of 933.5K [7].

However, one major issue with ultrasonic bonding is that it is limited in the total area that it can effectively bond at a time. Large bonds can be done but require a machine to bond smaller sections one at a time and then repeat throughout the overall bond area. This significantly increases the time that it takes for ultrasonic bonding in comparison to traditional welding for large bond sizes. That is the main reason that ultrasonic bonding is still a rather niche technology although it is widely used for wire, semiconductor, and battery connections [4].

As mentioned earlier, despite its fairly widespread use, the actual process of ultrasonic bonding is still not fully understood. This lack of knowledge means that it is hard to optimize ultrasonic bonding, which forces many companies to simply rely on experimentation in order to produce the desired bond qualities. Learning more about ultrasonic bonding should help increase the quality of ultrasonic bonds, speed up the development of new ultrasonic bonders, and perhaps lead to a wider range of applications for ultrasonic bonding. Thus, a large amount of research is being done on ultrasonic bonding and those researchers need devices that work for their needs. The main purpose of this project is to build an ultrasonic bonder specifically for research purposes. Currently almost all bonders are designed for industrial purposes, which leads them to prioritize aspects of the bonder that do not focus on the bonding process but on the final output.

1.3 Literature Review

1.3.1 Friction, Transverse Force, and Relative Amplitude

The evolution of friction during bonding is a nonlinear process that causes heating and stresses on the bonded surface [8, 9]. The friction coefficient changes with time depending on the amount of bonding between the substrate and the bonding material, making these two processes codependent. The temperature rise at the bonded area with ultrasonic vibration can be as high as 40K and a stress increase by a factor of about 20 compared to without ultrasonic vibration for aluminum ribbon bonding [8]. The actual frictional power that contributes to these effects is only about 5% of the electrical power delivered based on an experimental study of wedge-wedge bonding [9].

The relative amplitude between the ribbon and the substrate (A_{rel}) and the free air vibration amplitude (A_o) measurements all tend to follow a similar trend. The relative amplitude tends, A_{rel}, tends to have one main inflection point. Before it reaches this inflection point, the plot has negative concavity. After the inflection point, the plot has negative concavity and A_{rel} plateaus to a constant value. The free air vibration amplitude is larger than A_{rel} and tends to behave like a logistic growth [10].

1.3.2 Oxide Transport Mechanisms

The transport process is how surface oxides evolve over time during bonding. This is of concern since oxide layers normally negatively affect the bonding quality. Four different mechanisms of relating the oxides self-cleaning were classified: cracking, detachment, milling, and transport [11].

Cracking, detachment, and milling is caused by the normal force that is applied and subsequent ultrasonic vibrations over a period of ~20 ms. It was found that cracking forms around the peripheral region of the contact area after a normal force of about 5 N was applied. The vibrations then began with a ramping power output from 1.4 to 3 W. After 2 ms the cracks detached scales, starting from the periphery, and moving inward with increased power. The milling process happens concurrently and is described as the reduction in size of the oxide particles. The particles can be reduced in size after 100 cycles of vibration as much as 80% [11].

The transport process lasts over another period of ~20 ms and is mainly due to the normal force and vibration. The stress distribution at the bonded area radially decreases from the center to the periphery. The oxide particles follow this stress gradient with assistance from the vibration [11]. As the oxide particles roll, they can pick up other oxides [12].

1.3.3 Visualization of Ribbon Bonding

What makes this device specific to research is the capability of visualizing the bonding process in real time. This type of in-situ analysis is achieved by bonding a metal to a transparent silica substrate and recording the process with a high-speed camera. Areas where bonding occurs show up as darker streaks in the high-speed camera video. In previous analysis, it was shown these streaks where bonding is occurring tend to appear at aperities, or peaks in the surface roughness [2].

1.3.4 Factors Impacting Bond Quality

Microstructure

For wedge-wedge bonding, generally the bonded interface consists of nanoscale grains amongst nanoscale oxide particles and pores. These nanoscale grains grow further away from the bonded interface. Depending on the composition of the substrate and bonding material, these grains may contain intermetallic particles. Within these structures, dislocation loops are observed. These dislocation loops are thought to originate due to ultrasonic vibration during dynamic recrystallization and recovery. However, this is debated because dislocation loops can appear due to focused ion beam milling used for sample preparation [13].

Bonding Parameters

The bonding parameters (US power, normal force, bonding time, frequency) all impact bond quality. The qualitative trends of these different bonding parameters are shown in Table 1.

Table 1 - Qualitative trends of bonding parameters [1]

Parameter	Too Low	Too High
US Power	• Surface oxides are not broken up enough • lower bond strength	• Increased tool wear • More existing bonds dynamically fracture
Normal Force	• Longer bonding time required • surface oxides not broken • amplitude of vibration too great	• Not enough vibration amplitude to transmit energy
Bonding Time	• Not enough energy transfer	• Tool wear • More existing bonds dynamically fracture
Frequency	• Slows processing time	• Generally higher frequencies are better

Material Properties

When bonding similar or dissimilar pieces of metal the material properties of each sample can affect the bonding process. To verify the bonding methodology, research was conducted to understand which material properties affect bonding the most. After careful consideration, the following parameters are listed as they were considered during the design stages:

- Roughness means more frictional forces are present, which may aid bonding [1]
- Hardness means it is harder to transmit forces [1]
- Tendency to oxidize means bonder are more likely to become brittle and become reduced in strength [1]

2. System Planning

2.1 Customer needs

Within industry and research laboratories there are a multitude of diverse ultrasonic bonders that all operate differently to achieve a specific goal. There are parameters that change the size of the bond, the functionality of the device, the ability to automate a process, etc. The team understood that to narrow the scope of the project and set achievable goals there would have to be open communication between the team and the recipient of the final product. Consequently, we held a series of meetings and interviews with our customers to have a wholehearted understanding of the expectations of the project in terms of functionality and product specifications.

The main customer for our ultrasonic bonder is the materials science research laboratory at Santa Clara University (Table 2). Two of the research associates who lead the laboratory were asked to give their input on the device in addition to two students currently working there. A final interview was conducted with an alumnus who previously worked at the lab, yet, now conducts research for a 3D printing startup in the area. The Table below lists the individuals who were interviewed and their role at the Material's Science Laboratory.

Table 2 - Customers Interviewed and their work area

Interviewee	Work Area
Dr. Sepehrband	Research Advisor
Dr. Tszeng	Research Advisor
Milad Khajevand	Master’s Student Researcher
Bethany Hsu	PHD Student Researcher
Matt Mckay	Metal 3D Printing Startup

Each individual was asked the same thirteen questions which can be referenced in Appendix A. Their responses were recorded as they rated certain functionalities of the device based on a scale of 1-10. Qualitative input was also recorded to have a complete understanding of how the device should function and what parameters should have a higher priority. Moreover, the customer’s responses were also compared to current products in the industry, as their functionality serves a key form of comparison to designing an effective device.

This data was then analyzed to find common themes and needs among the different customers. Extra weight was put towards the requirements of our advisors who have the most impact on the project. The ultrasonic bonder is meant to be utilized for research purposes and not for industrial functionality. Thus, the interviewees emphasized that the goal of automation is not essential, as samples will generally be tested individually. The device should have the ability to input several parameters including geometry, force of bond, frequency of waves, etc. By inputting these parameters, the researchers can randomize variables and study the effects of ultrasonic bonding in ribbons and wires. As a result, the device must be capable of controlling the normal force, vibration amplitude, vibration frequency, and the time in which the bonding process is applied. These variables will become the inputs to the ultrasonic transducer. There is also a need to define the geometric bonding area where the metal bonding will occur. We realized the importance of having a flexible area in the XY plane where the bond will be made. This means that the size of the sample should have a large range to understand how ultrasonic bonding reacts to the bond size. The interviewees gave us an average input of having an XY area for bonding of at least 500 μm^2. Thus, the size of the device in comparison to the industry’s products will be significantly smaller. The ultrasonic bonder that will be designed during this investigation should be of desktop size in comparison to the human sized bonders of other companies.

Moreover, for the output side of the ultrasonic bonder there are a series of measurements and values that were desired by the materials science laboratory. The device needs the capability of in-situ analysis of bonds to study the effects of ultrasonic bonding in both wires and ribbons. It would also be useful for the device to be able to directly measure the force and vibration applied to the bonding area. By measuring these outputs, the research laboratory will have a device that can fulfill the necessary requirements to advance their studies in ultrasonic bonding.

Furthermore, we were informed that the device must be easily repaired and that any necessary changes should be accessible for future investigation and possible improvements. The ultrasonic bonder should not be complex when performing a repair or making changes to the inner parameters. If the device is easier to use, then new researchers do not have to go through long periods of training to learn how to perform ultrasonic bonds. The ability to perform repairs will allow the device to be used for a long period of time before a new component has to be purchased in case of malfunctioning or wear that hinders the quality of the bond. These needs were categorized and used throughout the design process to inform design decisions. All the needs were rated on a relative scale out of 5 and are shown in Table 3 below.

Table 3 - Relative Importance of Needs

Need #	Needs	Relative Importance (out of 5)
1	Possible to move	3
2	Easy to repair	4
3	Control normal force	4
4	Control ultrasonic vibration amplitude	4
5	Control ultrasonic vibration frequency	3
6	Control time for ultrasonic vibration to be applied	3
7	Measure temperature	1
8	In situ analysis of bond	5
9	Relatively large bonding area (500 micrometers^2)	3
10	Competitive price	3
11	Able to switch out parts	3
12	Device should have a relatively small footprint	2
13	Should not be complicated to operate	4
14	Should not take too long to operate	2
15	Electrical resistance measurements	1
16	Bond Strength	1
17	Should be relatively light	2

2.2 Market Research

We looked at three major companies involved in ultrasonic bonding, the first is a particularly interesting application from a company called Fabrisonic. Fabrisonic is a metal 3D printing company that uses ultrasonic bonding to bond sheets of metal together in tandem with CNC machining, as seen in Figure 7. They call their process Ultrasonic Additive Manufacturing and mostly deal with products that are large by ultrasonic bonding standards, yet, still relatively small in the overall welding world. Fabrisonic is able to overcome the disadvantages of large-scale ultrasonic welding by having a rolling ultrasonic vibration emitter that only bonds small areas of material together at a time [4]. Fabrisonic is taking advantage of the rapidly growing additive manufacturing market and are using ultrasonics to allow for a different, and mostly beneficial, way of 3D printing metal products.

Figure 5: High power fully automated welding head and machining center used by Fabrisonic for 3D printing [4] (used with permission)

The second company that was analyzed was Hesse Technologies. Hesse Technologies is a company specifically in the business of producing and selling ultrasonic bonders. They have quite a few different machines that they sell, each for a different purpose but their main focus is on wire bonding rather than ribbon bonding. An example of one of their small-scale bonders is shown in Figure 8a however these machines are still significantly larger and more complicated than the bonder that the team designed. Most of their machines do have some degree of ribbon bonding functionality but the focus is on wire bonding.

(a) (b)

Figure 6: Small Scale Ultrasonic Ribbon Bonders

(a):BJ855 fine wire bonder from Hesse Technologies [3]
(b):K&S Asterion model wedge bonder [14] (both used with permission)

The third company analyzed was K&S. K&S or Kulicke and Soffa is an electrical component manufacturing company with a broad range of products available including two types of ultrasonic bonders. An example of one of their small-scale bonders is shown in Figure 8b. They have the traditional wedge-wedge and ball wire bonders as well as something called a wafer bonder, which is similar to a ribbon bonder but specifically for Silicon wafers. K&S has a broad business model, which allows them to provide all the services necessary for manufacturing small scale electrical systems with a focus on semiconductor packaging [14].

When looking at these companies it was also important for the team to think about what differentiates the designed ultrasonic ribbon bonder from other bonders currently on the market. This then would allow the team to pursue different aspects of the project to form a strong niche market within the ultrasonic bonding market if a future business was desired.

In that vein one of the largest differences between the designed bonder and other ultrasonic bonders currently on the market is simply the size and complexity. Every single ultrasonic bonding company that was researched had quite large-scale bonders with a focus on automation and rapid bond development. These bonders are significantly more complicated than what is necessary for research purposes and that means they are also more expensive than required. Beyond research there are also almost certainly many small-scale companies or hobbyists who can't justify the expense of these more complicated ultrasonic bonders but would still like to use or benefit from an ultrasonic bonder. This is the market niche that the team's ultrasonic bonder could fill, providing simple and less comprehensive ultrasonic bonders but for a cheaper price that should hopefully allow for a significant level of market penetration.

2.3 Physical sketch with user scenario

Figures 9 and 10 depict the main steps to operating an ultrasonic bonder. First a user must input parameters such as the voltage signal frequency and magnitude, the magnitude of the normal force, and the bonding time. Depending on the level of automation, the user may need to input all of these parameters into separate consoles or control modules.

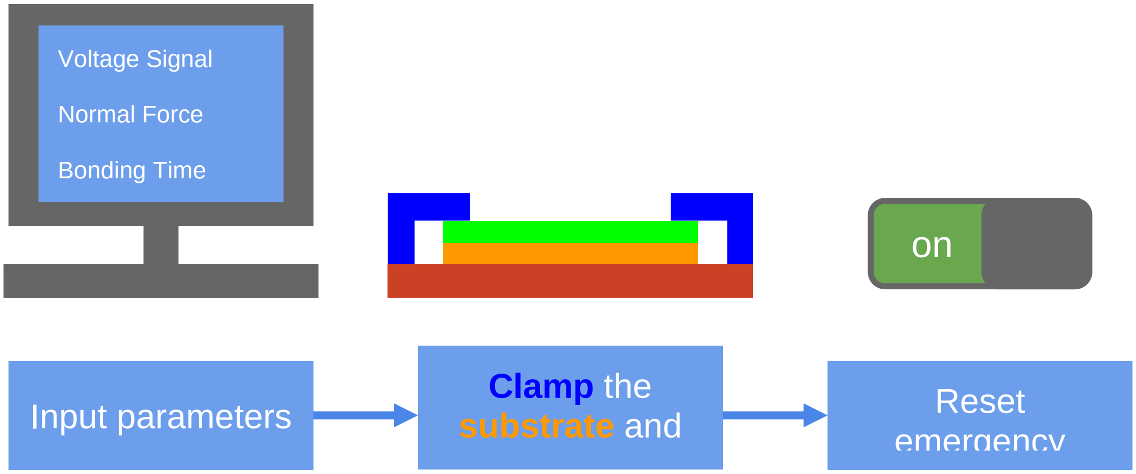


Figure 7: Steps 1-3 of the User Scenario

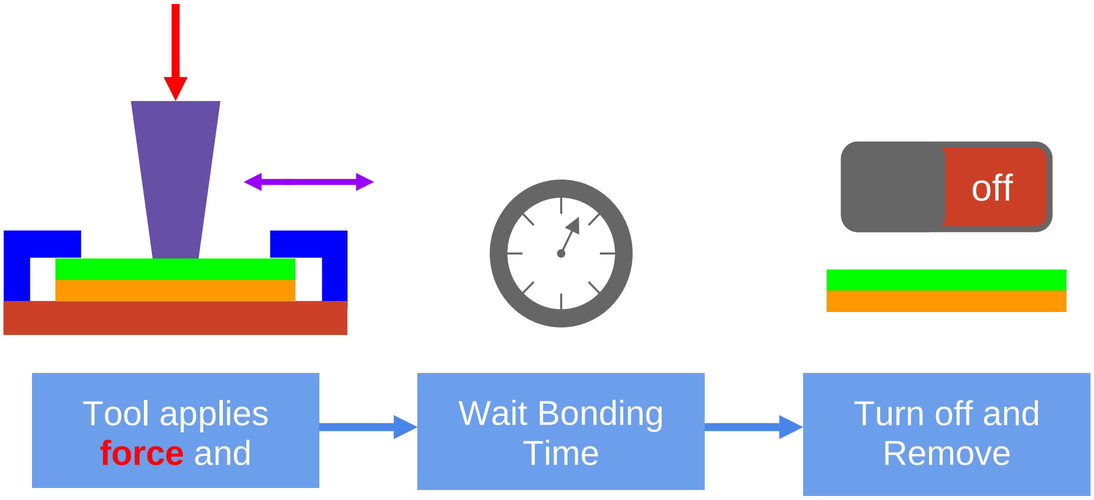


Figure 8: Steps 4-6 of User Scenario

While the machine is off clamp, the ribbon and substrate are mounted onto the stage. Some bonders again have automated processes that load the substrate and ribbon. After this the bonder can be turned on and bonding will begin. Some bonders perform multiple bonds on the same ribbon and substrate with the help of a translating bonding tool. Finally, the system can be turned off and the bonded component can be removed.

The subsystems in a bonder, such as the bonder depicted in Figure 2, will have dependencies. In Figure 11, the dependencies of different subsystems for a typical bonder are shown. The subsystems at the arrow ends depend on the subsystems at the arrow tips. The pneumatics and bonding tool are controlled with the electronics. In addition, the frame houses the bonding tool, the pneumatics, and the bonding platform. The electronics may or may not be integrated into the frame. Also, the bonding platform may have additional instrumentation or may be automated.

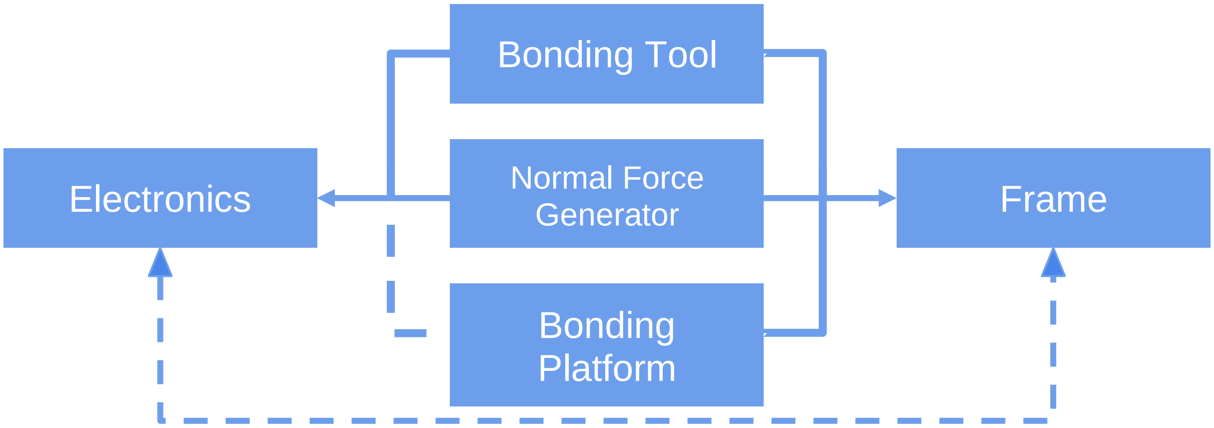


Figure 9: Dependencies of Subsystems. Arrow end depends on the arrow tip. Dashed arrows indicate optional dependencies for automated bonders

2.4 Preliminary Specifications

2.4.1 Required Specifications

In order to create a functional wire bonder, the key performance specifications need to be defined. These primary metrics are the 7 parameters affecting bond quality: bonding material, bonding area, frequency, normal force, amplitude of vibration, bonding time, and bonding power. Research articles gave limited information, and many had very different values but a list of the determined values are shown in Table 4.

Table 4 - Range of Bond Values from sources [15], [16],[17], [18], [2] [19]

#	**Al Alloy**	**Bonded Area (mm x mm)**	**Frequency (kHz)**	**Force (N)**	**Amplitude (μm)**	**Time (ms)**	**Power**
1 [15]	6061	-	20	1500	41.1	225	1-9kW
2 [16]	5754	24.4x102	20	4000	40	1500	3 kW
3 [17]	-	-	20	2500	25	-	-
4 [18][2]	Pure	2x1	60	30	1-2	100-800	20 W
5 [19]	Pure	-	-	7	4	400	3 W

Table 4 illustrates bond parameters for different bonders. In rows one through four, these devices are capable of bonding much larger areas than the bonder in row five, which results in vastly different force requirements. From general analysis of our customer needs, the bonder we are making is going to have a bonded area of 1-2 mm^2.

2.4.2 Benchmarking

Benchmarking was performed using both wire and ribbon borders made by two companies: Hesse technologies and K&S. A total of 16 comparison metrics were used, as shown in Table 5.

Table 5 - Partial Benchmark of Competing Products, voltage is representative of the power primary metric

Company			**Hesse Technologies**		**K&S**	
#	**Metric**	Units	BJ653	BJ855	4523D	4524AD
1	Frequency	kHz	100,60,120	100,120	60	60
2	Bond Force	gr	-	-	10-160	10-160
3	Bond Time	ms	-	-	10-1000	10-1000
4	Voltage	V	100-240	230	100-240	100-240
5	Ribbon Materials	List	Al, Au, Cu, AlCu	Al, Au	Au	
6	Weight	kg	330	1150	31	31
7	Area Footprint	m^2	0.714	1.098	0.476	0.476
8	Max Bond Area	mm^2	0.80	0.01	10	6
9	Min Bond Area	µm^2	210	210	-	-
10	Number of Bondheads	N/A	5	2	-	-
11	Working Area Footprint	cm^2	115	1251	180	231
12	Working Volume	cm^3	483	4002	-	-
13	Machine Total Volume	m^3	1.006	2.1	0.252	0.252
14	Wire Materials	List	Al, Au, Cu, AlCu	Al, Au,Ag, Cu	Al, Au	Au
15	Max Wire Diameter	µm	600	75	76	76
16	Min Wire Diameter	µm	12.5	12.5	20	18

2.4.3 Marginal and Ideal Specification Values

Based on the customer needs, the key specifications, and benchmarking, we determined the ideal and marginal values for 15 new design metrics as seen in Table 6.

Table 6 - Ideal and marginal Values with needs

#	Corresponding Need Numbers	New Design Metric	units	marginal	ideal value
1	1,12	Footprint of Device	m^2	1	0.6
2	1,2,9	Workspace Volume	cm^3	1500	3000
3	8,9	Bonding Area	mm^2	1	10
4	1,17	Weight	kg	40	30
5	10	Price	$	10,000	5,000
6	5	Frequency	kHz	60	60-120
7	7,15,16	Number of observations	No.	4	10
8	2,11	Number of subsystems	No.	3	6
9	3,4,5,6	Number of Control Parameters	No.	4	10
10	11,13	Ease of Use	subj. (1-5)	3	5
11	11,15,16	Number of materials	No.	2	3
12	11	Number of bond heads	No.	1	2
13	13,14	Time to setup	min	45	20
14	2	Easy to repair	subj. (1-5)	3	5
15	13,14	Automated Process	subj. (1-5)	1	3

It should be noted that all of the bonders that were analyzed during benchmarking are for industrial applications, while our bonder is for research use. To account for this, we used customer responses to formulate many of the marginal and ideal values.

2.5 Design Analysis

The products specification Tables provided a jumpstart to generate an array of diverse concepts that could accomplish ultrasonic bonding. The investigative team set out to create independent iterations of the ultrasonic bonder's functionality. The combinations of different designs for the whole system and subsystems was evaluated utilizing a set of criteria based on the products specifications. By assessing the functionality and effectiveness of each design, a final concept was generated with small changes to improve it. This design was then studied under vibration and stress analysis to understand whether the concept could survive the function of the ultrasonic bonder. This process led to a set of iterations that would perfect the final concept for the building stages. The following analysis details this process and expands on the methodology of designing the US bonder.

2.5.1 Concept Generation

The concept generation process was divided into two stages: individual and team brainstorming. During the first stage, each team member created a system, subsystem, and component concept design. This individual phase also included specific research into existing designs and products. In the second stage the team met as a group, compared designs, and brainstormed a new system design. A list of all of the system concept designs that were generated is provided in Table 7. In addition, sketches of concepts 1, 2, and 3, can be found in Figures 12, 13 and 14. Drawings of subsystem and components designs can be found in Appendix B.

Table 7 - Concept list

Concept #	**Descriptions**
1	Vertical Bonding System
2	Industrial Arm Controlled Bondhead
3	Pneumatic Bond head, Stationary Stage
4	Stationary Bond head Motor Controlled Stage

In all the concepts described in the following section, the bonding subsystem consists of a bonding tool, the horn, a booster, and transducer. Concept 1, as shown in Figure 12 uses vibrations that are normal to the bonding area and is based on a product designed by Branson Ultrasonics [20]. Some of the major features of this design are that it uses a joint horn and booster, and that it does not require a separate bonding tool. Thus, this concept reduces the cost of the system while achieving the desired amplitude gain for bonding. In addition, the bonding subsystem in this design consists of the horn/booster, transducer, and force application method in series. The idea behind this design was to reduce the footprint in order to make it more transportable while also maintaining space for expansion by further teams if necessary

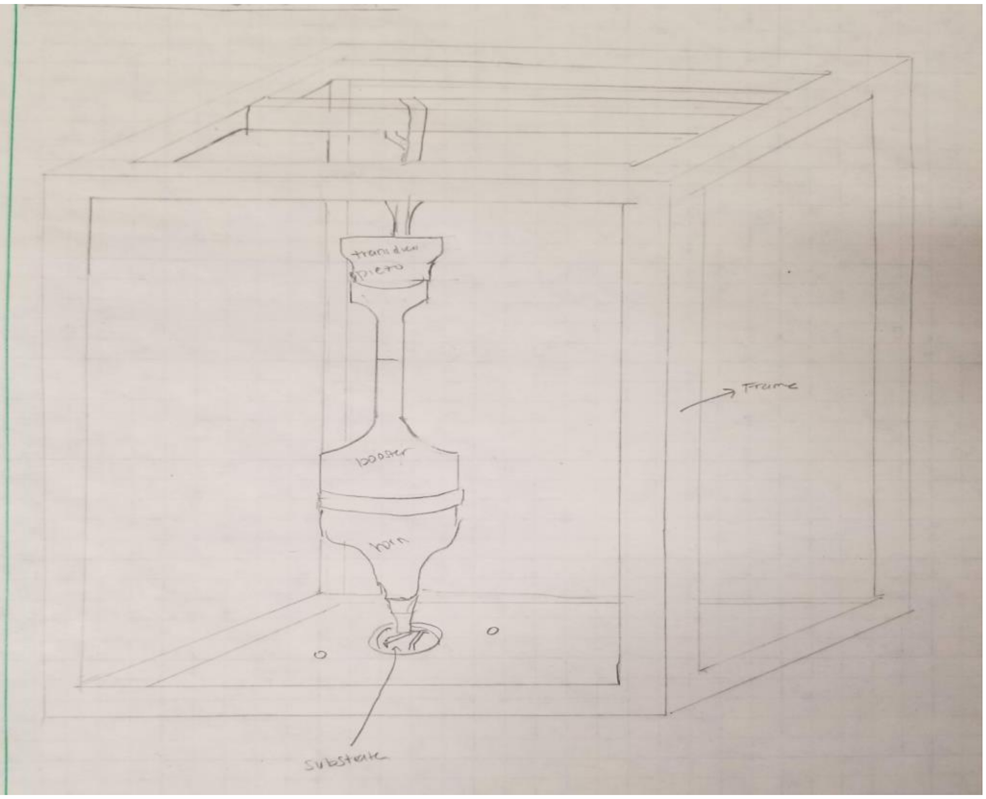


Figure 10: Concept 1, Vertical Bonding System

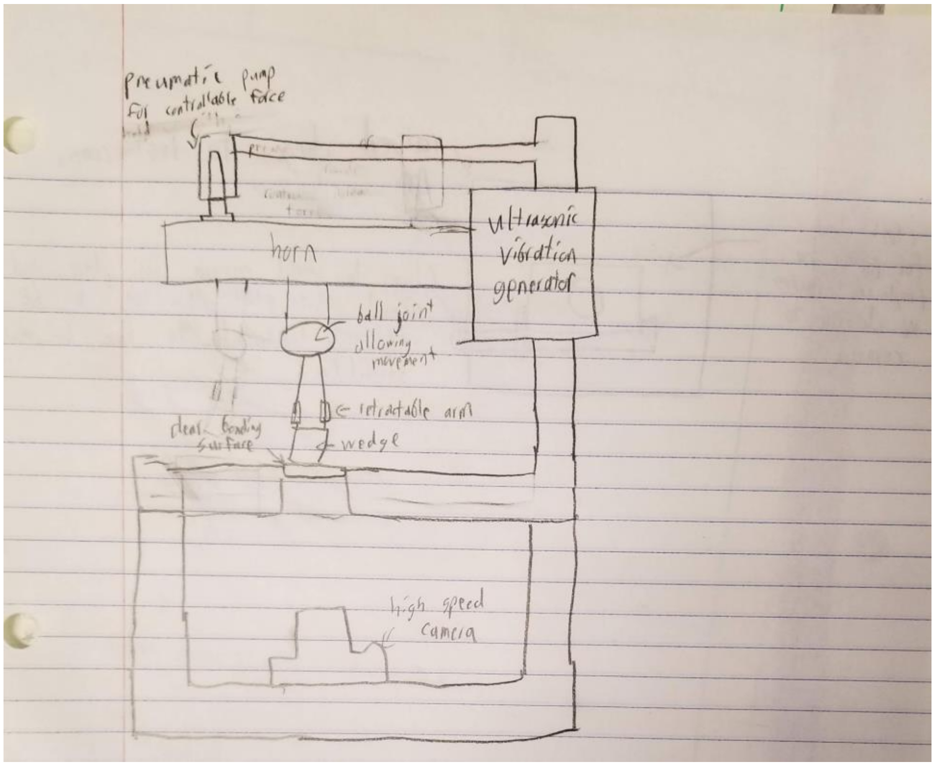


Figure 11: Concept 2, Industrial Arm Controlled Bondhead

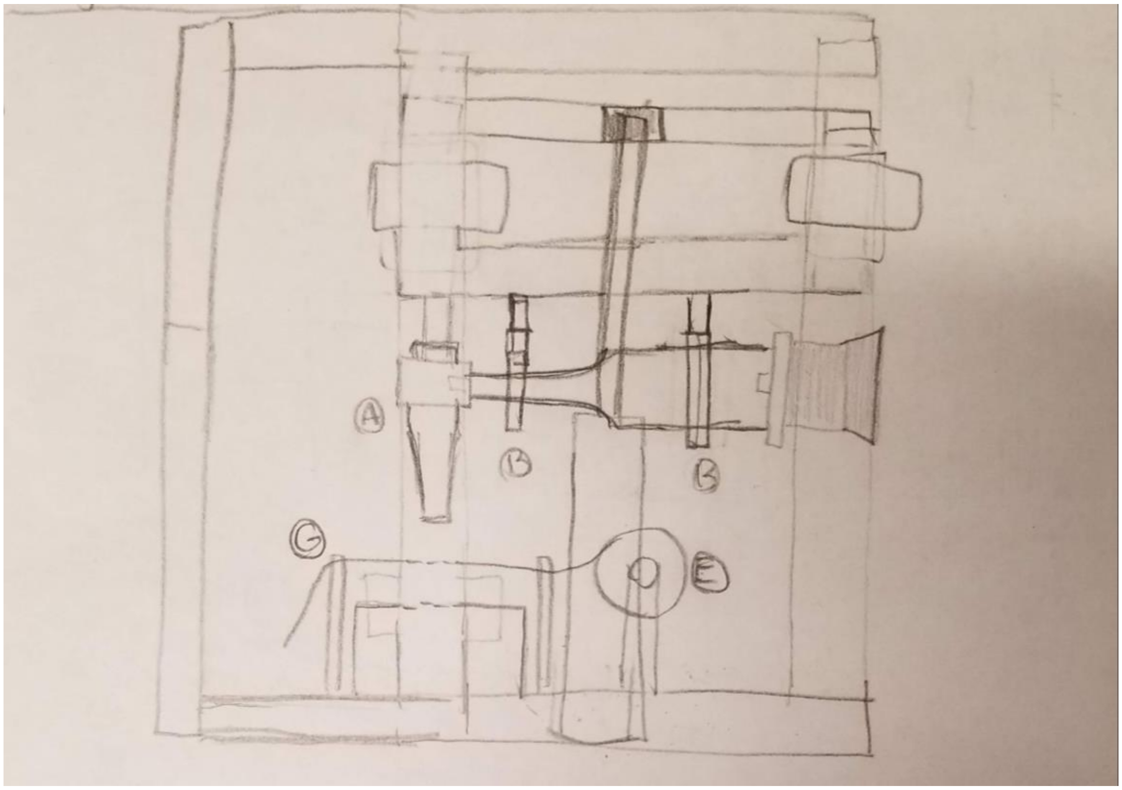


Figure 12: Concept 3, Pneumatic Bond head with a Stationary Stage

Concept 2, shown in Figure 13 uses a horizontal horn connected to a robotic arm. This concept is inspired by the setup used by the research paper by Takahashi [2]. To perform bonding, forces are generated using a pneumatic cylinder, which are then applied to the bonded area using a robotic arm. The arm is capable of locking position in order to transmit the vibrations. It is also able to move in between bonds and is equipped with an automatic ribbon loading system. This concept allows for a high degree of automation, which is desirable for efficient research.

Concept 3, depicted in Figure 14, is similar to concept 2 with a few simplifications. Like concept 2, it is inspired by the setup used in the research paper by Takahashi [2]. Unlike concept 2 however, it utilizes a pneumatic cylinder to apply the normal force and move closer to the bonded area. It does this by moving the entire bonding subsystem on a carriage guided by linear rails. In addition, the ribbon loading system is manual and is located adjacent to the bonding stage. This system does not move with the bonder but is a much simpler design.

The 4th and final concept is a combination of concepts 2 and 3, with again some small changes. In this case the sample stage moves in the x, y, and z directions, while the bonding subsystem is stationary. This design allows for multiple bonds to be performed on a given sample and uses the sample stage motion to apply the normal force using a lead screw and motor.

2.5.2 Concept Selection

After the creation of the fourth design, the team began concept selection. It was decided to use a single concept scoring matrix (Table 8) based on the ideal and marginal values metrics in addition to the hierarchy of the customer needs. There are 5 primary selection criteria with 12 sub-criteria. Weights were given to each of the selection criteria based on the relative importance of the customer needs. The ratings were determined by assigning a rank with 4 being the best design and 1 being the worst design for a given selection criterion. If two designs tie in a given criterion, their scores are given by the score they would each get normally plus or minus 1/2. The total score is then calculated by adding the weighted score for each selection criteria. The total rank in the last row of the matrix is then given to each design, with 1 being the best design and 4 being the worst.

The highest ranking based on the concept selection matrix is concept 3 by about a 15% margin. This concept is the stationary sample stage with a pneumatic controlled bond head. This design was the highest rated design in the ease of movement, ease of repair, and ability to add instrumentation. It also had a tied top score in the bonded area visibility, which is the highest weighted sub-criteria.

While concept 1 scored well across the board, it is not ideal compared to concept 3. The primary reason that the concept 1 design was not selected was because of its risk of failure, and the fact that it would be hard to implement as a modular design. It was rated as being the highest risk of failure because the direction of ultrasonic vibration is not the same as the direction of vibration in most ultrasonic bonders. Also, with the entire bonding subsystem being along one axis it would be harder to implement a modular design.

Table 8 - Concept Selection Matrix

		Concept 1		Concept 2		Concept 3		Concept 4	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Bonder Size	**13.3%**								
Machine Footprint	8.0%	4.00	0.32	2.00	0.16	3.00	0.24	1.00	0.08
Ease of Movement	5.3%	2.00	0.11	3.00	0.16	4.00	0.21	1.00	0.05
Engineering Concerns	**17.3%**								
Risk of Failure	8.0%	1.00	0.08	2.00	0.16	3.00	0.24	4.00	0.32
Ease of Repair	9.3%	3.00	0.28	1.00	0.09	4.00	0.37	2.00	0.19
Ability to Perform Analysis	**29.3%**								
Bonded Area Visibility	13.3%	2.00	0.27	3.50	0.47	3.50	0.47	1.00	0.13
Ability to Add Instrumentation	10.7%	2.00	0.21	3.00	0.32	4.00	0.43	1.00	0.11
Modular Design	5.3%	1.50	0.08	1.50	0.08	3.00	0.16	4.00	0.21
Ease of Use	**33.3%**								
Control of Normal Force	9.3%	3.00	0.28	4.00	0.37	2.00	0.19	1.00	0.09
Time to set up	10.7%	3.00	0.32	2.00	0.21	1.00	0.11	4.00	0.43
Ease of Operation	10.7%	3.00	0.32	2.00	0.21	4.00	0.43	1.00	0.11
Automation	2.7%	3.00	0.08	4.00	0.11	1.00	0.03	2.00	0.05
Competitive Price	**6.7%**	4.00	0.27	1.00	0.07	3.00	0.20	2.00	0.13
	Total		2.61		2.41		3.07		1.91
	Rank		2		3		1		4

The other two designs, concept 2 and 4, had the lowest ranks. Both designs suffer due to their complexity. For example, the robotic arm would require many moving parts and would need frequent and most likely complicated repairs. The moving stage has similar issues, while also severely limiting an operator's ability to observe bonding.

After this concept selection process, it is clear that concept 3, or the design with the pneumatic bond head and stationary stage, is the best design. It is not too complex to implement and is suitable for research use, as automation is not a large concern. This was the basis for all future design work. However, the initial idea was expanded upon and altered throughout the project, changing in design multiple times during that process.

2.5.3 Final Concept Description

The final concept consists of utilizing pneumatics to apply the normal force, and a mounted carriage that glides on linear rails. The linear rails also act as the frame to the bonding system. After several design iterations the design was created in solidworks and is shown in Figure 15.

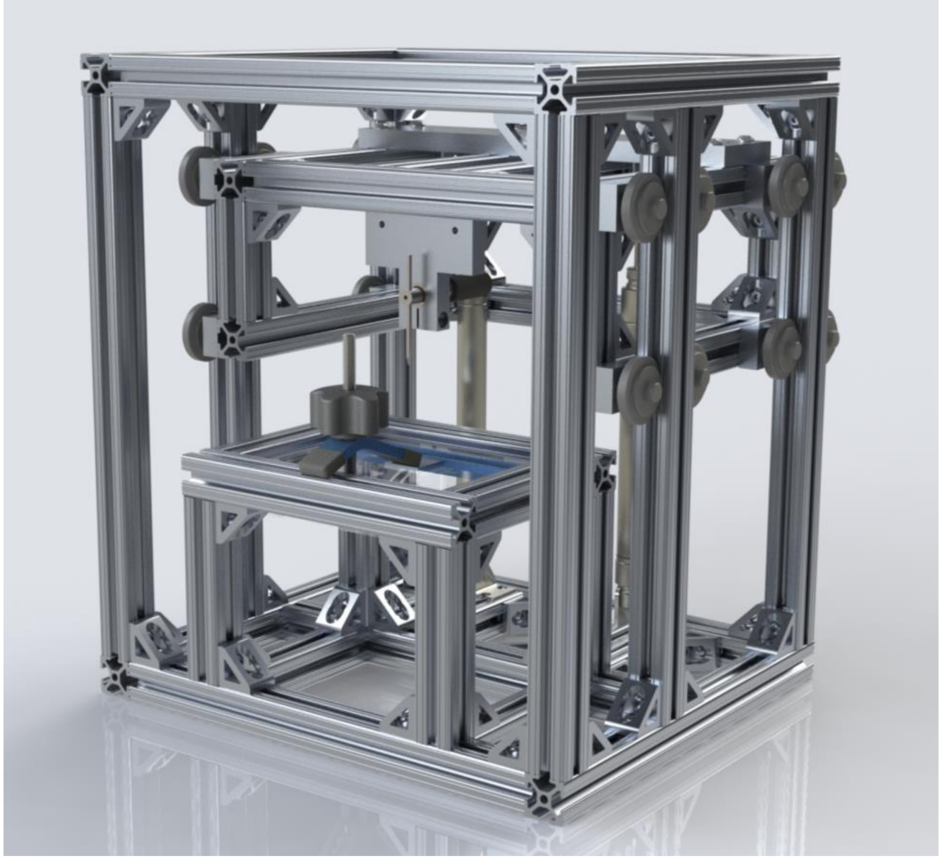


Figure 13: System Level Sketch

2.5.4 Finite Element Analysis of Final Design

The only forces that are present in the system are from the transducer and the pneumatics system. Forces from the pneumatics are less than 20 N which are small enough to disregard. The two tests performed were the resonance of the bonding system and the fatigue of the tool tip.

The analysis of the resonant frequencies of the bonding horn is the most important test. The purpose of this test was to ensure that the bonding system has a beneficial resonant frequency at 60kHz. Through this simulation the team could ensure that the tooltip would bond the aluminum sample. The simulation was able to prove that the axial resonant frequency resided at 67,199Hz (Figure 16).

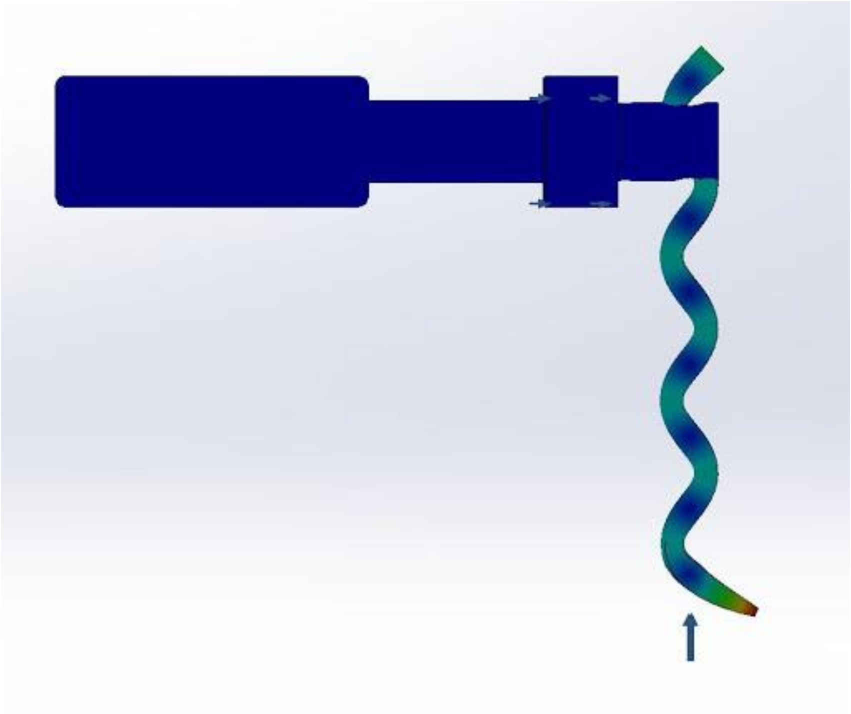


Figure 14: Greatly exaggerated axial deformation of bonding tool at 67,199Hz resonant frequency

While this value is higher than the desired 60kHz frequency, the difference is not significant enough to affect the ability to bond ultrasonically. A reasonable explanation for the different resonant frequencies is that K&S did not provide a detailed geometric sketch or diagram of the bonding tool or horn. All measurements to model the horn and tool in solidworks were done by hand. This type of measurement will cause a small amount of error especially when dealing with more complex shapes. In normal operations this would not matter; however, when addressing resonance at these very high frequencies even a small error can cause a significant change in the final simulation. Thus, this level of difference is not unexpected and shouldn't be a reason for concern.

Moreover, the fatigue life of the bonding tooltip was also studied to carefully understand the durability of the device. Even though it is made of titanium, the tooltip has a small area of 0.55 mm^2 and the team was worried that even with our small forces the tooltip might not have infinite life. A series of simulations were conducted to analyze how cyclic vibration and forces would impact the new tool tip. Through this study, it was found that the new tooltip has an infinite life where basic ultrasonic bonding operations should not compromise its integrity.

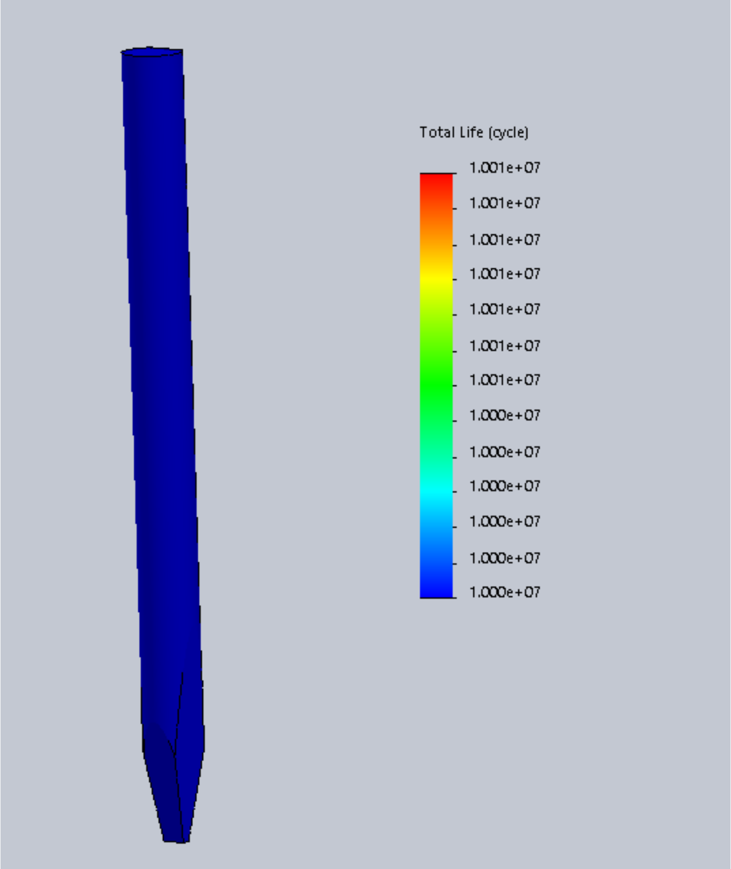


Figure 15: Lifespan of Bonding Tool Showing Infinite Life

2.6 Team and project management

2.6.1 Budget

The current budget for phase 1 of the project is shown below. At this point the vast majority of the objects have already been purchased and added to the bonder, however, there are still a few items related to the bonding stage that will not be bought or used by this team. Table 9 includes the total cost of the different subsystems and how much we have currently spent on each. Our full budget table is included in Appendix C

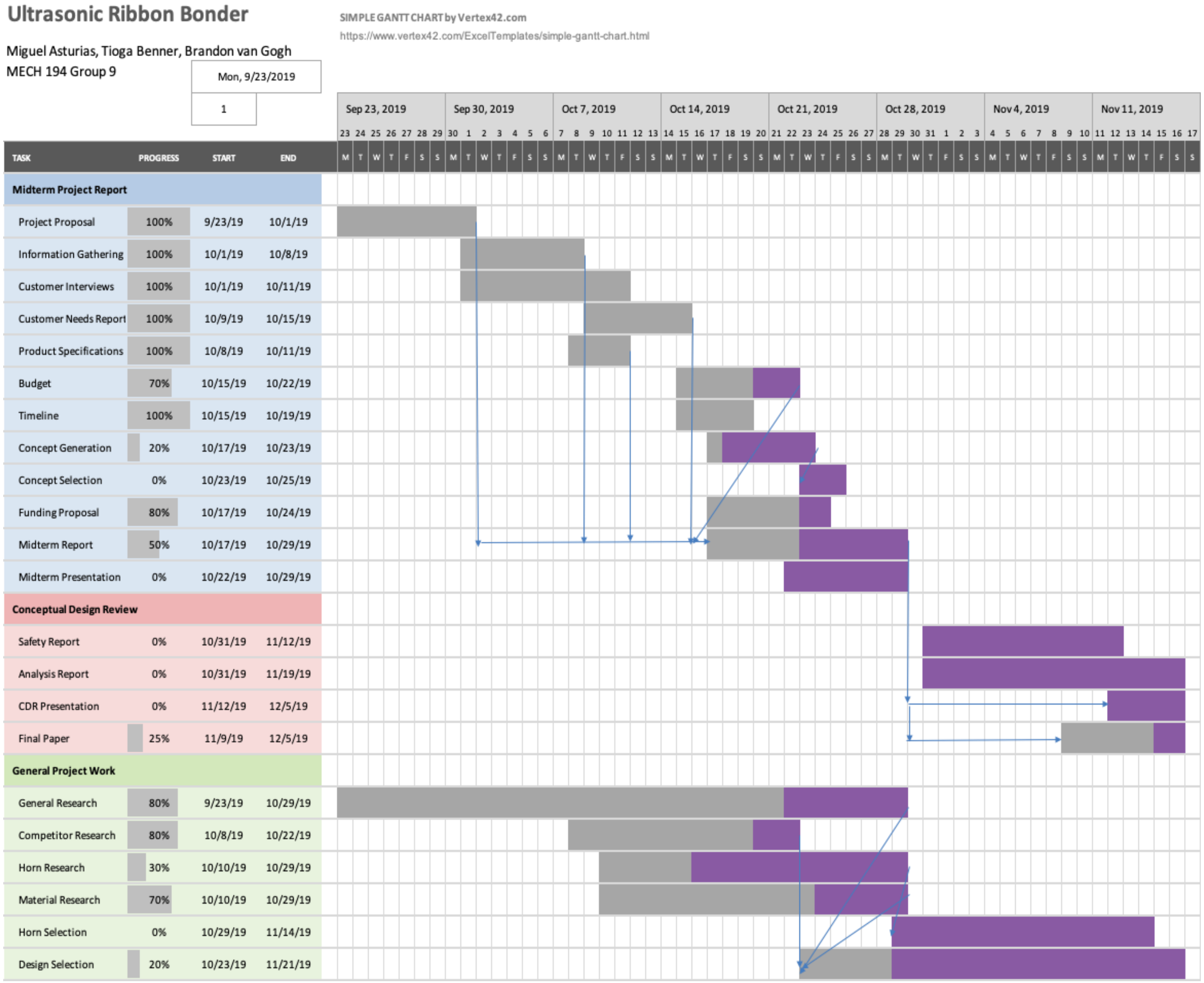
Table 9 - Subsystem Costs

Subsystem	**Cost**	**Spent**
Frame and Bonding Stage	748.16	685.17
Bonding Assembly	1,500	0*
Force Application	329.05	266.06
Hardware	153.08	153.08
Total	2,730.29	1104.31

*transducer and horn were donated by K&S but would have cost around $1,500

2.6.2 Timeline

Multiple timelines were created and changed over the course of this project as tasks changed and more information was gathered. The timelines were split up into different quarters to follow the general structure of the project itself and the timelines were further split up into smaller categories of specific types of tasks from both the professor and the team's advisors. Included in Figures 18, 19, and 20 are the most recent and relevant timelines for each of the three quarters.



Ultrasonic Ribbon Bonder

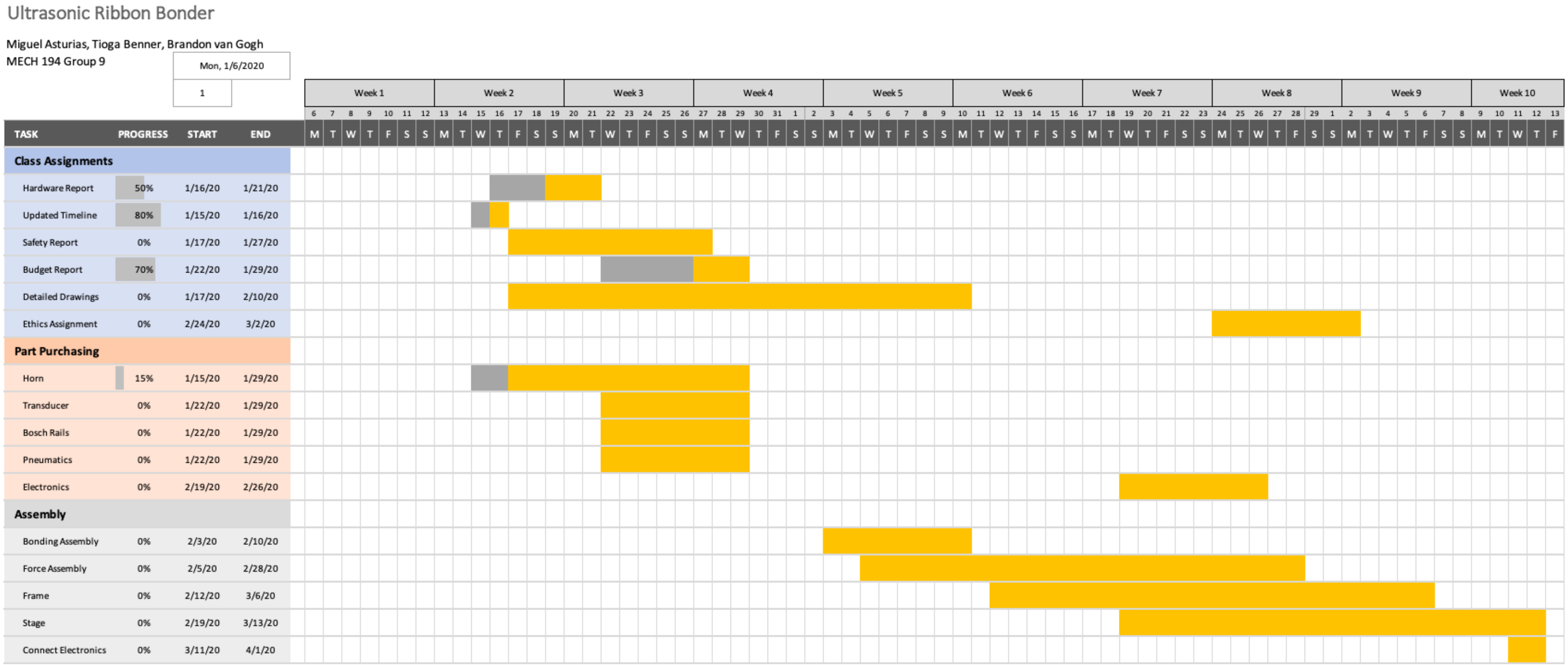
SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Miguel Asturias, Tioga Benner, Brandon van Gogh
MECH 194 Group 9

Mon, 9/23/2019
1

TASK	PROGRESS	START	END
Midterm Project Report			
Project Proposal	100%	9/23/19	10/1/19
Information Gathering	100%	10/1/19	10/8/19
Customer Interviews	100%	10/1/19	10/11/19
Customer Needs Report	100%	10/9/19	10/15/19
Product Specifications	100%	10/8/19	10/11/19
Budget	70%	10/15/19	10/22/19
Timeline	100%	10/15/19	10/19/19
Concept Generation	20%	10/17/19	10/23/19
Concept Selection	0%	10/23/19	10/25/19
Funding Proposal	80%	10/17/19	10/24/19
Midterm Report	50%	10/17/19	10/29/19
Midterm Presentation	0%	10/22/19	10/29/19
Conceptual Design Review			
Safety Report	0%	10/31/19	11/12/19
Analysis Report	0%	10/31/19	11/19/19
CDR Presentation	0%	11/12/19	12/5/19
Final Paper	25%	11/9/19	12/5/19
General Project Work			
General Research	80%	9/23/19	10/29/19
Competitor Research	80%	10/8/19	10/22/19
Horn Research	30%	10/10/19	10/29/19
Material Research	70%	10/10/19	10/29/19
Horn Selection	0%	10/29/19	11/14/19
Design Selection	20%	10/23/19	11/21/19

Figure 16: Fall Timeline



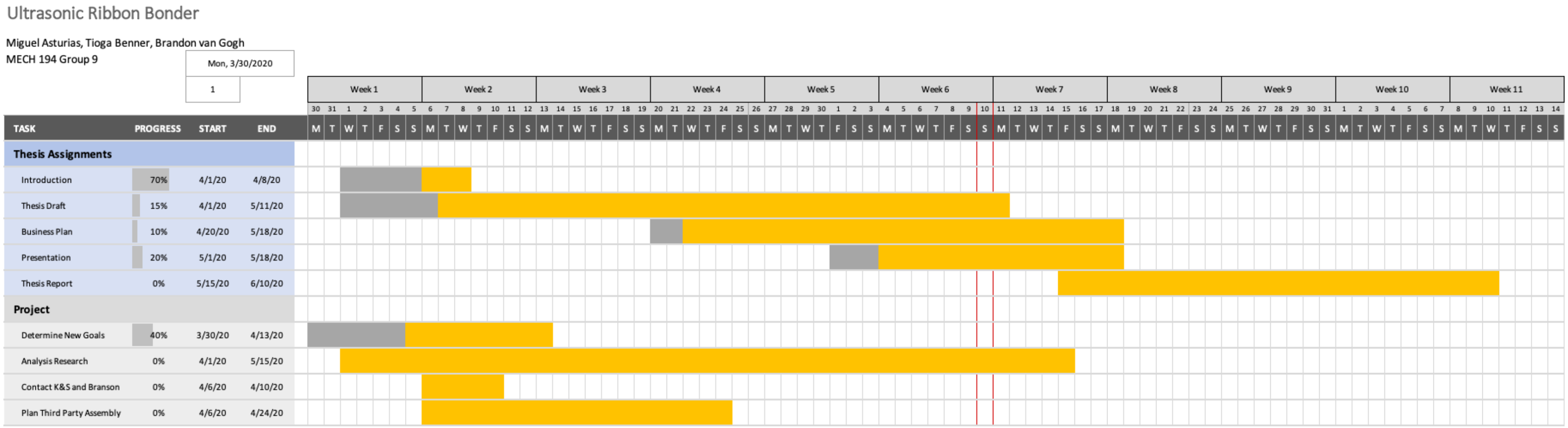
Ultrasonic Ribbon Bonder

Miguel Asturias, Tioga Benner, Brandon van Gogh
MECH 194 Group 9

Mon, 1/6/2020
1

TASK	PROGRESS	START	END
Class Assignments			
Hardware Report	50%	1/16/20	1/21/20
Updated Timeline	80%	1/15/20	1/16/20
Safety Report	0%	1/17/20	1/27/20
Budget Report	70%	1/22/20	1/29/20
Detailed Drawings	0%	1/17/20	2/10/20
Ethics Assignment	0%	2/24/20	3/2/20
Part Purchasing			
Horn	15%	1/15/20	1/29/20
Transducer	0%	1/22/20	1/29/20
Bosch Rails	0%	1/22/20	1/29/20
Pneumatics	0%	1/22/20	1/29/20
Electronics	0%	2/19/20	2/26/20
Assembly			
Bonding Assembly	0%	2/3/20	2/10/20
Force Assembly	0%	2/5/20	2/28/20
Frame	0%	2/12/20	3/6/20
Stage	0%	2/19/20	3/13/20
Connect Electronics	0%	3/11/20	4/1/20

Figure 17: Winter Timeline



Ultrasonic Ribbon Bonder

Miguel Asturias, Tioga Benner, Brandon van Gogh
MECH 194 Group 9

Mon, 3/30/2020

1

TASK	PROGRESS	START	END
Thesis Assignments			
Introduction	70%	4/1/20	4/8/20
Thesis Draft	15%	4/1/20	5/11/20
Business Plan	10%	4/20/20	5/18/20
Presentation	20%	5/1/20	5/18/20
Thesis Report	0%	5/15/20	6/10/20
Project			
Determine New Goals	40%	3/30/20	4/13/20
Analysis Research	0%	4/1/20	5/15/20
Contact K&S and Branson	0%	4/6/20	4/10/20
Plan Third Party Assembly	0%	4/6/20	4/24/20

Figure 18: Spring Timeline

2.6.3 Safety Report - Risks and mitigations

One of the largest safety concerns for this project was the actual vibration of the transducer and bonding tool. The team's ultrasonic bonder uses frequencies of 60kHz to induce bonding. The bonder has a vibration amplitude of only 4 micrometers but with the rapid vibration it could still be problematic for anything in its path. Beyond that, any strong axial force would break the transducer making the machine unable to operate making it imperative that nothing blocks the transducer. This issue was mitigated by the frame that provides a barrier around the bonding platform making it difficult to access the bonding area while a bond is being formed. All of the control systems are also located away from that section so that there is very little reason for anyone to have their hands present in the bonding area when the machine is active. Furthermore, the pneumatic cylinders raise the carriage when the bond is not being formed, allowing for easy access to the bonding stage only when placing new metals, decreasing the risk of hitting the transducer and breaking it.

Providing power to the bonder also created a safety concern. This ultrasonic bonder uses 100V and 1A to provide the power to the piezoelectric transducer to induce bonding. Precautions were taken to ensure that there was no chance of wires becoming disconnected and potentially causing harm. There is also an easily accessible shutoff switch to turn the entire machine off should any problems occur.

The last consideration was unexpected but also easily remedied. K&S informed the team that another safety consideration of ultrasonic bonding is a noise concern. The rapid vibration of the transducer creates subsonic noise that can potentially damage the hearing of those exposed to it. Thankfully, this noise can be very easily prevented from causing harm with simple ear plugs and so earplugs will be used and required for any operation of the ultrasonic bonder.

3. Subsystem Designs

3.1 Frame

The frame subsystem of the ultrasonic bonder is required to firmly hold together the different components that perform the bonding tasks. Nevertheless, additional requirements from the customer would add to the complexity of this design. The frame is responsible for maintaining the integrity of the ultrasonic bonder while assisting its functionality. The customers specified that the device should be easily repairable/improvable for future use. This way, the device could be updated according to the different needs a research team would have. Additionally, the device is required to occupy a small space so that it can be integrated into the Materials Lab at Santa Clara University. By taking these factors into account, the following design was implemented.

The Ultrasonic Bonder frame is designed as a cuboidal metallic cage made from T-Sided Bosch Rails with a 1x1 inch cross sectional area. When composing the specific geometry of the subsystem, the team worked to optimize the ability to perform ultrasonic bonding while maintaining an effective size. In its design, the frame would have three functions to aid in ultrasonic bonding. First, it would have to contain the rest of the subsystems and firmly withstand any vibrational or normal forces. Second, it would contain the stage and instrumentation devices necessary for in-situ analysis. Finally, it would be required to lift the bonding tool with a rail-cage system and apply forces using pneumatic actuators. Consequently, the frame was designed around the following 3 subsystems: the bonding stage, bonding tool, and normal force generator (pneumatics). The final frame design is portrayed in Figure 21.

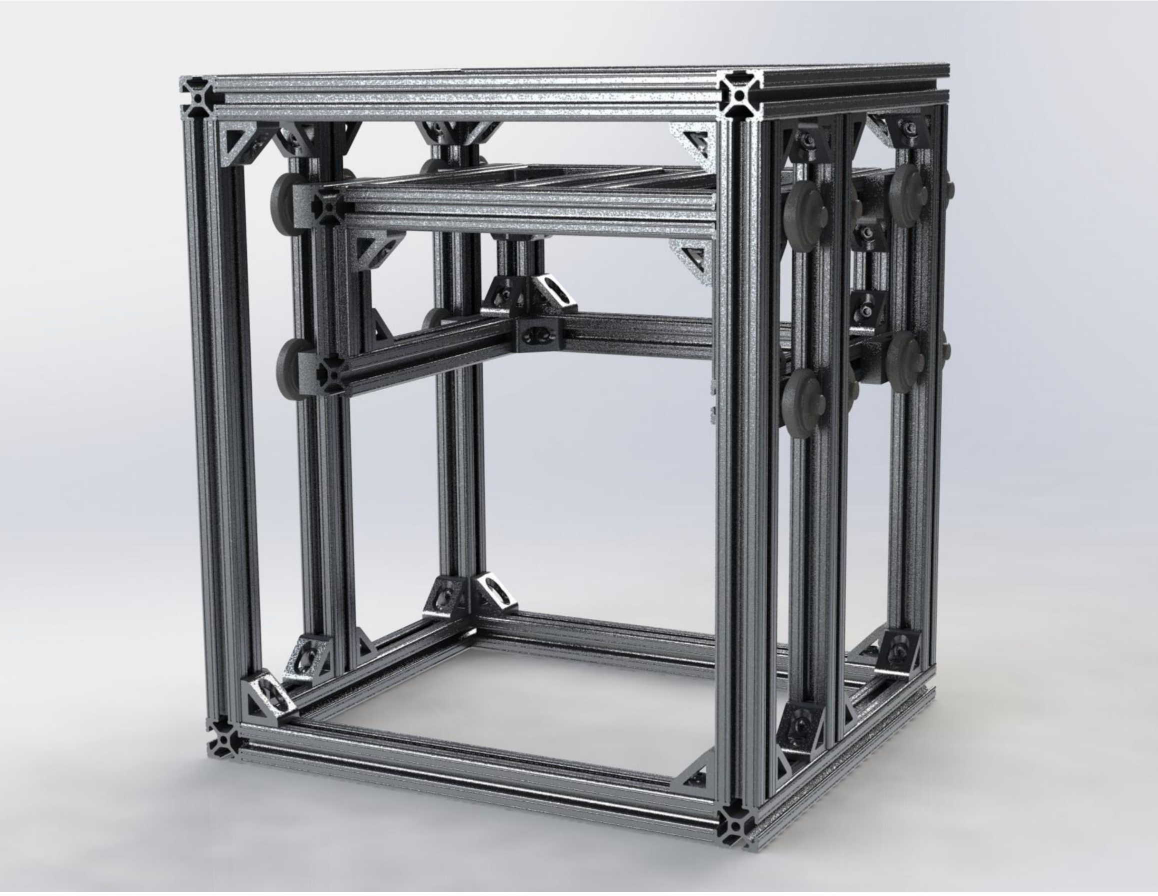


Figure 19: Solidworks Render of the Frame Subsystem

Thus, the construction of the frame is composed of several bosch rails of different lengths connected with corner gussets. The assembly was carefully implemented so that the bonding tool cage would smoothly roll using the truck roller carriages. As a result, the frame works in tandem with the different subsystems to deliver a process that can create aluminum bonds using ultrasonic vibration.

3.2 Bonding Platform

To effectively design a bonding platform for the ultrasonic bonder, the team had to consider the specific research-based approach of this investigation. A simple implementation of a bonding stage includes components that hold the raw material in place to ensure proper bonding. This design had two parameters that increased the complexity of the design. First, the stage had to include a transparent bonding platform in order to properly analyze the bonding process and study its parameters. Second, there had to be enough space around the bonding stage to include Phase II instrumentation and a high-speed camera for in-situ analysis of the bond. As a result, the bonding stage development was symbiotically produced with the design of the ultrasonic frame by utilizing the T-sided bosch rails with an acrylic stage at the top. While this design is not overly complicated, it does perform the necessary requirements for the design. Additionally, the design is simple enough to be easily repairable or to apply changes for the future needs of the device. The final design of the bonding platform is illustrated in Figure 22.

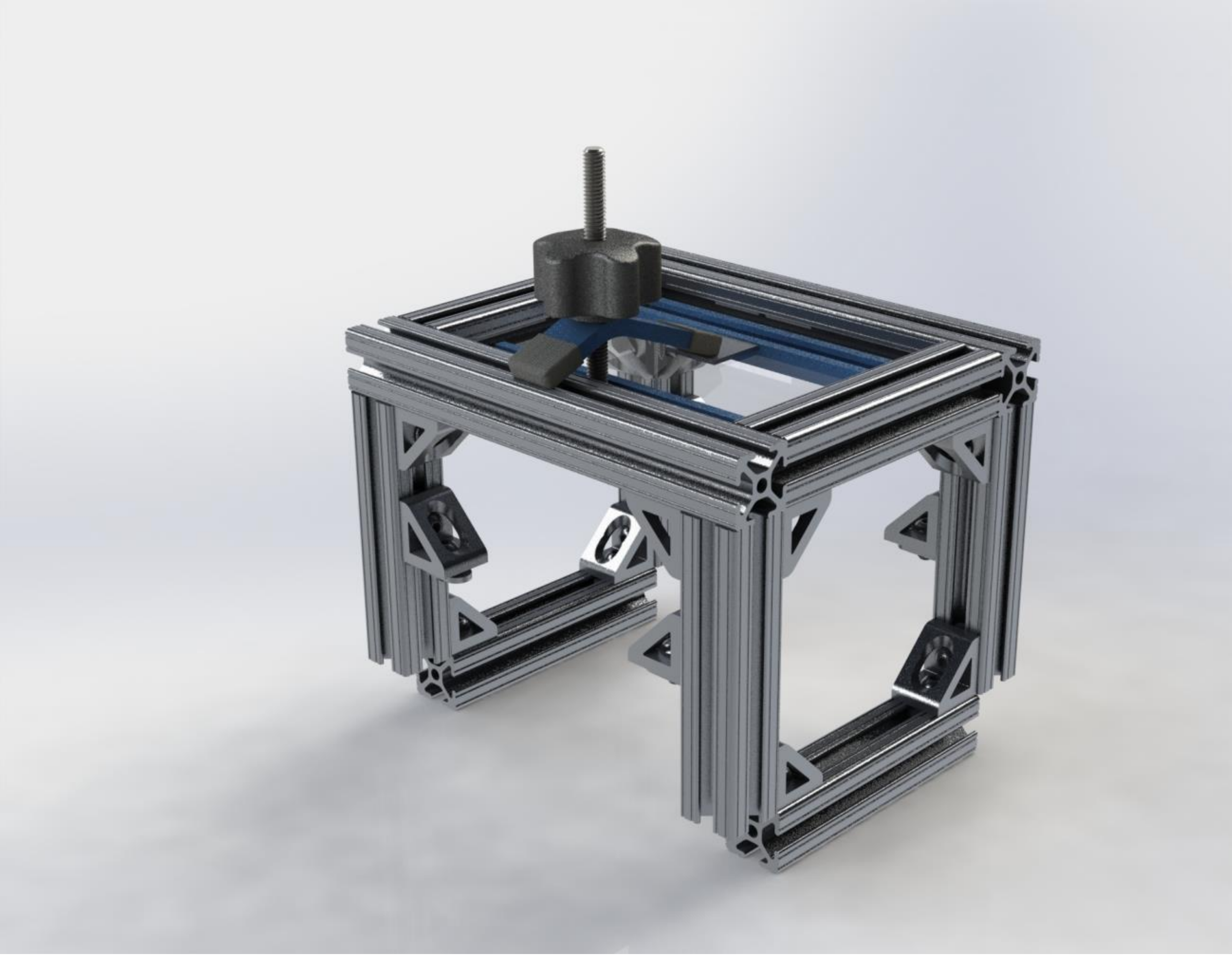


Figure 20: Solidworks Render of the Bonding Stage Subsystem

Additionally, a simple screw fitting was included in the design to hold the bond in place. This would ensure that while ultrasonic vibration is taking place, the raw material will not experience extreme displacements. This fixture is both essential to the safety of the device and the functionality of creating a bond using ultrasonic vibration.

3.3 Bonding Tool

An essential component to the ultrasonic bonder design is the bonding tool and its mount. To successfully bond aluminum to aluminum utilizing ultrasonic forces a mechanism to provide the necessary vibration is required. Initially, an electric signal is generated and sent to a piezoelectric transducer that transfers the signal to a mechanical output. The transducer is capable of generating an initial ultrasonic resonance that is later amplified by a booster and horn system that provides the necessary kHz frequency to soften the oxide layer. These frequencies are applied in a concentrated manner to the raw material through a small bonding tool that is specific to the type of bond desired. To properly implement this procedure, a carriage system had to be designed to firmly hold these components while they are vibrating at frequencies of 40 to 60 kHz. Additionally, it was necessary that this carriage system be light enough so that the pneumatic system could properly apply the bonding force to join the two materials together.

There were several delays when implementing the construction of the bonding tool especially regarding the acquisition of the booster, horn, and transducer. Once these parts were finally acquired through a generous donation by K&S Ultrasonics, the team was capable of using the geometric parameters to design the carriage and holder. The final design for the bonding tool and its holder can be seen in Figure 23.

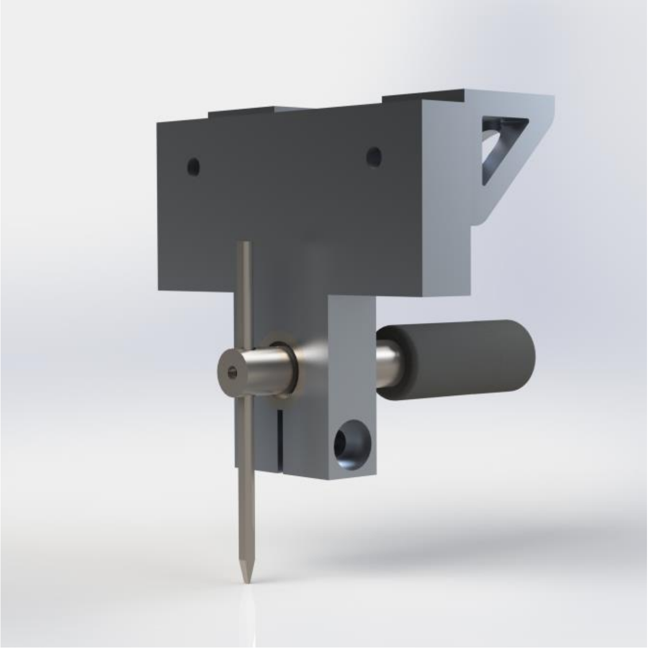


Figure 21: Solidworks Render of the Bonding Tool Subsystem

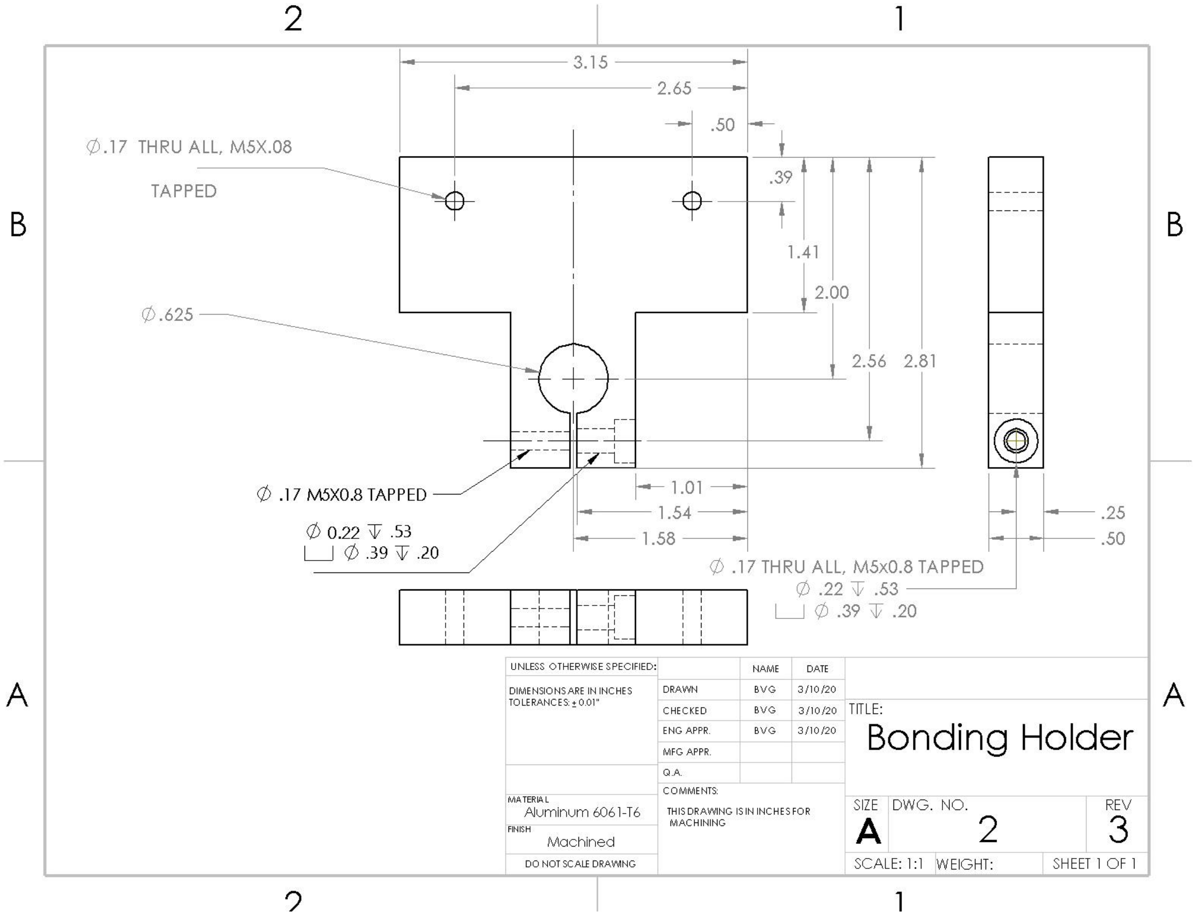


Figure 22: Updated Horn Holder Design

The horn holder design is shown in Figure 24. The original design for the horn holder also utilized a similar surface contact mount where a set screw elastically bends two cantilever members together. This increases the normal force on the mounting surface, thus keeping the component in place. Another iteration of this mount used 3 set screws to make contact with the transducer. After consulting with our industrial advisor and the machinist manufacturing the part, we changed back to a surface contact mount.

Also, in the original design the transducer was mounted in 2 places, but now it will only be mounted in one spot. This was also recommended by our industrial advisor, and it is acceptable because the force the pneumatics will be applying is 10 N.

3.4 Normal Force Generator (Pneumatics)

A pneumatic system was chosen to generate the 10N normal force to be transferred from the bonding tool to the ribbon. It was chosen because it is easy to keep track of the magnitude of the force compared to other options such as a motor and lead screw explored during the concept selection phase. Using pneumatics does sacrifice on the ability to control the displacement of the carriage with accuracy. It was later discovered after purchasing the pneumatics that a voice coil actuator [21] may be the best option to apply the force. Nonetheless, the pneumatics were chosen either to keep the overall design as simple as possible.

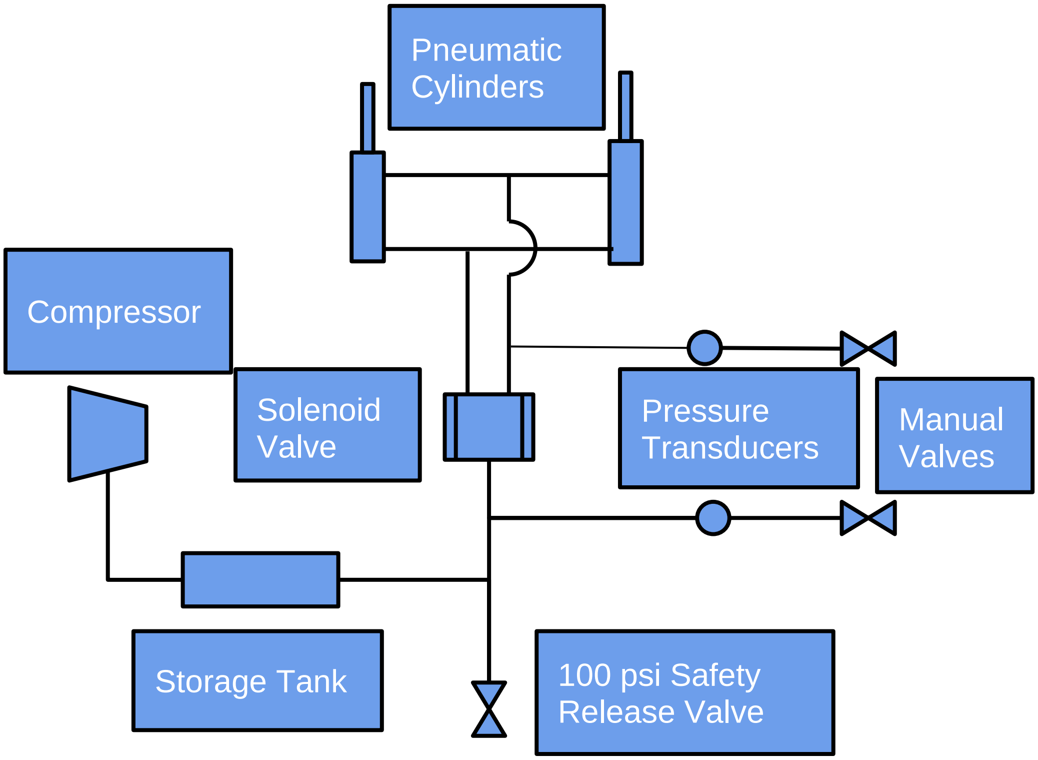


Figure 23: Pneumatics Circuit

Figure 24: Solidworks Render of the Pneumatics Subsystem

The normal force generator (pneumatics) subsystem is fully depicted in Figure 25 and Figure 26. It consists of the following

- 2 ¾" bore pneumatic cylinders in parallel
- Pneumatics mount
- 1 solenoid valve, 1 100 psi safety release valve, and 2 manual release valves
- 2 pressure transducers
- 574 mL storage tank
- Compressor

There are 2 pressure transducers and release valves on either side of the solenoid valve for safety reasons. Also, the 100 psi safety valve acts to limit the pressure to the storage tank, which can only hold up to 125 psi.

The pneumatics mount is a ½ plate that connects the piston rods of the pneumatics to the carriage. The only new addition to this part are the 6 holes closest to the center line. These new holes serve to secure the t-slot rail that the bonding subsystem is mounting to. This part was machined and is also shown in Figure 27.

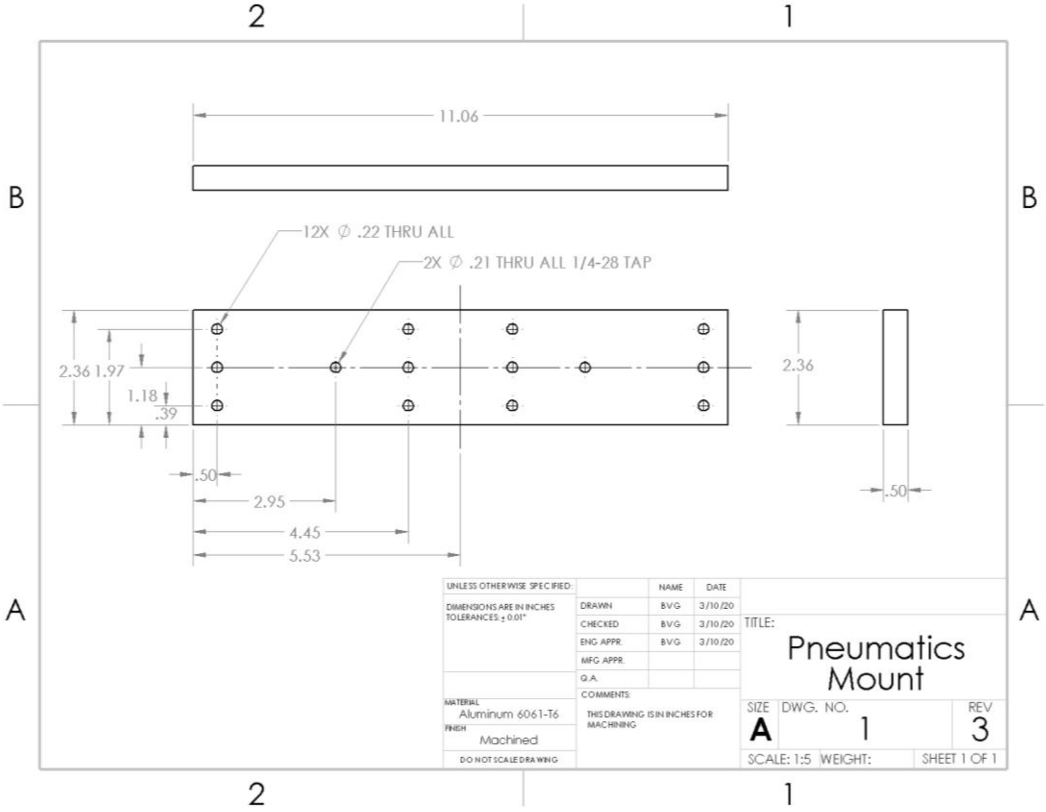


Figure 25: Updated Pneumatics Mount Design and Machined Component

3.4.1 Estimations of Required Pressure

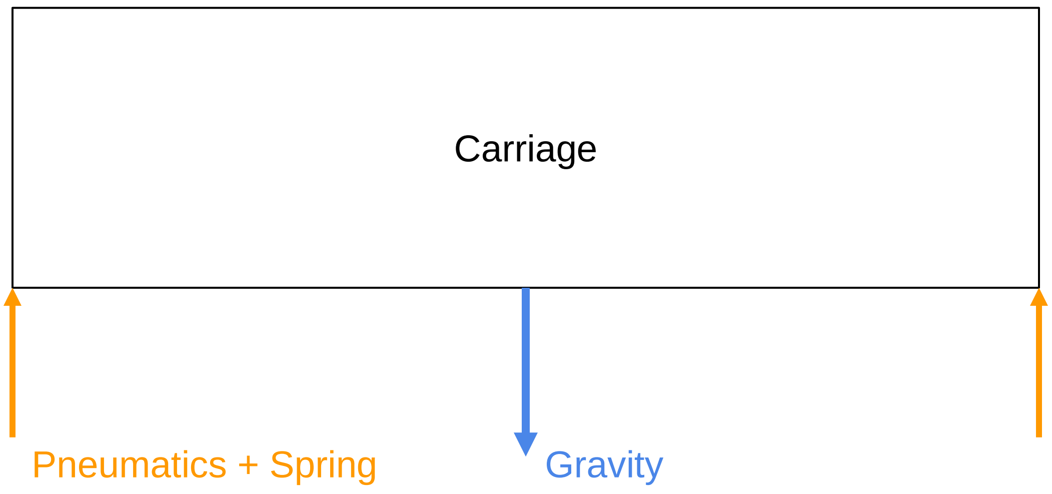


Figure 26: Forces on the carriage

The ultrasonic bond requires a net force of 10N from the carriage to the substrate. There are three forces acting on the carriage: the forces due to the springs in the pneumatic cylinders, the pneumatics air pressure force, and the weight of the carriage (Figure 28). Based on a rudimentary test, the springs exert 20 lbs after being compressed 4 cm which means the springs in the pneumatics have a spring constant of about 500 N/m. The carriage is about 2.2 kg. Based on all this information, the pneumatics together must push down with at most 60 N of force, which correlates to about 14.5 PSI.

The storage tank will need to be pressurized to a larger pressure. This is because when the solenoid opens, there is more volume for the air. The storage tank has a volume of 574 mL and the volume of the storage tank and the pneumatics is 613 mL. Based on the ideal gas law, the storage tank must be pressurized to about 15.5 PSI. This theoretically will result in a pressure of 14.5 PSI in the pneumatic cylinders. All details of these hand calculations can be found in the Appendix D.

In practice the pressure to cause the pneumatics to move is much larger. Further testing will need to be performed to accurately apply 10 N with the carriage to the bond.

3.5 Electronics

The electronics are responsible for generating the ultrasonic signal, sending the ultrasonic signal through the transducer, monitoring the voltage across the transducer, and controlling the pneumatics. Rather than manufacture a custom printed circuit board, it was decided to create a functional circuit using the equipment listed in Table 10. The function generator, oscilloscope, and amplifier are used to generate the correct signal and monitor the voltages, while the Arduino uno is used to control solenoid valves in the pneumatics.

Table 10 - Components of the Electronics Subsystem

#	Item	Manufacturer	Model
1	Oscilloscope	BK Precision	2120B
2	Function Generator	Agilent Technologies	33210A
3	Amplifier	Burleigh	PZ-150M
4	Arduino Uno	Agilent Technologies	E3630A

4. System Implementation

4.1 Final Product Specifications

The large-scale design of the project actually changed very little throughout the project. The actual method and general form of the ultrasonic bonder was left essentially unchanged. That being said, some of the specifics were quite different between the final product and the original intention. Due to Covid-19 the team was not able to actually create a finished bonder, however enough of the project was completed that the team has a very strong idea of the exact specifications of the final product. These values are shown below in Table 11 and are followed by small descriptions of the reasons for any differences between these values and the original design ideal values.

Table 11 - Current Specifications

#	Relative need #s (found in table 3)	metric	units	Current Value
1	1,12	Footprint of Device	m^2	0.1
2	1,2,9	Workspace Volume	cm^3	1700
3	8,9	Bonding Area	mm^2	0.55
4	1,17	Weight	kg	12
5	10	Price	$	3,000
6	5	Frequency	kHz	60
7	7,15,16	Number of observations	No.	4
8	2,11	Number of subsystems	No.	5
9	3,4,5,6	Number of Control Parameters	No.	4
10	11,13	Ease of Use	subj. (1-5)	2
11	11,15,16	Number of materials	No.	1
12	11	Number of bond heads	No.	1
13	13,14	Time to set up	min	15
14	2	Easy to repair	subj. (1-5)	2
15	13,14	Automated Process	subj. (1-5)	1

- Footprint of device - the design was made more compact to make it easier to move
- Workspace volume - the bonding Stage was made larger to give users more room to move
- Bonding Area - the bonding tool came with the transducer and is designed for smaller ribbon wires
- Weight - the design was made more compact to make it easier to move
- Price - The bonding tool and transducer are valued at $1,500. However, we used cheap T-rail connectors, which kept the price below $5,000
- Frequency - only one transducer made for aluminum bonding at 60kHz is installed
- Number of Observations - current, voltage, frequency, and pressure
- Subsystems - frame, electronics, pneumatics, bonding, stage
- Control Parameters - current, voltage frequency, and pressure
- Ease of use - timing constraints led to a much less developed control system for the various parameters, everything currently needs to be controlled separately
- Number of Materials - only one transducer made for aluminum bonding is installed
- Number of Bondheads - Only one transducer made for aluminum bonding is installed.
- Time to set up - The compressor is very large and will not take as long to pressurize the storage tanks. Also, the electronics will always be connected.
- Easy to repair - T-rail connectors were much harder to assemble and reassemble than expected
- Automated process - no automation was added to simplify the design

4.2 Timeline and Budget Changes

The timeline and budget requirements of the project also changed during the project implementation. The overall goal of the project remained consistent throughout the project but exactly when each part would be finished changed significantly throughout the project. One of the largest issues with the project was with budget constraints due to less funding from SCU than desired as well as more expensive requirements than expected for the ultrasonic horn and transducer.

The team's original budget called for $2,200, $700 of which was due to the horn and transducer but unfortunately Santa Clara University was only able to give $1,500 forcing the team to take a closer look at how costs could be reduced. This problem was further exacerbated later in the project when the team contacted Branson Ultrasonics, a company specializing in selling parts for ultrasonic bonders. The team was hoping to be able to use a cheap version of the ultrasonic horn for the bonder, this was an incredibly important part of the project and unfortunately not one that the team could make on their own, thus requiring a significant cost investment. Even the cheaper versions that the team were hoping to use cost around $700, only slightly less than half of the overall project budget. Unfortunately, a consultation with Branson revealed that for the desired purposes of bonding aluminum to silica or aluminum, it would be necessary to buy a more expensive horn that would cost around $1,500, most of the team's budget.

The team spent much of the winter quarter trying to find another option, specifically trying to get a company to donate or lend the team an ultrasonic horn and transducer. Thankfully one of the team advisors, Professor Sepehrband, had contacts in K&S and they were willing to donate a horn to us bringing the budget down to a reasonable level. This was incredibly helpful and allowed the team to once again reduce their budget to acceptable levels, unfortunately this meant that the actual timeline of building the bonder had to be pushed much later than originally intended. Rather than having most of winter quarter to build the bonder the actual construction was pushed to the last few weeks of the winter quarter. The team wanted to make sure that the bonder was finished early in spring quarter as it was believed that many adjustments would need to be made for the machine to create a strong ultrasonic bond. This required a significant amount of time investment on the project in a short span of time but the team was able to do a significant amount of work and it was believed that the project would be completed within the desired time frame but unfortunately this was done right before COVID-19 forced the closure of the SCU campus.

4.3 Issues Related to Covid-19

By the time that COVID-19 forced SCU to close the team was quite far along in the project. All the subsystems, besides the bonding stage were completely done and all that was left to do was to assemble the sections together and create the electronic circuit. Shown in Figures 29-32 are images showing the frame, bonding platform, some machined parts, and pneumatic system.

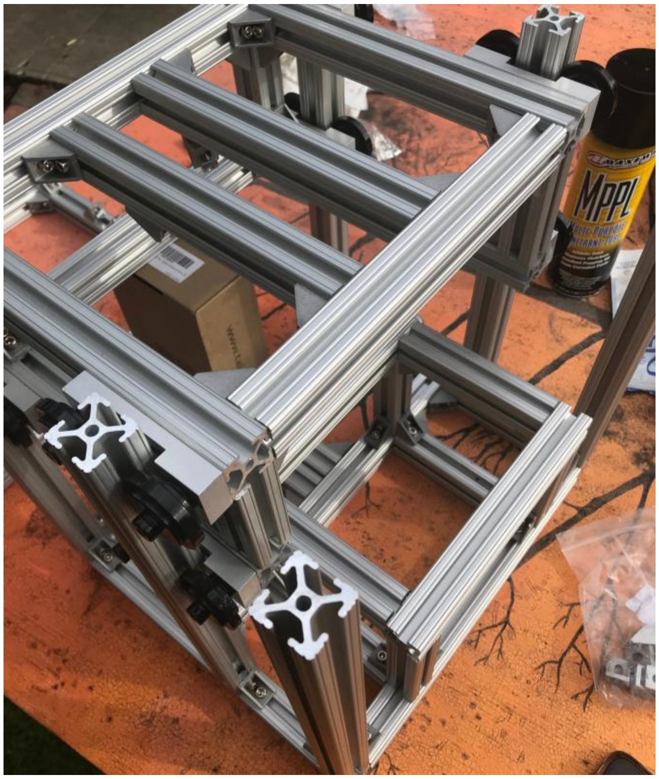


Figure 27: Ultrasonic Bonder Frame and Bond Platform

Figure 28: Ultrasonic Bonder Pneumatic System

Figure 29: Updated Pneumatics Mount Design and Machined Component

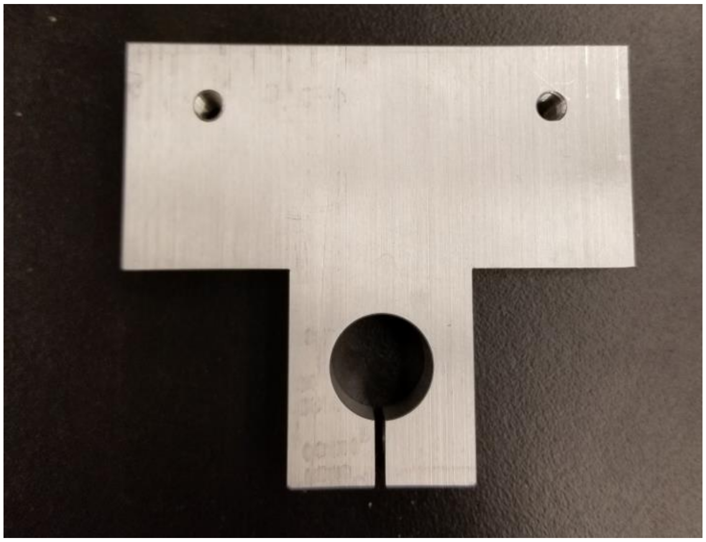


Figure 30: Updated Horn Holder Design

The original plan was to complete the electronics of the bonder and the bond tool subsystem during the last weeks of the quarter and then assemble everything together along with the bond stage during the first weeks of the spring quarter. With COVID-19 however, this became infeasible. When it was determined that school would not be resuming in the spring the team had to decide how they would proceed. The team did consider having one person build the rest of the bonder or perhaps getting some outside person to build the bonder with the team giving direction and advice as a way to potentially finish the actual physical project. Unfortunately with the earlier issues the team was not in a position where the bonder was almost done, significant work would still need to be done to get a functional project and some of that work would be very difficult for someone who was not knowledgeable about ultrasonic bonding. With this in mind the team decided to leave the physical project to a later group and decided to focus instead on detailed analysis modeling of ultrasonic bonding in general. This model is discussed in much greater detail below.

5. Modeling

The overall purpose of the analysis was to create a plot comparing the bonding tool amplitude with the tangential force on the bonding tool at different input powers. This was done to get a clearer sense of the actual movement of the tool during bonding as well as the required input power to produce desired outputs. Two models were combined in order to reach this goal, a piezoelectric model and an ultrasonic bonding model. The piezoelectric model was required as the actual ultrasonic bonder uses a piezoelectric transducer to create the desired forcing amplitude and frequency. The model used in this case was a lumped parameter model developed by Dr. Goldfarb and Dr. Celanovic that converts input current and voltage to velocity and position [22]. The other model was an experimental study done by Dr. Mayer and Dr. Schwizer, et al. on ultrasonic ball bonding [23]. While the team's bonder is a ribbon bonder the general formulas derived from Mayer's experiments should still be valid for our case. Mayer's work centered on the kinetics and force of the bonding tool and platform while the ultrasonic bond was being formed. Combining these two research papers together and substituting constants relevant to this project lead to a complete model comparing electronic input power to actual amplitude and forcing of the bonding tool as an ultrasonic bond is being formed.

5.1 Developing the Model

5.1.1 ElectroMechanical Model for the Transducer

A simplified model was first formulated based on previous work to help us understand the physical processes happening during bonding [22, 23]. Based on experimental evidence [22], it is acceptable to model a piezoelectric element below the first fundamental frequency based on the circuit shown in Figure 33 and mechanical diagram in Figure 34 based on Ref. [22].

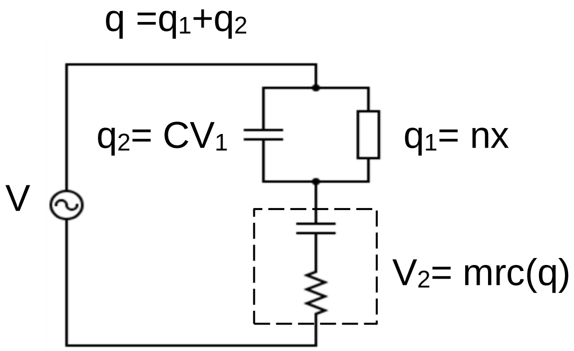


Figure 31: Circuit Diagram based on Ref. [22]

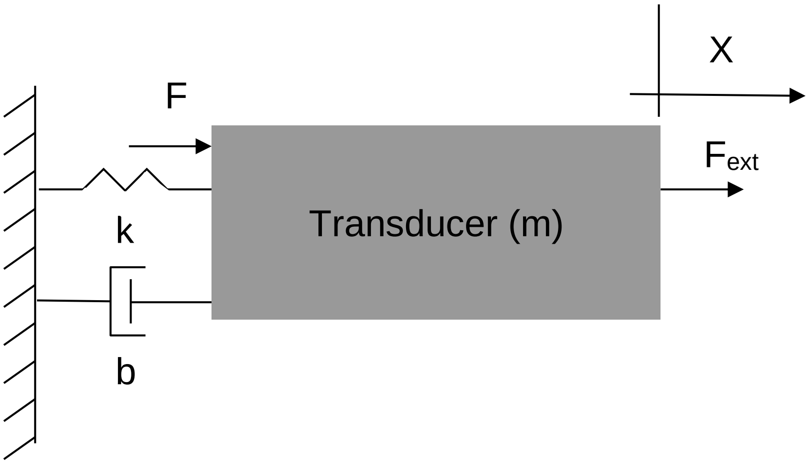


Figure 32: Mechanical Diagram based on Ref. [22]

The corresponding equations are

$$mx'' + bx' + kx = F + F_{ext} \tag{1}$$

$$F = nV \tag{2}$$

$$V_1 = V + V_2 \tag{3}$$

$$q = nx + CV_1 \tag{4}$$

$$V_2 = mrc(q) \tag{5}$$

where *n* is the electro-mechanical transformation ratio and F is the force of the piezoelectric transducer (PZT), V is the voltage, x is the displacement of the piezeoelectric element, q is the charge across the piezoelectric element, and F_{ext} is the external force on the piezo. The element in the dashed box considers the hysteresis behavior of a piezoelectric element. In addition, the PZT is modeled with capacitance. This is because a piezo stack is made by stacking the piezoelectric material, which is a dielectric, between electrode plates [22].

Hysteresis was ignored for this analysis to simplify the model and also as the actual hysteresis equation present in the team's system was unknown. This allows for the *mrc()* element to be removed, leaving equations 1, 2 and 4. It also causes the applied voltage to just be the voltage across the mechanical coupling element. This simplified model is depicted in Figure 35.

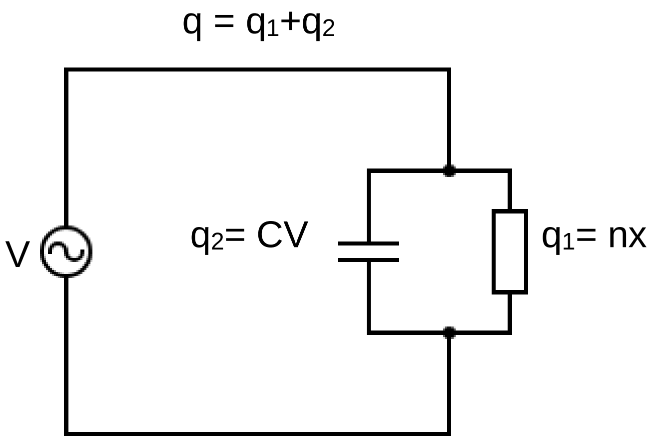


Figure 33: Simplified Circuit Diagram

$$V = V_o sin(\omega t) \tag{6}$$

$$F = nV \tag{7}$$

$$I = nx' + CV' \tag{8}$$

Where ω is the angular frequency of the AC source and V_o is the voltage amplitude. In this case $\omega = 2\pi 60{,}000$. In an actual case, the external force would be the transverse force due to friction and shear at the bonded interface.

5.1.2 Bond Growth and Transverse Force Model

The transverse force model diagram can be found in Figure 36 with descriptions for some of the variables given in Table 12. The transverse force is a combination of the frictional force at the ribbon-substrate interface and the shear force due to the bonded areas. A model explaining the relationship and describing the process was created by Mayer, et al. [23]

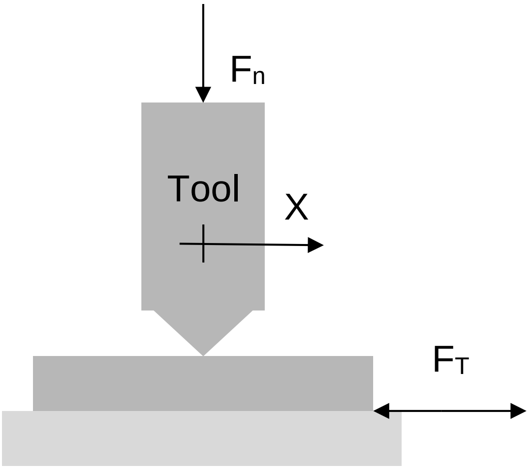


Figure 34: Transverse Force Model

$$S_{bonded} = \gamma(t)S \tag{9}$$

$$F_T(t) = [1-\gamma(t)]\mu F_n + \gamma(t)\sigma S \tag{10}$$

$$dS_{bonded} = \beta dE \tag{11}$$

This model assumes that the bonded area grows only with the energy that is supplied through the energy at the interface. The model also splits up the transverse force into a continuous and well-behaved function, which may not actually be the case [23].

Table 12 - Variables for transversal force model

Variable	Description
S	area of the interface
γ	ratio of the bonded area and the unbonded area
F_n	Normal force
μ	coefficient of friction
E	Energy at interface
β	Bond growth coefficient
σ	Shear yield stress of the bond

Based on experimental evidence in Ref. [23], it is shown that amplitude seen by the wire A_{rel} is a function of the free air amplitude, A_0, and the transversal force, F_T

$$A_{rel}(t) \;=\; A_o - cF_T(t) \tag{12}$$

Where v is the tool compliance. This free air amplitude is found from the free air response, or the response without any external force. The power can also be found based on the units of power. The entire function is multiplied by four to reflect the total movement after 1 cycle.

$$P(t) \;=\; 4A_{rel}(t)fF_T(t) \tag{13}$$

Where $A_{rel}(t)$ is the relative amplitude between the ribbon and substrate and f is the frequency. The authors of the paper assume only the friction power of the unbonded areas affect the bond growth to simplify the calculation so the $[1-\gamma(t)]$ factor is added [23].

$$P_{unbonded} \;=\; 4f[1-\gamma(t)][A_o - cF_T(t)]\mu F_n \tag{14}$$

Where $\gamma(t)$ is the bond growth ratio μ is the coefficient of friction, and F_n is the normal force. Putting everything together gives a differential equation for the bond growth ratio

$$\frac{d\gamma}{dt} = \frac{\beta 4f\mu F_n}{S}[1-\gamma(t)]][A_o - cF_T(t)] \tag{15}$$

The solution of this model presented in [23] lists two main conditions for using this model. The first, and already stated assumption, is that only friction power contributes to bond growth. Because this is the case, there should be a monomeric increase in the bond growth ratio, or in other word $\frac{d\gamma}{dt}$should always be greater than 0. This is not a fully realistic assumption as bonds may break and reform as the bonding is happening. Another condition is that when $Ao>cF_T(t)$, $A_{rel}(t)$ is set to be zero. This just means that when the bond completely forms there will be no relative amplitude between the ribbon and substrate [23]. When applying our model, this condition was not implemented because our model only looked at times such that $A_o<cF_T(t)$.

5.1.3 Linking the Two Models

The link between this model and the electromechanical model is through the free air amplitude A_o in equation (15) and the external force F_{ext} in equation (1). First, to find A_o equation (1) must be solved with F_{ext} set to zero. This equation can be analytically solved if the lumped constants are known. The constants used for solution of equation (1) and the coupled system equations (1) with (15) are taken from various papers and are described in Table 13. The linked model is depicted in Figure 37.

Table 13 - Constants used in model

m	0.00375 kg [23]	c	1.33 μm/N [22]
b	150 Ns/m [23]	S	207.5 mm^2 [22]
k	N/m [23]	F_n	0.15 [22]
n	10 [23]	μ	0.48 [22]
C	1.2 μF [23]	f	60,000 Hz
σ	125 Mpa [22]	β	55 $\mu m^2/J$ [22]

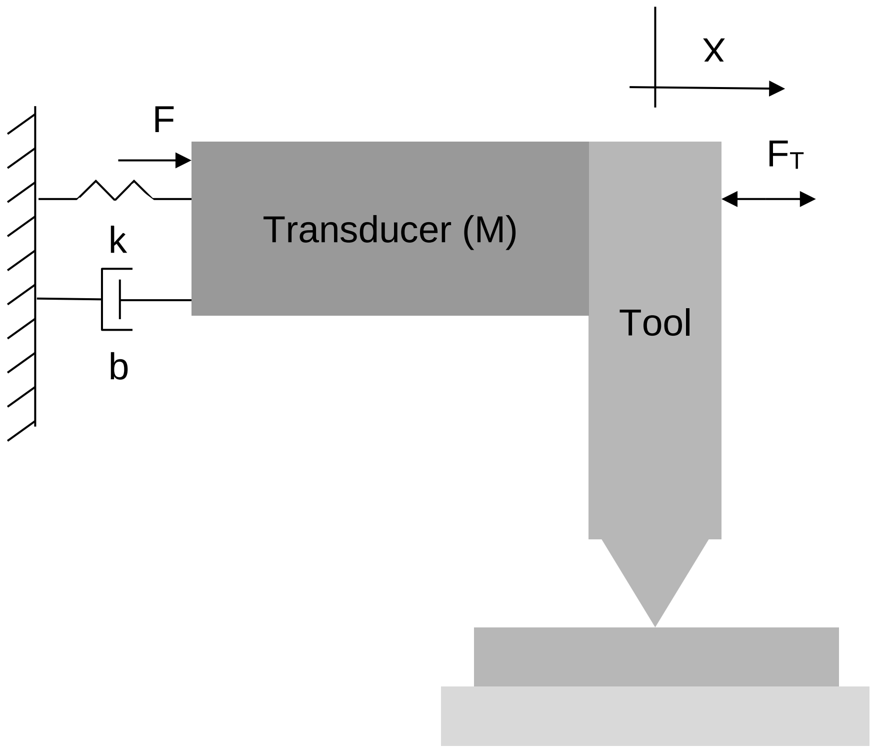


Figure 35: Linked Model Diagram

With these constants the response will be an underdamped. The solution of equation (1) with $x(0) \;=\; 0, x'(0) \;=\; 0$ when F_{ext} is zero is given by equations (16)-(18).

$$x(t) \;= e^{-\zeta\omega_n}[\,Asin(\omega_d t) + Bcos(\omega_d t)] + C_0 cos(\omega t) + C_1 sin(\omega t) \qquad (16)$$

$$C_0 = \frac{-b\omega_n V_o}{(k-\omega^2 m)^2+(b\omega)^2}\; C_1 = \frac{(k-\omega^2 m)nV_0}{(k-\omega^2 m)^2+(b\omega)^2} \qquad (17)$$

$$A = \frac{C_1 w - \zeta\omega_n C_0}{\omega_d}\; B = -C_0 \qquad (18)$$

Where ζ is the damping ratio, ω_n is the natural frequency, $\omega_d$is the damped natural frequency. The A_0 based on equation 16 can be estimated as the steady state amplitude or an amplitude depending on the exponential decay. This estimation is verified in Figure 38.

$$A_{0,ss} = \sqrt{{C_0}^2 + {C_1}^2}\;\; \text{(steady state)}\; A_0(t) \;\approx\; \sqrt{{C_0}^2 + {C_1}^2}\;\; (1 - e^{-\zeta\omega_n}) \qquad (19)$$

The solution for the free air vibration can be found for different voltage amplitudes/ powers. The power applied to the transducer can be calculated using equation (20).

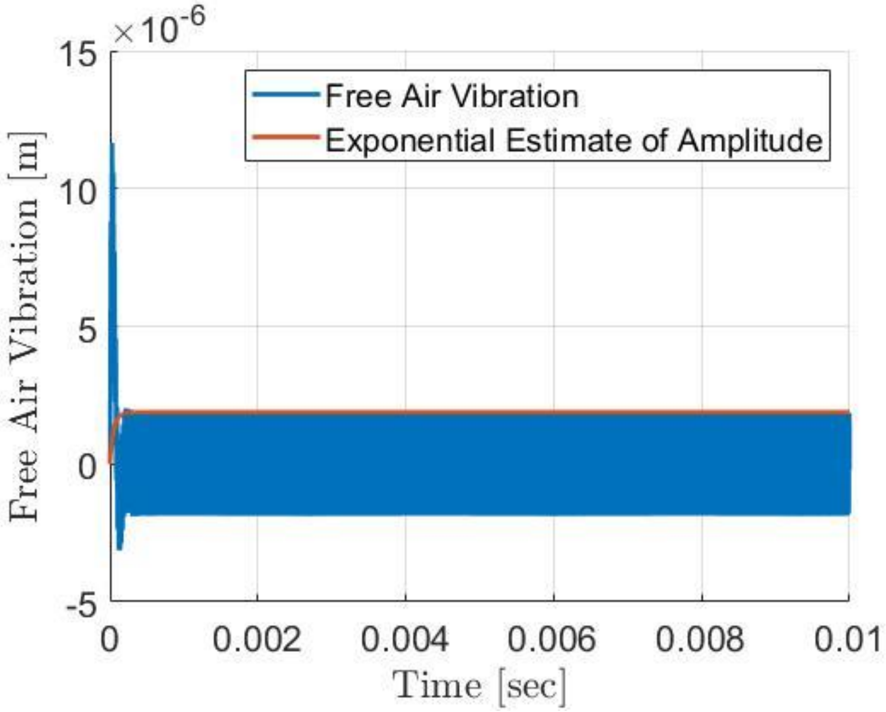


Figure 36: Exponential estimation of how free air amplitude changes with time

$$P \ = I_{rms} V_{1\,rms} \tag{20}$$

The complete model equation combining equation (1) and (15) is coupled by $F_{ext} = F_T$. This means that we are assuming there is no relative motion between the tool and the ribbon. These equations written as a system of first order ODEs as given by equations (21)-(23)

$$y_1{}' \ = \ y_2 \tag{21}$$

$$y_2{}' \ = \ -k/m \, y_1 - b/m \, y_2 + (\sigma S - \mu F_n) \, y_3 \ + \ \mu F_n/m \ + \ nV_0/m \, sin(\omega t) \tag{22}$$

$$y_3{}' == \frac{\beta 4 f \mu F_n}{S} [1 - y_3][A_o - cF_T(y_3)] \tag{23}$$

Either expression of A_0 can be used in equation (21) to solve these coupled first order ODEs. The boundary conditions for this model are $y_1(0) = 0$, $y_2(0) = 0$, and $y_3(0) = 0$. In addition, if $A_o - cF_T(y_3) < 0$ then $A_o - cF_T(t)$ is replaced with zero [22]. This condition is necessary because after the bond forms, there is no relative amplitude between the ribbon and the substrate.

5.2 Results

Using Matlab, equations (21)-(23) were solved numerically for 5 different voltage/power levels (80, 90, 100, 110, 120 V).

5.2.1 Transverse Force and Amplitude Curves for Different Powers

The results in Figure 39 and 40 show that the relative amplitude is linear with respect to the transverse force, which is consistent with equation 14. There are two important trends that can be seen. One is that as the power increases the relative amplitude increases. Since more energy is put into the transducer, it will produce larger forces, and thus produce larger amplitudes. The second is that as the transverse force increases the relative amplitude decreases. This is because the transverse force restricts the motion of the ribbon and the tool through friction and the shears strength of the bonds.

In Figure 39, with a changing amplitude the transverse force is almost constant for low relative amplitudes. This is because initially the bond does not grow very fast, which initially causes $\gamma(\mathrm{t})$ in equation 10 to be nearly zero. This means that the transverse force mostly comprises the friction force, which has a magnitude of 0.072 N.

After this initial rise the changing amplitude case reduces to the constant amplitude case. This is because the only difference between the changing amplitude and the constant amplitude is the initial exponential rise which occurs over a period of less than 1 ms.

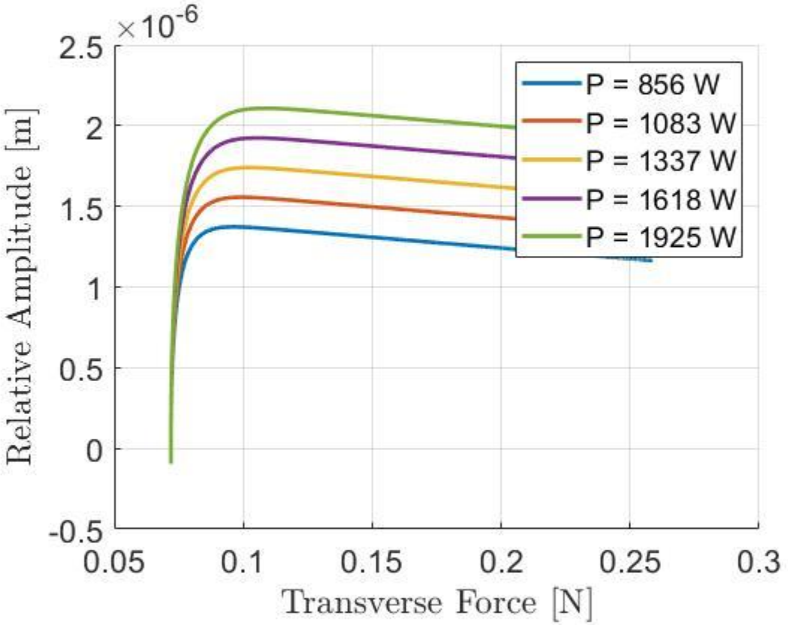


Figure 37: Transverse force and Relative Amplitude for different powers (80,90,100,110, 120 volt amplitude) with changing A0

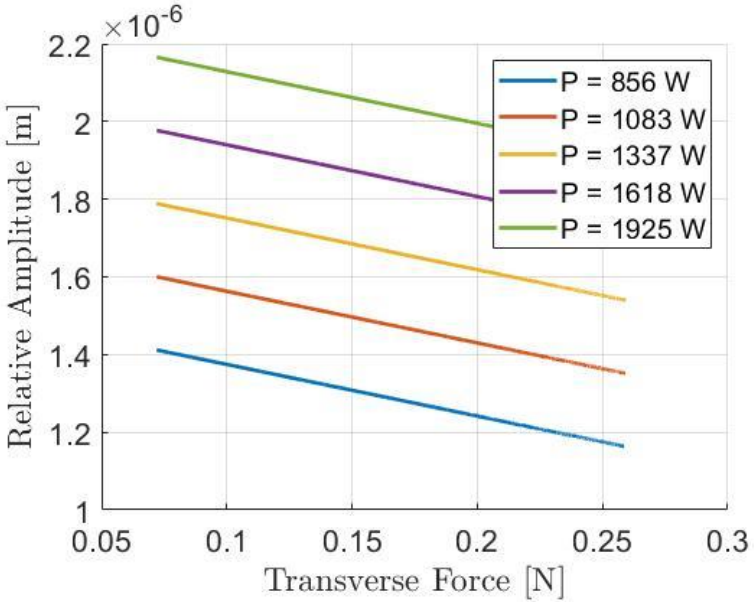


Figure 38: Transverse force and Relative Amplitude for different powers (80,90,100,110, 120 volt amplitude) with constant A0

In addition to the force-amplitude curves at different powers, other plots were created for the 100 V case, as this is the voltage our system will likely operate at. Figure 38 shows the accuracy of the estimated amplitude.

5.2.2 Bond Growth

From the solution to equations (21)-(23) the bond growth coefficient was found for both the changing and constant amplitude case. The results are shown in Figure 41. The bond growth ratio is always less than 1 [23]. This is expected since the bond that forms can never be larger than the initial interfacial area of the ribbon and substrate. Also, these Figures show that there is a monatomic increase in the bond growth, which confirms that these results are consistent with the conditions in [23].

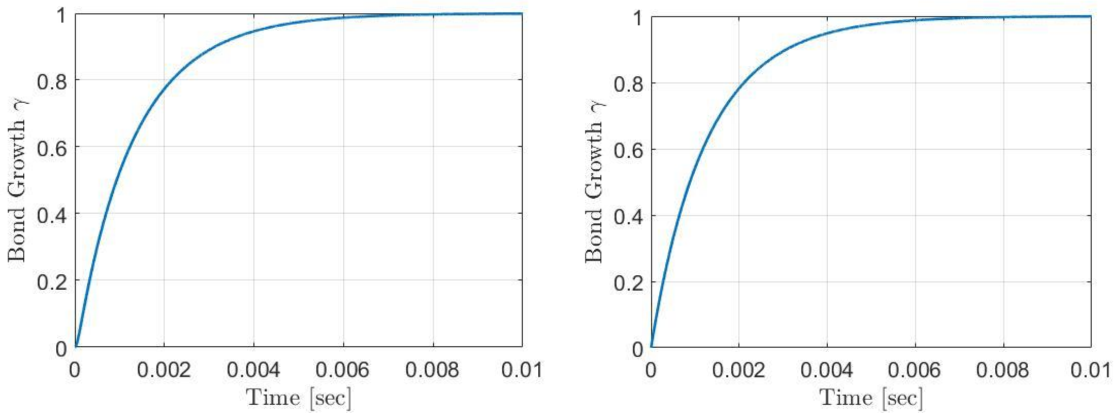


Figure 39: Bond Growth for Changing Amplitude (left) and constant amplitude (right) at 100 volts

5.2.3 Relative Amplitude

Based on Figure 42 the relative amplitude of the changing amplitude case reduces to the constant amplitude case after a short amount of time. The bond growth for the changing amplitude case does follow the expected trend of the relative amplitude [10].

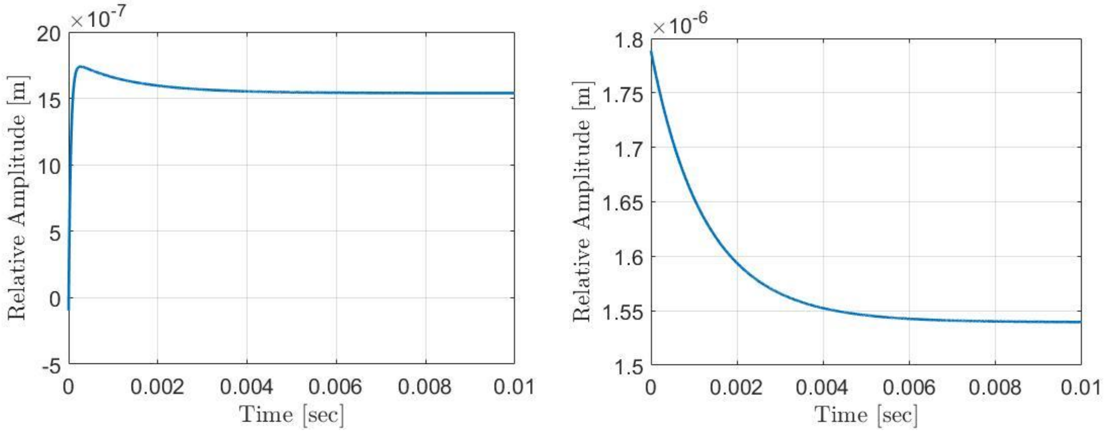


Figure 40: Relative Amplitude for Changing Amplitude (left) and Constant Amplitude (right) at 100 volts

5.2.4 Conclusion for Modeling and Analysis

This modeling and analysis involved a significant amount of research to determine exactly what approach would be best to pursue. Many different papers were analyzed before the team decided to use the two sources actually used for this analysis. It also required much more rigorous analysis of the papers in question to determine not just what the papers were doing but also how to translate that work to our system. This analysis demonstrated a simple linear relationship between tooltip amplitude and transverse force in the bond as it was being formed. It also demonstrated that increased input powers result in larger tooltip amplitudes but made no difference in the transverse force on the tooltip.

This deeper analysis also led the team to realize that the current ultrasonic bonder design may not work as expected. Specifically, the team now knows that a significant amount of control is required when applying normal force to the bond surface. The pneumatic system that was used for our design, while accurate, most likely will not give enough precision when applying the force leading to weaker and potentially ineffective bonds. A better, although more expensive design, would be to use a voice coil actuator, which would allow for much more precise application of force [21].

6. System Analysis

6.1 Business Plan

Currently ultrasonic bonding companies are focused on selling large scale ultrasonic bonders that allow for very rapid bonding and a significant amount of automation for use in assembly line type manufacturing for various semiconductor and electronics companies. In comparison, our team's ultrasonic bonder is much simpler and without automation. The benefit to this, however, is that our bonders could be made significantly cheaper than the large-scale bonders currently on the market and this is the niche that the proposed business would focus on.

6.1.1 Objective

Overall, the focus of our proposed business would be on cheap, simple but effective small scale ultrasonic bonders. This appears to be a market niche that is not currently being explored by any other companies and we believe it is a market where we could find significant success. The eventual goal would be to push into the large-scale ultrasonic bonders market as well but initially the company would focus on three major customer groups.

To reach this goal the team proposes to produce models similar to the current design created for researchers at Santa Clara University but with extra work done to ensure that the product is more customer friendly. The current design is very straightforward in terms of parts and construction, but its focus is solely on creating a machine that works rather than on aesthetics, size and ease of use. The first step of a future company would be to streamline this design while keeping the overall goal and functionality. It would be necessary to create some sort of casing to make the object more appealing to consumers and create a more robust control system for ease of use. This current design also has a significant amount of wasted space that could be removed for a smaller and more convenient product. More difficult to accomplish but very useful would be to allow for an easier mounting system for the actual bond components and a simple way to move the tool head or stage to allow for quick bonds to multiple places in the desired piece.

This machine would then be able to bond wires or ribbons onto the desired substrate with the press of a button. Unlike other bonders currently on the market it would require adjustment after each bond to ensure that the parts get to the correct position, but that will keep complexity and more importantly price. Exact pricing will be discussed later but with a very different focus as ultrasonic bonders currently on the market the team's bonder would be sold for significantly less, attracting a different market than current ultrasonic bonder companies.

6.1.2 Market

With this current plan of small-scale bonders, the team researched different areas where this type of cheap and simple ultrasonic bonder would be more useful than the high automation bonders currently on the market. Three markets have been identified and future advertising would be focused on these groups.

The first market are researchers analyzing the ultrasonic bonding process. For all its utility and fairly widespread use, the specifics of ultrasonic bonding are still not fully understood. Many researchers around the world are still working to better understand the specifics within the ultrasonic process both for simple scientific advancement but also to find the input parameters that directly affect the bond in order to optimize the bond strength or speed. These researchers may work for universities or in the research branch of companies. Regardless, these researchers simply do not need the automation present in ultrasonic bonders currently on the market and in many cases the extra complexity is almost certainly a hindrance rather than a product feature. These researchers need a simpler option without all of the unnecessary add ons that are required for large scale manufacturing and if this means a reduced price it is even better for the consumers.

The second group are small scale companies or companies that do not need to make that many ultrasonic bonds and don't need the rapid automation. This is a fairly broad category but generally speaking there are plenty of companies who need to use ultrasonic bonding for a small part of their product but don't require large scale automation and very rapid bonding. These companies can and do outsource this work and sometimes buy ultrasonic bonders that are much more expensive than required but this is where our proposed company would provide a solution. We would need to add basic automation to our ultrasonic bonder, but this could be done in a simple way that would still keep the price significantly lower than our competitors. This would allow the companies to keep their costs low and be able to do work in house while giving us a solid foothold in the electronics market.

The third market would be difficult but would essentially be hobbyists. With cheaper and cheaper costs for electronic components many people are becoming more and more interested in electronic based engineering hobbies. Currently these hobbyists are buying various semiconductors and small-scale electronics from various companies but if they could make their own semiconductor connections using ultrasonic bonding that could significantly improve the freedom available to them. It would allow hobbyists to create systems with no wasted space, memory, or cost, which would be very appealing to a significant proportion of the population. At the moment ultrasonic bonders are simply too expensive to allow this sort of use. Any benefit for a hobbyist from having more freedom is far outweighed by the initial cost of buying an ultrasonic bonder. But with our simple, non-automated design we could keep the price low enough to allow these hobbyists to very realistically purchase our products for the added freedom and control that it would give them.

6.1.3 Advertising

To properly compete in a niche market the team plans to adopt an effective marketing strategy to ensure that consumers have knowledge about this product. A small-scale research based ultrasonic bonder has such a specific purpose where the target consumer is a small group of research institutions that can benefit from the device. These institutions consist of universities with engineering facilities and laboratories that can extend the study of ultrasonic bonding. Additionally, they must have some interest in the extensive study of ultrasonic bonding in order to be attracted to purchasing the ultrasonic bonder. However, the team has also considered marketing the device to small scale corporations that do not need an industrial size ultrasonic bonder. Thus, with these considerations the team understood that an initial aggressive marketing strategy would greatly benefit the profit of selling a research intended ultrasonic bonder.

The team plans that by the time the bonders have been produced and developed in 3 months' time, an investment of $2000 a month in advertising and promotion can gather significant interest in the product. By travelling to institutions that have published previous research on ultrasonic bonding and pitching the superior instrumentation and flexibility of our device, this team hopes to gather significant interest in purchasing the device. The increase in interest can provide enough of a movement in the ultrasonic bonder market so that our company begins to compete with large ultrasonic bonder corporations. The target in this circumstance is to market our product to companies like K&S Ultrasonics or Hesse Technologies and sell the device to their consumers and split the cost of production and profits. Here, the costs of marketing and advertising will be reduced gradually from $1500 a month for 2 months until the cost is $800 a month in the tenth month of business. The investment in advertising will decrease because we believe natural advertisement will increase the more products are sold. Moreover, when working with a different company the cost of advertising can be split between the two companies.

Furthermore, as the company grows and more products are sold, the team believes that an increase in connections and business will help us lower the cost of production. By accessing bulk deals and getting a greater sense for the demand of the device, we can lower its cost and spend more money on accessing our third market. The increase in knowledge about ultrasonic bonding will attract greater interest from hobbyists. Our company would then look to take a separate approach to market the product for these individuals. As a result, with this strategy, the team believes that we could reach enough sales and popular demand to sustainably grow and become competitive.

6.1.4 Product Cost and Financial Plan

The ultrasonic bonder that the team made was constructed for around $1,300, however this was with a donated ultrasonic transducer and horn. During initial research, the team found that these parts could be bought from Branson Ultrasonics for around $1500. With plans to create a full business, however we believe that we could create an agreement with Branson allowing for a cheaper cost in exchange for a long-term exclusivity deal as well as bulk purchasing. In this case we will assume we can pay 85% of market price. This brings the total cost of the bonder to $2575 but this still is not accounting for wages. With the benefit of a specific assembly plan as well as general experience the team believes that the construction time for the bonder could be reduced to only 13 hours. With a $25 an hour wage this would put the overall price of the ultrasonic bonder to $2900. With this number in mind the team decided to sell the bonder for $4000, which would still allow for significant product but keep the bonder significantly below current market price.

A financial plan was created based on previous work done in the class based on estimates found during preliminary research as well as the team's experience during the project. Figure 42 below shows an estimate for return on investment (ROI) for an initial cost of 46,000. With an interest rate of 2% and an inflation rate of 1% the bank will return a value of $46,602 while this proposed ultrasonic bonder business plan will return a value of $46,655. Unfortunately, with our estimates it looks like this venture will have a very poor ROI for the first two years, however, it is certainly on an upward trend and will very quickly become highly profitable assuming that the estimations are exact.

A table can be found in the Appendix E that shows the exact values used for this calculation but a few of the more important parameters will be discussed here. In order for this business to function it will be necessary to rent a house or warehouse to use for construction. It was assumed that the rental cost would only be $2000 a month as the proposed production plan will not need a lot of space and the building itself does not require many amenities. The initial development plan would require an additional $3000 a month for three months, predominantly to pay wages for researchers. Most of the research for this product is already done, however it will be required to input further measures to make the bonder more consumer friendly as well as perform more research into the best way to approach our desired markets. During this development time it will also be necessary to buy parts for testing and manufacturing. This cost was estimated to be $9000, which should provide the team with everything it needs for basic construction including a small-scale milling machine.

With these initial costs the team can begin production, advertisement and sales. The team decided to begin with advertising posts of $2000 then this advertising budget is reduced over the course of two years down to $800. This will hopefully ensure initial interest but then allow the brand to spread mostly by word of mouth to avoid unnecessary expenses. In terms of sales the team believes that an ultrasonic bonder can be produced for $2900 and will then be sold for $4000. The team plans to sell and produce 2 for the first two months, 3 for the second two months and so on until 12 are being sold per month at the end of two years.

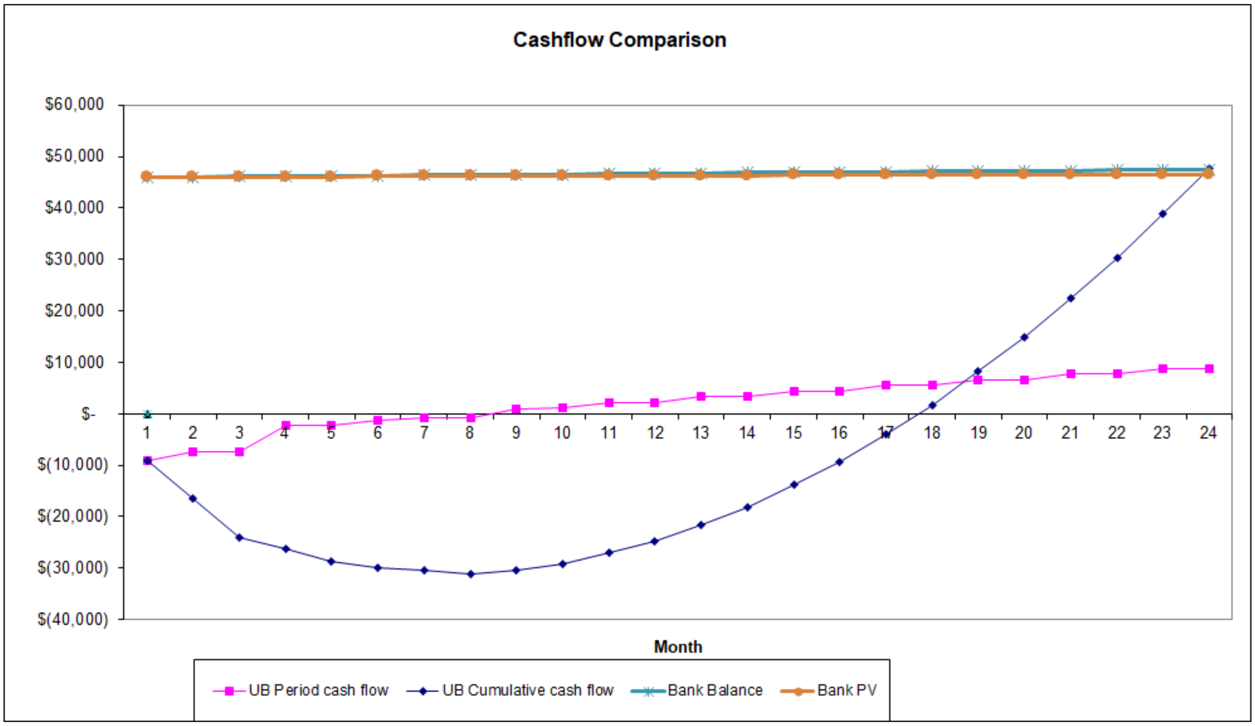


Figure 41: ROI Comparison Between Bank and Proposed Business for initial two years

6.2 Ethical and Environmental Analysis

The never-ending battle that will always plague any engineer throughout his career is the analysis that any general improvement to a piece of technology will create new issues or inefficiencies. Engineers must consider the wholehearted impact that innovation can have to different facets of life. In today's time, it is crucial to consider how new technology will impact society and the environment to promote healthy and sustainable growth. Further research and understanding of ultrasonic bonding will have long-lasting impacts to the electronic packaging industry and the technology markets that utilize the practice of ultrasonic bonders. Thus, the following analysis will expound on the scope of the design project and the environmental and societal considerations.

6.2.1 E-Waste Management

While having extensive research on ultrasonic bonding can improve the state of bonds in the future, this design team must assess the impacts to the environment and society. The most popular use of ultrasonic bonding is in the electronic packaging industry to create solid state bonds for clean integrated circuits. Nevertheless, as improvements are made in the electronic packaging industry, there is an increase in technology infrastructure supply that is outputted to the world. With this increase in supply comes an increase in the production of E-Waste (Electronic Waste). E-Waste is a term that considers the electronic equipment that no longer has any viable use to its owner. Since the beginning of the technological era, the production of e-waste has grown exponentially due to the high demand for technology and the consistently shorter lifespans of hardware [24]. According to a study in 2009, the production of E-waste globally per year was about 20-25 million tons [25] A different study in 2013 reported that the yearly production had increased to 40 million tons a year [26]. The constant growth of E-waste combined with increasingly difficult methods to dispose of the hazardous materials used within electronics is creating an unsustainable environment for the future.[1] As a result, when addressing projects that directly impact the manufacturing process of technology, one must consider how it will impact E-Waste.

The production of an ultrasonic bonder for research purposes could create both solutions and problems to the predicament of overwhelming E-Waste. By allowing scientists to achieve a greater understanding of ultrasonic metal welding, improvements could be made to the manufacturing process that could allow companies to rapidly produce technology and deliver more hardware. In addition to an improvement of manufacturing costs and time the increased knowledge could allow scientists to develop new technologies that could markedly outperform previous models to the point that they would become obsolete.

Consequently, by quickly developing new technology there would be a noticeable increase of E-Waste as consumers would flock to purchase innovative models and dispose of their previous devices. Such a pattern has been pertinent over the past two decades as the lifespans of devices are becoming shorter and individuals are consistently incentivized to unnecessarily upgrade their devices. In 2005, it was reported that the lifespan of a CPU in a computer dropped from 4-6 years in 1997 to 2 years by 2005 [24]. Thus, the trend exists where improvements to the manufacturing of new technology will lead to an increase in E-Waste being produced.

Nevertheless, one must consider that a research based ultrasonic bonder might also allow scientists to make improvements that ease the accumulation of E-Waste. An increase in the knowledge of the bonding process could lead to improvements in the quality and efficiency of the bonds. Such a process could result in creating integrated circuits that could have longer life expectancies and maybe even easily replaceable parts allowing the consumer to own and use the device for a longer period of time. There are current studies that suggest how increments in available power can allow for different material bond combinations and decreases in voids in ultrasonic additive manufacturing [27]. While most of these improvements could be considered simply an increase in knowledge in the field of ultrasonic welding, it is crucial that they are linked to the decrease in E-Waste production by creating longer lasting technology.

6.2.2 Addressing the Technology Gap in Underdeveloped Nations

Furthermore, the team decided to address how advancements in the field of ultrasonic welding could help narrow down the technological gap that exists between the developing and developed world. Less developed countries will often fall behind in developing the necessary infrastructure to provide highly beneficial technological services to its population. This issue is often a cause for trapping countries in a poverty cycle where they reach an economic growth ceiling. Technology not only helps countries by increasing intercommunication, but it also creates new sectors that readily promote job creation. One of the major issues with increasing the technology infrastructure of a country is the cost and supply of materials [28]. However, the team believes that increased research in ultrasonic bonding could provide lower cost manufacturing, allowing products to become more readily available to developing nations. It’s crucial for the technology gap to close, which means providing opportunities for developing nations to foster a tech market [29] By providing a device that can advance the practices in ultrasonic bonding, the cost will become lower as assemblies become more efficient, which will allow developing nations to create a tech base to build upon. As a result, the team believes that by building a ultrasonic ribbon bonder for research purposes, there will be a positive impact to society by helping reduce the tech gap in the developing world.

Moreover, as a general and narrow impact to society, it is evident that building an ultrasonic bonder for research purposes will advance the knowledge of the field. This impact to society is difficult to quantify without a long-term assessment. Nevertheless, the wide range of uses for ultrasonic welding practices gives insight into how further research could impact multiple fields of study. Ultrasonic Welding Manufacturing is used in the electronic packaging industry, in CNC frameworks to create complex parts, and in 3D printing technologies. Advancements in research have allowed for a great range of uses for ultrasonic welding, and further advancements could increase the range of uses even further. Extensive research has allowed for new combinations of metals and greater surface areas to be bonded together [27].

The first and foremost goal of building the ultrasonic bonder is for researchers at Santa Clara University to be capable of analyzing bond formation and perform different studies. While this is the direct impact of the project, such an assembly can have long lasting effects on the environment and the society. As mentioned before, progress in ultrasonic bonding could have both negative and positive effects on the issue of E-Waste production globally. While it could increase the life of many technological devices and circuit boards, it could also cause issues in delivering products faster where consumers dispose of outdated models. In addition, by making ultrasonic bonding more effective, it could reduce the cost of technology infrastructure in order for developing nations to invest in these advancements. Finally, the direct impact of building an ultrasonic bonding purely for research is the impact in the knowledgebase of the field. The understanding of these consequences is intricate to the design of this team’s ultrasonic bonder as it ensures evaluates the value of the project and the possible issues to watch out for.

6.3 Future Work and Lessons

As with any research and design project, there always exists components of the process that could be further improved. Certain design selections do not perform in their desired purpose or they could interfere with a fully effective implementation. As a result, it is the duty of an engineer to recognize what future improvements could perfect the functionality of the device. Thus, when reflecting upon last year of building and designing a research based ultrasonic ribbon bonder, there are a series of system changes and lessons that could improve the experience of researchers in their work.

Throughout the past year, one of the largest issues that the team had to maneuver was to build a fully functioning ultrasonic bonder with a limited budget. Upon initial calculation, the bonder was designed to cost around $2,200. This value was much lower than the budget of industry grade bonders ranging between $5000 to $11,000. Nevertheless, even with this smaller budget, the team was only funded with $1,500 to build the ultrasonic bonder. This required a series of budget changes that could reduce cost while still achieving the final functionality and goal of Phase I. One of these decisions was to purchase cheaper T-Slot Rail connectors to assemble the frame subsystem of the bonder. Throughout the assembly, it became evident that while these connectors significantly impacted the cost, they would hinder the device's ease of repairability and upgradability. This negatively impacts one of the specific customer specifications that was emphasized by the Materials Laboratory at Santa Clara University. Thus, even though the connectors allowed for the frame subsystem assembly, the team believes that with new funding, an investment in higher quality T-Slot Connectors would greatly improve the modularity of the ultrasonic bonder by making it simpler to upgrade and add different instrumentation.

Moreover, during the building stages of this project, it was noted that advancements to the force application system could improve precision in ultrasonic bonding. During ultrasonic bonding, there is a need for very small force to stimulate the formation of metallic bonds after the oxide layer has been softened. The force application must be strong enough to hold the two samples together but not interfere in the desired amplitude of ultrasonic vibrations. This team's design utilizes pneumatic cylinders that apply a force by utilizing an exterior air compressor. While this system could provide the necessary level of forces for ultrasonic bonding, it is simply not precise enough to apply an exact force of 10N. One must calibrate pneumatic cylinders to the exterior air compressor and the solenoid. It became very clear during construction that a precise 10N of force would be difficult to achieve. Thus, upon review the team discovered that utilizing a voice coil actuator could provide higher precision and a greater universal control. Voice coil actuators utilize an electric current to interact with a magnetic field that can generate a vertical force. This force can be applied and reverted by changing the polarity and strength of the magnetic field [30]. This type of force application system has greater precision and could be directly included in the control system of the device. With no need of an exterior air compressor and separate mechanical process. Therefore, the team highly recommends that the force application system be replaced during Phase II of this project if the budget allows for this investment.

Now, due to the Covid-19 obstacles that this team encountered over the past three months, there is a series of additional work that must be finished to deliver a final product. The final assembly of the project could not be accomplished as it was not safe to return to Santa Clara University. Thus, there is a need to finish the assembly of the electronics and bonding stage subsystem. While all the components of these subsystems have been purchased and delivered to Santa Clara, the specific assemblies must be completed. Once this work has been accomplished, the assembly of all five subsystems must be completed to produce the final ultrasonic ribbon bonder. Following the assembly, a method of testing the bond samples must be achieved to test the quality of the ultrasonic bonder. To facilitate this work, the team researched different methods of testing ultrasonic bonds and contacted individuals in industry to verify the methodology. Upon a conversation with Carlos Aponte, an engineer at Branson Ultrasonics in the Bay Area, the team decided that constructing a peel test device could provide sufficient verification of the device's ability to bond two metals.

A peel test is conducted by attempting to separate the two samples that have been bonding together by applying two tensile forces in opposite directions at a 180-degree angle. Through this method, two different outcomes provide the necessary information to verify the functionality of the device. The two samples could completely separate from one another or part of one sample could rip apart leaving the bonded area stuck to the secondary sample. If the second outcome proves true, then this demonstrates a proper bonding functionality as the bonded area withheld higher localized levels of stress [31]. This method of testing is not highly technical or quantitative. Nevertheless, it provides the necessary information to verify that the design and assembly of the ultrasonic bonder can create bonds between two pieces of aluminum. Which was the goal provided by the customer requirements.

These suggestions provide a path forward for the growth of the research based ultrasonic ribbon bonder. This team took a monumental challenge in designing this device while researching and learning the process of ultrasonic bonding. Challenging ourselves to gain the necessary knowledge to perform the work effectively and safely. Performing the design and building process with a limited budget compared to large scale corporations. Nevertheless, through extensive teamwork and dedication the team believes that an affordable ultrasonic bonder with research capabilities is definitely achievable and applicable within its niche market.

7. Conclusion

The main focus of the team's work has been on the design and construction of an ultrasonic bonder for research at Santa Clara University. This bonder will significantly aid the efforts of the material science laboratory and would hopefully be used for years to come. Unfortunately, with the COVID-19 pandemic the team was only able to partially build the final design and were not able to assemble everything together. However, significant work and research was done on the project such that another group could move on from what has been accomplished to finish construction, and hopefully implementation in a year. From the offset this project was initially intended to take two years so this delay hopefully should not be too problematic for the overall scope and state of the project as a whole but it is unfortunate. At its current state, the bonder design is finalized while the frame, bonding platform and pneumatic system are all complete. The parts necessary for construction of the bonding assembly and bond stage are made and organized for easy use in the future. All that needs to be done to finish the construction is to assemble the different parts together, which can hopefully be completed in around 3 to 4 weeks by a new group. This bonder was created using a total of $1,231 along with a donation from K&S worth around $1,500 and should function as a basic ultrasonic ribbon bonder. It does not allow for automation, but it should allow for instrumentation to be easily added to help increase research into ultrasonic bonding at Santa Clara University.

The other part of this project was a research-based analysis project chosen because it allowed for work to be done remotely during the COVID-19 pandemic. This research resulted in the creation of several plots detailing the amplitude of the tooltip compared to the transverse force acting on the tool for different input powers. These plots are useful for determining the desired input parameters into the final ultrasonic bonder as well as better understanding some of the differences that occur in bond formation due to different input parameters. This research could also potentially be used and expanded upon by later groups to produce a more robust model or to develop related plots showing different bond parameters.

Overall, this project greatly increased the team member's knowledge and expertise in ultrasonic bonding and gave a significant amount of practice in understanding and working from complicated research papers. This project also paved the way for a future team to work with what has been done to create a full ultrasonic ribbon bonder for Santa Clara University to significantly help them with their research on the subject.

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9. Appendix

Appendix A: Interview Questions

1. What do you like about existing wire bonders that you used for research?
2. What improvements does the wire bonder need for research?
3. Should the device be easily transportable or should it sit in a specific location in a lab? Rate from 1-10 (1 being the device sits on a location and is never moved)
4. How automated should the process be? Rate from 1-10 (10 being press one button and the device goes to work)
5. Should it be modular? Easy to repair? Rate the ease of “self-repair” from 1-10 (10 being completely repairable by self)
6. What price range would be acceptable for such a device?
7. How large should the device be? Please elaborate and give an approximate footprint (length,width,height).
8. What is the range of bonded area for your desired research? What is the order of magnitude of the areas that will be bonded?
9. What type of controls do you want?
10. How many inputs should the device have?
11. What applications does this device have outside of university research?
12. What is the maximum amount of time the device should take to bond?
13. How often is the device used on a typical work day? Rate from 1 to 10 10 being 8 hours a day
14. What type of analysis can be produced with an ultrasonic ribbon bonder?
15. What would you like to see in the bonder? What would you expect from it?

Appendix B: Design Drawings

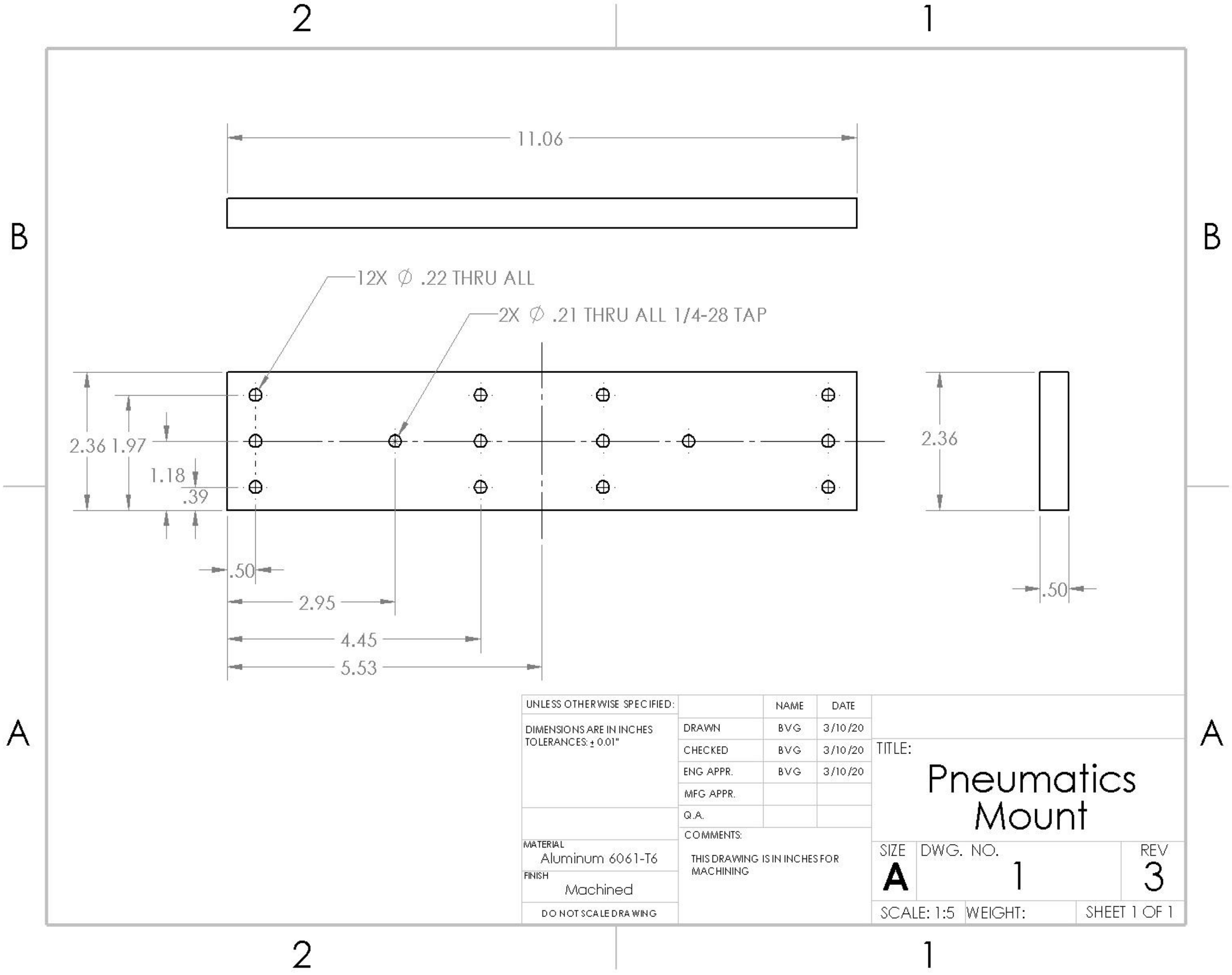
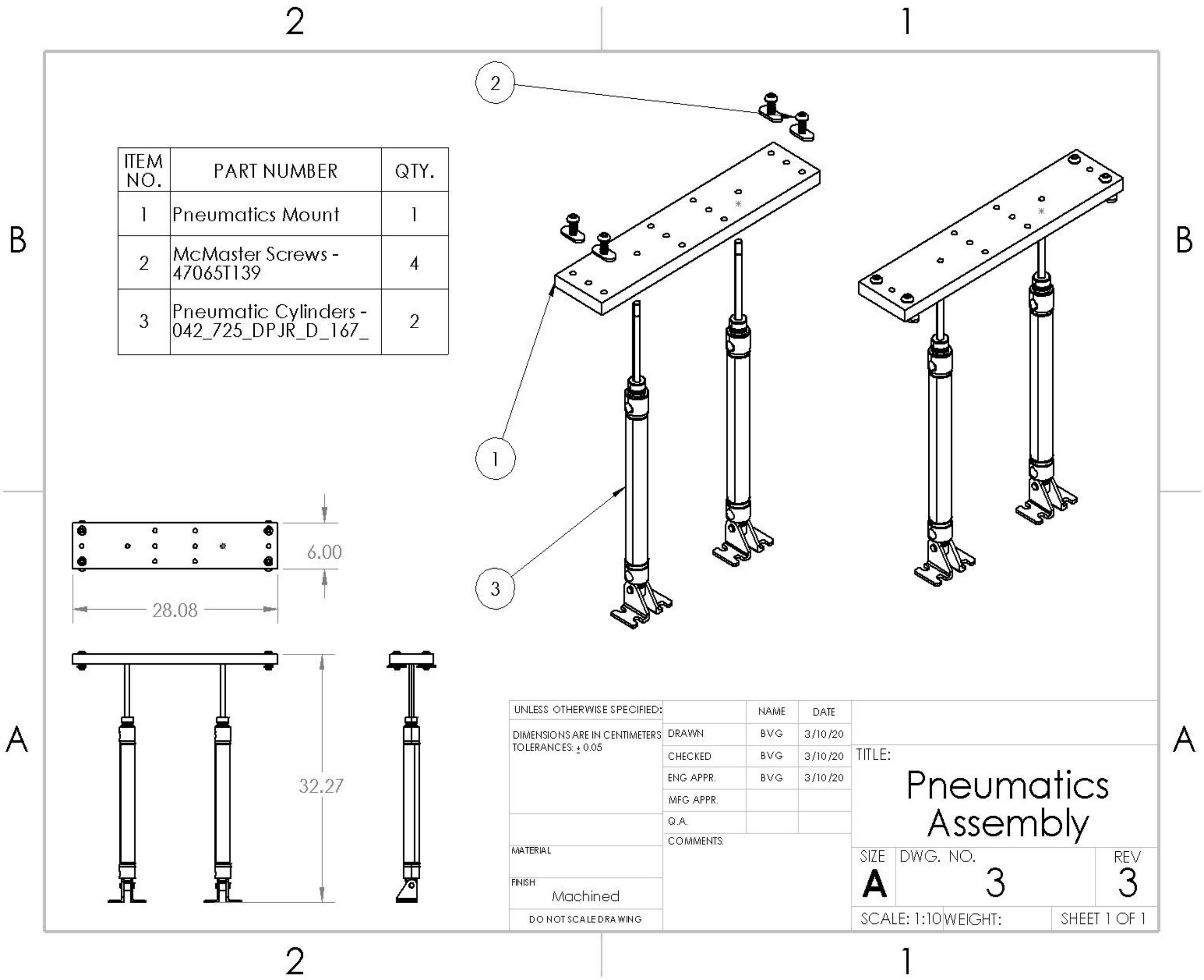


Figure 42: Pneumatics Mount Drawing



ITEM NO.	PART NUMBER	QTY.
1	Pneumatics Mount	1
2	McMaster Screws - 47065T139	4
3	Pneumatic Cylinders - 042_725_DPJR_D_167_	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN CENTIMETERS
TOLERANCES: ± 0.05

	NAME	DATE
DRAWN	BVG	3/10/20
CHECKED	BVG	3/10/20
ENG APPR.	BVG	3/10/20
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL

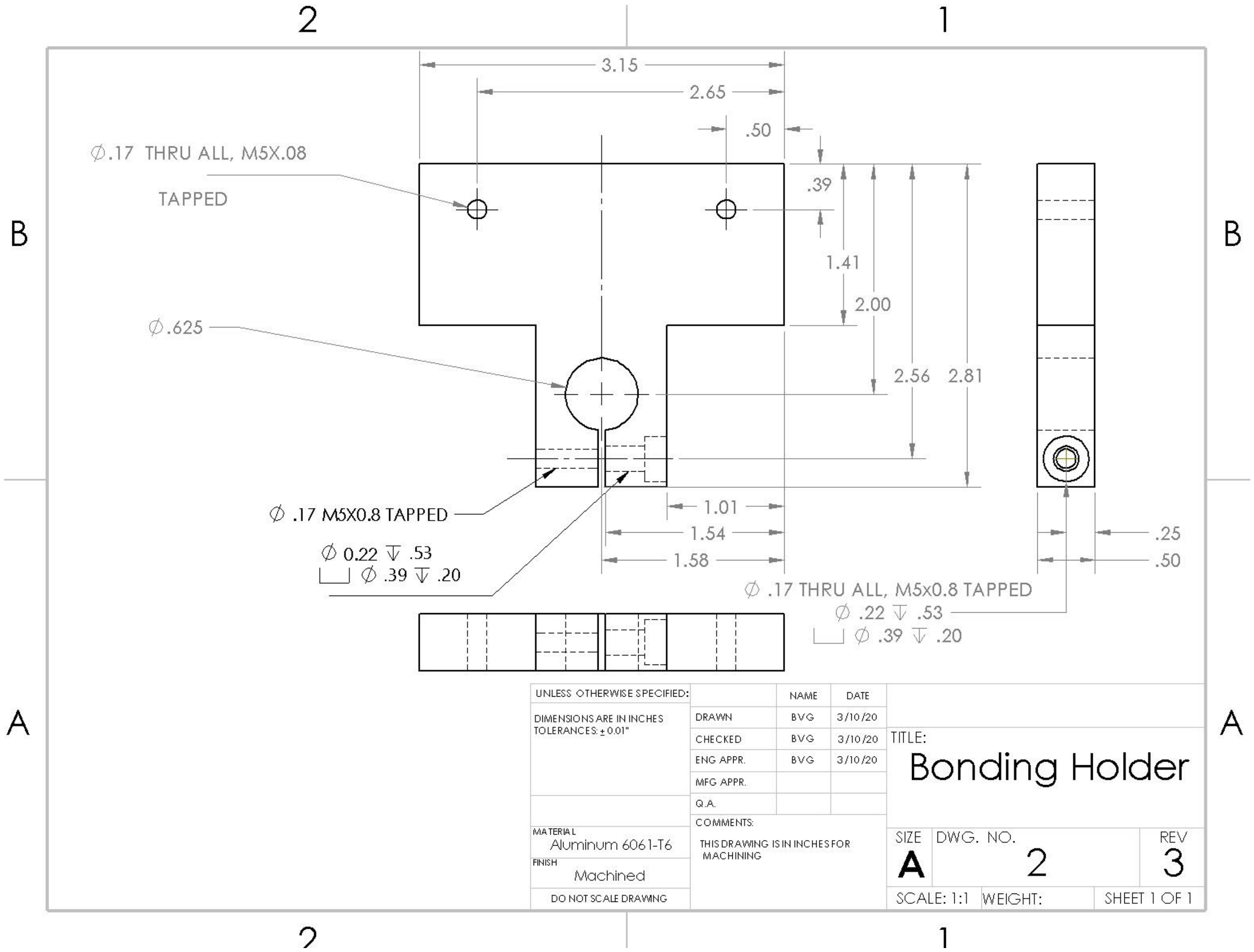
FINISH
Machined

DO NOT SCALE DRAWING

TITLE:
Pneumatics Assembly

SIZE A
DWG. NO. 3
REV 3
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1

Figure 43: Pneumatics Assembly Drawing

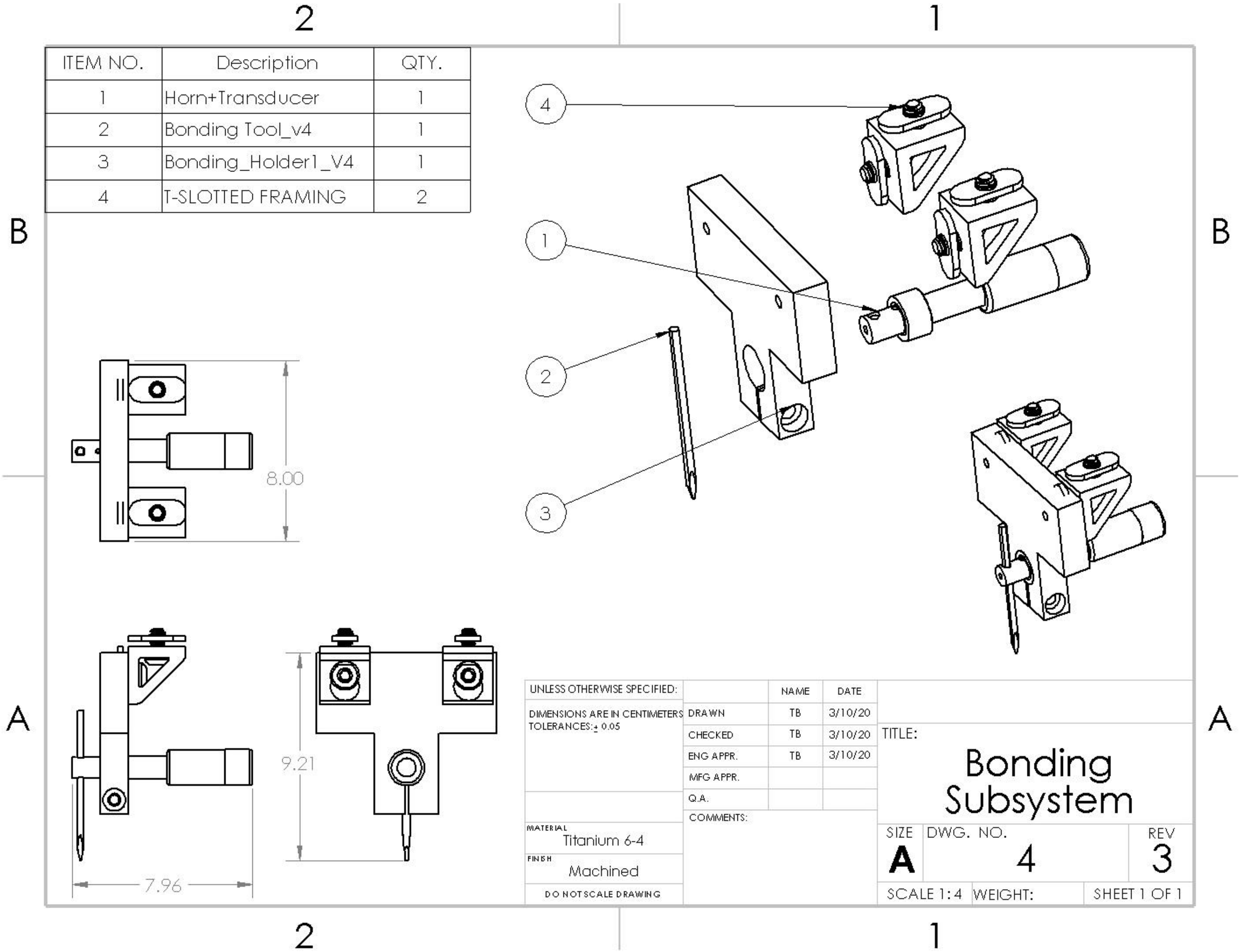


UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ± 0.01"	DRAWN	BVG	3/10/20
	CHECKED	BVG	3/10/20
	ENG APPR.	BVG	3/10/20
	MFG APPR.		
	Q.A.		
MATERIAL Aluminum 6061-T6	COMMENTS: THIS DRAWING IS IN INCHES FOR MACHINING		
FINISH Machined			
DO NOT SCALE DRAWING			

TITLE:
Bonding Holder

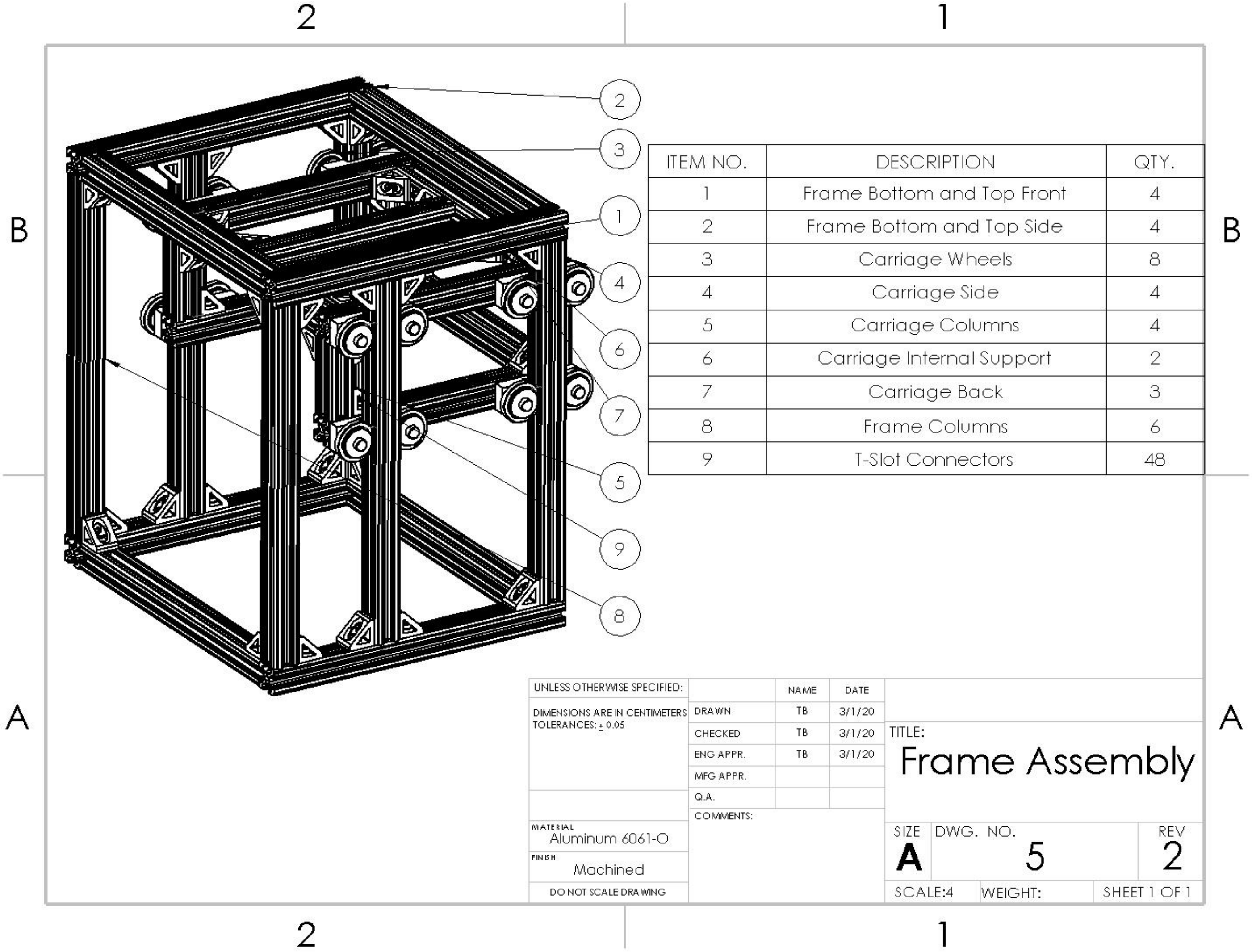
SIZE	DWG. NO.	REV
A	2	3
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

Figure 44: Bonding Holder Drawing



ITEM NO.	Description	QTY.
1	Horn+Transducer	1
2	Bonding Tool_v4	1
3	Bonding_Holder1_V4	1
4	T-SLOTTED FRAMING	2

Figure 45: Bonding Subsystem Drawing



ITEM NO.	DESCRIPTION	QTY.
1	Frame Bottom and Top Front	4
2	Frame Bottom and Top Side	4
3	Carriage Wheels	8
4	Carriage Side	4
5	Carriage Columns	4
6	Carriage Internal Support	2
7	Carriage Back	3
8	Frame Columns	6
9	T-Slot Connectors	48

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES: ± 0.05

	NAME	DATE
DRAWN	TB	3/1/20
CHECKED	TB	3/1/20
ENG APPR.	TB	3/1/20
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL Aluminum 6061-O

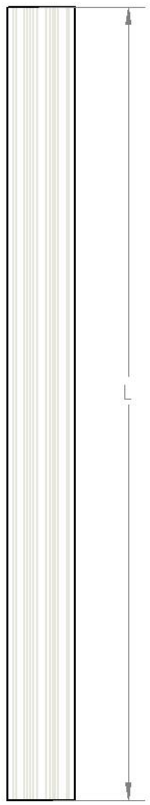
FINISH Machined

DO NOT SCALE DRAWING

TITLE: Frame Assembly

SIZE A
DWG. NO. 5
REV 2
SCALE:4
WEIGHT:
SHEET 1 OF 1

Figure 46: Frame Assembly Drawing



Frame

NUMBER	DESCRIPTION	LENGTH (cm)	QUANTITY
1	Frame Bottom and Top Front	30	4
2	Frame Bottom and Top Side	30	4
4	Carriage Side	25	6
5	Carriage Columns	7.5	3
6	Carraige Internal Support	19.92	4
7	Carriage Back	23	4
8	Frame Columns	35	6

Stage

NUMBER	DESCRIPTION	LENGTH (cm)	QUANTITY
10	Stage Fronts	20	2
11	Stage Sides	12	4
12	Stage Columns	11.5	4
13	Stage Cross Bar	30	1
14	Bottom Pneumatic Mount	10.38	4

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN CENTIMETERS
TOLERANCES: ± 0.05

MATERIAL
Aluminum 6061-O

FINISH
Machined

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	BVG	3/10/20
CHECKED	BVG	3/10/20
ENG APPR.	BVG	3/10/20
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
T-Slot Lengths

SIZE A
DWG. NO. 6
REV 3

SCALE: 1:5
WEIGHT:
SHEET 1 OF 1

Figure 47: T-Slot Lengths Drawing

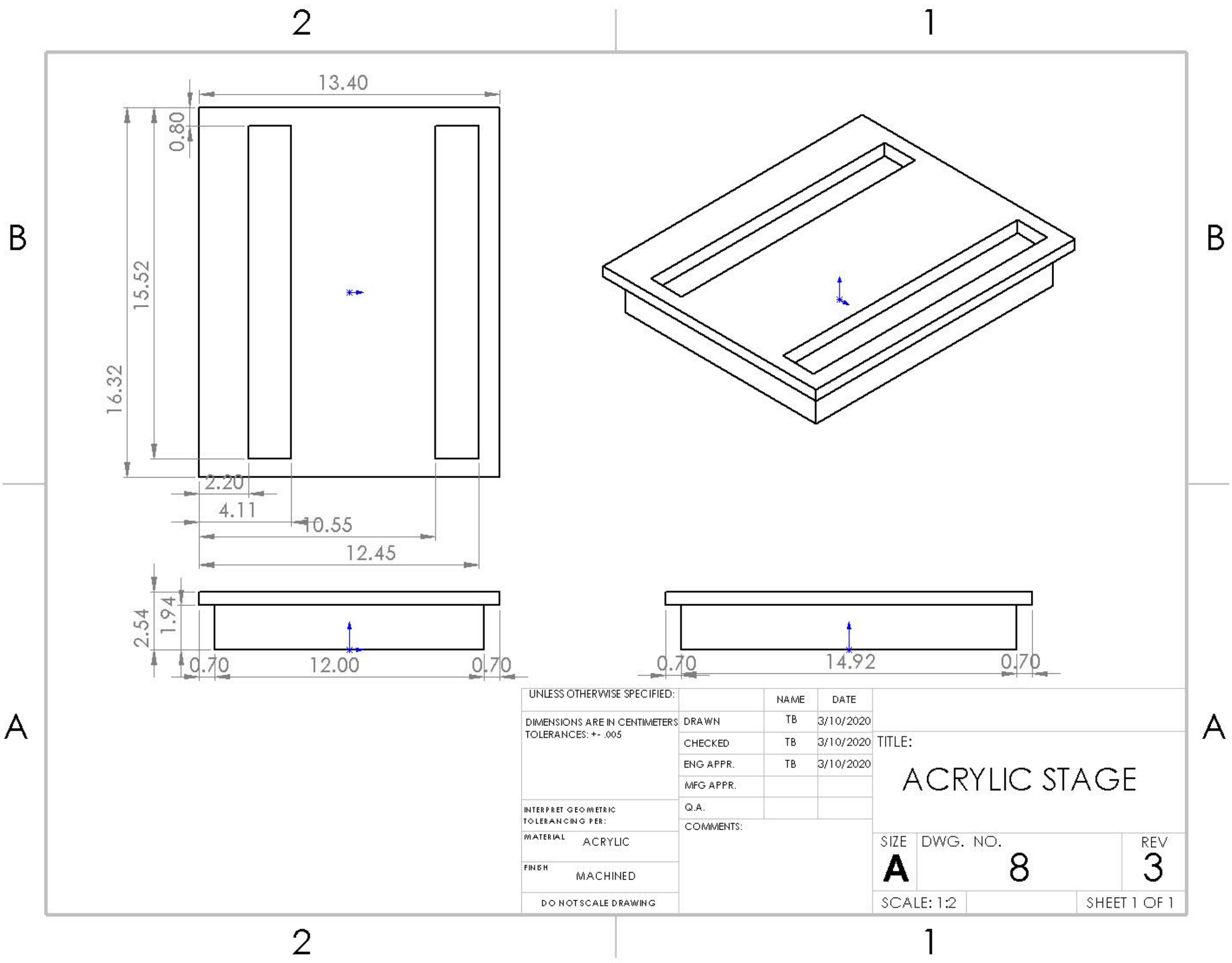
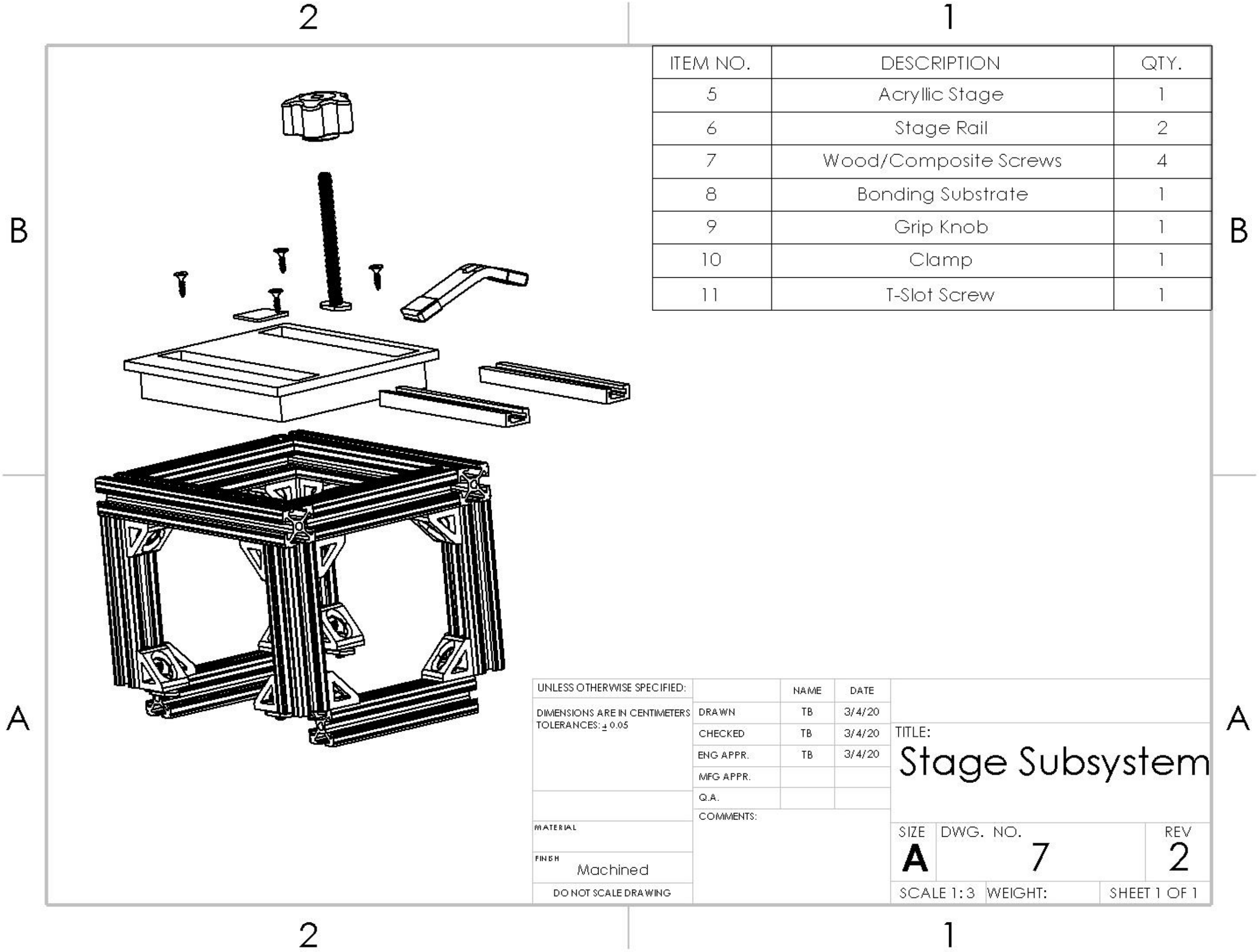


Figure 48: Acrylic Stage Drawing



ITEM NO.	DESCRIPTION	QTY.
5	Acrylic Stage	1
6	Stage Rail	2
7	Wood/Composite Screws	4
8	Bonding Substrate	1
9	Grip Knob	1
10	Clamp	1
11	T-Slot Screw	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN CENTIMETERS
TOLERANCES: ± 0.05

MATERIAL

FINISH
Machined

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	TB	3/4/20
CHECKED	TB	3/4/20
ENG APPR.	TB	3/4/20
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Stage Subsystem

SIZE A
DWG. NO. 7
REV 2
SCALE 1:3
WEIGHT:
SHEET 1 OF 1

Figure 49: Stage Subsystem Drawing

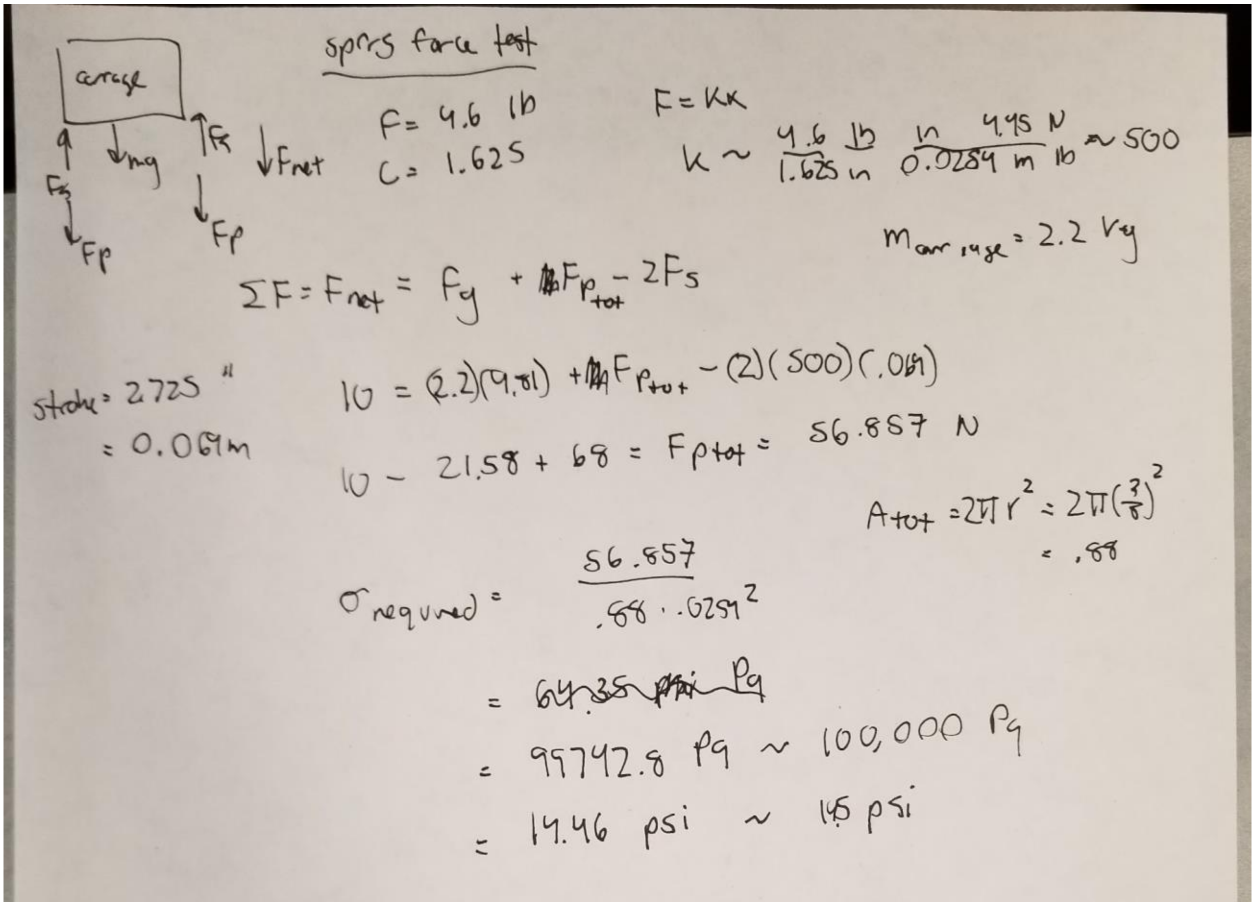
Appendix C: Budget

Table 14 - Entire Budget

Component	Vendor	Bulk Cost	Spent
Frame and Bonding Stage			
Bosch Rails	McMaster	$117.85	$117.85
Corner Gussets	Amazon	$63.96	$63.96
Track Roller Carriage	McMaster	$453.36	$453.36
Aluminum slab	McMaster	$50.00	$50.00
1" sheet of cast acrylic	McMaster	$33.12	
T slot rails	Amazon	$16.83	
Back up Clamps	Amazon	$13.04	
Subtotal		**$748.16**	**$685.17**
Bonding Assembly			
Horn	Branson	$0.00	$0.00
Ultrasonic Transducer	Amazon	$0.00	$0.00
Subtotal		**$0.00**	**$0.00**
Force Application			
Pneumatic Cylinders	BIMBA	$82.80	$82.80
Pneumatic Mount	BIMBA	$9.02	$9.02
Solenoid Valves	Amazon	$17.76	$17.76
Pressure Transducer	Amazon	$13.98	$13.98
Storage Tank	AndyMark	$18.00	$18.00
Compressor	Amazon	$119.00	$119.00
Relay	Amazon	$5.50	$5.50
24 V Battery	Amazon	$62.99	$62.99

100 psi Release Valve	Amazon	$6.02	$6.02
Subtotal		**$329.05**	**$266.06**
Electronics and Hardware			
Pneumatic Tubing	Amazon	$15.90	$15.90
Miscellaneous Arduino Electronics	SCU/Team Donations	$0.00	$0.00
Teflon Tape	Home Depot	$0.98	$0.98
Tube to Tube Fittings	Amazon	$15.00	$15.00
Tube to Thread Fittings Male 1/8 NPT	Amazon	$15.99	$15.99
Tube to Thread Fittings Female 1/8 NPT	Amazon	$13.49	$13.49
Tube to Thread Fittings Male 1/4 NPT	Amazon	$15.99	$15.99
Tube to Thread Fittings Female 1/4 NPT	Amazon	$13.99	$13.99
Shut Off Valve	Amazon	$11.78	$11.78
m5 Screws	McMaster	$13.13	$13.13
Arduino	Arduino	$0.00	$0.00
Zip Ties and Anchors	Amazon	$12.95	$12.95
m5 Tap and drill set	Amazon	$10.79	$10.79
m5 set screw	McMaster	$4.39	$4.39
1/4-28 tap and #3 bit	Amazon	$8.70	$8.70
Subtotal		**$153.08**	**$153.08**
Total		**$1,230.29**	**$1,104.31**
Total With Shipping		**$1,371.43**	**$1,231.00**

Appendix D: Pressure calculations



springs force test

$F = 4.6$ lb

$C = 1.625$

$F = kx$

$k \sim \frac{4.6\ \text{lb}}{1.625\ \text{in}} \frac{\text{in}}{0.0254\ \text{m}} \frac{4.45\ \text{N}}{\text{lb}} \approx 500$

$m_{carriage} = 2.2$ kg

$\Sigma F = F_{net} = F_g + F_{p_{tot}} - 2F_s$

stroke = 2.725 "
= 0.069m

$10 = (2.2)(9.81) + F_{p_{tot}} - (2)(500)(.069)$

$10 - 21.58 + 68 = F_{p\,tot} = 56.857$ N

$A_{tot} = 2\pi r^2 = 2\pi(\frac{3}{8})^2$
$= .88$

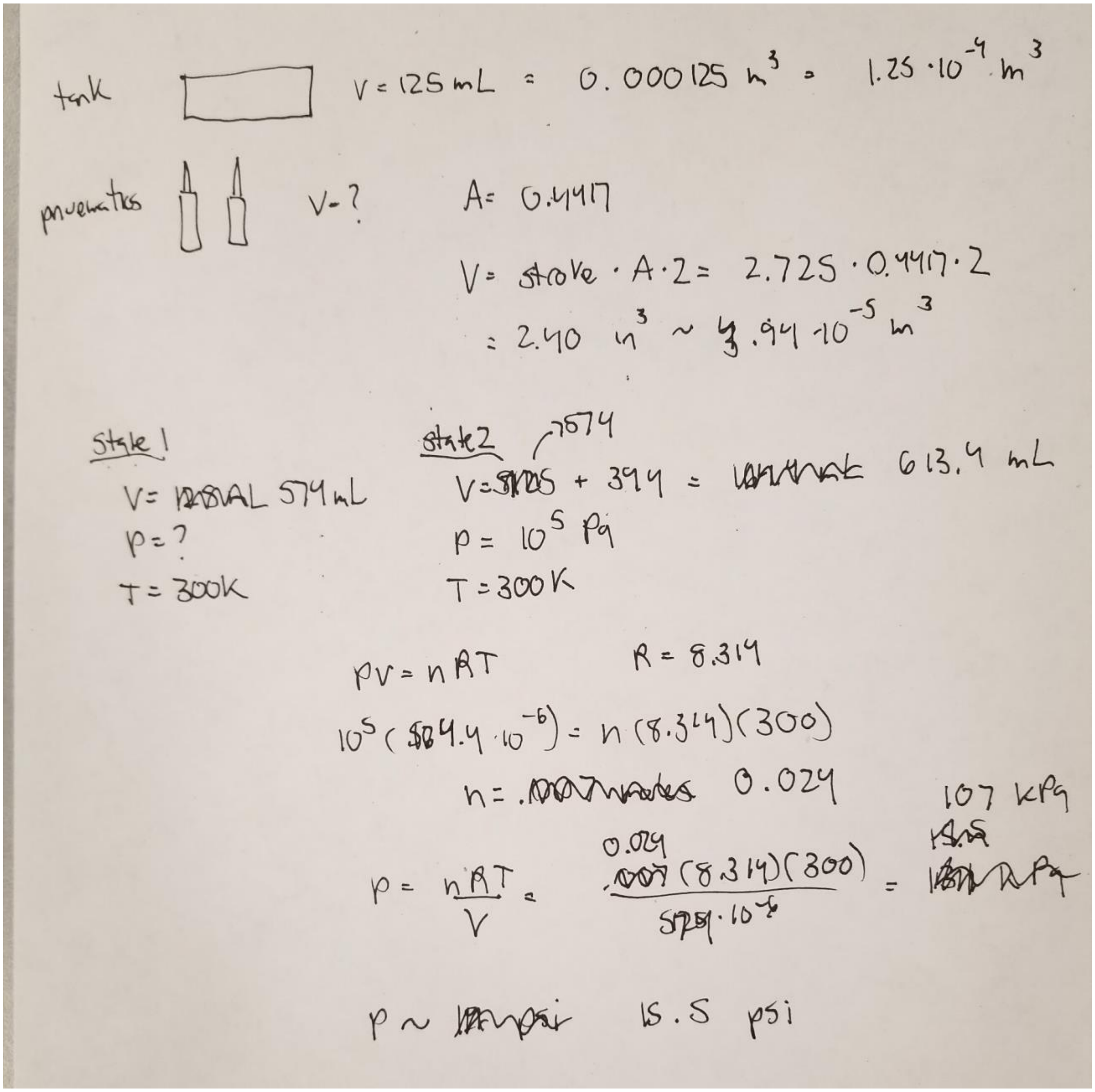
$\sigma_{required} = \frac{56.857}{.88 \cdot .0254^2}$

= ~~64.35 psi~~ Pa

= 99742.8 Pa ~ 100,000 Pa

= 14.46 psi ~ 14.5 psi

Figure 50: Forces on the Carriage



tank $V = 125\,mL = 0.000125\ m^3 = 1.25 \cdot 10^{-4}\ m^3$

pneumatics $V - ?$

$A = 0.4417$

$V = \text{stroke} \cdot A \cdot 2 = 2.725 \cdot 0.4417 \cdot 2$

$= 2.40\ in^3 \sim 3.94 \cdot 10^{-5}\ m^3$

state 1

$V = 574\,mL$

$p = ?$

$T = 300K$

state 2

$V = 574 + 39.4 = 613.4\ mL$

$p = 10^5\ Pa$

$T = 300K$

$pV = nRT$ $R = 8.314$

$10^5(584.4 \cdot 10^{-6}) = n(8.314)(300)$

$n = 0.024$

$p = \frac{nRT}{V} = \frac{0.024(8.314)(300)}{574 \cdot 10^{-6}} = 107\ kPa$

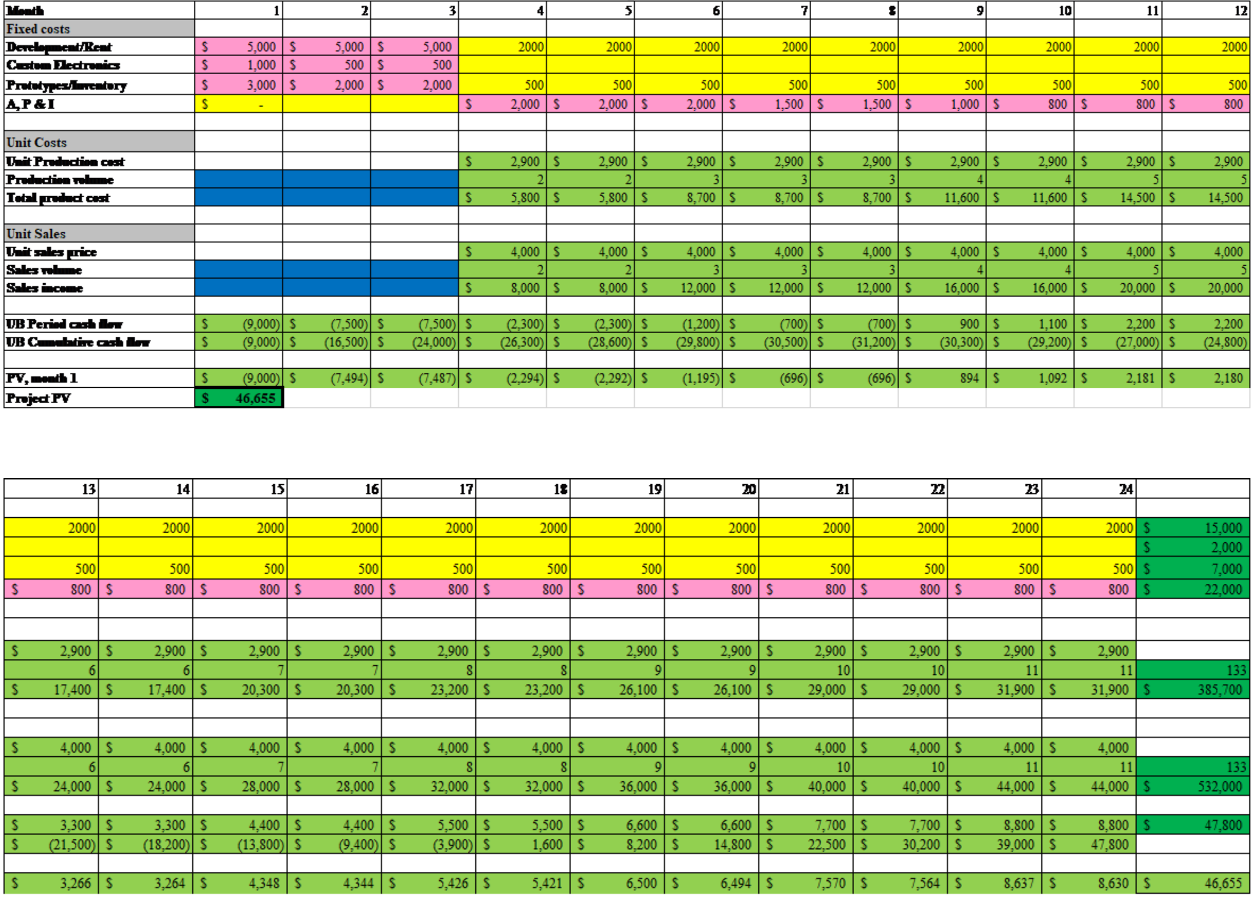
15.5

$p \sim 15.5$ psi

Figure 51: Pressure for the storage tank

Appendix E: Business Plan Estimates

Table 15 - Estimated revenue from small scale ultrasonic bonder for first two years of development



Month	1	2	3	4	5	6	7	8	9	10	11	12
Fixed costs												
Development/Rent	$ 5,000	$ 5,000	$ 5,000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Custom Electronics	$ 1,000	$ 500	$ 500									
Prototypes/Inventory	$ 3,000	$ 2,000	$ 2,000	500	500	500	500	500	500	500	500	500
A, P & I	$ -			$ 2,000	$ 2,000	$ 2,000	$ 1,500	$ 1,500	$ 1,000	$ 800	$ 800	$ 800
Unit Costs												
Unit Production cost				$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900
Production volume				2	2	3	3	3	4	4	5	5
Total product cost				$ 5,800	$ 5,800	$ 8,700	$ 8,700	$ 8,700	$ 11,600	$ 11,600	$ 14,500	$ 14,500
Unit Sales												
Unit sales price				$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000
Sales volume				2	2	3	3	3	4	4	5	5
Sales income				$ 8,000	$ 8,000	$ 12,000	$ 12,000	$ 12,000	$ 16,000	$ 16,000	$ 20,000	$ 20,000
UB Period cash flow	$ (9,000)	$ (7,500)	$ (7,500)	$ (2,300)	$ (2,300)	$ (1,200)	$ (700)	$ (700)	$ 900	$ 1,100	$ 2,200	$ 2,200
UB Cumulative cash flow	$ (9,000)	$ (16,500)	$ (24,000)	$ (26,300)	$ (28,600)	$ (29,800)	$ (30,500)	$ (31,200)	$ (30,300)	$ (29,200)	$ (27,000)	$ (24,800)
PV, month 1	$ (9,000)	$ (7,494)	$ (7,487)	$ (2,294)	$ (2,292)	$ (1,195)	$ (696)	$ (696)	$ 894	$ 1,092	$ 2,181	$ 2,180
Project PV	$ 46,655											

	13	14	15	16	17	18	19	20	21	22	23	24	
	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	$ 15,000
													$ 2,000
	500	500	500	500	500	500	500	500	500	500	500	500	$ 7,000
	$ 800	$ 800	$ 800	$ 800	$ 800	$ 800	$ 800	$ 800	$ 800	$ 800	$ 800	$ 800	$ 22,000
	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	$ 2,900	
	6	6	7	7	8	8	9	9	10	10	11	11	133
	$ 17,400	$ 17,400	$ 20,300	$ 20,300	$ 23,200	$ 23,200	$ 26,100	$ 26,100	$ 29,000	$ 29,000	$ 31,900	$ 31,900	$ 385,700
	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	$ 4,000	
	6	6	7	7	8	8	9	9	10	10	11	11	133
	$ 24,000	$ 24,000	$ 28,000	$ 28,000	$ 32,000	$ 32,000	$ 36,000	$ 36,000	$ 40,000	$ 40,000	$ 44,000	$ 44,000	$ 532,000
	$ 3,300	$ 3,300	$ 4,400	$ 4,400	$ 5,500	$ 5,500	$ 6,600	$ 6,600	$ 7,700	$ 7,700	$ 8,800	$ 8,800	$ 47,800
	$ (21,500)	$ (18,200)	$ (13,800)	$ (9,400)	$ (3,900)	$ 1,600	$ 8,200	$ 14,800	$ 22,500	$ 30,200	$ 39,000	$ 47,800	
	$ 3,266	$ 3,264	$ 4,348	$ 4,344	$ 5,426	$ 5,421	$ 6,500	$ 6,494	$ 7,570	$ 7,564	$ 8,637	$ 8,630	$ 46,655