Jaws: The Educator

ME 450 Final Report

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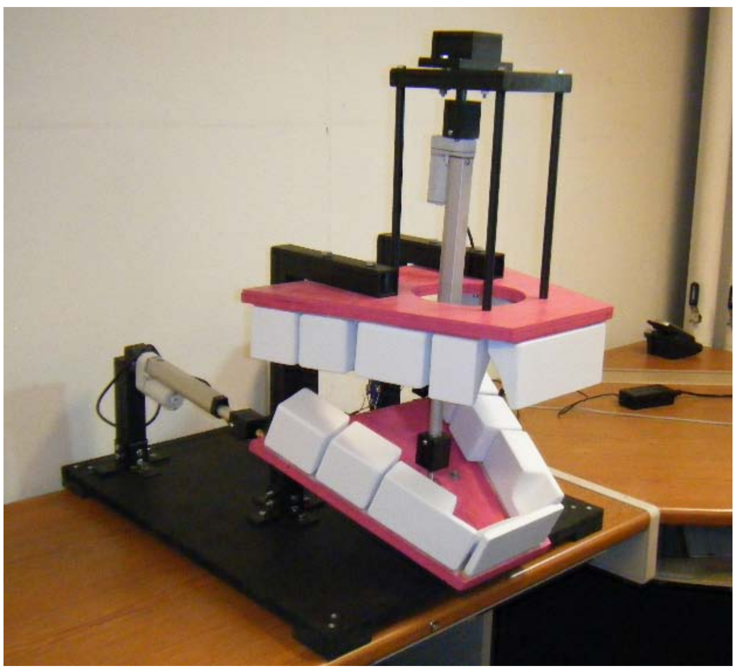


1. ABSTRACT

Current methods used by graduate dental professors to teach occlusion (dental anatomy) are ineffective as educational tools. The small scale and limited versatility of existing teaching methods make it difficult to efficiently convey complicated and interconnected dental concepts to students. This prototype identifies a solution to this problem by creating a large scale physical model capable of replicating several dental concepts, simultaneously creating an efficient tool to be used by educators while providing a physical model large and straightforward enough to simplify the learning process for students. The goal of this project is to create an effective teaching tool to assist dental professors in educating students.

2. EXECUTIVE SUMMARY

This project aims to create a physical model of the human jaw that can be scaled and actuated to improve the teaching efficiency of dental professors in large classrooms. Current teaching methods limit the professor's ability to effectively convey difficult multi-dimensional dental concepts.

An alpha design was generated through a concept comparison that utilized a Pugh Chart for design ranking. The design included mutually exclusive jaw actuation and teeth adjustability. Jaw actuation was to be accomplished through four linear actuators controlled electronically and mounted with ball and socket joints to allow 6 DOF motion. The teeth were designed with a removal system similar to dentures and would be anatomically accurate through 3D scanning and rapid prototyping capabilities. Due to limitations in drivers and resources, the alpha design was refined into a feasible prototype design.

The prototype design is eight times the size of a typical human jaw and is comprised of three linear actuators with removable sections of teeth attached using Velcro®. The prototype includes a weight bearing vertical linear actuator and two horizontal linear actuators. Due to size restraints of the linear actuators an extra support extends above the upper jaw to hold the vertical support. The ball and socket joint design was retained to allow for the 6DOF motion. A passive elastic support is attached between the jaw palates to provide support about the joints. Automation of the actuators is accomplished through the use of an Arduino microcontroller and programs. Each actuator can also be manually activated independently through three way switches. The teeth are simple shapes to allow for more exaggerated demonstrations of variability and are simply and easily adjusted.

A final design was generated (but will not be assembled) to increase the capabilities of the prototype given extended resources and time. The final design will have anatomically accurate teeth, a more stable structure with a spring instead of elastic, and a wider range of motion through angled linear actuators.

Fabrication and assembly of the prototype was completed in a safe and effective manner through the processes outlined in the fabrication plan and safety report. The prototype was tested as thoroughly as possible, in the constraint of time, to validate its ability to meet the design specifications. All quantitative testing was conducted and the prototype accomplished all of the requisite dental motions. Extensive qualitative testing has not yet been completed, but a detailed scientific method is included for the possibility of further testing. Despite this, conversations with our sponsor indicate that the prototype successfully accomplishes all but one design specification. The specification that was not met is not critical for prototype functionality and was designed out of the prototype such that all other specifications could be met.

An in-depth engineering critique was performed to analyze the strengths and weaknesses of the design. The design was evaluated using material selection software and SimaPro for functional and environmental performance. The feasibility of mass production for the design was also investigated. Future work on the design is proposed and includes integration of a virtual model, open source programming, a motion limiting device, and wireless control.

Overall Team Jaws is proud of our work for this project. The prototype was presented at the University of Michigan Engineering Design Expo on 10 December 2009 and we are looking forward to delivering the prototype to our sponsor for classroom integration.

3. TABLE OF CONTENTS

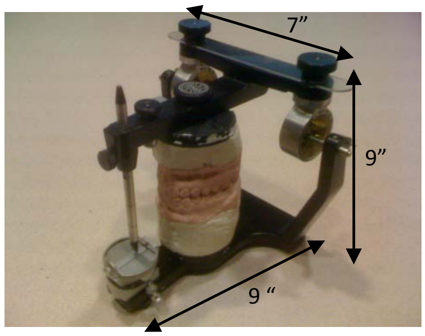
4. INTRODUCTION

This section introduces the project through a discussion of the background, motivation, and scope of the project.

4.1 Problem Background and the Project Sponsor

Our sponsor and customer, Dr. Geoffrey Gerstner DDS, MS, PhD, is an undergraduate professor at the School of Dentistry at the University of Michigan – Ann Arbor. He teaches the dental concepts of occlusion to a class of about 100 students, covering mainly the concepts of protrusion, retrusion and laterotrusion and how certain variables such as the Curve of Spee and the Curve of Wilson dictate jaw configuration and alter the path of jaw motion (see section 5, pg. 3 for specific terminology). These concepts are particularly difficult to teach because they are complex, highly interrelated, and refer to jaw motions that are rather subtle and small.

Currently, the teaching methods include a physical (the articulator) and virtual model (Microsoft PowerPoint Presentation). Other examples of prior art and technology benchmarks can be found in Section 6. These methods are ineffective as teaching tools. The articulator has a manually manipulated upper jaw, which is not anatomically accurate. It is also is not big enough to provide demonstration to a large class (about 9”x9”x7”), and does not allow for teeth variability (teeth are fixed stone castings). The PowerPoint presentations are 2-dimensional representations of 3-dimensional motions, and do not allow any variation or manipulation by the instructor. At best these teaching methods limit the professor’s ability to accurately and intuitively teach fundamental dental concepts.



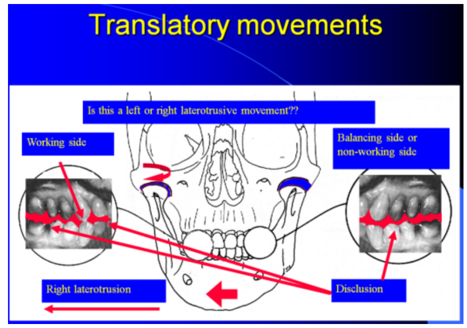


Figure 1. The current dental teaching methods for occlusion: (a) the articulator and (b) the difficult to understand Powerpoint ® slides

4.2 Motivation

The primary project motivation is to provide a more enriching and understandable educational tool by improving the current dental teaching methods. By accomplishing this we can make the job of the professor easier and more efficient while simultaneously maximizing concept and material retention capability for the students. As a secondary source of motivation, should the prototype be a unique invention, there may exist other business opportunities in the form of an educational product or research tool.

4.3 Scope

4.3.1 *Project Scope*

The solution to the identified problem involves fully redesigning the physical/virtual teaching method currently used by dental professors. The physical redesign incorporates scaling up the physical model, adding more functionality and automating as many of those functions as possible. For the virtual model, the redesign would enable controlling or mimicking the physical model motions via hardware/software integration. For this term, we are focusing on the physical aspect of the redesign, with the end goal of presenting a semi-automated, pre-programmed physical prototype. The virtual teaching method elements of the redesign will be left for future ME 450 terms. The aforementioned prototype was fabricated, assembled, and presented at the University of Michigan Design Expo on 10 December 2009. It will be delivered to our sponsor by 22 Decemember 2009 for integration into his future lectures.

4.3.2 *Scope of Final Report*

This paper presents the complete process for the creation of the prototype that is a semi-automated, large scale suspended lower jaw articulating device. The report will begin with an explanation of dental terminology and explore the relevant benchmarks for the project. The customer requirements and the subsequent engineering specifications will be detailed to focus the project. The concept generation and selection will highlight the steps taken to create a design that solves the engineering problem. The prototype design will be presented, as will the engineering justification for the design. The fabrication plan for the assembly of the prototype will be presented in detail. A method of validating our model as an effective dental teaching tool will be presented, along with minor design improvements for a future model. Design critiques are then explored, while future work to improve the prototype and recommendations for its use are provided. Final thoughts on the overall project will conclude the report.

5. NOMENCLATURE

The dental concepts discussed throughout this report are tabulated and summarized below. Images accompanying terms denoted with asterisk (*) shown in Appendix A.

Table 1. Dental Terminology

Term	Definition
Articulator	Mechanical device that simulates jaw motion, molds of teeth fixed to device
Bennett Angle*	The angle of the jaw when it translates forward and laterally to the right or left
Condyle	The smooth surface area at the end of the mandible which is a part of the jaw joint
Condylar Inclination	The shallowness of the skull with respect to the jaw joint and the mandible
Curve of Spee*	Anatomic curvature of the occlusal alignment of the teeth [1]
Curve of Wilson*	The angle of the posterior teeth with respect to one another as they sit in the lower jaw
Disclusion	A space between teeth of the upper and lower jaw, a non-contact point
Incisal	Of, relating to, or being the cutting edge of an incisor or canine tooth
Laterotrusion*	The outward lateral thrust given by the muscles of the condyle during movement of the mandible
Mandible	The bone of the lower jaw
Occlusion	The relationship between all of the components of the masticatory system in normal function
Protrusion*	A condition characterized by the forward displacement of a tooth or teeth
Retrusion*	A condition characterized by the backward displacement of a tooth or teeth [1]

6. TECHNICAL BENCHMARKS AND LITERATURE REVIEW

There are two aspects of jaw morphology that are variable in current dental teaching methods: jaw motion and teeth representation. The ability to highlight the different motions of the jaw and how teeth interact during these motions are essential for teaching dental concepts. There is not currently, to our knowledge, one benchmark that allows the user to vary the jaw motions and the teeth configuration in the jaw, therefore the two concepts will be treated independently. This section will present the relevant dental benchmarks for simulating the motions of the jaw and representing the anatomy of the teeth.

6.1 Jaw Motion

The motion of the jaw is currently simulated using a physical model called the articulator, and virtual models.

6.1.1 *Manual Articulator*

The articulator (Fig. 1a, pg. 3) is a mechanical device that simulates the relative motion of the lower jaw by moving a casting of the upper jaw, and has been the standard technology benchmark used by dental professors as a teaching tool since the early 1900s. The device allows the upper jaw to move with six degrees of freedom as an actual healthy jaw would. The mandibular joint provides these six degrees of freedom through the use of a 'ball and channel', allowing for both translational and rotational motion along and around each coordinate axis. Adjustments to the articulator can be made to vary and set the condylar inclination and Bennett angle of the mandible, allowing the user to demonstrate their effects on jaw motion. This section provides a brief overview of the history of articulators and concludes with a discussion of the current standard articulator.

6.1.1.1 *Brief History of Articulators*

One of the first articulators was patented in the early 1900s and many more have been put on the market since [2]. In addition to using articulators as a teaching tool, they are most commonly used in clinical practice [3]. Articulators are frequently used to fit a patient for dentures, crowns, or bridges. After an impression is made, dentists can use the articulator to simulate the patient's bite and jaw movements, allowing them to identify possible regions of undesirable teeth contacts and/or interferences. There are two main types of articulators used for clinical purposes, arcon and nonarcon, that differ in the structure of their mechanical joint [3]. An arcon articulator has the condylar guides attached to the upper jaw and the hinge axis attached to the lower jaw. For a nonarcon articulator, the opposite is true. Vojvodic et al. compares the accuracies of an arcon and nonarcon articulator and concludes that the arcon articulator reproduces more accurately the movement of an actual jaw [3].

6.1.1.2 *Current Standard Articulator*

The SAM (School Articulator Munich) model has a patented adjustable incisal table attached to the upper member of the articulator to measure protrusion and retrusion [4]. This provides a more accurate reading than one with a stylus, which may slip or stick to the stylus plate. The SAM model also has user-friendly features such as tilt supporting rods for angular positioning without interfering with the mechanical motion of the articulator. The tilt supports provide different view angles for simulation.
For all patented articulators, the upper jaw moves while the lower jaw remains stationary, contrary to an actual jaw [Conversations with Dr. Geoffrey Gerstner]. The standard articulator also lacks a jaw model that can be manipulated to show various curves of Wilson and Spee. For more examples of existing articulating devices see Appendices B.1 and B.2.

6.1.2 *Motorized Articulators*

In order to provide automated motion to the prototype, we discussed using an electronic system composed of a microcontroller and either motors or linear actuators. The following is an overview of the information we gathered on this topic. For a more detailed discussion, refer to section 9.

6.1.2.1 Motors

Several versions of motor operated jaws can be found in the literature, including one paper where two anthropomorphic robotic jaw designs were presented for use in dentistry, speech, and facial gesture affect research [5]. The first model uses four DC gear motors and a motorized cross-roller slider. The other model uses six DC motors to simulate jaw movement. For pictures of these two designs, and other existing jaw simulators see Appendix B.2.

6.1.2.2 Linear actuators

Three types of linear actuators exist that could directly allow for linear motion: electromagnetic, hydraulic or pneumatic [6,7]. Hydraulic and pneumatic systems require external pressurized systems that include tanks, compressors, hoses, fittings and valves, all of which increase the complexity of the system as well as create noise. Electromagnetic actuators are quiet and come in various sizes, but are the most expensive of the three. Hydraulic systems tend to be the most precise, reliable and robust, while pneumatic systems are the cheapest [Conversations with Dan Johnson].

6.1.2.3 Microcontrollers (the Arduino)

Control of linear actuators is accomplished through a microcontroller. A DC electronic microcontroller that can be used with linear actuators is called an Arduino model Duemilanova, an open-source product with 6 of its 14 channels capable of pulse-width modulation (PWM) that can be used to drive the actuators [8]. It is also possible to drive the electronics in forward and backward motions by incorporating a DC/AC converter called an H-Bridge on each actuator channel. The Arduino is also programmable, with a JAVA based software system and language fairly unique to Arduino [Conversations with Dan Johnson].

6.1.3 *Virtual Models*

Virtual models designed with 3D modeling software can also be effective teaching tools. Drs. Alan Hannam and David Tobias designed an interactive virtual model that simulates occlusion [9]. The 3D model allows one to zoom, rotate, and translate the entire model. At a desired angle and size, one can observe protrusion, retrusion, cyclical laterotrusion and cyclical lateroprotrusion. This model is anatomically accurate but only shows the movement of the teeth and does not include the jaw. This prevents one from adjusting the condylar inclination and observing more than one jaw variation. The teeth cannot be adjusted, thus omitting jaw movements affected by the varying curves of Wilson and Spee. There is a virtual 3D model more advanced then Hannam and Tobias' that describes a method of recreating an individual's mandiblular movement in 3D with a virtual articulator system [10]. Their system includes a synchronized 3D mandibular, sensor movement device that accurately mimics the natural occlusion of an individual. With teeth stabilizer castings and tracking plates on the upper and lower jaw, they were able to measure all six degrees of freedom for a testing subject, and were consequently able to produce a virtual image of the test subject's actual jaw that mimics their actual movements *in situ*. The limitation of this, however, is that castings must be made for each test subject, or the individual using the device, to model their natural occlusion movements, and the model not available for professors or students.

6.2 Teeth Configuration

The orientation and size of teeth directly determine the motion that the jaw can accomplish. This section will present the different methods of attaching teeth to the jaw and compositions of the reproduced teeth.

6.2.1 *Teeth Attachment to the Jaw*

Current methods of attaching teeth, whether it be an articulator or a patient, include stone casting clamps, dentures, and epoxy removable teeth.

6.2.1.1 *Stone Castings*

The articulator uses stone casts of teeth to show occlusions. Dentists make stone casts by first using a shape-memory alginate to take a mold of the patients' teeth. Once the mold hardens, the dentist pours plaster into the mold which hardens into a stone casting [Conversations with Dr. Geoffrey Gerstner]. The stone casting attaches to the articulator by a locking mechanism to hold it securely in place.

6.2.1.2 Denture Method

While not currently used in dental teaching models, Dentists create dentures as replacement teeth that are then attached to the patients jaw. To make dentures, the stone casting is split into sections of teeth and attached to pins which are implanted into the jaw bone. This method is useful for life-size teeth models and could potentially be replicated for enlarged teeth. To enlarge the teeth, we explored the methods and advantages of three-dimensional scanning and printing (or rapid prototyping) [Conversations with Steve White, Graduate Student in ME].

6.2.1.3 Removable Teeth

Viade, a dental appliance company, specializes in creating anatomically accurate jaw models with removable teeth [11]. These models only allow for removing and replacing the teeth and cannot be adjusted. The teeth fit securely into the fitted slot into the gums, and are made of a hard epoxy, while the gums are a rubber-type mold.

6.2.2 *Epoxy Teeth Composition*

Epoxy has a wide variety of uses and consistencies ranging from fishing lures to crack sealants [12]. The hardness or softness of an epoxy mold can be changed by varying the ratio of epoxy resin to a hardener. Epoxy can be soft and flexible like rubber or strong and rigid like a hard plastic. The recipe for a desired strength is determined by trial-and-error.

7. ENGINEERING SPECIFICATIONS

The table below summarizes the various engineering specifications we created to meet the customer requirements. The following sections go into more detail over how these specifications were developed, what trade-offs and correlations exist between them, and how they evolved. The coordinate system referenced is in Figure 2.

Table 2. Design Requirements and Specifications

	Design Requirements	**Design Specification**
1	Incorporate large scale model of human jaw system	8X physical model
2	Incorporate 6DOF jaw joint capability	Motion along and about all 3 axes
3	Properly simulate protrusion/retrusion motion	Motion of +2.5/-0.5” in x and -0.5” in z direction
4	Properly simulate laterotrusion	Motion of -0.5” in x, ±2.5” in y, -0.5” in z direction
5	Incorporate variable condylar inclination	Variation of ±20° around x axis

6	Incorporate variable Curves of Wilson/Spee	Variation of ±20° around both x and y axes
7	Properly simulate intruded/extruded front teeth	Variation of ±0.5" in z direction
8	Incorporate a suspended lower jaw	0DOF upper jaw, >0DOF lower jaw motions
9	Incorporate adjustable/fixable parts	Able to change movable parts from >0DOF to 0DOF
10	Provide clear views of parts during operation	Leave condylar joints & teeth exposed for viewing
11	Capable of completely opening jaw	Lower jaw range of motion from 0-90° around x-axis
12	Easy to use/minimal manual manipulation	Incorporate motion controlling mechatronics
13	Durable and robust	Withstand 20 lbf
14	Incorporate software	Programmed motions
15	Able to show effects of variables on jaw motions	Teeth withstand 5 lbf impact

Appendix C contains a preliminary evaluation matrix of the current dental teaching methods (the precursor to defining our customer requirements), and Appendix D contains our QFD chart, which relates the customer requirements to the engineering specifications.

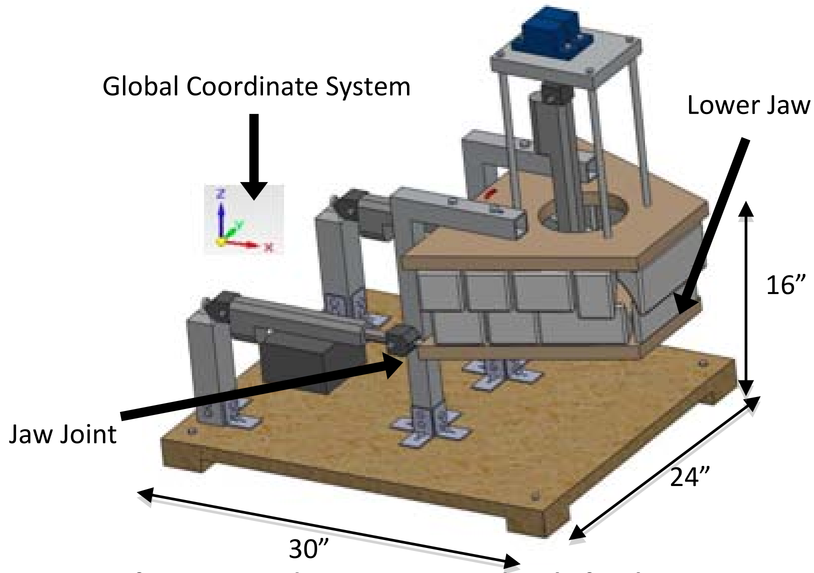


Figure 2. A reference coordinate system and scale for the engineering specifications

7.1 Large Scale Model

The final prototype will be eight times larger than a normal human jaw with overall dimensions of 30” wide, 24” deep and 32” high in order to be anatomically proportional, large enough to be understandable to the target audience (about 100 graduate students), and allow reasonable clearances for moving parts. This translates to expected lower jaw dimensions of 18.5” wide, 14” deep, and a height of 9” off the board. The upper jaw dimensions are similarly proportioned to fit this lower jaw size, and will be 20” wide, 15” deep, and a height of 16” off the board.

These were the optimal dimensions for students sitting in the back of a lecture hall to view during lectures [Conversations with Dr. Geoffrey Gerstner]. Additionally, larger models would be difficult to move from room to room, more costly due to more materials, and more difficult to actuate due to the larger size and weight.

7.2 6DOF Jaw Joint

The final prototype should be able to move the lower jaw in all six degrees of freedom (DOF) corresponding to motion in the x-, y- and z-directions, as well as rotations about each of these axes (roll, pitch, and yaw).

To accurately mimic the range of motion of the actual human jaw, the final prototype should be able to move in six degrees of freedom in some fashion, either via some kind of approximating actuation or incorporation of a jaw joint that allows for six degrees of freedom.

7.3 Simulate Protrusion/Retrusion

Protrusion: With a fully closed jaw as a starting point, the final prototype should be capable of moving the jaw in the +x direction, while letting the contact points of the teeth determine the z-axis motion of the jaw. The range of motion should be 0.5” in the +x direction and 0.5” in the - z direction.

Retrusion: Retrusion is the reverse of protrusion (which is why these two are together as one engineering specification). The final prototype should be capable of moving the jaw 0.5” in the –x direction and 0.5” in the - z direction with the final position being a fully closed jaw.

After discussions with Dr. Geoffrey Gerstner, became clear that the motions of protrusion and retrusion were dependent on jaw joint dynamics, jaw size and tooth configuration. Given the aforementioned jaw dimensions, we expect that the x-direction motion necessary would be approximately 17% of lower jaw depth (y-axis), with z-axis motion limited to approximately 6% of lower jaw height off of the board.

7.4 Simulate Laterotrusion

With a fully closed jaw as a starting point, the final prototype should be capable of moving the jaw in the side-to-side motion dictated by laterotrusion. This includes expected combined motion of 0.5” in the +x direction and 2.5” in the +y direction for motion to the ‘left’, and of 0.5” in the +x and 2.5” in the –y direction for motion to the ‘right’, and with 0.5” in the - z-direction.

The motion of laterotrusion is dependent on jaw joint dynamics, jaw size and tooth configuration just as are retrusion and protrusion. The expected maximum motion as a percentage of the lower jaw dimensions is the same as the above estimates for retrusion and protrusion.

7.5 Variable Condylar Inclination

The final prototype should be capable of mimicking several condylar paths that vary by approximately ±20° from a ‘standard’ inclination setting that corresponds to an ‘average’ condylar path. Figure 3 on page 10 is a schematic of one of our concepts that shows the various condylar inclines of a human jaw. Figure 3 a) is the average incline, 3b) is a relatively flat incline, and 3c) is a steep incline of the condylar motion.

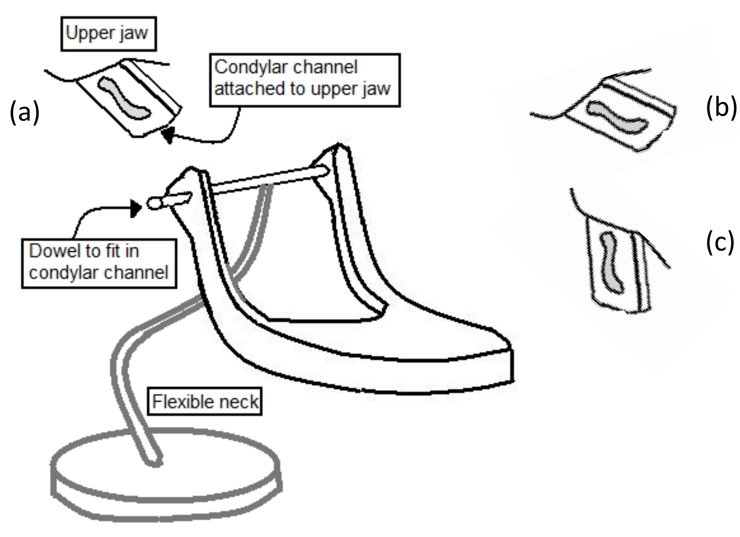
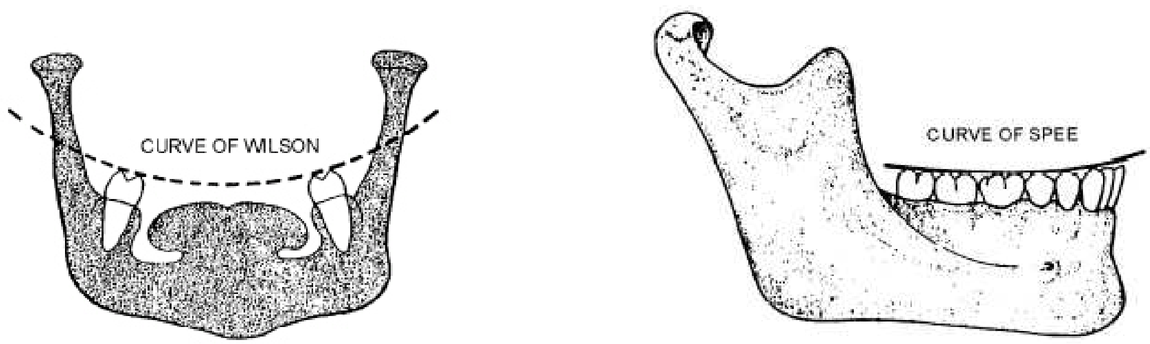


Figure 3. Illustrating the concept of variable condylar inclination, showing (a) an average inclination, (b) a shallow inclination and (c) a steep inclination

The condylar path does not need to be extremely variable [Conversations with Geoffrey Gerstner]. A ±20 degree variation in the condylar path would be sufficient in illustrating the effects of different condylar paths on the motion of the jaw and the interaction of the teeth.

7.6 Variable Curves of Wilson/Spee

Figures 4a) and 4b) below are representations of the 'Curve of Wilson' and 'Curve of Spee' respectively. The final prototype should provide for 2DOF angular motion for the back two upper and lower molars. The back molars vary in angular position around two axes parallel to the y- and x-axes of approximately ±20° from molars oriented normally within the jaw [Conversation with Dr. Geoffrey Gerstner].



(a) (b)

Figure 4. Showing the dental concepts of (a) the Curve of Wilson, where the molars are tipped towards/away from the inside of the mouth, and (b) the Curve of Spee, where the molars are tipped towards/away from the front of the mouth

7.7 Simulate Extruded/Intruded Teeth

For final prototype, the front two teeth and upper two canines will adjust 1" in both the – and + z-directions for 1DOF. The linear movement in these directions of ±1" magnitudes will be sufficient in portraying how the jaw path can be affected during protrusion, laterotrusion and retrusion [Conversation with Dr. Geoffrey Gerstner].

7.8 Suspended Lower Jaw

Accurate human anatomy incorporates a suspended lower jaw that moves in relation to a fixed upper jaw. The design is to include a suspended lower jaw that is capable of being actuated. The actuation method of the final prototype should move the suspended lower jaw. The actuation joints attached to the lower jaw should be capable of moving with reference to the global coordinate system, and the actuation joints attached to the upper jaw of the prototype support structure should be fixed with reference to the global coordinate system.

To provide for a suspended lower jaw while simultaneously allowing for the capability of motion, any joints attached to the lower jaw will have to be movable as well. The remaining joints that are not attached to the lower jaw (necessarily attached to either the support structure or the backside of the upper jaw part) must be fixed.

7.9 Adjustable/Fixable Teeth

To allow for maximum variability, all of the teeth should be able to be removed from the jaw. When attached, the teeth should also be allowed to rotate within the x and y planes.

All adjustable/movable teeth in the final prototype should be capable of being fixed in any and all of their allowable positions. They should also be capable of fully resisting any forces acting on them as a result of normal operation during laterotrusion, retrusion, protrusion and whenever the teeth are in contact. To have any positions 'fixed', the mechanisms designed to 'fix' them have to be strong enough to hold them in place during normal operation of the final prototype.

7.10 Clear Views of Parts During Operation

The final prototype should leave the jaw joint between the lower/upper jaw of the physical model exposed, thus allowing views of both its behavior and the relative motion of the outside of the teeth during motion. In order to see the relative motion of the inside of the teeth, supplementary software will be used.

Since this issue is entirely qualitative, we had to attack it as such. Since the eye can only really see what is within the line-of-sight, we are focusing on illustrating with the physical model what can be seen with the outside of the teeth and the jaw joint. Views that cannot be seen easily (such as views from the inside of the mouth) can be shown on screen via integrated software.

7.11 Completely Open Jaw

The final prototype should provide for opening of the upper and lower jaw to a maximum relative angle of approximately 90°. In order to most easily access all the teeth in the jaw by hand, we expect a maximum relative angle of 90° between the upper and lower jaw will be sufficient.

7.12 Easy to Use

The motion of the jaw will be controlled by full automation of all the prototype parts. This includes preprogrammed electronics and integration of micro-controlled linear actuators to control the motion of the jaw, and similar control and actuation for the teeth extrusion/intrusion and angling actions inside the gums. Thus, the model should provide automated operation for as many parts as possible.

7.13 Durability/Robustness

The materials composing the final prototype should be capable of resisting failure when acted on by any loads created during normal operation. Additionally, the motions and components that make up normal jaw operation should be adequately designed so as to not allow for any of the jaw parts to interfere, and thus become warped or bent as the jaw is actuated. Basically, in order to create a robust design, the materials have to be durable, and we also need to make sure that the design can't push or pull on itself to the point where it breaks.

7.14 Effective Educational Tool

The final prototype should incorporate a large physical model with smooth motions and clear visual understanding of what the jaw is doing during its motions, and a software component that is capable of mimicking the physical prototypes motions.

The target audience that the final prototype will be educating consists of about 100 undergraduate dental students. As such, the final prototype must be visible to those sitting in front and back of the class, while still being easily manipulated by the lecturer. We expect that a large physical model will be the best tool for those sitting up front in class and the easiest for a lecturer to use, while software up on a projector screen is the best tool for those sitting far away.

7.15 Incorporate Software Component

The final physical prototype system should incorporate a computer component that provides a software representation of the physical part of the prototype.

It was recognized by the customer that a physical prototype would be insufficient for showing both the inside and the outside of the jaw to the audience at the same time. The best way to do that would be to incorporate software to show on screen what can't be seen with line of sight vision on the physical model.

7.16 Show Effects of Variables on Jaw Motions

This engineering specification can be considered an aggregate of basically all the other specs, but it is still important because it helps keep us focused on the purpose of all of these specifications. That focus is to make sure that all of the variability and motions we are trying to include in the final design are designed to enhance the understanding of the underlying dental concepts, and not just to recreate their motions or configurations, while designing to ensure that the interactions of the jaw components will not damage the prototype. Therefore the components must be able to withstand 5lbf applied without a loss in their integrity or serviceability.

8. CONCEPT GENERATION

8.1 Functional Decomposition

In order to find out how the old method could be improved, it was decomposed into its basic functions, as in Figure 5. When completed, it was determined that the main areas capable of significant improvement dealt with the use of the articulator and the Powerpoint® slides. The aforementioned engineering specifications were generated based on finding ways to improve upon these lecture components.

It should be noted that the lecturing method as outlined in Figure 5 incorporates a physical model (the articulator) and is assisted with visual software (Powerpoint®). The design scope required in order to address improving both of these components simultaneously was determined to be outside the capabilities of a single semester research project. Consequently, this project focused on improving the physical model and leaves improvements to software assistance as a future research topic. A functional decomposition of the lecturing method using the Jaws: The Educator prototype can be found in Appendix E.

Improvements to the physical model were broken down into two mutually-exclusive topics: (1) how to replicate the jaw motions of laterotrusion, protrusion and retrusion, and (2) how to replicate the various jaw configurations (Curves of Wilson/Spee, varying condylar inclination, etc). The following sections show the initial concepts and ideas generated to interchangeably solve both of these issues.

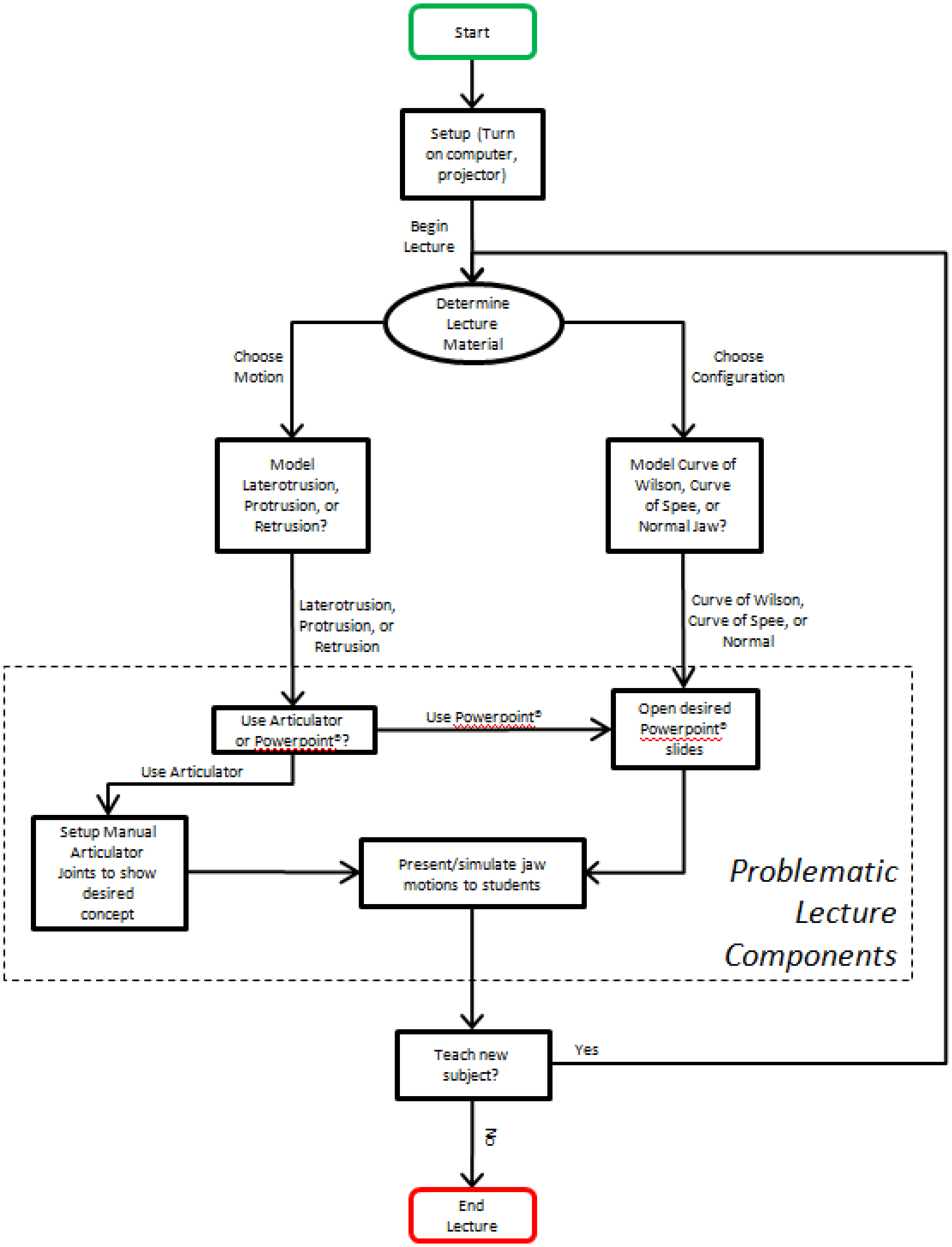


Figure 5. Functional decomposition of the old dental occlusion teaching method

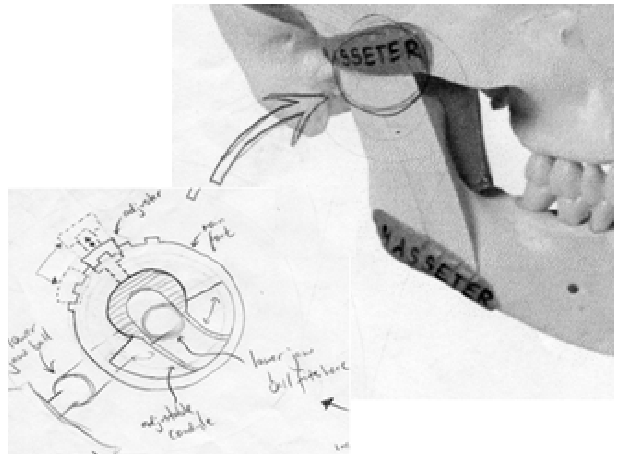
8.2 Concept Generation: Jaw Motion

All of the required dental concepts that the proposed model must address are directly related to the motion of the jaw. The accurate replication of the human jaw joint and the resultant obtainable motion is paramount to the successful completion of this project. Below are several brief descriptions of the proposed concept designs and a summary of their advantages and disadvantages.

8.2.1 *Updated Articulator*

This concept is an improved version of an articulator, the existing 6DOF benchmark technology. The condylar channel would be slightly curved instead of linear, making it more anatomically accurate (Fig. 6). This concept would also change the existing technology by featuring a suspended lower jaw.

Articulators are constantly being updated to take advantage of advancing mechanical technology. Creating something already familiar to those in the field of dentistry would allow this concept to be easily integrated into current practice. Though easy to integrate, this concept is not as innovative as several other concept designs.



F igure 6. Updated Articulator

8.2.2 *Rubber Condylar Joint*

Anatomically, the jaw joint is little more than a constrained socket in a bone and cartilage channel allowing for 6 DOF. This concept takes advantage of this by creating a jaw joint that is made of a flexible, malleable epoxy to account for the jaw motion while being strong enough to support the weight of the lower jaw (Fig. 7).

Creating the condylar joint exclusively of rubber is the simplest and easiest way to create a useful jaw model. This concept is manually controlled and relies on the user of the model to know what motions are possible for the jaw to perform. The joint itself does not limit any motion and does not allow for easy manipulation of the teeth.

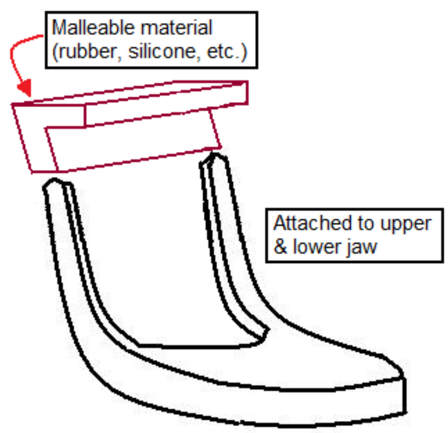


Figure 7. Rubber Condylar Joint

8.2.3 *Flexible Neck with Condylar Joint*

A flexible connection (neck) between the base and lower jaw is what makes this concept unique (Fig. 8, pg. 16). The neck would rigidly connect to the lower jaw by means of a dowel that can move throughout the condylar channel. The neck would be flexible enough to allow the user to easily move the jaw and strong enough to support the weight of the lower jaw in 6DOF.

The simplicity of this concept would make it very easy to use. Because this concept considers the lower jaw as being able to demonstrate all of the requisite motions of the system independent of the upper jaw, we would have complete freedom as to how we design the upper jaw. All motions would be performed manually and the success of this concept would be highly dependent on the creation or integration of an existing material that is both flexible and strong enough to meet the needs of the proposed neck.

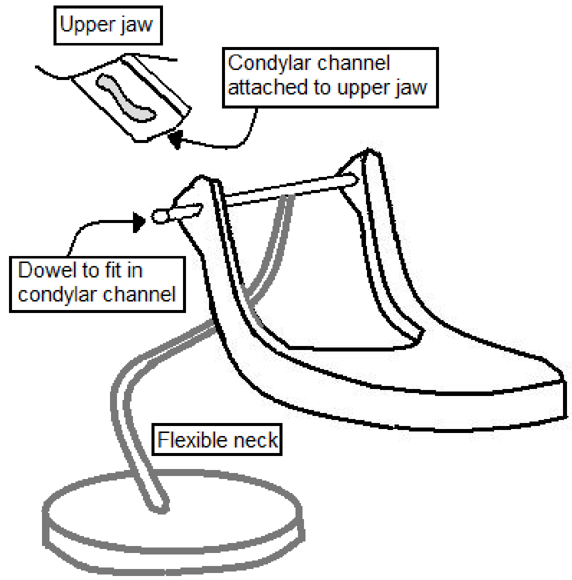


Figure 8. Flexible Neck with Condylar Joint

8.2.4 *Motorized Jaw*

This concept would address all six of the degrees of freedom of the jaw joint using four servomotors (Fig. 9). Three motors would be used to move the jaw in the translational x, y, and z planes and the other three would control the rotational tilt of the jaw in the roll, pitch, and yaw directions. The lower jaw would be mounted on a platform that is controlled by the motors. Computer programs would be created to control the timing of each motor to mimic the desired jaw motion.

The integration of motors into the design adds complexity but would open up options for adapting this project in the future. The motors would have to be synchronized with one another to effectively mimic the desired motion which could be completed using a computer program that could be reused and adjusted as needed. Though innovative, this concept would also stretch the proposed budget and would force us to focus the majority of our time on this specific problem.

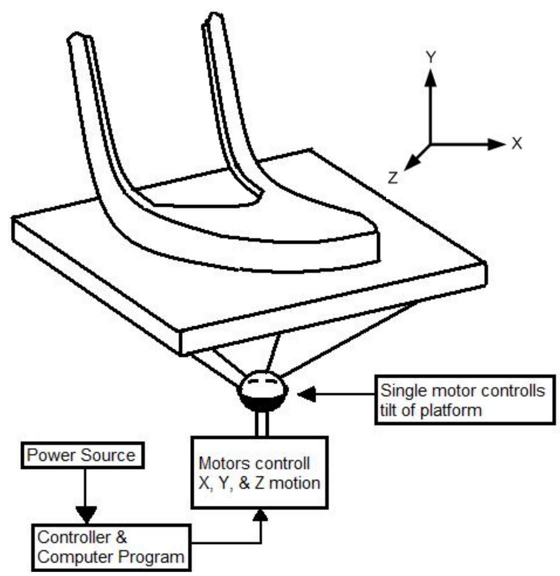


Figure 9. Motorized Jaw

8.2.5 *Linear Actuators*

The motions of the jaw are predominantly controlled by two groups of muscles on either side of the jaw. This concept proposes using linear actuators (pneumatic, hydraulic, electric, etc.) to simulate these groups of muscles, ultimately controlling the jaw motion using computer software (Fig. 10). Each end of the four linear actuators would connect to the jaw and frame using a ball and socket joint to allow for 6 DOF. The jaw joint itself would be modeled using flexible epoxy to provide a visual of the motion while not constraining the jaw in any way.

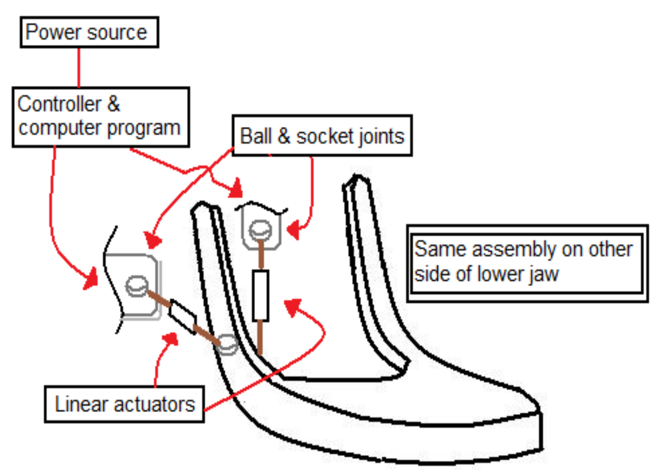


Figure 10. Linear Actuators

This concept relies heavily on mechatronic integration of the controller and actuators to the physical model of the jaw and teeth. The actuators would need to be precise in their ability to demonstrate jaw motions as well as strong enough to support the weight of the lower jaw assembly. This concept also allows for a 'hands off' demonstration, creating additional educational opportunities and many future development possibilities.

8.2.6 *Additional Jaw Concepts*

Several additional concepts regarding jaw motion were discussed during concept generation. See Appendix E.2 for summary of additional concepts as well as variations on the above.

8.3 Concept Generation: Teeth Adjustability

For the model to demonstrate several of the required dental concepts, certain teeth must be adjustable. The following sections detail several design concepts that meet the variability requirements and briefly summarize some of the advantages and disadvantages of each concept.

Note: The below concepts take advantage of anatomical constraints of the teeth. In general, teeth can be grouped in sections based on their location in the mouth and their function. For example, the back two molars in the lower jaw for our purposes can be grouped together because they perform similar functions in the concepts we are trying to replicate. As such, several of the below concepts take advantage of the anatomical constraint that only certain teeth or groups of teeth need to be adjustable to remain fully functional.

8.3.1 *Rigidly Attached Removable Teeth*

This concept involves creating rigid sections of teeth to be manually placed and adjusted into a flexible epoxy mold (Fig. 11). The mold, shaped and modeled after human gums, features cavities that the teeth would be force-fit into to lock them in place. The force-fit could be strengthened by lining the inner layer of the gums (rubber, adhesive, Velcro, etc.) to increase friction between the cavity and the tooth.

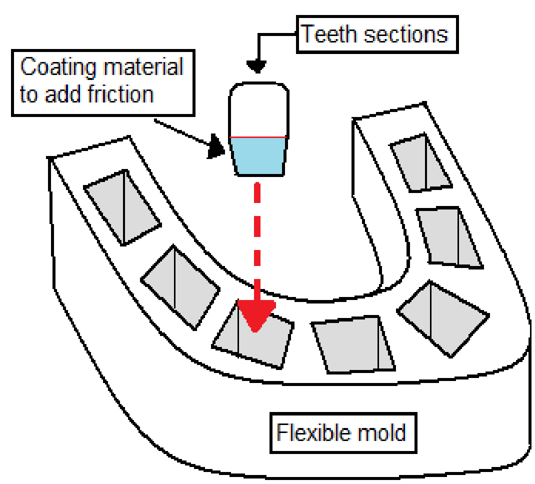


Figure 11. Rigidly Attached Removable Teeth

The simplicity and ease of use of this concept are among its strongest attributes. The user would be able to remove and replace the teeth to exaggerate any of the dental concepts (Curves of Wilson and Spee, dental varaition). Manual adjustments would be easy to perform. The lifetime of this concept would be largely dependent on the model's ability to retain enough friction to hold the teeth in place.

8.3.2 *Flexible Epoxy Mesh Mouth Guard*

Both the top and bottom gums will be made of a malleable material (epoxy, silicone, clay, etc.) for this concept (Fig. 12, pg. 18). The malleable material would be covered by a mesh mouth guard similar to those used by dentists to make impressions. Individual teeth sections would then be mounted on pins and these pins would be stuck through the holes of the mesh into the malleable material, locking the teeth in place.

This concept would be especially easy to adjust as the teeth could just press into and pull out of place. With the appropriate malleable material, the pins would have plenty of friction to lock them in place for any demonstration. The pins would also be flexible to change the angle of the teeth. The reliability over time of the material would need to be verified before continuing with this concept. Also, pins in the teeth could pose a safety hazard for the user of this model.

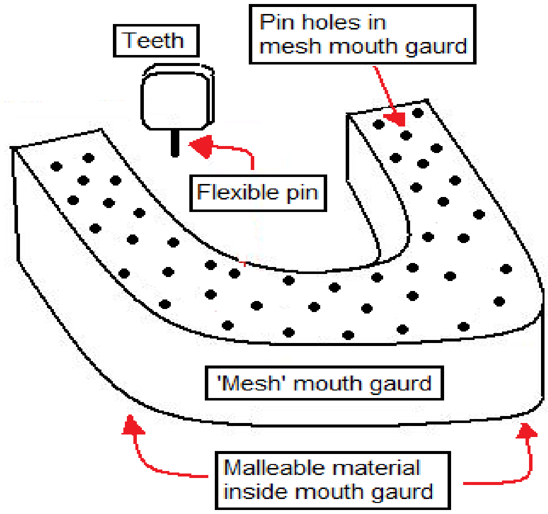


Figure 12. Flexible Epoxy Mesh Mouth Guard

8.3.3 *Actuated Teeth with Magnets*

This concept features actuated teeth motion (Fig 13). Sections of the teeth would be mounted on linear actuators (pneumatic, hydraulic, electric, etc.) and would move in and out of the gums using a controller with adequate clearances between the teeth and the gums. The tilt of the teeth would be manually adjustable by mounting one curved magnet to the base of the teeth and another magnet of the opposite curve to the end of the actuator.

Though complex, this concept opens a wide range of options that could make this project successful now as well as opening doors for future technology improvements and additions. With robustness, technology additions will also have an immediate impact on fabrication time and budget considerations.

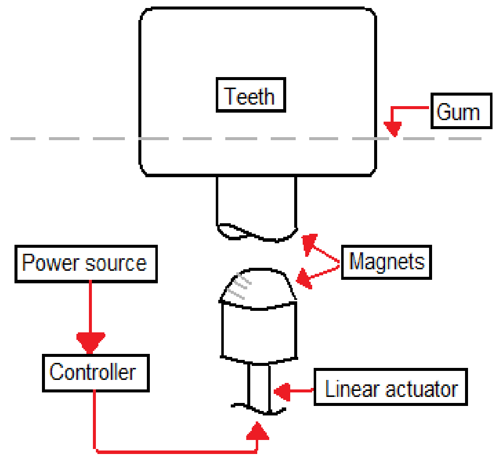


Figure 13. Actuated Teeth with Magnets

8.3.4 *Ball and Socket Joint Teeth*

This concept features teeth sections mounted on pins that are connected to a ball and socket joint allowing the teeth to incline about the joint (Fig. 14). The joint would then be attached to a screw that allows the teeth to extrude, within a certain range, in and out of the gums. The ball and socket joint would have the ability to lock in place, rigidly fixing the teeth in place.

This design concept allows the user to quickly tilt the teeth while maintaining the ability to intrude & extrude as needed. This concept is more aesthetically realistic in terms of the limitations to where human teeth actually may be located, but would also require a relatively high quantity of manual adjustment mechanisms.

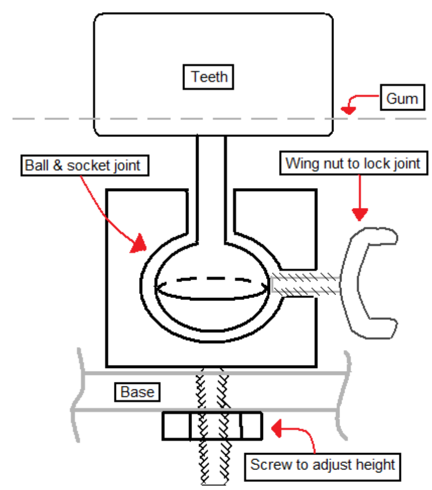


Figure 14. Ball and Socket Joint Teeth

8.3.5 *Rigid, Removable, and Variable Teeth*
For this design concept the teeth would be anatomically correct and detailed by way of rapid prototyping (3D modeling). This would allow us to take a computer model of the teeth and jaw and create a plaster mold of the teeth sections (Fig. 15). From there the molds would be used to make epoxy casts of the sections. These models would then be formed into replaceable sets of teeth, attached to denture pins, which enable demonstration of an individual dental concept of interest.

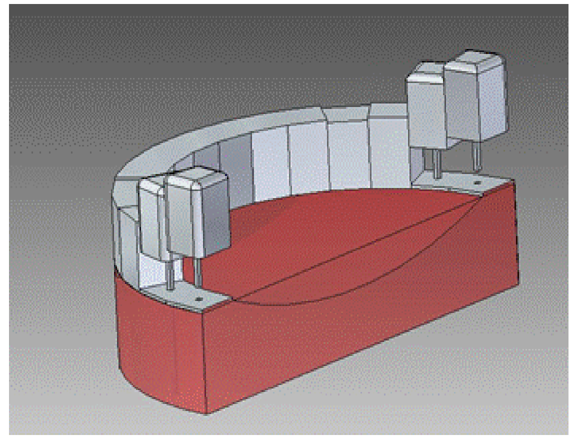


Figure 15. Rigid, Removable, and Variable Teeth

This concept allows for the most anatomically accurate creation of teeth by utilizing rapid prototyping techniques. Rapid prototyping could also be used to create other parts of the model that would be time consuming to machine. Though this concept is beneficial, there are additional costs associated with using the 3D modeling equipment. All models would have to be made into negative casts and then recast to ensure they would be strong enough.

8.3.6 Additional Teeth Concepts
Several additional concepts regarding the adjustability of teeth were discussed in the concept generation phase of the project. See Appendix E.3 for summary of additional concepts as well as variations on the above.

9. CONCEPT SELECTION

The preliminary concept selection was made based on a scoring system that analyzed each concept's ability to accomplish the design requirements. This scoring system is represented using Pugh Charts, see Appendices F.1, F.2, and F.3. The following sections will briefly outline the Pugh Chart and highlight how this metric led to an alpha design selection. As in the concept generation, design of the jaw motion is independent of the design of the teeth, and therefore will be scored separately.

9.1 Pugh Chart
A Pugh Chart is a graphical tool that scores the ability of a design to meet the design requirements. It functions by setting one design as a control, called a 'datum', such that all of the other designs can be ranked against it. The datum is the design that most closely performs the functions of the benchmark design, and the idea is that the other designs either improve/detract from the benchmark's ability to accomplish the design requirements. If the design accomplishes the requirement better than the Datum, it is given a positive score. If it does not accomplish this goal, it is given a negative score. Each design requirement is given a weight based upon its importance, and this weight is multiplied by the score. The scores are then summed for each design and the design with the highest score is the theoretical 'best'.

It should be noted that the Pugh Chart shown in Appendices F.1 and F.2 were completed using specifications that differ from the ones listed in Section 7. The concept selection was completed under the specifications listed in the appendices, and therefore were not changed as the project specifications have changed.

9.2 Individual Concept Scores: Jaw Motion

The motion of the jaw is both the most complex and most important feature of the design. A successful design must be an effective educational tool in its ability to accurately replicate the motions of the jaw. As an educational tool, it must be scalable and allow for easy viewing of the teeth and motions. Finally, it must be able to accomplish these requirements in a feasible, cost-effective manner. The following sections will analyze the results of the Pugh Chart for each jaw motion concept (Appendix F).

9.2.1 *Modified Articulator-Datum*

The modified articulator (Fig. 6, pg. 15) is the datum for the jaw motion Pugh Chart analysis. As such, it has a reference score of 0, and its attributes are the basis for other concept comparison. The modified articulator is taken to be the reference because the design only modifies the existing benchmark for our project. Modifications of the articulator design would retain all of the functional jaw motions while suspending the lower jaw for a lifelike representation. Due to its similarity to the current dental benchmark, it would be easy to use for professors. However, merely suspending the lower jaw does not resolve the issues with the present articulator. It would be difficult to scale, and issues of visual clarity would remain. All of the following designs will incorporate a suspended lower jaw as well. Also, the parts employed by current articulators are not commonly available; thus the price and feasibility of the design are concerns. Finally, the modified articulator lacks the innovative engineering techniques. As an improvement on an already widely used device, this design creates little in the form of tangible benefits to what is currently in use.

9.2.2 *Rubber Condylar Joint*

This design is a simplified, low cost version of the articulator with a rubber, maneuverable jaw joint (Fig. 7, pg. 15). It received the lowest relative Pugh score of 14. Not only can this design perform all of the requisite jaw motions, it can do so without the intensive condylar joint parts found in the articulator. This allows for easy and repeatable manipulation of the lower jaw. All 6DOF can be accomplished manually by the user. The professor must be constantly holding the jaw up, as gravity will pull the jaw into a wide open pose if it is not being manually held. The rubber must be rigidly attached to the support fixture, thus variations in the condylar inclination will not be possible. Since the professor must be in contact with the lower jaw during any operation of the model, the ability to see the motions will be severely limited. Therefore, the rubber condylar joint concept is an innovative modification to the articulator but it does not address the current articulator design issues.

9.2.3 *Flexible Neck with Condylar Joint*

The flexible neck joint incorporates a low cost jaw joint design that requires manual manipulation (Fig. 8, pg. 16). It received a Pugh score of 37. Similar to the rubber condylar joint in operation, it replaces the parts intensive jaw joint with an easily manipulated joint guided bar. With the upper jaw fixed, the lower jaw is maneuverable thus increasing the visual effectiveness as an educational tool. It is scalable and easy to move, however, the larger the model becomes, the more difficult it is to move and the more expensive the material. All of the jaw motions are possible, including a variable condylar inclination. As in the previous designs, the effectiveness of this model is diminished by its manual requirements. In order to replicate all of the motions of the jaw, the user would have to hold the front of the jaw, which would significantly decrease the visibility of the motions. Despite its relatively low estimated cost and high feasibility, it still retains the articulator's inability to clearly show all of the motions of the jaw due to user manipulation.

9.2.4 ***Motorized Jaw***
The motorized jaw joint design incorporates compounded motors for mechanical replication of the jaw motion (Fig. 9, pg. 16). The motorized jaw received a Pugh score of 77. In terms of jaw movement abilities, this is the most complete concept. The motors are controlled electronically, allowing for easy use and clear views of the jaw motion. All of the jaw motions would be achievable without manual manipulation of the joint. This design has considerable drawbacks; it is a complex and mechanically intensive system that requires much detail because of inter-connected movements, and would require many parts. The specific mechanical parts and motors are too expensive within the provided budget. Finally, safety is a concern as the mechanized motions would not be able to stop if someone or something interfered with the motions. Even though the design potentially satisfies the design requirements, construction of the motorized jaw is not feasible within the scope of time requirements and budget.

9.2.5 ***Linear Actuators and Elastic Jaw Joint***

Linear actuators are a low cost method of mechanically replicating the jaw motions that received the highest Pugh score of 93 (Fig. 10, pg. 16). Similar to the motorized jaw, the linear actuators replicate the motion of the jaw through electronic controls. This allows for full visual clarity and ease of use. The design is scalable, but limited to the loads being applied on the linear actuators. At the jaw joint there is an elastic opening, such that the jaw joint can move easily. This is so the linear actuators can be attached strategically on the jaw itself, which takes the engineering complexity out of the jaw joint. This should make the design less complex and more feasible. Linear actuators can be built at a relatively low cost, therefore more money and time can be spent on the rest of the design. The design has limitations; due to the size and nature of the actuators, it is unlikely that the lower jaw will be able to open completely nor can variable condylar inclination be achieved. Even though the jaw joint will be mechanically simpler, the electronic controller will be difficult to program. As in the motorized jaw, there are also safety concerns associated with any mechanized movement. Overall, the linear actuator with an elastic jaw joint is a relatively low-cost, feasible mechanical design.

9.3 Individual Concept Scores: Teeth Adjustability

To accurately present both normal and abnormal jaw motions, the teeth must be adjustable. The design must be adequately variable and fixable in a low-cost, easy to use manner. The following sections will analyze the Pugh Chart results for teeth adjustability.

9.3.1 ***Rigidly Attached Removable Teeth - Datum***
An improvement on the benchmark articulator design, the teeth are fixed in the gums but have the ability to be removed (Fig. 11, pg. 17). The teeth are set in such a way that during interaction with other teeth they remain fixed in the gum, allowing for clear views of interactions. The teeth can be removed and their positions altered, increasing the visual clarity of the model. However, the limitation of the design is that the height and angle of the teeth are not adjustable. This makes the design an incomplete teaching tool.

9.3.2 ***Flexible Epoxy Mesh Mouth Guard***
The flexible mesh is a low cost gum and tooth design that would allow tooth variability but cannot be adequately fixed (Fig. 12, pg. 18). The design received the lowest Pugh score with a 7. Since the mesh is flexible, the teeth can be angled, positioned, removed, and replaced with ease. The material used in the design is cheap and malleable, making it simple in production. However, there is no way to effectively

secure the teeth in place, repeatedly. This limits the teaching effectiveness of the design, because interaction of the teeth is a major aspect of the jaw motion, therefore the design is impractical.

9.3.3 *Magnets and Linear Actuators*

A complex system of magnets and linear actuators can be used to vary the height and angle of the teeth in the gum (Fig. 13, pg. 18). This design received a Pugh score of 38. It varies the teeth in the vertical direction by activating small linear actuators. The angle of the teeth can change by rotating the tooth cap in a magnetic socket. The teeth can be easily removed as well. All of these factors make it useful as an educational tool. However, the system is complex and expensive. It also will not be completely fixable; the magnets will barely resist horizontal movement due to teeth interaction. This limits the effectiveness of the variability of the teeth, and in combination with the complexity and cost of the design makes it infeasible.

9.3.4 *Ball/Socket, Compressive Tightener, Screw Adjusted*

A simplified, fixable version of the magnets and actuators model, this design received a Pugh score of 50 (Fig. 14, pg. 18). The ball and socket design allows for angle variations in the teeth, and the screws adjust the height of the teeth. There is also a compressive fastener on the screw, which fixes the system in place. Together, these systems accomplish all of the variations required of the teeth in a way that ensures the teeth will not move during interaction. The teeth can be removed in this system by using the adjustable screw attached to the socket joint. Also, the design is difficult to use, as each tooth or set of teeth must be manually adjusted and tightened. There are many parts, so assembly and cost are issues. Despite allowing the teeth to be completely adjustable and fixable, the difficulty of use makes this design impractical for the required use.

9.3.5 *Rigid, Removable, and Variable Sets of Teeth*

A modification of the datum, this concept accomplishes all of the design requirements in an easy to use, cost-effective way. It scored a 77 on the Pugh Chart. The individual or sets of teeth that need to be adjusted are easily removed and replaced with variable sized and angled teeth (Fig. 15, pg. 19). With rapid prototyping, different sets of teeth can be made at a minimum cost and time. The different sets of teeth will satisfy all of the design requirements for variability, and are fixed in the gum, which maximizes their effectiveness as a teaching tool. The difficulty of the design is that the user must manually change out the tooth or sets of teeth each time they want to show a different jaw movement. However, the combination of addressing all of the design requirements at a low cost makes this concept the most feasible.

10. ALPHA DESIGN DESCRIPTION

The chosen alpha design combines the linear actuators and elastic jaw joint concept (from section 9.2.5) and the rigid, removable and variable sets of teeth concept (from section 9.3.5). Figures 16a), b) and c) below are views of a CAD model of the alpha design which is detailed in the following sections. It should be noted that Figure 16 is only a visual aid and not the final concept version, and the teeth are not to scale with respect to the model. Figure 16 on page 23, shows how the teeth will be attached to the jaw.

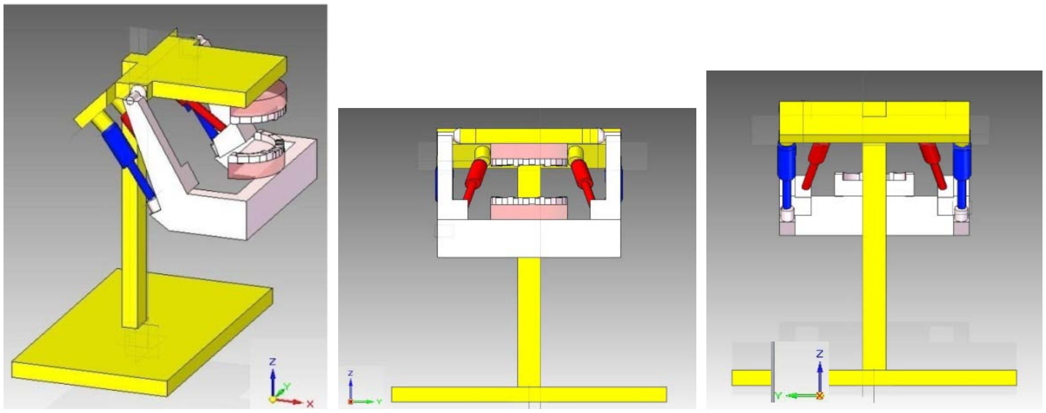

(a) isometric view (b) front view (c) rear view

Figure 16. Alpha Design CAD Representation: Jaw Joint

10.1 Alpha Design Components

The jaw has been divided into five subsections: (1) the supporting base structure, (2) the upper jaw, which is connected to the supporting base structure, (3) the lower jaw, which is held suspended below the upper jaw by four electronically controlled linear actuators and two elastic joints, (4) the lower jaw teeth and (5) the upper jaw teeth.

The supporting base structure consists of a flat plate at the bottom and a rigidly connected beam that holds up the upper jaw section. This upper jaw section is also a flat plate, but it has an angled section on its rear that provides connection points for the linear actuators, in addition to providing two contact points on its sides that will house the elastic joints for the lower jaw. The upper teeth connect to it on the underside of the front of the plate. The lower jaw and teeth connected on the top-side of the front of the lower jaw structure, is suspended beneath the upper jaw section by the four linear actuators at its rear and the elastic joints at the condyles, located on each side of the lower jaw.

10.2 The Linear Actuators and Lower Jaw Motion

The four actuators (two on each side of the jaw) are all connected to the jaw model with ball and socket type joints. One end of the actuators is connected to the angled rear section of the upper jaw plate, while the other end is connected to the rear side of the lower jaw. We chose ball and socket type joints to help mimic the six degrees of freedom of the human jaw. The combination of linear motion (provided by the actuators) with the rotation allowed by the joints makes available a limited type of six degree of freedom capability, depending on how each of the actuators are used. Thus, through independent operation of each of the four actuators, all necessary paths of motion required by the customer can be accomplished.

10.3 Teeth Adjustability

The teeth are divided into two sections: upper teeth and lower teeth. Both sections are solid pieces; the model does not incorporate individual teeth (see Figure 16). Sections of multiple teeth will be modeled similar to teeth implants (dentures) with magnets and pins, as seen in Figure 15, pg. 19. Each denture has pins on the side that contacts the jaw, while each jaw section has holes to guide the pins into place. The pins serve to keep the teeth from sliding with respect to the jaw. Magnets will also be incorporated in the jaws to attract the magnets in the dentures, thus holding the dentures to the jaws. In this fashion, we can create several denture models that represent the various tooth configurations required by the customer, and use them interchangeably in the physical jaw model to complement all the customer required jaw motions.

11 ENGINEERING FUNDAMENTALS

Various engineering fundamentals will be used to plan, test and prototype the proposed concept. These fundamentals include statics and solid mechanics, dynamics, and controls. Materials selection, manufacturing methods, and safety will also be important fundamentals to complete the alpha design.

11.1 Statics, Solid Mechanics

The proposed model needs to be stable both in and out of use. As a result of potentially long storage periods, model creation will take into account static analysis and solid mechanics properties to forecast the effects of static forces due to gravity during prolonged storage periods on the model. The biggest concerns during these storage periods are the stresses on the joints due to gravity. Based on these fundamentals, additional features may be added to ensure project quality throughout storage.

11.2 Dynamics

Fundamentals of dynamics will be essential when designing the motions of the jaw and when fabricating the linear actuators. The jaw motion resulting from the linear actuators must be precise to accurately demonstrate the required dental concepts. Analysis of the model's dynamics must be shown to ensure repeatability for the project to be a success.

11.3 Controls

In creating a mechatronic model, fundamentals of controls will be important in selecting exactly what motions the model is to perform. Fundamentals of controls will be paramount throughout the process of connecting the computer software (using the aforementioned Arduino) to the linear actuators. Without precise controls, the model will be unable to do what is necessary.

11.4 Materials Selection, Manufacturing Methods, Safety

Though not specifically an engineering fundamental, materials selection, manufacturing methods and safety will be just as important as any other method throughout the design process. The design process is only as good as the ability to actually create the prescribed prototype. Within the constraints of each fundamental, materials selection, manufacturing methods, and safety will further focus the design process.

12. ENGINEERING ANALYSIS

Using these fundamentals, several models and tests must be performed to ensure that the proposed design satisfies the design criteria. The analysis relating to the linear actuators is the most critical design aspect for the success of the project. Other project aspects that require analysis include mechatronic integration and joint load capacity.

12.1 Linear Actuator Analysis

The linear actuators will only support a finite weight. Due to budget constraints, the actuators to be used in this project will be fabricated using DC motors. As a result, a data sheet specifying applicable loads is unavailable. Before fabrication, tests must be performed on the linear actuators to determine how much weight can be supported.

12.2 Mechatronic Integration

The success of the project will be largely dependent of the ability of the model to replicate specific motions of the jaw. These motions will be electronically controlled using programs written specifically to reproduce each movement. To ensure the precision of these motions and quality of the mechatronic equipment, the actuators will need to be calibrated and tested alone prior to any testing attached to the model.

12.3 Joint Load Analysis (Storage)

Because the model will spend a significant amount of time in storage, analysis on the materials, particularly at the joints, must be performed to ensure model quality throughout long periods of time in storage. This analysis will include modeling the jaw design as a static object with applied loads (mostly due to weight). As a result of this analysis, additional precautions may need to be taken to mitigate the risks associated with project storage.

13. PROTOTYPE DESCRIPTION

The prototype is the feasible physical model of the final design that is to be completed given the time and budget constraints. It will perform all of the functions of the final design and will meet all of the same engineering/customer specifications. This section will detail the prototype design and how the prototype will satisfy the engineering parameters identified in the previous section. First, the general design will be presented, and will then be described in more detail as subsections. These subsections include prototype structure, jaw actuation, teeth representation, and electronic controls.

13.1 Prototype Design

In accordance with the sponsor requirements, the prototype will be scaled to eight times the size of the typical human jaw and teeth. The prototype, shown in Figure 17 on page 26, will simulate several motions of the human jaw and will replicate the 6 DOF of actual jaw joints. The 6 DOF will be accomplished through the use of three linear actuators attached to ball and socket joints. Two of the actuators will be mounted horizontally to the back of the lower palate. The third actuator will be mounted vertically and will be attached to a structure above the upper palate. Each of the actuators will be attached to the lower jaw and to the support structure through ball and socket joints. The main assembly will be supported by two aluminum square tubes. The base will support the weight of the entire structure. The actuators can be automated using a microcontroller (programmed motions) or manually using switches. All electronic components will be mounted to the base.

All prototype parts are referenced by their part number in parts list in Appendix G.1, and the final bill of materials in G.2. Their corresponding engineering drawings are in Appendix H.

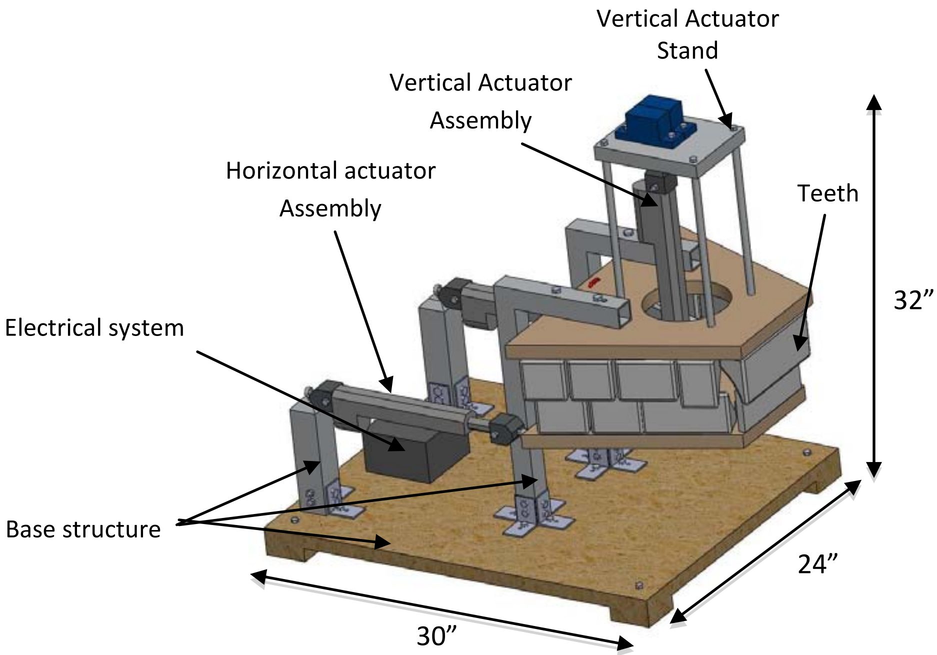


Figure 17. Full prototype isometric view with important sub-assembly designations.

13.2 Prototype Structure

The base and supporting structure are the anchors of the design. Each component was designed or selected in contingency with the parameter analysis detailed in the Section 14 below. The following section will detail the prototype structure (shown in Figure 18, pg. 27), and will include the base, the actuator supports, and upper jaw supports.

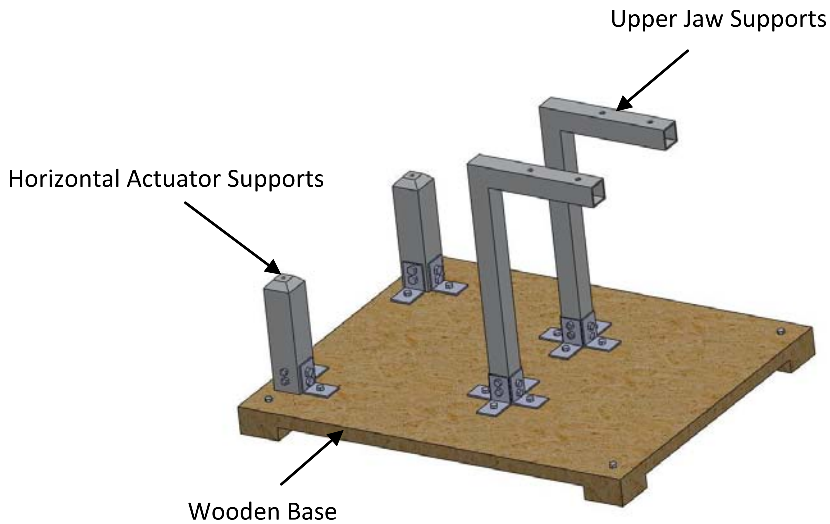


Figure 18. Prototype structure isometric view. The horizontal actuator supports and upper jaw supports are fastened to the base.

13.2.1 Base

Appendix H.2 details the design of the wooden base mounting board (Part 17). Wood was selected as the material because of its low weight and the ease with which mounting holes can be drilled. The base was sized to easily fit through a doorway while supporting the entire prototype. It will sit on four wooden legs located in each corner. The legs will be fixed to the base board using wood screws. These legs will allow room for fasteners to be set on the underside of the board as well as provide finger clearance for lifting the prototype. The base will also support the forces caused by the weight of the prototype, linear actuation, and teeth manipulation. The base structure will need to be drilled to accommodate the prototype structure fasteners and legs.

13.2.2 Horizontal Actuator Supports

Two vertical supports will be rigidly attached to the base using angle brackets (Part 18), and will serve as the connection for the horizontal actuators to base. These vertical supports will be symmetrically mounted about the centerline of the base, located near the back of the base to accommodate the length of the actuators. The supports will be made from aluminum so that the top can be threaded to accommodate a ball and socket joint. The aluminum will also provide support for the horizontal actuators and therefore was selected for its additional strength over alternative materials (wood).

The attachment of the rear horizontal actuator supports to the base is shown in Figure 18, and individually in the engineering drawing in Appendix H3. They will be mounted to the board using angle brackets (Part 18) and fasteners. The vertical supports will need to have holes machined into their lower section to accommodate the bracket mounting bolts.

The top face of the horizontal actuator supports will be tapped and threaded (Appendix H3). A right angle ball and socket joint (Part 3), will be screwed into the threads, and will be connected to the horizontal linear actuator. The top face of the vertical support will be chamfered to allow the clearance necessary for motion.

13.2.3 Upper Jaw Supports

The upper jaw will be supported by two aluminum square tubes, angled at 90 degrees (Part 14). The tubes were selected as aluminum because of its high strength to weight ratio and its availability. These square tubes were determined, by the parameter analysis below, to adequately support the weight and motion of the prototype. Engineering drawings of the supports can be found in Appendix H8. The total height of the upper jaw supports was determined to provide clearance for the most extreme positions in motion. The supports were spaced such that they will not interfere with the motions of the two horizontal linear actuators.

The upper jaw supports will be rigidly attached to the base in a similar manner as the horizontal actuator supports. Angle brackets will be mounted on each face of the supports, and the supports will be drilled to accommodate the bracket fasteners. The brackets will be fixed to the base using fasteners as described in the previous section.

The top of the angled support will be drilled as shown in the engineering drawings. These holes will accommodate the fasteners connecting the upper palate to the supports. The spacing of the top angled support tubes (8”) was determined to maximize the connection area on the upper jaw palate, while not interfering with the placement of the teeth on the underside of the palate.

13.3 Jaw Actuation

All movement of the lower jaw will be controlled through the use of three linear actuators. These linear actuators, with specified ball and socket mounting joints, will be able to provide the prototype with 6 DOF of motion and simulate all of the motions specified in the parameter analysis. Two linear actuators will be connected to control motions in the X and Y planes while the vertical linear actuator will control motion in Z plane (Fig. 19, page 29). The upper jaw, as mentioned above, will be rigidly attached to the support structure. This section will detail the design of the jaws, linear actuators, and linear actuator connections.

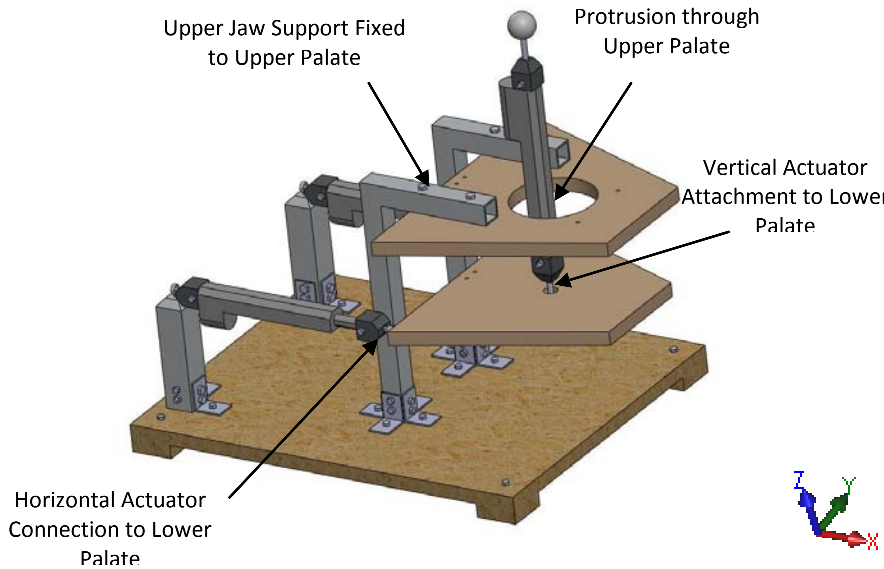


Figure 19. Attachment of the jaw palates to the structure and linear actuator attachments to the lower jaw.

13.3.1 ***Lower Jaw***

The design of the lower jaw is dependent on the anatomy of the lower teeth structure and the relevant connections for the three linear actuators.

Anatomical accuracy of the teeth was determined to be non-essential in the customer requirements and therefore the teeth alignment is approximated by a trapezoidal shape, shown above in Figure 19. The teeth alignment mirrors the jaw shape. Therefore the lower jaw palate design will also be trapezoidal. To minimize the weight, the palates will be made of wood. The edges of the jaw will be rounded for aesthetics and safety.

In a human jaw, the upper jaw remains stationary and the lower jaw moves. For the prototype design, all three actuators will be attached to the lower jaw (Figure 19). The two horizontal actuators will be symmetrically attached to the back ends of the jaw. The back of the lower palate will need to be drilled and fitted with tee-nuts (Part 19) to fix the inline ball and socket joint (Part 4) to the palate.

The vertical linear actuator will be attached to the lower jaw by a different ball and socket joint. This joint requires a counter-bored spherical hole drilled into the bottom face of the jaw. The ball will sit in the counter-bore, and the hole through the remaining palate will be large enough for a threaded rod to move for the entire range of motion of the upper actuator.

13.3.2 ***Upper Jaw***

The design of the upper jaw is dependent on the anatomy of the upper teeth structure, as well as the relative range of motion of the vertical linear actuator. The upper teeth structure will be similar to the lower teeth trapezoidal shape, except that the maximum width of the upper jaw is larger (20”) than the lower jaw (18.5”). As mentioned before, the upper jaw will be rigidly supported from the base by angled square tubes.

Due to the size of the vertical linear actuator, the linear actuator must protrude through the upper jaw structure as shown in Figure 19. It will be secured by a separate support structure and mounted on top of the upper palate (detailed in section 13.3.4.1 below). In addition, to allow the full range of motion for the vertical actuator, there will be a 6.5 inch diameter hole in the center of the upper palate, inside which the actuator can move.

13.3.3 ***Horizontal Linear Actuators***

The location of the horizontal linear actuators (Part 1) on the outer back edge of the jaw allows for several specified motions: laterotrusion, protrusion, and retrusion. The ball and socket joint connections allow the linear actuators to rotate freely. The horizontal actuators have a 6 inch stroke and will be purchased from Progressive Automation. Due to the need for retrusion, the horizontal actuators must be able to move backwards. With this in mind, the horizontal actuators were positioned on the base such that typical jaw rest position will occur when the actuators are each extended 2 inches. An exploded view of the horizontal linear actuator assembly is shown in Figure 20 below for clarity.

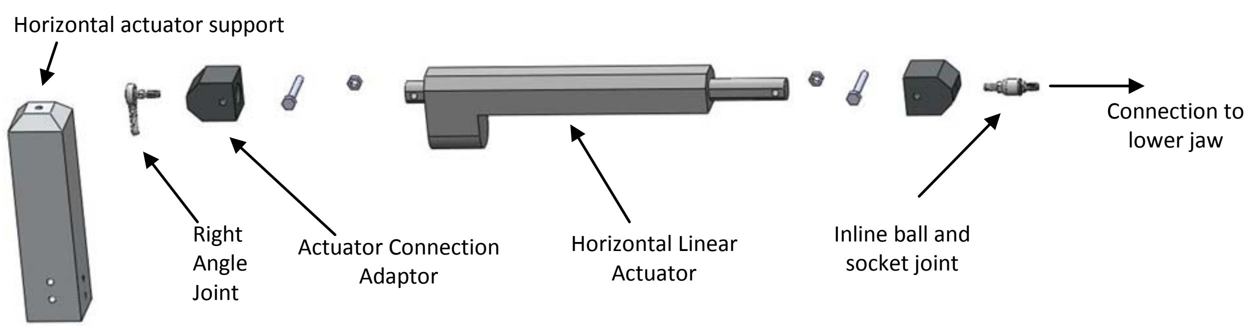


Figure 20. Exploded view of the horizontal actuator assembly. The view, from left to right, represents the assembly from the back of the prototype to the connection to the lower jaw.

As mentioned previously, the inline ball and socket joint (Part 4) will be threaded into the back face of the lower jaw. The opposite end of the ball and socket joint is also threaded. The front end of the actuator consists of a hole for a pin to go through for attachment. To connect the front of the actuator with the ball and socket joint attached to the lower jaw, a cylindrical connection needs to be fabricated. This connector (Part 7) will be referred to as the actuator connection adaptor. It will have a female shank on the front face for the ball and socket to thread into, and will have a cavity on the back end, with pin-holes drilled into the sides, such that the actuator’s front end will fit into the cavity (see Appendix H4). A pin will be fit through the coincident holes hindering rotation (the ball and socket joints already allow the 6 DOF). On the back end of the actuator, there is a similar connection piece. The same actuator connection adaptor can be used for the back end, to connect the actuator to its vertical support. This support will be a right angle ball and socket joint, which has a male threaded end. This end will thread into the back of the actuator connection adaptor and the front will be attached to the actuator in the same fashion as the front. These connections are identical for both horizontal linear actuators.

13.3.4 *Vertical Linear Actuator*

The vertical linear actuator (Part 2) has a 9 inch stroke and will be purchased from Progressive Automation. The vertical actuator bears the majority of the weight of the lower jaw assembly. It will connect to the lower jaw through a ball and socket joint. It also protrudes through the upper jaw because of the size necessary to open the jaw the required distance. Due to the large size, a separate support structure is to be mounted on top of the upper jaw and will be the upper connection point for the vertical actuator. To adequately support the rotation of the horizontal ball and socket joints due to gravity, a passive elastic support system will be suspended between the upper and lower jaw palates.

13.3.4.1 Connection to Lower Jaw

The vertical linear actuator is to be downward facing, such that an extension in the actuator will either push or pull the lower jaw (see Figure 21 for vertical actuator assembly). The lower jaw has a counter-bored hole in its bottom face for a threaded ball (Part 5) to be set in. The threads will face up, such that a threaded rod (Part 6) can be inserted through the lower palate into the ball. This threaded rod will then be threaded into an actuator connection adaptor (Part 8) which is larger than the adaptor for the horizontal actuators. This connector will fix the threaded rod to the front of the vertical actuator.

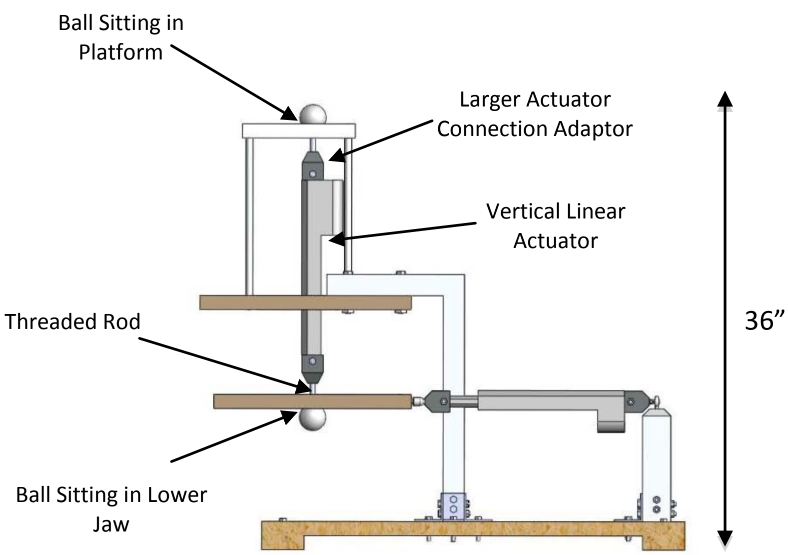


Figure 21. Prototype side view with vertical actuator caps removed for clarity. The upper ball will sit in a recessed section of the vertical actuator support platform while the lower ball will sit in a recessed hole in the underside of the lower jaw.

To ensure that vertical linear actuator will push or pull the lower jaw, the threaded ball must be attached to the jaw and allowed to rotate. This is accomplished by fixing an enclosure (Part 9) around the ball. This case is shown in the assembly in Figure 22 below, and individually dimensioned in Appendix H6. The ball cap will be manufactured out of PVC, and will have winged ends to allow for attachment to the lower jaw. The lower jaw is to be drilled such that the ball cap fasteners can go through the jaw.

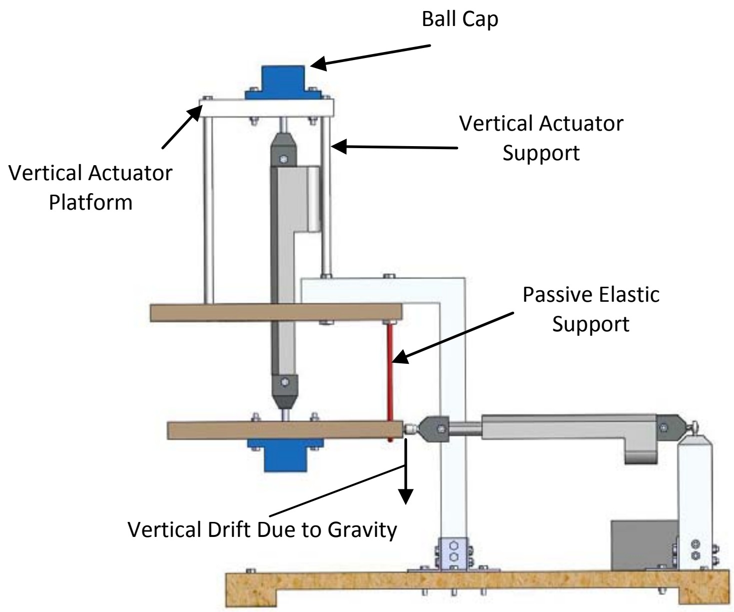


Figure 22. Side view of the prototype highlighting the ball caps to secure the vertical actuator.

13.3.4.2 ***Vertical Actuator Support Structure and Connection***
The vertical actuator support structure is a platform raised up on 4 aluminum rods (Figure 22). The rods will be threaded on each end for fastener attachment. The rods are aluminum to allow for the threading, structural stability, and low weight. Like the lower jaw, the platform will have a spherical counter-bore for a threaded ball to sit in. The counter bore will recess into the top face of the platform, and the bottom half of the platform will have a hole through it. The platform is to be 8x6 inches to straddle the hole for the vertical actuator in the upper jaw without interfering with the teeth on the underside of the palate, and will be made out of aluminum stock due to availability and low weight.

The ball size was selected to have a long threaded internal area as well as allow for a 1 inch hole opening in the platform so that the actuator can move freely. The long threaded area is for safety because the actuator and ball joint are weight bearing. To ensure that the ball, when pushed by the actuator, can resist movement in the vertical direction, a cap is to be placed over the ball. This cap is identical to the cap on the lower jaw. It will be attached to the support platform by fasteners through its winged sides onto the support platform. See Figure 22 for the connection between the upper threaded ball and the vertical actuator. The threaded ball will be connected to a threaded rod, such that the larger actuator connection adaptor can be used to connect the ball and the back of the vertical actuator.

13.3.4.3 ***Passive Elastic Support***
To account for instabilities arising from the ball and socket joints, a passive elastic support (Part 40) will be employed. There is a tendency for the horizontal linear actuators to drift down at the connection between the ball and socket joint and the lower jaw (Figure 22). This is a limitation of the three actuator design, because there are not enough vertical restrictions in place to support the model. As a result, the model can rotate vertically around three independent locations (horizontal actuator support, horizontal connection to the jaw, vertical connection to the jaw). To sufficiently restrict the vertical drift of the

horizontal actuator, and thus ensure precise motions of the jaw, there will be a passive elastic support system mounted on the jaws. Located symmetrically (with respect to the centerline of the jaws) at the back end of the jaw, there will be two holes drilled into the upper and lower palates. Two elastic support bands will be attached to the hooks mounted in the upper and lower palates. This elastic support will be located near the back of the palate (1/2” off back edge), such that the elastic is supporting a portion of the actuator weight to counteract vertical drift. The elastic will be a passive support system and will have no direct impact on the motion of the jaw except to support the ball and socket joint connection. The elastic is sized such that the strength of the actuators can easily overcome the force of the elastic, and therefore no motion will be impaired.

13.4 Teeth

The prototype of the teeth assembly is eight times the size of a typical set of human teeth and will be manufactured using balsa wood. Balsa was chosen for its low weight as well as various environmental considerations. Anatomical intricacies of the teeth may actually make it more difficult to demonstrate dental concepts in a classroom setting as well as add unnecessary complexity to the design. As a result, anatomical accuracy is not a priority for the prototype and therefore the teeth will not be greatly detailed. The teeth will be shaped as either “cubes” or “shovels,” depending on the tooth or group of teeth (Fig. 23). These simple teeth will still enable clear demonstrations for occlusions and replicate all necessary concepts. The teeth will be attached to the palates using hook and loop fasteners which will allow for simple and efficient removal and replacement.

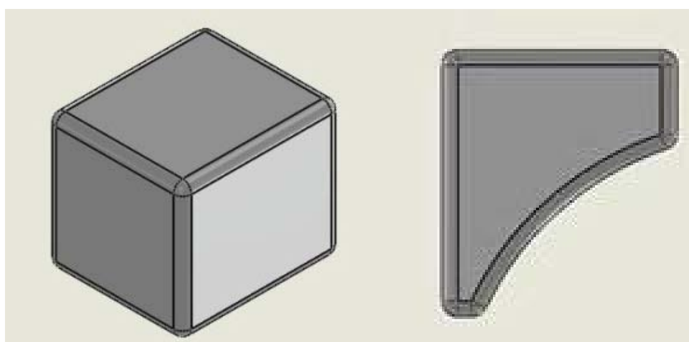


Figure 23. Cube and shovel shapes for the teeth

13.4.1 *Upper and Lower Palates*

Like a typical jaw, the upper palate of the prototype is slightly larger than the lower palate. The upper palate will extend over the lower palate, as shown in Figure 24 pg. 24, to create a small overbite typical of human teeth (See Appendix H.14 for dimensions and engineering drawings for teeth).

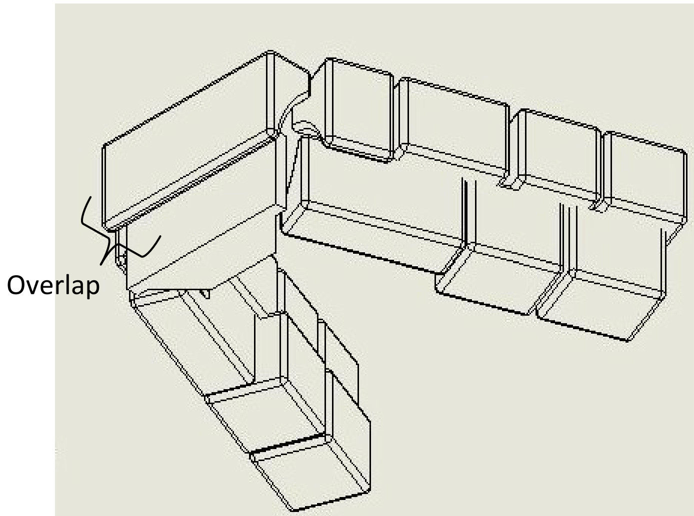


Figure 24. Isometric view of upper and lower palates creating a slight overbite

13.4.2 *Teeth Alignment*
The teeth will mimic the typical teeth alignment of a human jaw. To avoid crowding, the prototype is designed with adequate spacing in between the teeth. Table 3 below includes all the dimensions and shapes for each teeth section, seen below.

Table 3. Description and Dimensions of Teeth

Teeth Section	**Description**	**Dimensions (h x w x l)**
Lower Incisors	4 teeth – shovel – front teeth	3" x 2" x 7"
Lower Premolar	3 teeth – shovel + cube – either side of front teeth	3" x 2" x 6"
Lower Molars	1 tooth – cube – back 4 teeth, two each side	3" x 3" x 3.5"
Upper Incisors	4 teeth – shovel - front teeth	3.5" x 3" x 8"
Upper Canines	1 tooth – shovel – either side of front teeth	3.5" x 3" x 2.5"
Upper Premolar	2 teeth – blocks – between canines and molars	3" x 3" x 4"
Upper Molars	1 tooth – cube – back 4 teeth, two each side	3" x 3" x 3"

13.4.3 *Replaceable Teeth*

Replaceable teeth to show the effects of the Curve of Wilson, Curve of Spee, intrusion, and extrusion will be manufactured. Figures 25 a) and b) compares the jaw with and without the replaceable teeth respectively. Figure 25 b) shows both sides of an open jaw with the replaceable teeth. The four back molars, two upper and two lower, will be created to demonstrate the Curve of Wilson and the Curve of Spee on either side. Replaceable upper canines and upper incisors will provide demonstrations involving intrusion and extrusion.

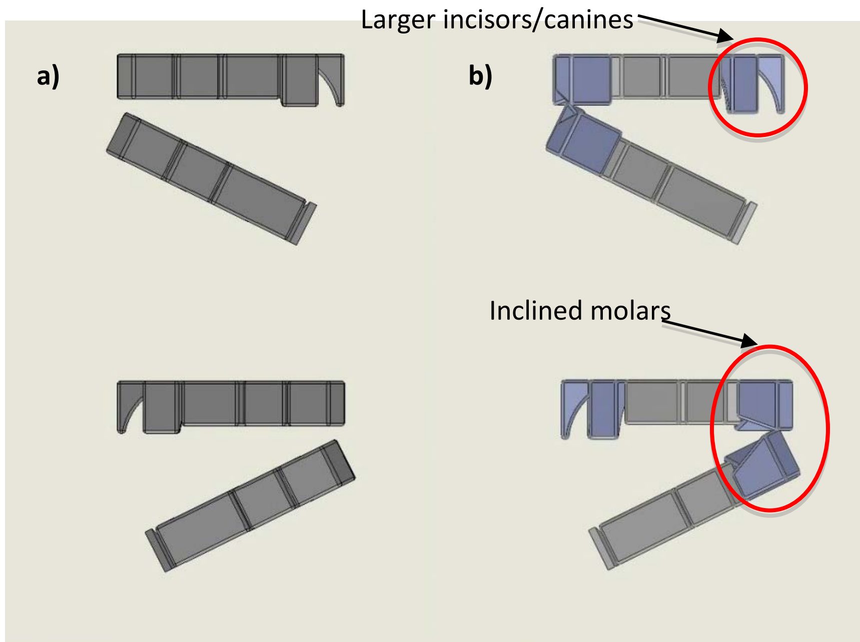


Figure 25 a) Side views of the open jaw with normal sized teeth and b) side views with replaceable incisors, canines, and molars

13.4.3.1 Alignment of Replaceable Teeth: Teeth alignment will be determined by the user, depending on the concept to be modeled.

13.5 Electrical Components

The three linear actuators, connected in parallel, will be powered by a ViewSonic® 12V, 3.8A transformer that can be plugged into any normal three-prong 100-240VAC, 50-60Hz electrical outlet. To control the delivery of that power, two methods may be utilized: (1) computer programming via an Arduino® Duemilanove microcontroller and three National Instruments® LMD18200T H-bridges, or (2) three manual DPDT (dual-pole, dual-throw) switches. Figure 26 below shows the final wiring schematic for the prototype. All of the electronics will be housed in a PVC enclosure.

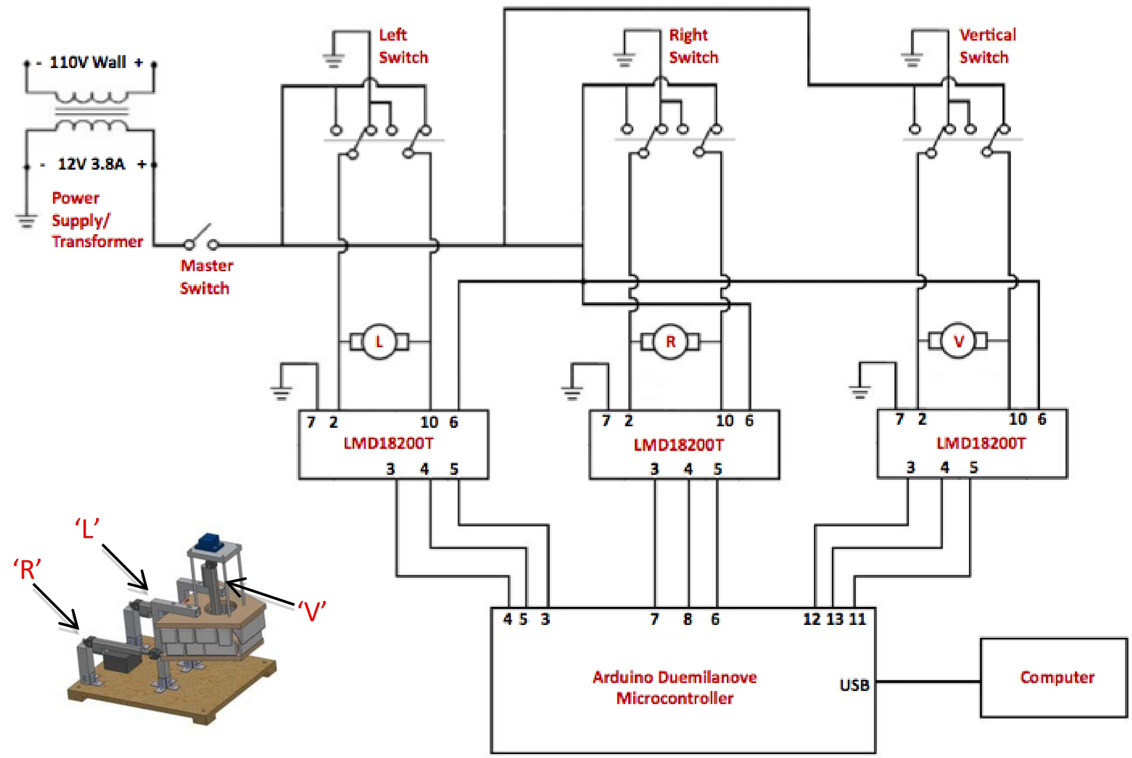


Figure 26. The wiring schematic of the electrical setup, showing the ports used to connect the computer, the microcontroller, the LMD18200T H-Bridges, the three linear actuators ('L' = left actuator, 'R' = right actuator, and 'V' = vertical actuator), the power supply, and the three DPDT switches.

13.5.1 *Transformer/Power Supply*

The power supply is a ViewSonic® 12V, 3.8A wall transformer that plugs into any standard 3-prong wall outlet capable of 100-240VAC at 50-60Hz, many of which are found in the lecture halls where the prototype will be used. Each linear actuator is connected to the power supply in parallel.

13.5.2 *Arduino® Microcontroller*

Figure 27 on page37 shows the Arduino® Duemilanove microcontroller used in this project, which is powered via the standard USB plug connected to the computer. The full datasheet for the microcontroller can be found in Appendix I.1.

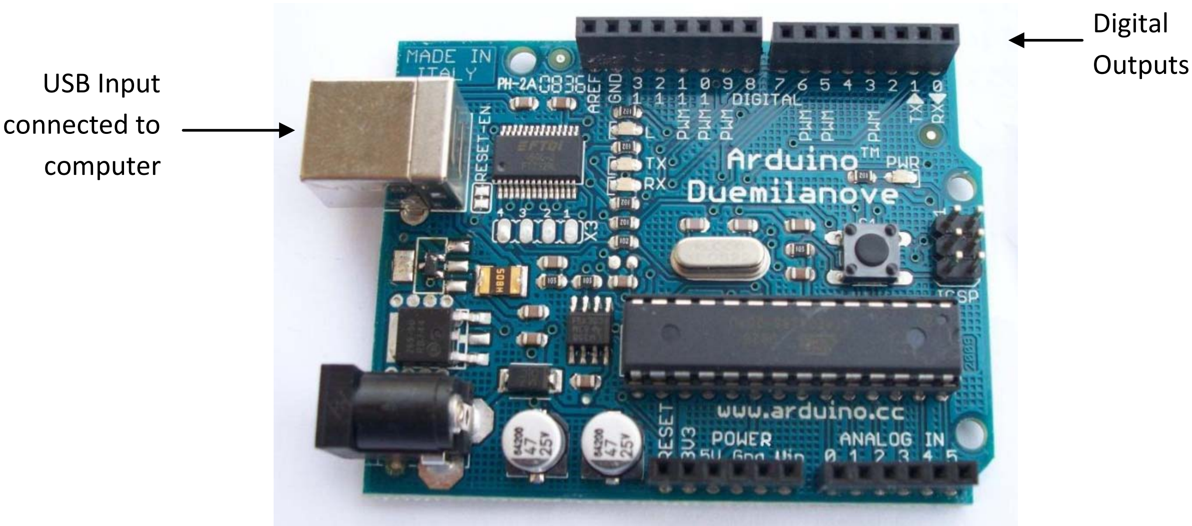


Figure 27. The Arduino® Duemilanove microcontroller with labels showing the USB plug (the interface for powering and programming the board) and the digital output plugs that control the H-Bridges.

Three digital pins will be connected to each H-Bridge (see wiring diagram on pg. 36). These ports are called 'PWM', 'direction' and 'brake', and they control the direction and speed of the actuator via the logic table shown in Table 4 below.

Table 4. Logic table for the H-bridges that control the direction of current flow to the actuators

PWM	Dir	Brake	Active Output Drivers
H	H	L	Source 1, Sink 2
H	L	L	Sink 1, Source 2
L	X	L	Source 1, Source 2
H	H	H	Source 1, Source 2
H	L	H	Sink 1, Sink 2
L	X	H	NONE

Digital output channels, such as the ones being used, are normally only capable of outputting two static signals, HIGH (= 'H' in Table X) or LOW (= or 'L' in Table X). The 'X's in the 'dir' column mean the signal is either 'H' or 'L'. In the Active Output Drivers column, the numbers 1 and 2 correspond to the two wires physically connected to the actuator. 'Source' means that current will flow to the actuator through that driver, whereas 'Sink' means it will flow from the actuator through the driver. 'None' means no current flow is allowed.

The PWM (or 'pulse width modulation') channels are able to transmit signals at duty cycles between 0% (or LOW) and 100% (or HIGH), in between that of normal digital outputs. In other words, by varying the duty cycle of the outputted signals between 0% or LOW and 100% or HIGH duty cycle, the PWM channel is able to vary the speed of the actuator. In the logic table, the PWM signal is read 'L' for 0% and 'H' for every other duty cycle.

13.5.3 *H-Bridges*

Figure 28 on page 38 shows the National Instruments® LMD18200T H-Bridge used in this project (one H-Bridge connected to each actuator). The full datasheet for the H-Bridges can be found in Appendix K.

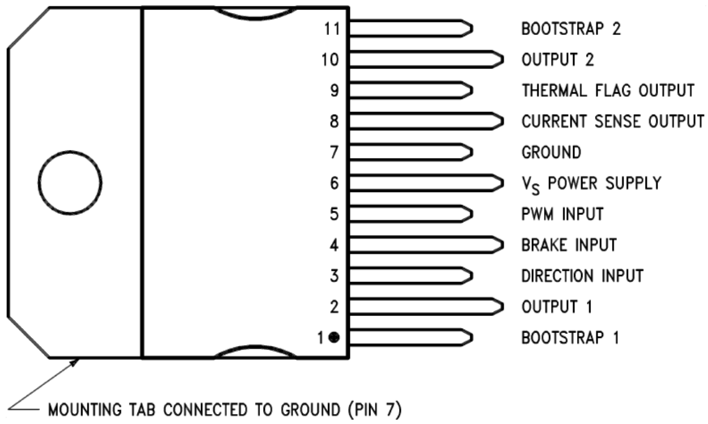


Figure 28. The National Instruments ® LMD18200T H-Bridge used to control the supply of power to the linear actuators.

13.5.3.1 ***Inputs:*** The inputs used correspond to pins 3-6, excluding pin 4. Pin 3 is the 'direction' input, which controls the direction of actuation (LOW = forward, HIGH = backward); pin 5 is the 'PWM' input that controls the speed of actuation; pin 6 is the 'Vs power supply' that provides the gate between the external 12V power supply and the actuator; pin 7 is the 'ground' pin.

13.5.3.2 ***Outputs:*** The outputs used are the actuator outputs (pins 2 and 10). The bootstraps would be used to connect 10nF capacitors to the outputs, thus increasing the frequency with which signals could be sent to the actuators (as was recommended in previous reports), but this was determined unnecessary for proper performance of the prototype.

13.5.4 ***Voltage/Current Considerations***

Each electrical component was chosen so as to not overload the elements supplied by it, or be overloaded by the elements that supply it. Table 5 below lists the power requirements, which are discussed in more detail below.

Table 5. Power limits for each electrical component. Adherence to these power ranges is critical to avoid failure by system overload.

		Ranges for Normal Operation		
Component	Interface	Min (V)	Max (V)	Max A (mA)
Computer	Inputs	n/a	n/a	n/a
	Outputs	0	5	500
Microcontroller	Inputs	0	5	500
	Outputs	0	5	40
H-Bridges	Input (HIGH)	2	12	0.010
	Input (LOW)	-0.1	0.8	0.010
	Outputs	0	55	3000
Actuators	Inputs	0	12	1500
Power Supply	Output	0	12	3800

Starting with the computer, we are assuming that it is running on its own manufacturer supplied power, and thus not problematic. The output to the microcontroller is via USB, and is capable of 5V and 500mA, which matches the input restrictions for the microcontroller. The microcontroller is then capable of outputting 0-5V and 0-40mA to each H-Bridge channel, which need 2-12V and draw 0-10μA, therefore the two can operate without problems. The H-Bridges then operate by regulating the power between the power supply and the actuators. The power supply is capable of delivering 0-12V and 0-3.8A to each actuator through the H-Bridges, which are each capable of withstanding 0-55V and 0-3A continuously.

Since each H-Bridge is connected to only one actuator, which consumes 12V and 1.5A max, this means that each H-bridge will only need to transfer 12V and 1.5A max, which is within the 0-55V and 0-3A limited range. Lastly, since each actuator is connected in parallel to the power supply and can pull max 1.5A, the power supply needs to be able to deliver 4.5A continuously in order to accommodate the actuators when running at maximum load of 150lbs. However, during testing, the maximum current pulled by each individual actuator (as read with a multimeter) was 12.7mA. This means that altogether, the actuators need 12.7(3)=38.1mA, which is well below the 6A limit provided by the supply. All things considered, the electrical system is designed for fully functional operation and within the power constraints of each component.

13.5.5 *Manual DPDT Switches*

In order to allow a capability for manual operation of the actuators in addition to the programming capability, three DPDT (or 'dual pole dual throw') switches were used to connect the power supply to the actuators as in the wiring diagram above. Figure 29 below illustrates the GC Electronics® On-Off-On DPDT switches used.

Figure 29. The GC Electronics® DPDT switches used. (LEFT) On-Off-On 1/4" Miniature Bat Handle Toggle, Part No. 35-012 (RIGHT) On-Off-On 1/2" Heavy Duty Bat Handle Toggle, Part No. 35-0148-0000

The DPDT switches, when wired to a DC power supply and an actuator as in the above wiring diagram, are used to switch the direction of DC current flow across a circuit element. These switches act as manual H-bridges. On-Off-On switches were used because the two 'on' toggles correspond to the two current directions, and 'off' corresponds to no current flow at all. The choice of specific switches was arbitrary; GC Electronics® switches are no different than other simple DPDT switches.

13.5.6 *Master Switch*

The Master Switch used was a GC Electronics® On-Off SPST (single pole single throw) Rocker Switch, as in Figure 30(pg. 40). It is used as a safety switch to cut off current to all circuit elements. The reason for this specific switch was arbitrary, as with the DPDT switches.

Figure 30. The Master Switch used. GC Electronics® On-Off SPST Rocker Switch, Part No. 35-693

13.5.7 Arduino Code and Programming

An illustration of working code can be found in Appendix J. For purposes of writing your own code, a good resource for examples can be found at http://www.arduino.cc/playground/.

Every Arduino program basically consists of three main blocks: (1) definitions, (2) setup and (3) loop, as shown in Figure 31.

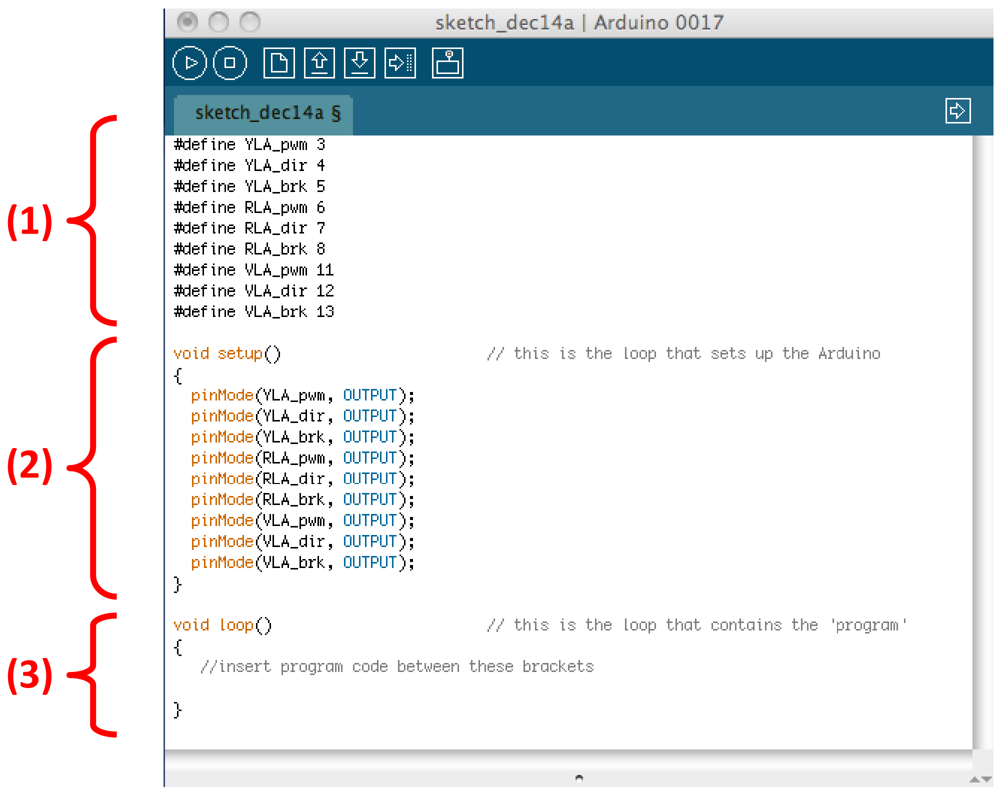


Figure 31. Arduino program template

- Block (1) in the Figure defines the name of each pin (numbered at the right of each definition line) with the name in the middle of the definition line. Pin names that begin with 'YLA' refer to the 'L' Actuator as in Figure 31 above, 'RLA' pins refer to the 'R' actuator, and 'VLA' pins refer to the 'V' actuator. 'PWM' pins refer to the 'PWM Input' pins in the H-bridges, as in Figure 31 above, and similarly 'dir' refers to 'Direction Input' and 'brk' refers to the 'Brake Input'.

- Block (2) uses the command ‘pinMode’ to set each of the defined pins as output pins, as opposed to inputs.

- Block (3) is where the motor control code goes (as described in Appendix J).

13.5.7 *Electrical Box*

The electronics will be housed on the back of the board in a PVC enclosure. PVC was chosen for its light weight and ease of manufacturing. The electronics box is shown in Appendix J.12, will be placed between the two back horizontal supports and fastened to the base. It will have 1/4 inch holes drilled for the wiring to be fed through.

13.6 Actual Prototype

The actual prototype was fabricated and assembled using the manufacturing plan that will be detailed later in the report. It is critical to note that all changes to the prototype during fabrication have been accounted for in the prototype description mentioned above. The assembled prototype was presented on 10 December 2009 at the University of Michigan Design Expo, with both manual and automated motions simulating the requisite dental concepts. Figure 32 below shows the actual prototype.

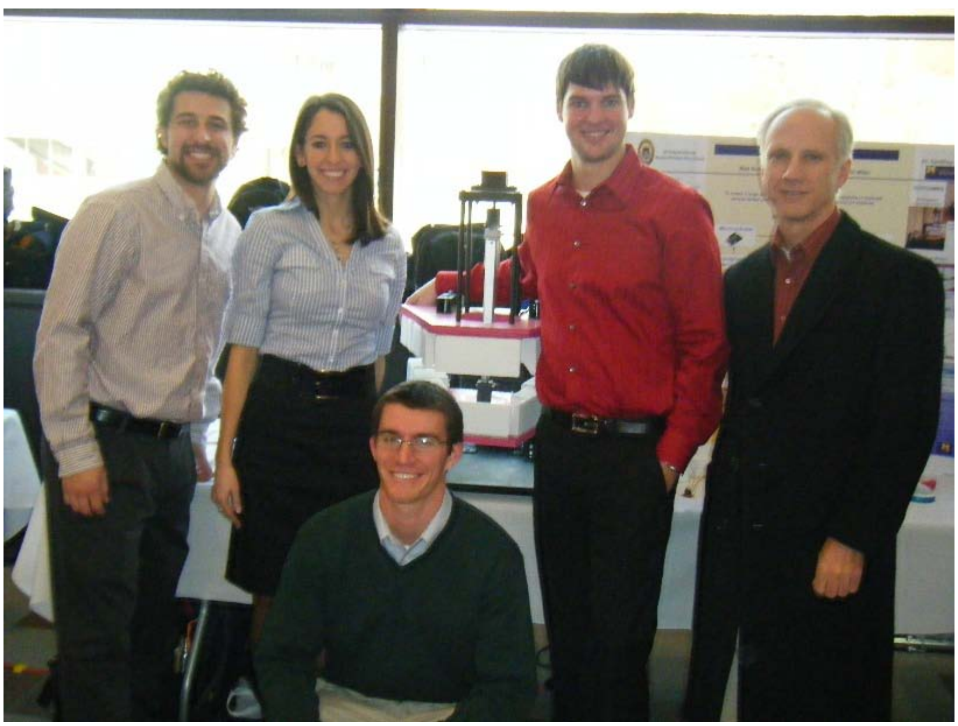


Figure 32. Actual prototype (center) at the University of Michigan Design Expo on 10 December 2009. Jaws Team shown on left with sponsor, Dr. Geoffrey Gerstner, shown on right.

14. PARAMETER ANALYSIS

The following section provides a comprehensive analysis of the rationale behind the decisions made while progressing from the alpha design to the final design. This analysis will begin by looking at the specific parameters that had the most significant impact on the design ('drivers'). A detailed failure analysis will describe the degree of confidence in the final design. Finally, additional analysis will be provided on joints, system stability, and additional technical issues currently outstanding.

14.1 Design Drivers

Throughout the design process, certain parameters relating to the most important specifications, called design 'drivers,' had the most significant impact on the prototype and final designs. The drivers for this design are the requisite size of the model and ranges of motion the model must demonstrate.

14.1.1 *Model Size*

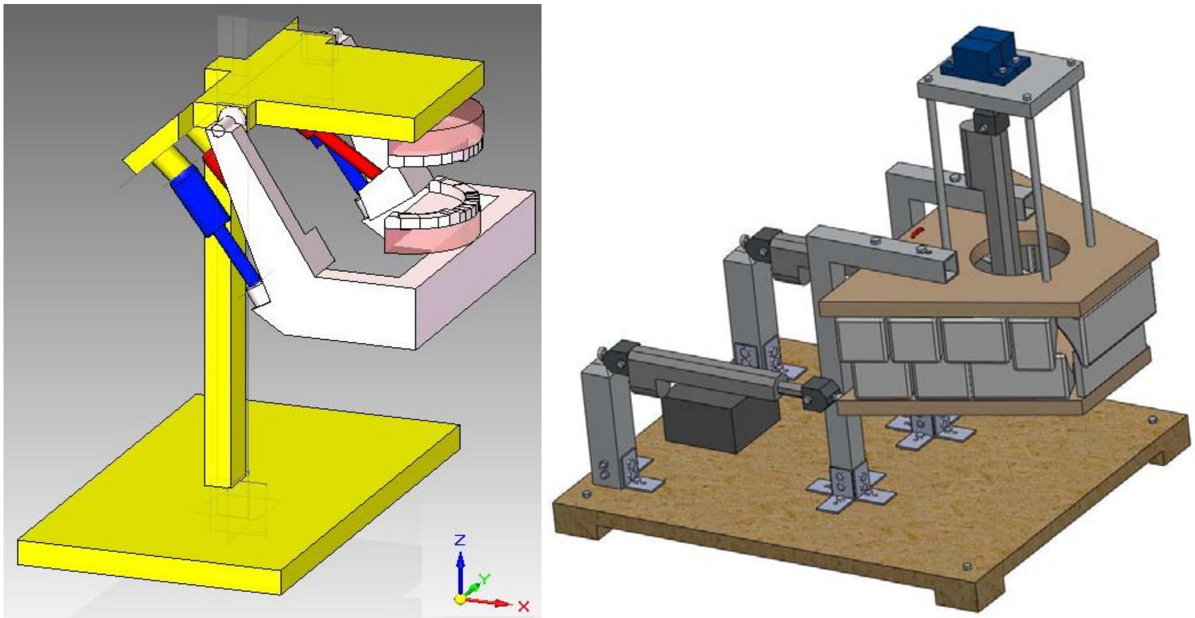
Several of the specifications for a successful model relate back to the ability of the model to be utilized as an effective teaching tool in a large audience setting. As such, the prototype and final design are designed to be significantly (approximately 8 times) larger than current teaching tools. Given the size of the model, component weights and resultant forces mandate specific components and processes for fabrication of our design.

14.1.2 *Model Motions*

The vast majority of the educational utility of our model stems from its ability to accurately replicate motions of the human jaw. In order to create a successful model, these motions need to be programmed in conjunction with the setup of the teeth and the calibration of the linear actuators. Without accurate motions, the prototype would be unsuccessful. As a result, the ability to mimic actual motions as they relate to several specified dental concepts dictated the design process.

14.2 Design Evolution

Through an iterative design process, the alpha design was improved to most efficiently meet the design criteria. Lead by the design drivers, these changes improved the models stability, ease of manufacturability, cost, and adaptability for future uses. A side by side comparison of the alpha and prototype designs is shown below in Figure 33, pg. 43.



(a) (b)

Figure 33. Overall comparison of (a) alpha design with (b) final design.

In moving from alpha design toward the final prototype, all parts and materials were selected to best meet the design criteria within the given constraints of fabrication time and cost.

14.3 Ranges of Motion

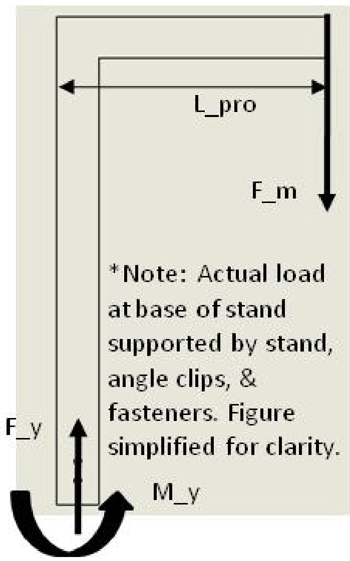
Given the specifications of the prototype, the analysis focused on three specific motions: pro-/retrusion, laterotrusion, and opening/closing the jaw. For each planned motion, clearances were incorporated into the design to allow for adequate movement. The three linear actuators are the sources of all output motions. Ball and socket joints were utilized to allow the appropriate rotations in the motions. See Appendix I.1 for a summary of limiting factors to ranges of motion.

14.4 Failure Analysis

Failure analysis is an important step in the design process of a model this large and susceptible to unintentional forces. Within the prototype design, several types of failure were analyzed to guarantee a mechanically sound design. The performed analysis comprises of calculations determining static loads, potential deflections, critical loads for buckling, and system stability with respect to the changing loads on the lower palate resulting from the elastic support. For each type of analysis performed, a sample figure and calculation is documented for reference in Appendix K.5.

14.4.1 *Static Load Analysis*

Static loads are particularly important within the scope of our model given the length of time between uses and the duration of inactivity. The most dangerous location that static loads could negatively impact the design comes from the weight supported by the stand. Hanging a weight, especially a dynamic weight, from a cantilever support creates forces and resultant moments that are magnified by the size of our model. See Figure 34 and Table 6, page 44, for a summary of static load analysis at the base to stand connection.



L, CG [in]	8.00	Location composite mass away from stand
L_pro [in]	12.50	Max CG location, protrusion
F_m, Force [lbs]	31.50	Mass attached to stand (composite)
MAX Force [lbs]	150.00	Force from actuator
Resultant moment & force		
M_y [lb*in]	252.00	Moment at base of stand
M_y_max [lb*in]	1875.00	Moment if load at end of stand
F_y [lb]	15.75	Vertical force supported by single stand
F_max [lb]	75.00	Force supported by single stand
Downward Force Effect on system		
A_stand [in^2]	0.36	Area of contact (2 stands) on base
A_effective [in^2]	12.36	Area including angle brackets
Stress [lb/in^2]	1.27	Downward stress on board/support
Stress_max [lb/in^2]	6.07	Max downward stress on base
Moment Effect on system		
x_bolt [in]	1.25	Distance between bolt and center of stand
A_bolt [in^2]	0.79	Effective area from nut/bolt*
F_bolt [lb]	100.80	Force to balance moment (=M/2x)
F_boltMAX [lb]	750.00	Force to balance MAX moment (=M/2x)
Stress [lb/in^2]	128.34	Stress on bolts (2) to support static load
Stress_max [lb/in^2]	954.93	Stress on bolts (2) to support MAX load
Max_vonMises [lb/in^2]	1653.99	Max stress using von Mises approximation
Yield Stress [lb/in^2]	5800.00	Wood
Safety Factor_normal	45.19	Normal static load
Safety Factor_MAX	3.51	Worst case scenario static load

Figure 34(a) and Table 6(b). Simplified free body diagrams (FBD) and resulting calculations for cantilever stand. Given a maximum force of 150 pounds, by the weight bearing actuator, the current safety factor for this connection is 3.5, which is a reasonable safety factor because the design must provide for potential unintended forces on the model. The parameter with the most flexibility in strengthening is the connection of the stand to the board (by adjusting parameters A_bolt and x_bolt). Note: F_m (applied force on stand) modeled as acting at a point to be conservative. In reality the load will be distributed, however modeling as a point force magnifies the failure potential and provides additional confidence in design integrity.

14.4.2 *Deflection Analysis*

Specific attention was allotted to the cantilever support with respect to the possibility for deflection. The same forces and resultant moments of the static loads were analyzed to make sure the most dangerous location of these forces will not adversely impact the design over time. Given the loading of the model, the aluminum tubing is the part most likely to deflect. The stresses applied to the tubing of the worst case scenario are far below the yield stresses of the parts used. See Appendix K.5 for a summary of deflection calculations utilized.

14.4.3 *Buckling Analysis*

The structure that supports the vertical linear actuator must be able to support the maximum loads placed on it by the model (150 lbs). Using this maximum load, the aluminum support rods for the actuator would not buckle with a large safety factor. See below for representative FBD in Figure 35, and supporting calculations in Table 7.

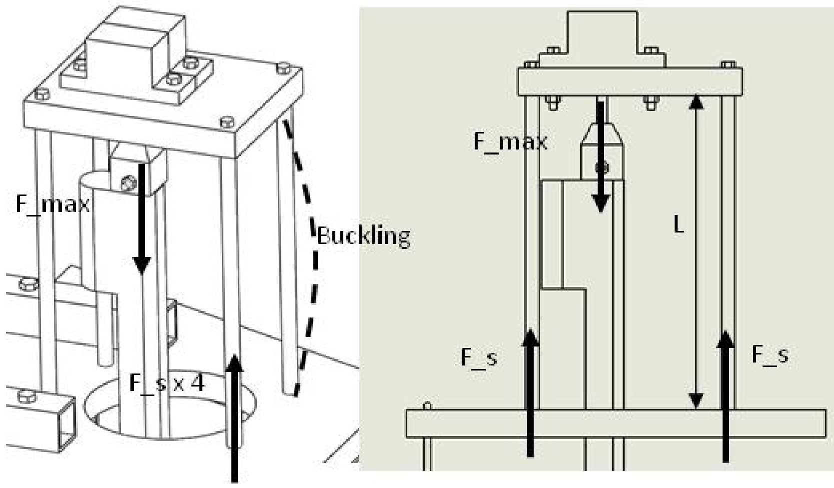


Figure 35. Vertical actuator supports analyzed to ensure critical buckling load not exceeded

Buckeling - Aluminum rods supporting vertical actuator		
P_cr = (pi)^2 *EI/L^2		
	Assumptions:	Weight equally distributed on each (4) supports
Area moment of Inertia (I) circle = (PI*L^4)/4		
I [lb*in^2]	12358.39	
L [in]	11.2	
E [lb/in^2]	10152282	Aluminum Young's Modulus, E = 70GPa [Dowling]
P_cr [lbs]	9.87E+09	Critical buckeling load for each rod
*Critical load enormously higher than anticipated loads		

Table 7. Sample calculations to determine support rods for upper actuator do not buckle under maximum loading

14.4.4 *Stability Analysis*

Given the configuration of the prototype, if the three actuators were the sole supports for the weight of the model, the system would be unstable. See Figure 36 below for instability justification.

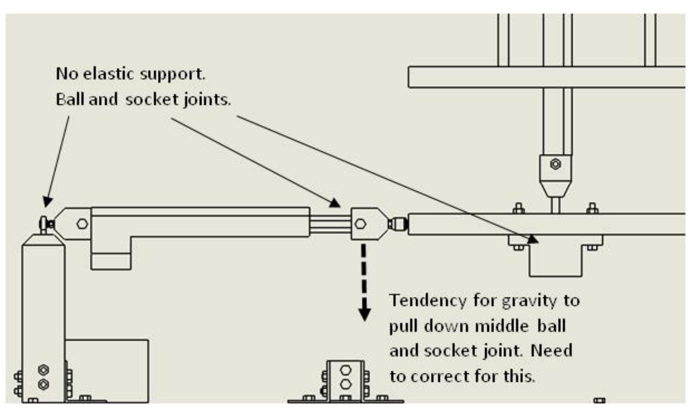


Figure 36. Side view of select assembly parts shows that the three ball and socket joints connected allows system to sink to lowest energy position due to gravity.

As discussed in the prototype description (Section 13.3.4.3), an elastic support is used to support a portion of the weight of the lower palate. This elastic support will continue to support the palate throughout the programmed motions. The elastic supports were analyzed to ensure that they will hold the required weight and allowing the actuators to overcome the forces placed on the system by the elastic. See Figure 37 and Table 8 below for a summary of resultant forces due to elastic supports.

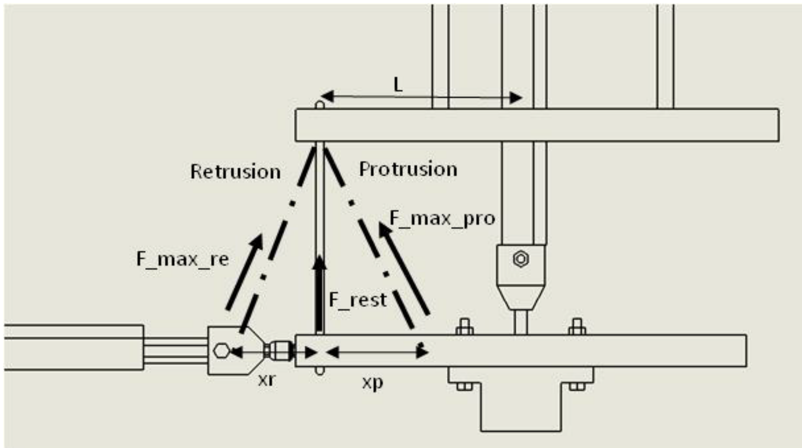


Figure 37: Side view of select assembly parts shows pro- and retrusion will cause elastic to elongate, producing a tensile force on the system

Stability/Elastic - Resultant forces due to motions (pro- & retrusion)		
F = kx		
Initial force of elastic must support		
F_rest [lbs]	4.4	
k = 6 lbs/in for appropriate spring (McMaster #9654K535) in application		
xp_max [in]	4	Maximum protrusion displacement
xr_max [in]	2	Max retrusion displacement
~if elastic initial length [in] is	6	
d_xe_pro	1.211103	Change in elastic length due to motion
d_xe_re	0.324555	Change in elastic length due to motion
~if elastic initial length [in] is	8	
d_xe_pro	0.944272	Change in elastic length due to motion
d_xe_re	0.246211	Change in elastic length due to motion
L [in]	6.25	Distance between elastic & actuator at rest
Resultant forces created by elastic in tension (in addition to F_rest)		
F_max_pro [lbs]	7.266615	Given single 5.5" vertically oriented spring
F_max_re [lbs]	1.947332	with k = 6 lb/in
* Forces easily fall within actuator range		

Table 8: Resultant forces created by stretching elastic support when model in motion can be overcome by actuators for all motions. Elastic selected provides adequate support to stabilize system.

14.5 Kinematic Analysis

Lower jaw motion is required for the prototype and final designs to successfully meet the desired specifications. This motion is to be driven by linear actuators (Appendix I.3) that will be purchased and integrated into the design. Using the data provided on the actuators and the loads applied to the actuators (weight & overcoming elastic force), it is possible to analyze the actuation speeds and resultant time it will take to move each actuator a specified distance. A summary of actuation speeds and times for specific displacements are detailed in

14.6 Outstanding Technical Issues

Though the design is finalized, the manufacturing and validation of the design is yet to be completed. Due to the inability to calibrate the actuators before building the prototype (need to test when appropriately loaded), it is impossible to quantify how 'precise' the programmed motion will be. Given the specified equipment, motions can theoretically be made very precise, however until the prototype is validated, it is only possible to speculate the exact precision of the jaw motions.

15. FABRICATION PLAN

The below sections begin with a discussion on the total time spent fabricating and debugging the prototype, followed by detailed discussion of the fabrication plan for each manufactured part. Lastly, instructions on building the electronic control circuit are given. For the simple parts, short textual instructions are given, while detailed process plans are provided for the more complex pieces. Fabrication of the final design will use similar processes, but the variables (such as blank and tool sizes) may differ.

Though many parts we manufacture will be different, all of the various processes used involve manual machining processes. The mill will be used for precision cutting and drilling, and the various bits and tools used will be made of High Speed Steel (HSS). Other equipment used includes the band saw, TIG welder, and drill tapping press. All fabrication operations can be accomplished by one person.

The materials we will use include balsa wood, plywood, PVC, aluminum and steel, and the cutting speeds required to machine these materials were obtained from either Bob Coury (for the wood) or the Machinery Handbook (for the metals). For more detail on the reason for choosing two of these specific materials, see Appendix L.1 using CES. These speeds were then converted into RPM via the following equation

$$RPM = \frac{12V}{\pi d} \tag{1}$$

where V is the cutting speed in feet per minute and d is the diameter of the drill bit in inches. The exact manufacturing procedure and cutting RPMs for each part are detailed in the below sections. The parts are all manufactured according to the CAD diagrams presented in Section 13.

Additionally, since the machining operations are all manual, preset feed rates are unnecessary. All operations will be undertaken at a slow enough pace where feed rates aren't an issue, as we discussed it with Bob Coury.

In order to increase safety, all machining operations will be undertaken by following the Shop Rules for the ME Undergraduate Machine shop, which include such restrictions as wearing safety glasses and tucking in all loose clothing.

15.1 Discussion of Fabrication Time

Several hindrances to manufacturing caused the required time in the Machine Shop to extend much longer than anticipated. The four most significant factors were (1) machine availability, (2) the unavailability of needed tools, (3) the need to wait in line for tools and (4) electrical/program debugging. Table 9 below shows the estimated total time spent fabricating the prototype, including the time spent dealing with the aforementioned hindrances, and does not differentiate between times when two or more people were working simultaneously. As mentioned in the previous section, however, all fabrication could be done by one person without problem.

Table 9. Total time spent fabricating the prototype

Fabrication Stage	Time required (hrs)	% of Total
Machining Parts	27	52
Painting	5	10
Physical Assembly	1	2
Wiring and Programming	18.5	36
TOTAL	**51.5**	**100**

The programming noted here refers to double checking that the microcontroller circuit would actuate the linear actuators as intended (see Appendix J– Arduino Programming). As can be seen, the most time consuming procedures were machining the parts in the shop (52% of total time) and wiring the electronics together (36% of total time). For the majority of the time during machining, however, two or more people were working together, whereas only one person was working on the electronics at one time. So per person, machining the parts took much more time than is evidenced by Table 9.

Table 10 below estimates the total time spent fabricating the prototype when the hindrances to fabrication are taken out of the equation (i.e. in an ideal manufacturing setting with all necessary tools and equipment free to be used).

Table 10. Total time spent fabricating the prototype in an ideal setting

Fabrication Stage	Time required (hrs)	% of Total
Machining Parts	13.5	57
Painting	5	21
Physical Assembly	1	4
Wiring and Programming	4	17
TOTAL	**23.5**	**100**

The estimated difference between real and ideal settings were that Machining Parts would take 50% less time and Electrical Wiring would only take 4 hours (or 78.4% less time). The estimate for the reduction in time for Machining Parts came from discussions with Bob Coury, whereas the reduction for Electrical Wiring was estimated by the group member in charge of wiring. Much of the time was spent reconfiguring and debugging the H-Bridge and Microcontroller setup until it was determined that two of the three H-Bridges originally installed were defect, requiring fabrication of new ones. For more on this, see Appendix J – Arduino Programming.

Lastly, it should be mentioned that the following fabrication plan has been updated to reflect all significant changes made to it during time in the shop.

15.2 Proper Manufacturing of Part Blanks

It is important to note proper procedure in creating the blanks for each part. Each blank dimension should be cut slightly larger than needed when using cruder instruments such as the band saw. This is because of the high difficulty inherent in trying to cut precise and straight lines with it. These 'rough cuts' should then be machined down to the proper dimensions using the mill (or the lathe, if more preferable) in order to prepare properly dimensioned blanks with properly flat and perpendicular edges where needed.

15.3 Base Pegs

The Base Pegs are just wooden blanks that are attached to the Mounting Board with wood screws, so there isn't any specific machining process other than creating a wood blank of dimensions 2" W x 2" D x 1" H. Tolerances for this part are not very important. See Appendix H.1 for engineering drawing.

15.4 Mounting Board

The Mounting Board has 16 locations for 1/4" holes, but the 4 locations in the corners, where the Base Pegs will attach with wood screws, will be marked but not drilled. The fabrication of the Mounting Board will consist of first inspecting the blank for proper dimensions (24" W x 30" D x 1" H), then marking the locations of the remaining 12 1/4" holes with a marker and ruler. These locations do not have to be highly precise, so hand marks will be adequate. After the locations are known, the holes will be drilled with a battery powered hand drill equipped with a 1/4" Drill Bit. The final stage will be double checking the final dimensions of the part with a ruler or calipers. Tolerances for this part aren't super important. See Appendix H.2 for engineering drawing.

15.5 Rear Support Columns

The 1/4”x28 hole tolerances are important, so the highest degree of precision possible should be held. See Appendix H.3 for engineering drawing.

Table 11. Manufacturing Process Plan for the Rear Support Columns

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect aluminum blank for proper dimensions (2"Wx2"Dx8"H)	-	Calipers	-
3	Mount workpiece into vise to drill tap hole for 1/4"x28 threaded hole	Mill	Vise	-
4	Align Mill to workpiece	Mill	Alignment Tool	1000 RPM
2	Drill pilot hole for 1/4"x28 hole	Mill	Center Drill	1800 RPM
5	Drill 1/4"x28 tap hole	Mill	#3 Drill Bit	1800 RPM
6	Mount workpiece into vise to mill first tapered edge	Mill	Vise	-
7	Align Mill stock at 45° angle to vertical (parallel to gravity) direction	Mill	Mill stock	-
8	Align Mill stock to workpiece edge	Mill	Alignment Tool	1000 RPM
9	Mill first tapered edge	Mill	1" End Mill	1200 RPM
10	Repeat steps 6-9 for the other three tapered edges	-	-	-
11	Mount workpiece into tapping machine to tap 1/4"x28 threaded hole	Tap	1/4"x28 tap	-
12	Inspect part	-	Calipers	-

15.6 1/4" Actuator Fasteners

These parts need to be machined precisely in order to fit robustly to the rest of the prototype. See Appendix H.4 for engineering drawing.

Table 12. Manufacturing Process Plan for the 1/4" Actuator Fasteners

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect aluminum blank for correct dimensions (1.5"Wx1.5"Dx1.75"H)	-	Calipers	-
2	Mount workpiece into vise to drill 3/4" hole	Mill	Mill Vise	-
3	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
4	Drill Pilot hole for 3/4" hole	Mill	Center Drill	1800 RPM
5	Drill 3/4" hole	Mill	3/4" Drill Bit	1200 RPM
6	Mount workpiece into vise to drill 1/4" through-hole	Mill	Mill Vise	-
7	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
8	Drill Pilot hole for 1/4" through-hole	Mill	Center Drill	1800 RPM
9	Drill 1/4" through-hole	Mill	1/4" Drill Bit	1800 RPM
10	Mount workpiece into vise to drill tap hole for 1/4"x28 threaded hole	Mill	Mill Vise	-
11	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
12	Drill Pilot hole for 1/4"x28 hole	Mill	Center Drill	1800 RPM
13	Drill 1/4"x28 tap hole	Mill	#3 Drill Bit	1800 RPM
14	Mount workpiece into vise to mill first tapered edge	Mill	Mill Vise	-
15	Align Mill stock at 45° angle to vertical (parallel to gravity) direction	Mill	Mill stock	-
16	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
17	Mill first tapered edge according to diagram	Mill	1" End Mill	1200 RPM
18	Repeat steps 12-15 for second, third and fourth tapered edges	-	-	-
19	Mount workpiece into tapping machine to tap 3/8"x16 hole	Tap	Vise	-
20	Tap 3/8"x16 hole	Tap	3/8"x16 tap	-
21	Inspect Part	-	Calipers	-

15.7 Lower Palate

Only the placement of the t-nuts need to be precisely machined for the Lower Palate, because the t-nut position directly affects actuator motion. See Appendix H.5 for engineering drawing.

Table 13. Manufacturing Process Plan for the Lower Palate

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect wood blank for proper dimensions (18"Wx14"Dx1"H)	-	Calipers	-
2	Mark hole locations for two 1/4" holes and 1" center hole	-	Calipers/Marker	-
3	Mark lines to cut angled sides	-	Calipers/Marker	-
4	Mount workpiece into vise to drill first 1/4" hole	Drill Press	Vise	-
5	Drill first 1/4" hole	Drill Press	1/4" Drill Bit	1500 RPM
6	Mount workpiece into vise to drill second 1/4" hole	Drill Press	Vise	-
7	Drill second 1/4" hole	Drill Press	1/4" Drill Bit	1500 RPM
8	Mount workpiece into vise to drill 1" center hole	Mill	Vise	-
9	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
10	Drill 1" center hole	Mill	1" Drill Bit	1500 RPM
11	Ball Mill 1" center hole seat	Mill	15/8" Ball Mill	1500 RPM
12	Mount workpiece into vise to drill first t-nut center hole	Mill	Vise	-
13	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
14	Drill/Countersink first t-nut center hole	Mill	3/8" Drill Bit w/ 3/4" Shoulder	1500 RPM
15	Repeat steps 12-14 for the second t-nut center hole	Mill	15/8" Ball Mill	1500 RPM
16	Mount workpiece into vise to cut first angled side	Wood Band Saw	Vise	-
17	Cut first angled side	Wood Band Saw	Wood Band Saw	(preset)
18	Round off corners to 0.5" radius fillet	Wood Band Saw	Wood Band Saw	(preset)
19	Repeat steps 11-14 for the other angled side	-	-	-
20	Hammer 1/4"x28 t-nuts into place	-	Hammer	-
21	Inspect part	-	Calipers	-

15.8 Ball Enclosures

The 15/8" cavity needs to be precisely machined in order to provide a secure fit over the 15/8" Actuator Balls. See Appendix H.6 for engineering drawing. For step 4, the first cuts are made by approaching from the face normal, milling the cavity first, then finishing with the 0.438" shaft cavity.

Table 14. Manufacturing Process Plan for the Ball Enclosures

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect aluminum blank for correct dimensions (4.5"Wx1.5"Dx2.0"H)	-	Calipers	-
2	Mount workpiece in vise to ball mill 15/8" cavity	Mill	Vise	-
3	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
4	Mill 15/8" cavity	Mill	15/8" Ball Mill	1500 RPM
5	Mount workpiece in vise to end mill first flange	Mill	Vise	-
6	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
7	Mill first flange according to diagram	Mill	1" End Mill	1200 RPM
8	Drill pilot hole for 1/4" hole	Mill	Center Drill	1800 RPM
9	Drill 1/4" through-hole	Mill	1/4" Drill Bit	1800 RPM
10	Repeat steps 5-9 for the other flange and 1/4" hole	-	-	-
11	Inspect Part	-	Calipers	-

15.9 Upper Ball Plate

The placement and depth of the 15/8" seat are the most important features, so precision should be high when machining them. Otherwise the 15/8" Actuator Balls won't fit securely into the Plate. See Appendix H.7 for engineering drawing.

Table 15. Manufacturing Process Plan for the Upper Ball Plate

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect aluminum blank for correct dimensions (6.0"Wx8.0"Dx1.0"H)	-	Calipers	-
2	Mount workpiece in vise to drill/mill 15/8" seat and two 1/4"x20 holes	Mill	Vise	-
3	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
4	Drill pilot hole for 1" hole	Mill	Center Drill	1800 RPM
5	Drill 1" hole	Mill	1" Drill Bit	1200 RPM
6	Mill 15/8" seat	Mill	15/8" Ball Mill	1500 RPM
7	Drill pilot hole for first 1/4"x20 hole	Mill	Center Drill	1800 RPM
8	Drill tap hole for first 1/4"x20 hole	Mill	#7 Drill Bit	1800 RPM
9	Mount workpiece in vise to drill other two 1/4"x20 tap holes	Mill	Vise	-
10	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
11	Repeat steps 7-8 for second two 1/4"x20 tap holes	-	-	-
12	Mount workpiece in vise to tap first two 1/4"x20 holes	Tap	Vise	-
13	Tap first two 1/4"x20 holes	Tap	1/4"x20 Tap Bit	-
14	Repeat steps 12-13 for other two 1/4"x20 holes	Tap	1/4"x20 Tap Bit	-
15	Inspect Part	-	Calipers	-

15.10 Upper Support Bars

The important dimensions here are the length and the flatness of the threaded ends. If the length of each piece is different and/or the ends aren't perfectly flat, the Upper Ball Plate would be mounted at an angle to the Upper/Lower Palates instead of parallel. Parallelism is important because it makes the geometry of the programmed motions easier to calculate. See Appendix H.8 for engineering drawing.

Table 16. Manufacturing Process Plan for the Upper Support Bars

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect aluminum blank for correct dimensions (0.25"Rx11.16"L)	-	Calipers	-
2	Mount workpiece in vise to drill first 1/4"x20 tap hole	Mill	Vise	-
3	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
4	Drill pilot hole for first 1/4"x20 tap hole	Mill	Center Drill	1800 RPM
5	Drill first 1/4"x20 tap hole	Mill	#7 Drill Bit	1800 RPM
6	Repeat steps 2-5 for other 1/4"x20 tap hole	-	-	-
7	Mount workpiece in vise to tap first 1/4"x20 hole	Tap	Vise	-
8	Tap first 1/4"x20 hole	Tap	1/4"x20 Tap Bit	-
9	Repeat steps 7-8 for other 1/4"x20 hole	-	-	-
15	Inspect Part	-	Calipers	-

15.11 Upper Palate

The bolt holes that allow connection to the Jaw Support Columns are the most important features of the Upper Palate, so precision should be used when determining their position. For the steps using the Wood Band Saw, perfect precision is not of critical importance. See Appendix H.9 for engineering drawing.

Table 17. Manufacturing Process Plan for the Upper Palate

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect wood blank for proper dimensions (19.6"Wx15"Dx1"H)	-	Calipers	-
2	Mark hole locations for the two 1/4" holes and the 6" center hole	-	Calipers/Marker	-
3	Mark lines to cut angled sides	-	Calipers/Marker	-
4	Mount workpiece in vise to drill first 1/4" hole	Drill Press	Vise	-
5	Drill first 1/4" hole	Drill Press	1/4" Drill Bit	1500 RPM
6	Mount workpiece in vise to drill second 1/4" hole	Drill Press	Vise	-
7	Drill second 1/4" hole	Drill Press	1/4" Drill Bit	1500 RPM
8	Mount workpiece in vise to drill 6" center hole	Hole Saw Mill	Vise	-
9	Align Mill to workpiece	Hole Saw Mill	Edge Finder	1000 RPM
10	Drill 1/2" starter hole	Hole Saw Mill	1/2" Drill Bit	(preset)
11	Drill 6" center hole	Hole Saw Mill	6" Hole Saw	(preset)
12	Mount workpiece in vise to cut first angled side	Wood Band Saw	Vise	-
14	Cut first triangular section off workpiece according to diagram	Wood Band Saw	Wood Band Saw	(preset)
15	Round off corners to 0.5" radius fillet	Wood Band Saw	Wood Band Saw	(preset)
16	Repeat steps 11-14 for the other side	-	-	-
17	Inspect part	-	Calipers	-

15.12 Jaw Support Columns

Similar to the Upper Palate, the connecting bolt holes have to be positioned precisely. See Appendix H.10 for engineering drawing.

Table 18. Manufacturing Process Plan for the Jaw Support Columns

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect aluminum blank for proper dimensions (1.5"Wx1.5"Dx28"H)	-	Calipers	-
2	Mark 45° cut position at 17.5" from one end of blank	-	Calipers/Marker/Strike	-
3	Make 45° saw cut	Band Saw	1/8" saw blade	300 ft/min
4	Inspect new dimensions of two workpieces according to diagram	-	Calipers	-
5	Scrub and clean surfaces to be welded	-	Brush/Cleaner	-
6	Clamp the two workpieces to make 90° angle	Weld Table	Clamps	-
7	Weld the 90° joint	Weld Table	TIG Welder/Filler	-
8	Let weld cool to room temp	-	-	-
9	Inspect welded part for proper dimensions according to diagram	-	Calipers	-
10	Cut off excess material to get proper dimensions (according to diagram)	Band Saw	Band Saw	(preset)
11	Mount workpiece in vise to drill two of the bottom four 1/4" through-holes	Mill	Vise	-
12	Align Mill to workpiece	Mill	Alignment Tool	1000 RPM
11	Drill Pilot hole for first 1/4" through-hole	Mill	Center Drill	1800 RPM
12	Drill first 1/4" through-hole	Mill	1/4" Drill Bit	1800 RPM
13	Drill Pilot hole for second 1/4" through-hole	Mill	Center Drill	1800 RPM
14	Drill second 1/4" through-hole	Mill	1/4" Drill Bit	1800 RPM
15	Repeat steps 9-12 for the second two of the bottom four 1/4" through-holes	-	-	-
16	Mount workpiece in vise to drill the two 3/8" through-holes	Mill	Vise	-
17	Align Mill to workpiece	Mill	Alignment Tool	1000 RPM
18	Drill Pilot hole for first 3/8" through-hole	Mill	Center Drill	1800 RPM
19	Drill first 3/8" through-hole	Mill	3/8" Drill Bit	1500 RPM
20	Drill Pilot hole for second 3/8" through-hole	Mill	Center Drill	1800 RPM
21	Drill second 3/8" through-hole	Mill	3/8" Drill Bit	1500 RPM
22	Inspect part	-	Calipers	-

15.13 3/8” Actuator Fasteners

All features of these pieces must be machined with precision (similar to the 1/4” Actuator Fasteners). See Appendix H.11 for engineering drawing.

Table 19. Manufacturing Process Plan for the 3/8” Actuator Fasteners

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect aluminum blank for correct dimensions (1.5"Wx1.5"Dx2"H)	-	Calipers	-
2	Mount workpiece into vise to drill 3/4" hole	Mill	Mill Vise	-
3	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
4	Drill Pilot hole for 3/4" hole	Mill	Center Drill	1800 RPM
5	Drill 3/4" hole	Mill	3/4" Drill Bit	1200 RPM
6	Mount workpiece into vise to drill 1/4" through-hole	Mill	Mill Vise	-
7	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
8	Drill Pilot hole for 1/4" through-hole	Mill	Center Drill	1800 RPM
9	Drill 1/4" through-hole	Mill	1/4" Drill Bit	1800 RPM
10	Mount workpiece into vise to drill tap hole for 3/8"x16 threaded	Mill	Mill Vise	-
11	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
12	Drill Pilot hole for 3/8"x16 hole	Mill	Center Drill	1800 RPM
13	Drill 3/8"x16 tap hole	Mill	5/16" Drill Bit	1500 RPM
14	Mount workpiece into vise to mill first tapered edge	Mill	Mill Vise	-
15	Align Mill stock at 62.3° angle to vertical (parallel to gravity) direction	Mill	Mill stock	-
16	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
17	Mill first tapered edge according to diagram	Mill	1" End Mill	1200 RPM
18	Repeat steps 12-15 for second, third and fourth tapered edges	-	-	-
19	Mount workpiece into tapping machine to tap 3/8"x16 hole	Tap	Vise	-
20	Tap 3/8"x16 hole	Tap	3/8"x16 tap	-
21	Inspect Part	-	Calipers	-

15.14 Electrical Box

For step 20, even though the CAD diagram calls for sharp edges, they aren't necessary. Also, using the ball mill for this step will expedite the manufacturing process for this part. See Appendix H.12 for engineering drawing.

Table 20. Manufacturing Process Plan for the Electrical Box

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect PVC blank for correct dimensions (6.0"Wx8.0"Dx3.0"H)	-	Calipers	-
2	Mount workpiece in vise to drill the four 1/4" corner thru holes	Mill	Vise	-
3	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
4	Drill pilot hole for first 1/4" hole	Mill	Center Drill	1500 RPM
5	Drill first 1/4" hole	Mill	1/4" Drill Bit	1500 RPM
6	Repeat steps 4-5 for the other three holes	-	-	-
7	Mount workpiece in vise to mill large cavity	Mill	Vise	-
8	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
9	Mill out the main cavity (including the recessed portion by the switches)	Mill	1" End Mill	1200 RPM
10	Mount workpiece in vise to drill and mill the switch holes	Mill	Vise	-
11	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
12	Drill pilot hole for first 1/4" hole	Mill	Center Drill	1500 RPM
13	Drill first 1/4" hole	Mill	1/4" Drill Bit	1500 RPM
14	Repeat steps 12-13 for second 1/4" hole	-	-	-
15	Drill pilot hole for 1/2" hole	Mill	Center Drill	1500 RPM
16	Drill 1/2" hole	Mill	1/2" Drill Bit	1500 RPM
17	Mill rectangular switch hole	Mill	1/8" End Mill	1500 RPM
18	Inspect Part	-	Calipers	-

15.15 Mounting Brackets

The process plan for the front and side mounting brackets is the same, as below. See Appendix H.13 for engineering drawing.

Table 21. Manufacturing Process Plan for the Mounting Brackets

Step	Operation	Instrument	Tool(s)	Speed
1	Inspect L-shaped aluminum blank for correct dimensions (1.5”Wx1.5”Dx1.5”Hx1/4” T)	-	Calipers	-
2	Mount workpiece in vise to drill the two 1/4" thru-holes	Mill	Vise	-
3	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
4	Drill pilot hole for first 1/4" hole	Mill	Center Drill	1800 RPM
5	Drill first 1/4" hole	Mill	1/4" Drill Bit	1800 RPM
6	Repeat steps 4-5 for the other 1/4" thru-hole	-	-	-
7	Mount workpiece in vise to drill the solitary 1/4" thru-hole	Mill	Vise	-
8	Align Mill to workpiece	Mill	Edge Finder	1000 RPM
9	Drill pilot hole for 1/4" hole	Mill	Center Drill	1800 RPM
10	Drill 1/4" hole	Mill	1/4" Drill Bit	1800 RPM
21	Inspect Part	-	Calipers	-

15.16 Electrical Wiring and Programming

The necessary operations to properly complete all electrical fabrication included cutting wires and stripping their ends, soldering, connecting stripped wire ends by twisting them together and wrapping them with electrical tape. A detailed description of the electrical assembly is to follow here. For a discussion on the Programming, refer to 13.5 (Prototype Description).

The Arduino IDE (Interactive Developer Environment), the software used to program the Arduino, can be downloaded from http://www.arduino.cc for Windows®, Linux and Mac OS®. For more info on programming, refer to Appendix J – Arduino Programming.

15.17 Electrical Assembly

The wiring diagram from Section 13.5 has been reproduced in Figure 38 here for convenience.

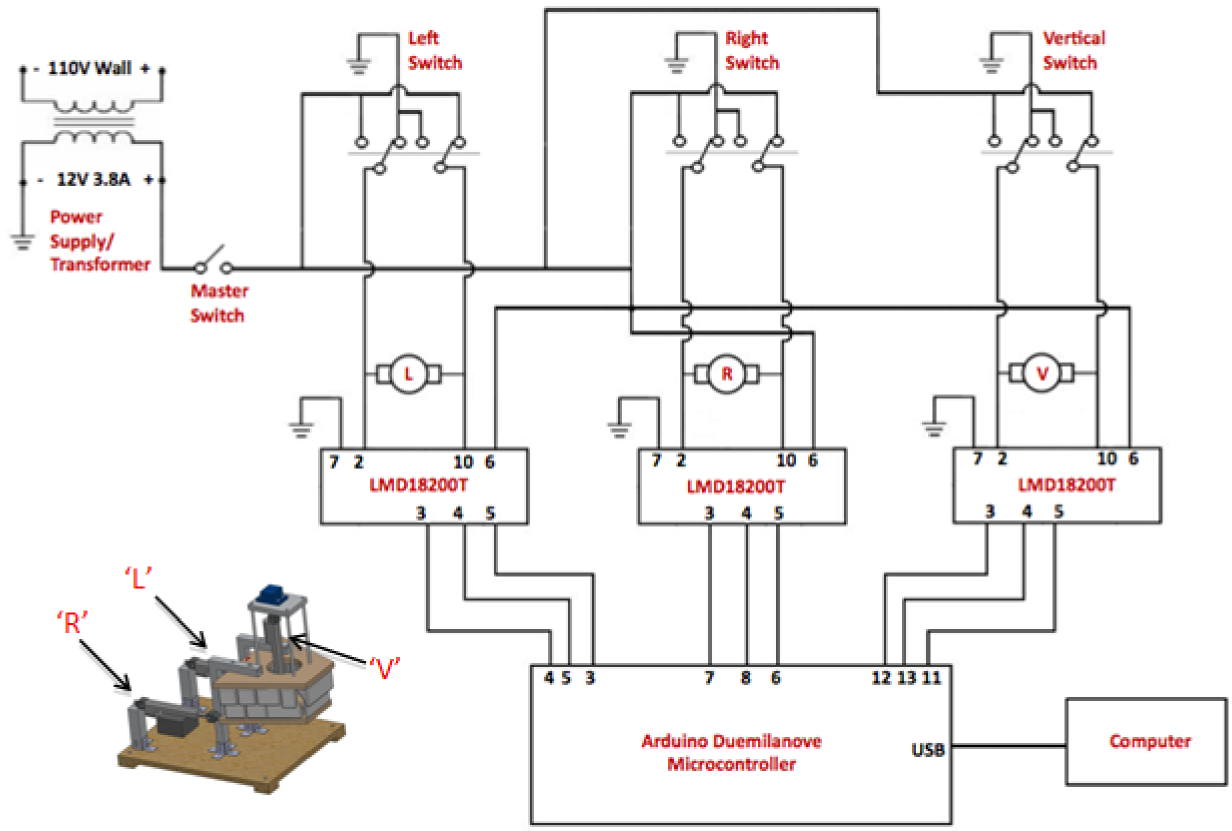


Figure 38. The wiring schematic of the electrical setup, showing the ports used to connect the computer, the microcontroller, the LMD18200T H-Bridges, the three linear actuators ('L' = left actuator, 'R' = right actuator, and 'V' = vertical actuator), the power supply, and the three DPDT switches.

The following Figures (39 and 40)show labels for the wire connection points of some of the electrical components. For the components not shown here, see section 13.5. Table 22 shows where to connect the electrical components on the breadboard. A basic knowledge of circuit assembly is assumed (i.e. use of soldering iron and solder, an ability to cut and strip wires, and how to attach stripped wires to a breadboard).

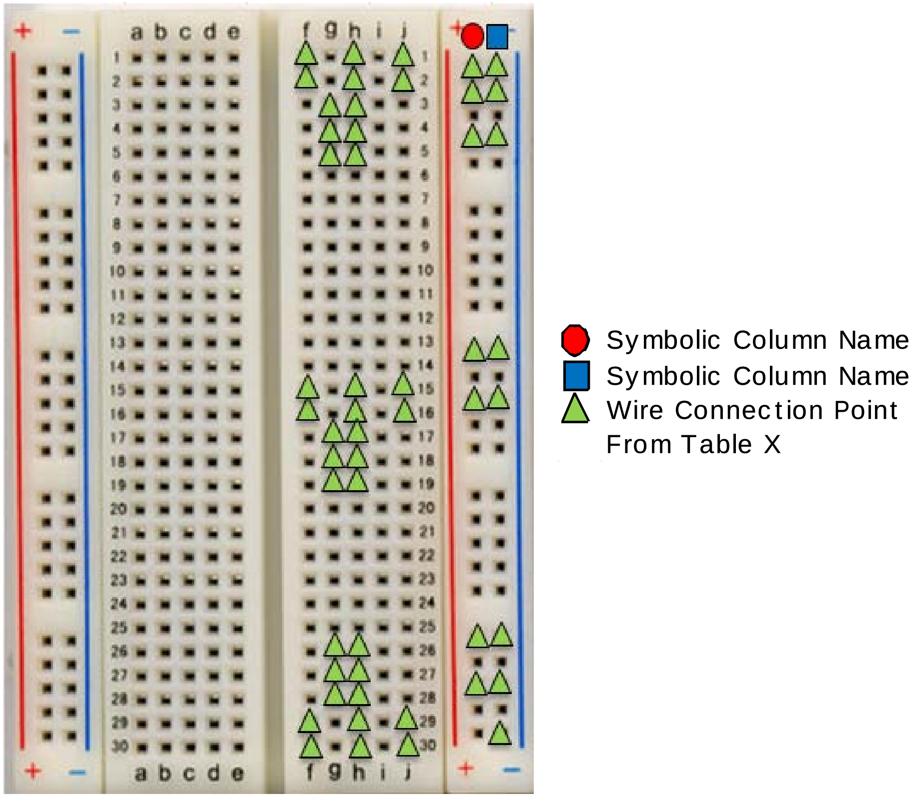


Figure 39. The breadboard configuration for the electrical wiring. The Circle and Square designate those specific columns (like columns F-J), while the triangles represent wire connection points as designated in Table 22.

Figure 40. (LEFT) One of the DPDT switches, designated 'α', 'β' and 'γ' in Table22. The letters A-F correspond to the nodes wires are to be soldered onto. (RIGHT) The Master Switch, designated 'δ' in Table 22.

Table 22. The connection points of the various components on the breadboard.

Item	Terminal Symbol	Terminal Name	Connection Point
Power Supply 'ε'	n/a	Wall Plug	(wall outlet)
	+	positive	δ+
	-	ground	🟦1
H-Bridge 1	2	OUT1	H1
	3	DIR	H4
	4	BRAKE	H5
	5	PWM	H3
	6	PWR	🔴 2
	7	GND	🟦 2
	10	OUT2	H2
H-Bridge 2	2	OUT1	H15
	3	DIR	H18
	4	BRAKE	H19
	5	PWM	H17
	6	PWR	🔴 13
	7	GND	🟦 13
	10	OUT2	H16
H-Bridge 3	2	OUT1	H29
	3	DIR	H27
	4	BRAKE	H26
	5	PWM	H28
	6	PWR	🔴 23
	7	GND	🟦 23
	10	OUT2	H30
'L' Actuator	+	red	F30
	-	black	F29
'R' Actuator	+	red	F16
	-	black	F15
'V' Actuator	+	red	F2
	-	black	F1

Item	Terminal Symbol	Terminal Name	Connection Point
Arduino Microcontroller	3	PWM	G28
	4	digital	G27
	5	digital	G26
	6	PWM	G17
	7	digital	G18
	8	digital	G19
	11	PWM	G3
	12	digital	G4
	13	digital	G5
	GND	ground	🟦 25
	USB	USB	(computer)
DPDT Switch 1 'α'	A	-	α-F and 🔴11
	B	-	α-E and 🟦11
	C	-	J30
	D	-	J29
	E	-	α-B
	F	-	α-A
DPDT Switch 2 'β'	A	-	β-F and 🔴21
	B	-	β-E and 🟦21
	C	-	J16
	D	-	J15
	E	-	β-B
	F	-	β-A
DPDT Switch 3 'γ'	A	-	γ-F and 🔴 4
	B	-	γ-E and 🟦 4
	C	-	J2
	D	-	J1
	E	-	γ-B
	F	-	γ-A
Master Switch 'δ'	+	red	ε+
	-	black	🔴1

Table 23 on page 64, gives the recommended procedure for building the circuit connections as seen in Figure 39 and Table 22, above. In building the prototype, 24-gauge solid wire was used.

Table 23. The recommended procedure for building the electrical circuit

Step	Operation
1	Cut, strip the ends and solder wires to the necessary terminals for H-Bridge 1 (as in Table X)
2	Repeat for H-Bridges 2 and 3
3	Cut, strip the ends and solder wires to the necessary terminals for DPDT Switch α (as in Table X)
4	Repeat for DPDT Switches β and γ
5	Cut, strip the ends and twist-connect wires to the Power Supply wires
6	Cover the twisted-together wires with electrical tape
7	Repeat 5-6 for the linear actuator wires
8	Repeat 5-6 for the Master Switch
9	Connect the Master Switch terminals, the Power Supply and the Breadboard (as in Table X)
10	Connect the three DPDT Switches to the Breadboard (as in Table X)
11	Connect the three Actuators to the Breadboard (as in Table X)
12	Connect the three H-Bridges to the Breadboard (as in Table X)
13	Connect the Arduino to the Breadboard (as in Table X)
14	Connect the Arduino to the Computer (as in Table X)

16. VALIDATION APPROACH

A series of tests must be conducted to validate that the prototype meets the design specifications. This section outlines each specification and what tests need to be done to prove that our prototype meets the customer specifications. Due to time constraints, not all of the validation methods were tested. All quantitative testing was accomplished and the results are provided in Table 24 below. Qualitative testing was not completed; however preliminary conversations with our sponsor indicate that all but one design specification was met by our prototype.

Table 24. Validation of critical specifications.

#	Design Requirements	Design Specification	Prototype Specification	Design Spec Met? (Y/N)
1	Incorporate large scale model of human jaw system	8X physical model	8x physical model	Y
2	Incorporate 6DOF jaw joint capability	Motion along and about all 3 axes	See 16.2.4	Y
3	Properly simulate protrusion/retrusion motion	Motion of +2.5/-0.5" in x and -0.5" in z direction	+4/-2" in x, -8" in z	Y
4	Properly simulate laterotrusion	Motion of -0.5" in x, ±2.5" in y, -0.5" in z direction	-0.5" in x ±4.5" in y -8" in z	Y
5	Incorporate variable condylar inclination	Variation of ±20° around x axis	N/A	N
11	Capable of completely opening jaw	Lower jaw range of motion from 0-90° around x-axis	35^0 around x-axis	Y* (see 16.2.8)
12	Easy to use/minimal manual manipulation	Incorporate motion controlling mechatronics	N/A	TBD
13	Durable and robust	Withstand 20 lbf	>20 lbf	Y

16.1. Large Scale Model, Clear Views, and Effective Teaching Tool

The main driver for the project is to create a better teaching tool of dental concepts to students. This section will detail the validation approach of our prototype for effectively teaching dental concepts from the student and professor perspectives.

16.1.1. *Testing Large Scale Model*

The prototype is approximately eight times the size of a typical jaw to provide clear views of occlusion to a large lecture hall. The prototype's maximum dimensions are 24 inches wide by 32 inches tall by 30 inches long. These dimensions meet the design specification requested by our sponsor but may or may not be large enough for a lecture of 100 students. To determine if the model is suitable for a large lecture hall, we will observe the prototype from different locations in a large lecture hall

16.1.2. ***Testing Clear Views***
The prototype is simply and minimally supported to provide clear views from many angles. Before using it in front of a live class, the prototype will be tested for clear views during simulation. During actuation, we will observe the model at various angles and views that a classroom may have. We will test to see if the demonstrations of each occlusion concept can be shown and if there are any components that may obstruct different views. Once we have validated that the prototype can demonstrate different occlusions at many angles, we will test the prototype in front of a class of dental students.

The series of test runs will be short lectures given by our sponsor, Dr. Gerstner, who will use his normal teaching method and then use the prototype to teach different concepts of occlusion. The first lecture with be the control test; Dr. Gerstner will use his 'old' method to teach a concept on occlusion, say protrusion, as he has done in the past. After the lecture, he will teach protrusion but using only our prototype to facilitate his lecture. For the third lecture, he will teach a different concept, say laterotrusion, and continue to only use the prototype. For the final lecture, Dr. Gerstner will teach laterotrusion again but using only his 'old' method. At the end of the test series, students will fill out a a Likert survey (explained in the following section) indicating where they sat in the lecture hall, how well they could see the model and the various jaw motions, and how effective the prototype was as a teaching tool versus the lecture slides and articulator. With this survey, we will be able to validate that the prototype is large enough for each student in the lecture hall to see. This will also validate that the prototype is a more effective teaching tool than the professor's old methods.

16.1.3. ***Testing Effective Teaching Tool***
Another survey will be given to Dr. Gerstner to evaluate his experience using the prototype during a live class. A sample Likert survey for Dr. Gerstner is in Appendix M which asks about using the prototype in front of the class, performing simple procedures, and ease of use. This Likert survey is a fair method to measure the effectiveness of Jaws: The Educator as a teaching tool. The questions are asked in a certain way to measure the level of agreement and disagreement with certain statements. An equal number of questions are asked in a positive light as well as a negative light. This removes the possibility of bias that may encourage the survey taker to judge our prototype more favorably then actuality. Appendix X has 10 statements with possible answers of 'strongly agree', 'agree', 'neither agree nor disagree', 'disagree', and 'strongly disagree'. Each answer has a corresponding score (unknown to the person taking the survey) that will be used to add up the total score. For questions that positively state that the Jaws is an effective teaching tool (1-5) will rank 'strongly agree' with the most points and 'strongly disagree' with only 1 point. For the questions that are negatively stated (6-10), 'strongly agree' will have the 1 point and 'strongly disagree' will be worth 4 points. If one strongly agrees that the prototype is not an effective teaching tool, then the score should accurately report this. The highest possible score, meaning a very effective teaching tool, is 40 and the lowest in 10.

16.2. Jaw Actuation Specifications

A major issue with the current teaching benchmarks included the manual manipulation of the articulator. The articulator demonstrated dental concepts through movement of the upper jaw, which is not realistic. This section will detail the validation of lower jaw electronic motion control.

16.2.1. ***Suspended Lower Jaw***
The prototype is designed to support and move a suspended lower jaw through programmed linear actuators. The three actuators, one weight bearing in the vertical direction and two in the horizontal direction, connect to the lower palate using ball and socket joints to allow for 6 DOF. These ball and

socket joints allow the jaw to rotate downward due to gravity creating instability in the model. To ensure stability in the suspended lower jaw, a passive elastic system has been employed.

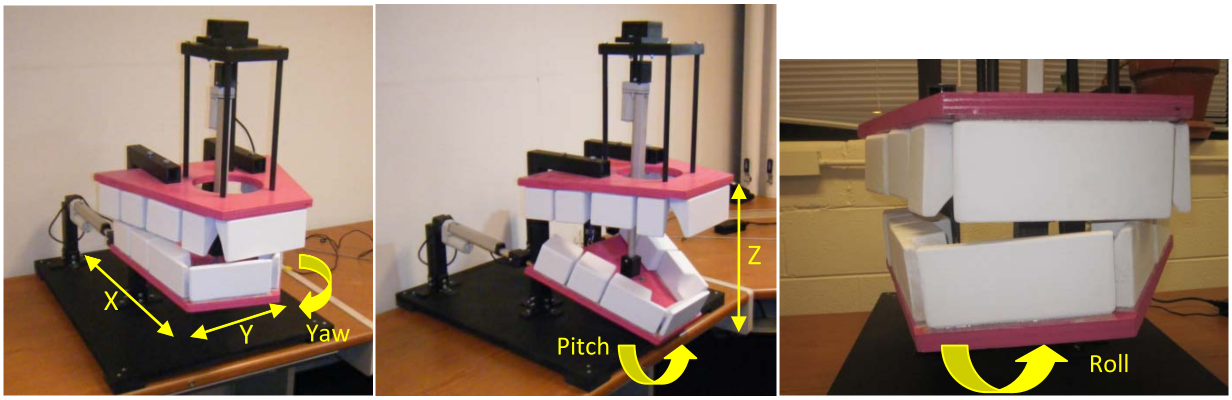
16.2.2. ***Testing Stability and Strength of Linear Actuators***
The actuators must be tested to validate that they are stable and strong enough to support the lower jaw and additional forces. While this testing is not directly related to our specifications, it is crucial that these unpredictable forces may be applied during the removal and replacement of the teeth to the jaw plates, movement of the model in transit to and from lecture halls, and other unforeseeable actions. Given the level of unpredictability, we will design safety factors into all aspects of the prototype. The linear actuators of the prototype are designed to support 150 lbs, which is enough to support the static lower jaw with a safety factor of 452. To test the linear actuators, added weights to the lower jaw that act as possible forces. The loaded jaw must be able to move exactly as it does when unloaded.

16.2.3. ***Testing Correct Suspension of Lower Jaw During Simulation***
While not explicitly listed as a design specification, the effect of the passive elastic support on the ability of the prototype to fulfill the prescribed motions is critical to understand. Once the lower jaw is suspended at the desired position, we tested to see if the elastic bands restrict the motion of the linear actuators. Each actuator was fully extended and retracted such that all requisite motions were evaluated. When the resultant forces from the elastic bands prevented any of the required motions the test was be repeated; the band placement & strength were adjusted to ensure motion quality.

16.2.4. ***Jaw Motion and Six Degrees of Freedom***
To move in six degrees of freedom, the actuators must work simultaneously to create smooth jaw motions. To move in a certain direction, each linear actuator must be programmed to move at a specific speed for a specific period of time. For the linear actuators to work simultaneously and accurately, they will be programmed to move using pulse-width modulation. This will break up the speeds over a period of time in pulses to move a desired distance.

The 6 DOF will be dependent on the mobility of the actuators. The ball and socket joints attached to the linear actuators will allow for actuation of the lower jaw in the three translational and three rotational degrees of freedom. Each ball and socket joint will be inspected for rotational ability prior to assembly.

We conducted simple programs to determine that all 6 DOF can be attained by the lower jaw. Each horizontal actuator was tested individually, and each moved the lower jaw in the X and Y (horizontal and translational) planes as well as accomplished the Yaw rotation. These motions are shown in Figure X.A. The upper actuator was activated such that motion in the Z (vertical) plane, as well as rotation in the pitch direction (Figure 40.B).



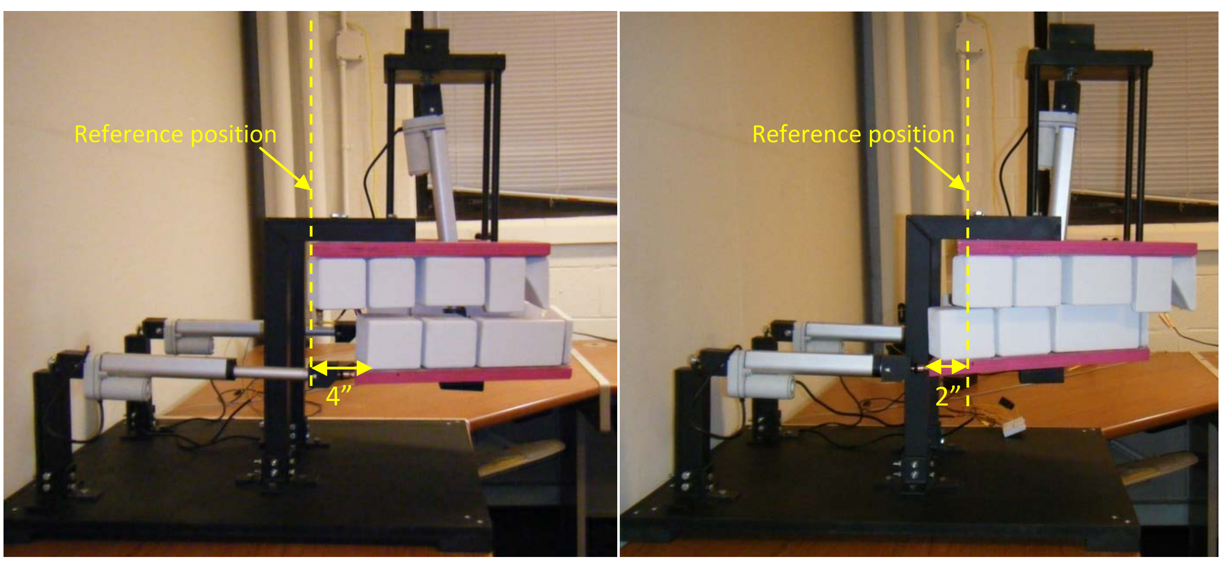
(a) (b) (c)

Figure 40: 6 DOF Joint Confirmation: a) X, Y and Yaw; b) Z and Pitch; c) Roll

16.2.5. *Testing Accuracy of Linear Actuators to Show Pro- and Retrusion*

A simple program will be developed to test the accuracy of the actuators. The program will move the jaw forward and backward a specified distance. The speed and time of linear actuation is to be set such that a theoretical distance travelled can be calculated ($x = v*t$). A stylus pen will be attached to the lower jaw so that the distance travelled will be traced on paper. The measured distance traced by the stylus pen will be compared with the theoretical distance to determine the accuracy and offset of the linear actuator system. This procedure will be used to measure the distance the lower jaw travels in protrusion and retrusion.

The aforementioned testing was completed and the ability of the prototype to show protrusion and retrusion was confirmed. Figure 41 is provided below to highlight the prototype functionality.



(a) (b)

Figure 41: Photos of the prototype at: a) Protrusion; b) Retrusion

16.2.6. *Testing Accuracy of Linear Actuators to Show Laterotrusion*

Similar to pro- and retrusion, the accuracy of laterotrusive motion will be measured using a stylus pen. The jaw must translate forward, downward, and laterally to show laterotrusion. The horizontal and translational (X and Y) movements of the jaw will be performed as detailed in the previous section for protrusion. To test the vertical movement, the pen will be attached to the lower jaw, with the tip of the pen 2" above ground. The lower jaw will be programmed to move downward 1". At the end of the jaw actuation, the distance between the tip and the ground will be measured and the offset from 1" will be determined. With this offset in mind, the linear actuators can be programmed to move vertically the desired amount.

The prototype was tested and verified to be able to simulate a laterotrusion movement for the specified distances. Figure 42 below shows the prototype in the laterotrusion position.

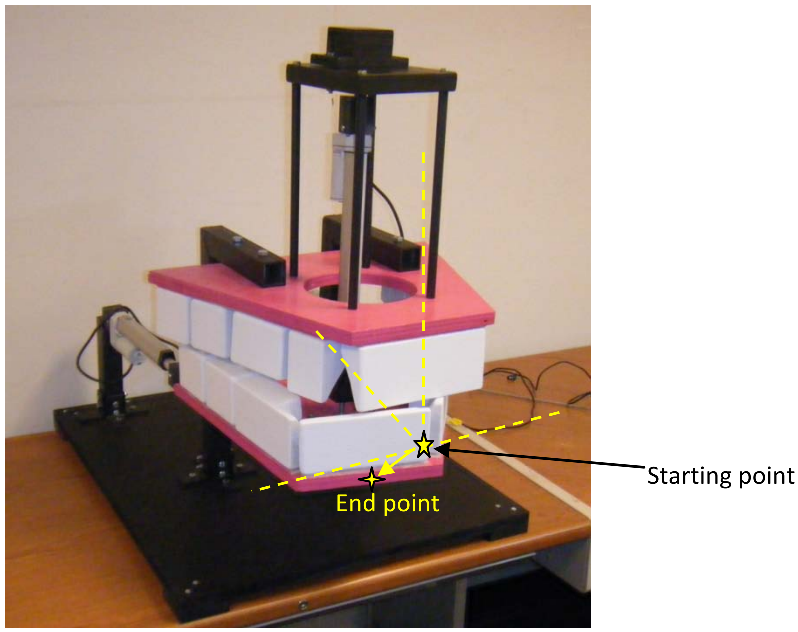
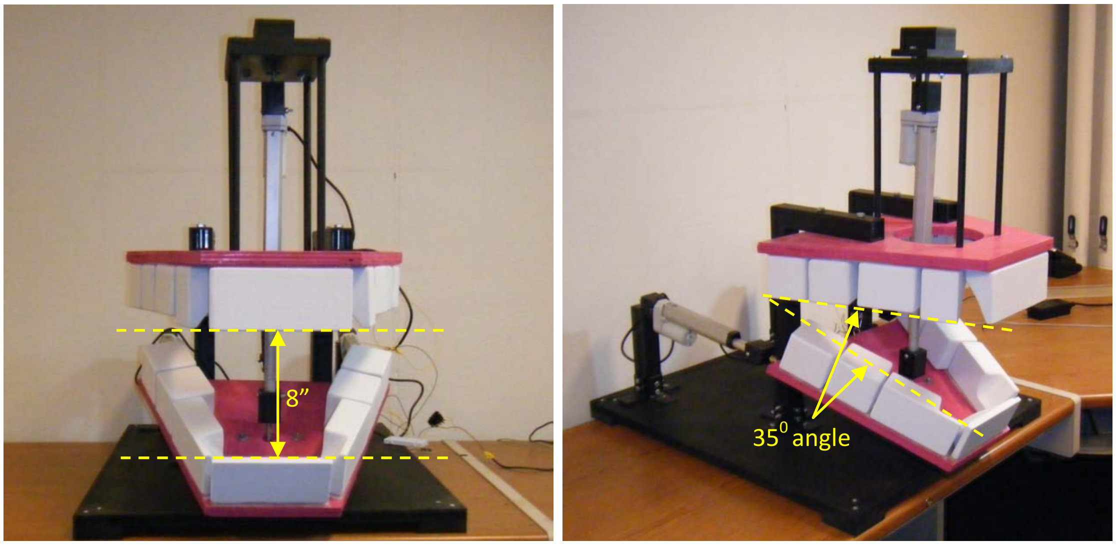


Figure 42. Photo showing the prototype in full laterotrusion

16.2.7. ***Flexibility of Linear Actuators During Simulation***
Because of a slight overbite of the teeth, the jaw must be able to protrude and retrude without complications. The ball and socket joints should allow the linear actuators to automatically adjust when the upper and lower incisors contact. The teeth should be strongly attached to the jaw plate so they remain rigid like normal teeth. If the linear actuators do not adjust for this contact, additional programming will be necessary for the lower incisors to move around the upper incisors.

16.2.8. ***Open Jaw to Remove/Replace Teeth***
The jaw must open a sufficient amount for removing and replacing the teeth. The weight bearing linear actuator must be fully extended 9 inches and must be strong enough to bear forces when the teeth are removed and reattached to the palates. This specification is validated through our engineering analysis of the weight bearing actuator.

The prototype is capable of completely opening a vertical distance of 8 inches to allow for the removal and adjustment of the teeth. The completely opened jaw is shown in Figure 43 on page 70. While the specification called for a 90^0 angle to be completely "opened," this number was found to be excessive. The goal of the specification was to allow removal and replacement of the teeth and due to the size of the prototype the angle needed to accomplish this was considerably decreased. The prototype can produce a 35^o angle below horizontal, and is experimentally validated to be sufficient to allow easy removal of the teeth.



(a) (b)

Figure 43. Fully opened jaw that allows for teeth adjustment and removal

16.3. Teeth Verification

The motions of the jaw are important for dental concepts due to the interferences of teeth. These teeth interferences are dictated by the teeth structure, and this section will address the prototype teeth adjustability.

16.3.1. ***Adjustable and Fixable Teeth***
The teeth must be removed easily by the user and then reattached securely back onto the jaw plate. We will test different forms of attachment, specifically different types of hook and loop (Velcro) fasteners. The tests will validate that the chosen method will hold the teeth in place during occlusion, endure wear, and allow for detachable teeth.

16.3.2. ***Testing for Curve of Spee***
The prototype will demonstrate the effects of a steep Curve of Spee. Additional molar inserts will be manufactured in order to replicate a steep Curve of Spee. With the guidance of Dr. Gerstner, the molars will be shaped (angled) to most effectively demonstrate the concepts associated with an atypical Curve of Spee.

To correctly demonstrate the effects of the Curve of Spee, the upper and lower back molars must be separated by a gap and the back molars should be pressed together during protrusion. To test this interaction, the back molars will be angled with the inserts to represent the Curve of Spee. The actuator will then go through the programmed protrusion movement. When a normal jaw protrudes, the upper and lower incisors are aligned and touching with a gap between the back molars. If there is interference due to the Curve of Spee, then the protrusion motion will be limited due to contact between the back molars and the upper premolar. This contact will result in a disclusion between the two front incisors and is verified as a gap between the two.

The prototype shows that, using angled molars to represent variable Curves of Spee, the jaw cannot protrude fully due to contact between the back molars and upper premolars and results in a disclusion between the front incisors. This is shown in Figure 44 below.

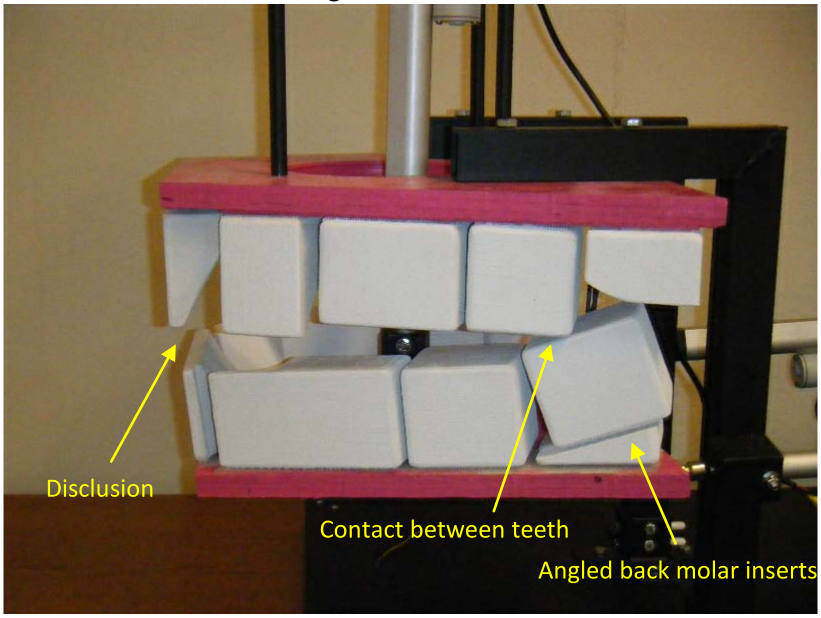


Figure 44. Curve of Spee simulated through teeth variability, causing teeth contact at back molars which results in a disclusion between the front incisors

16.3.3. *Testing for Curve of Wilson*

The back molars (upper and lower) must be at the proper angle to show variations in the Curve of Wilson. We will determine the appropriate angle of the back molars by testing the protrusion-laterotrusion movement of the teeth. Similar to the testing for Curve of Spee, the back molars will be angled with inserts, but this time the angle will be towards the interior of the mouth. This angle represents the Curve of Wilson. The prototype will then run the laterotrusion programmed motion. When a normal jaw actuates, the upper canine of the laterotrusion side will make contact with the lower teeth. When the jaw with a steep Curve of Wilson laterotrudes, the upper canine on the laterotrusion side should not make contact with the lower teeth.

The prototype was tested and the Curve of Wilson variation will induce a disclusion between the upper canine and the lower teeth. This is shown in Figure 45 on the following page.

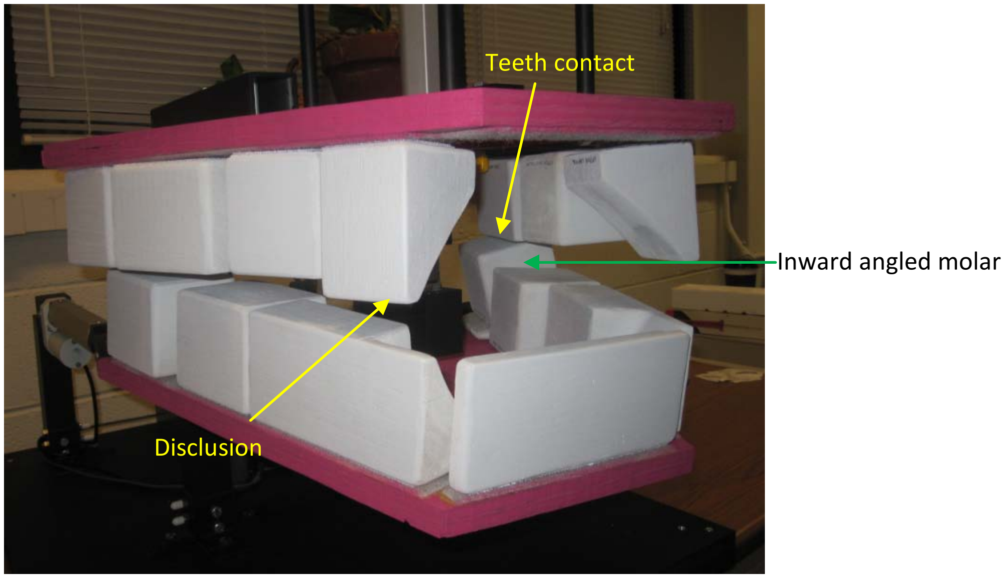


Figure 45. Curve of Wilson verification showing the angled lower molar contacting the upper molar; disclusion between upper Canine and lower teeth. Note: Front upper incisor removed for clarity

16.3.4. ***Intrusion and Extrusion of Teeth***

The prototype includes extra replaceable teeth to provide for multiple teeth alignments and variations, including extrusions and intrusions of teeth. Intrusion and extrusion of teeth describe how much the teeth extend from the gums. Extra upper incisors and upper canines were manufactured slightly taller (+0.5 inches) than the normal set of teeth. The extra replaceable teeth validate that the prototype will show intrusion and extrusion of the teeth. Additional inserts were also manufactured to allow for variability of all teeth.

17. FINAL DESIGN DESCRIPTION

The prototype design is the feasible deliverable given the scope of the project; however, a final design was developed for future improvements. The final design was created with the same capabilities of the prototype, but will not limited by the cost and time constraints of the project. The final design comprises of a modified prototype, shown in Figure 46 with altered features listed in Table24, and will be discussed in this section.

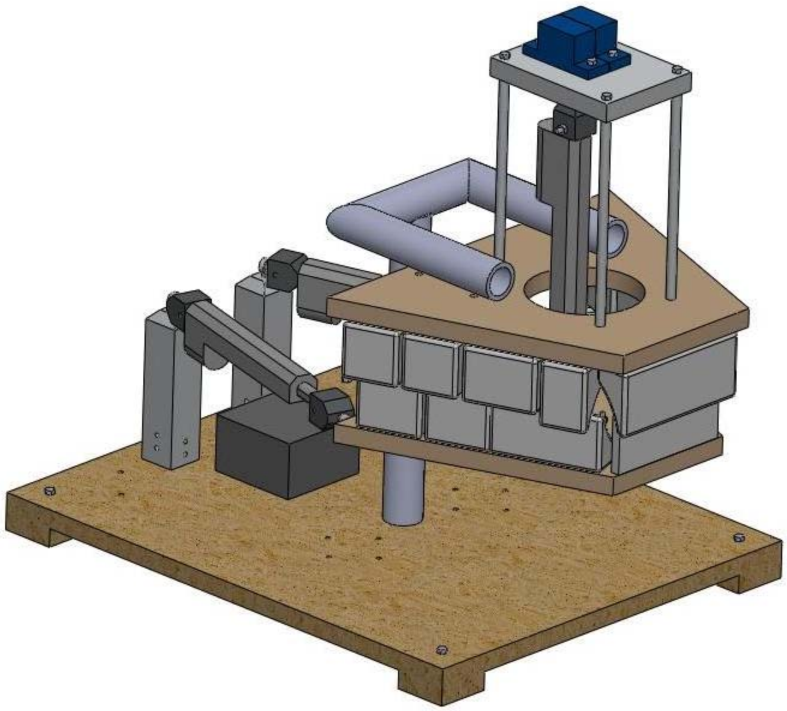


Figure 46. Final design visualization isometric view (Extension spring shown in Fig 35)

Table 24. Summary of component changes from prototype to final design (not including material changes)

Component	Prototype	Final
Passive Elastic Support	Elastic Band	Extension Spring
Upper Jaw Support	Two L-Bar Supports	Single Support Bar
Horizontal Actuators	In Plane Positioning	Angled Positioning
Teeth	Simple Shapes	Rapid Prototyping

17.2 Spring Replacement of Passive Elastic Support

The final design will address the inherent instability of the prototype. The prototype design includes a passive elastic support, suspended between the upper and lower jaws. This elastic support is necessary to overcome the static force of gravity on the horizontal actuator connection to the lower jaw (for more complete description see Section 13 above). The passive elastic support is a quick and easy solution that fits within the cost and time restraints. The final design will replace this passive elastic system with an extension spring (Part 42). The spring will be placed in the same location as the passive elastic support, such that it is as close to the horizontal actuator and jaw connection as possible. The spring will work in conjunction with the vertical actuator for the prescribed motions. The spring and actuator combination will work on either side of the center of mass of the lower jaw to compensate for the gravitational pull on the horizontal actuators and balance the lower jaw. There may be a potential interference when the jaw completely opens. This motion would load the spring significantly and create a safety hazard. The spring will be mounted between the jaws by hooks, so that it can be easily removed when completely opening the jaw. The extension spring provides additional stability and control to the design and does not detract from any of the necessary motions.

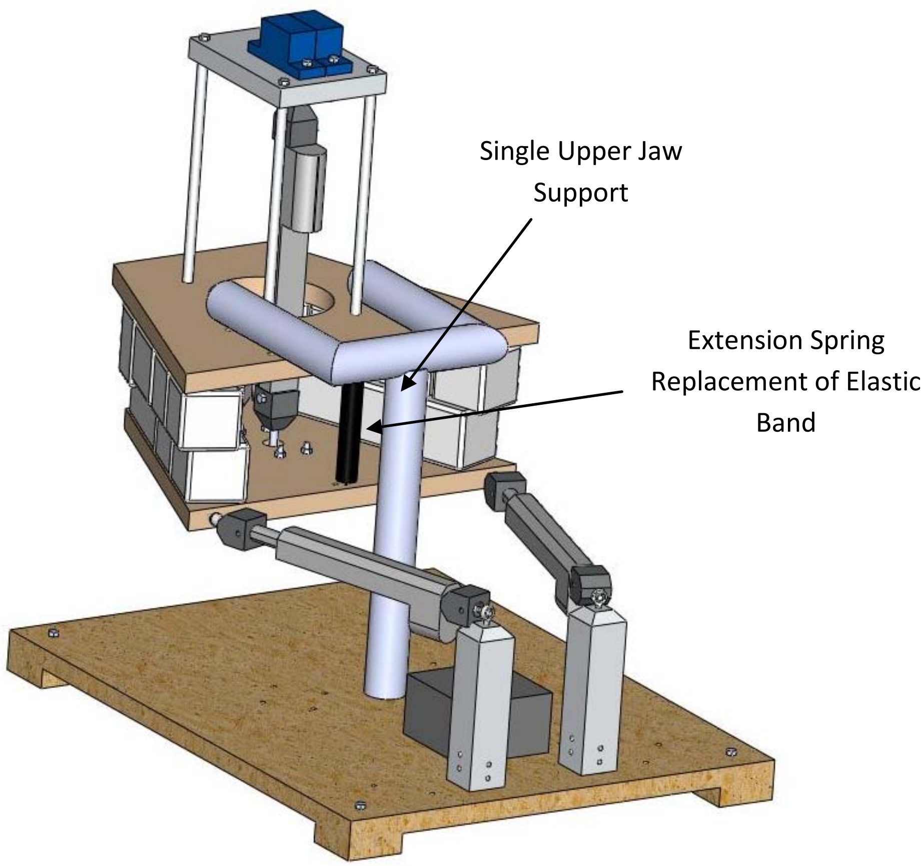


Figure 47. Final design isometric back view highlighting the addition of a spring support and single support stand

17.3 Single Upper Jaw Support

The upper jaw support of the final design, shown in Figure 47 above, will replace the two upper jaw supports of the prototype. The single upper jaw support will be as stable as the prototype design while providing for more views. The single support will be titanium for maximum strength characteristics and relatively light weight, rather than the cheaper aluminum tubing of the prototype. The alloy will allow for adequate support using only one support stand. The support will have two upper extensions that straddle the vertical actuator range of motion thereby avoiding possible interferences. The adjustment to a single support will also allow for a wider range of locations for the horizontal actuators.

17.3 Angled Horizontal Actuator Location

The horizontal linear actuators in the final design are angled to provide a wider range of motion (Figure 48). The placement of the horizontal actuators in the prototype design is limited by the two upper jaw support stands and the length of the linear actuators; angling the actuators would be ineffective. The single support in the final design allows the horizontal actuators to be angled from the lower jaw, allowing more exaggerated motions of laterotrusion while maintaining all other necessary motions.

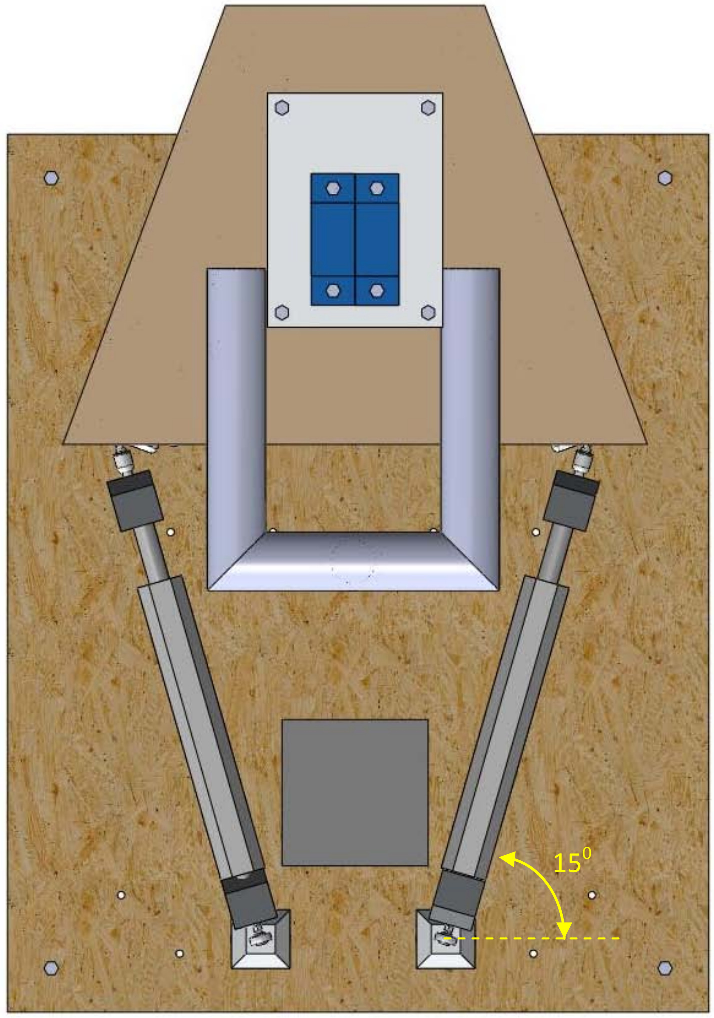


Figure 48. Top view of final design highlights the angled horizontal actuators

17.4 Rapid Prototyping of teeth

Anatomical accuracy of the design will add to the effectiveness of the model as a teaching aid. The prototype focuses on delivering a mechanized model for the dental lectures, instead of anatomic accuracy. Additional aesthetic changes to the teeth will be made for the final design. These changes will incorporate rapid prototyping to deliver accurate teeth/jaw representations. Anatomical accuracy would be beneficial to dental students as it allows actual viewing of the teeth interactions between the cusps of the teeth. The prototype design will have block and shovel representations of teeth due to the cost and time limitations of the project.

Fabricating large-scaled, lightweight, anatomically accurate teeth will require the use of 3D scanning and rapid prototyping capabilities. To produce a detailed set of teeth, a stone casting must first be made of a desired set of teeth. A 3-D scanner will take a detailed, 3D image of the stone casting and convert it into a CAD-compatible file. After scaling the teeth through CAD, the new accurate teeth model will be delivered to the rapid prototyping lab. The lab will make a 3D print of the CAD model out of plaster of Paris, which will be the mold for the teeth set. This mold will be fabricated using epoxy, to create large-scaled, anatomical teeth.

The cost of rapid prototyping one set of teeth is approximately $80, which is outside the scope of the project. Without the limitations of time and budget, the final design would be improved with rapid prototyping both the upper and lower teeth, as well as variable curves of Wilson and Spee,

17.5 Material Changes

The materials selected for the prototype were greatly limited by cost. The final design includes improvements in material selections for the board, upper jaw stand, and teeth, with a summary of the material changes shown in Table 25 below. First, the base board will have a reduced thickness and width. A reduction in the size of the board allows for a change of material to thin-walled aluminum that would improve the strength and durability of the board, while not significantly increasing the total weight of the structure. Secondly, a high strength, lightweight alloy (preferably titanium) would replace aluminum in the upper jaw stand. A stronger material in the stand, in conjunction with a stronger base board, will allow the upper jaw stand to be condensed into one support, as detailed in Section 17.3. Finally, as mentioned above, the balsa wood teeth in the prototype will be replaced by epoxy molded teeth. The upper jaw will have a stronger support structure therefore the teeth can be slightly denser. The epoxy teeth will provide benefits in anatomical accuracy as well as durability.

Table 25. Material changes for the final design

Component	Prototype	Final Design
Passive Support	Elastic	Extension Spring
Teeth	Balsa Wood	Epoxy
Base Board	Wood	Aluminum
Stands (Structural)	Aluminum	Titanium

18. DISCUSSION

Throughout the evolution of the prototype and final designs, several strengths and weaknesses have surfaced during the planning, fabrication, and validation phases of the project. Though we are pleased with the design's ability to meet the specifications established at the beginning of the project, there are several successes and weaknesses of the design worthy of discussion now that the design is complete. The following section will provide a detailed critique of the prototype and proposed final design.

18.1 Design Strengths

According to the goals laid out at the onset of the project, the prototype qualifies as a successful project. The following sections will detail the strengths that allow the prototype to be characterized as such.

18.1.1 ***Teeth Variability***
One of the biggest shortcomings of existing technology, as described in Section 4.1, is the inability to adjust the teeth individually. The designed prototype features inserts of varying size and shape, which allow the user to replicate different oral anatomies. This additional variability will be especially useful in an educational setting to serve as a means of making simple demonstrations with which to demonstrate.

18.1.2 ***Independent Actuation Control***
The original prototype exclusively called for pre-programmed motions that would control the motion of the jaw. Each individual concept replicated by the jaw is directly related to the unique way the teeth are set. Given the variability of the teeth, the number of programs which replicate each concept would need to reflect this variability. The manufactured prototype incorporates switches that control each linear actuator. This allows the user to manually adjust the jaw to any position in the available range of motion. Though the motion of the jaw will be difficult to achieve, a specific location will be very easy to obtain. This added strength allows for usefulness of the design if a program has not been created to fit a specific motion given a specific combination of teeth as well as increasing the professor’s ability to teach other concepts in the future.

18.1.3 ***Simple, Open-Source Programming***
The microcontroller integrated in the prototype takes advantage of open-source programming, while much of the existing technology for virtual dental models is highly proprietary. By utilizing open-source programming, anyone will be able to create programs to simulate jaw motion. With this added feature to the design, it is reasonable to imagine a comprehensive list of programs that can mimic jaw motions for the large variety of teeth configurations.

18.2 Design Weaknesses
Despite the prototype’s many strengths, there were weaknesses in both the project planning stages as well as in the final product that could make the prototype a more effective educational tool. The following sections will describe various changes to the design plan and prototype that could be improved should the design problem be addressed again in the future.

18.2.1 ***Weight, Mobility***
One weakness of the prototype is its weight and bulkiness. These factors combine to make it difficult to maneuver, especially for one person. This weakness is addressed in our final design proposition by utilizing light weight, high strength materials to create a durable design that can be easily moved by one person. However, even after the weight is minimized, the model will still be bulky and relatively heavy. As a result, the transportation requirements of the design may limit its use.

18.2.2 ***Strength of Actuators***
The strength of the actuators used for the design can be viewed as both a strength and weakness. They are strong enough to support the jaw and perform the requisite motions. However, they are also strong enough to damage the prototype itself. There is no feedback in the programming or electrical circuit itself. As such, the actuators will continue to open or close as long as the circuit dictates. Given that the actuators are capable of pushing/pulling with 150 lbs of force (Appendix I.3), this force is enough to indent the teeth (balsa wood) if a specific set of teeth is in place. As such, this weakness limits the use of the prototype to a user who knows what the programs do in combination with which teeth need to be in place to facilitate the motion.

18.2.3 ***Limitations to Current Technology***

Though a strength of the prototype is the open-source technology utilized, the same microcontroller is only capable of storing one program at a time. As such, a computer interface is needed to upload each program individually when changing motions. Given the nature of programmed motions and the variability of the design, it is impossible for the prototype or proposed final design to function without a computer interface.

18.2.4 ***Hardware Usage (Tee Nuts)***

A weakness that may be easy to overlook when critiquing the design is the way in which certain fasteners, specifically the tee nuts, were used. Tee nuts are designed to hold threaded objects in tension with the flange of the tee nut supported by the surface it is set into (i.e. wood). In our design the tee nuts merely linked the lower palate to the in-line ball and socket joints and were not relied on to support force in tension. As such, the tee nuts were fastened in an orientation that they are not meant to be used. Though this did not negatively impact our design because little weight is supported at this joint, it is difficult to perform failure analysis on this location of the design and is impossible to obtain a reliable safety factor for this design aspect.

18.2.5 ***Imprecision of Elastic Supports***

The precision of the obtained motions of our model is limited by the least precise controlling factor of the design, the elastic supports at the back of the upper and lower palates. The existing elastic supports suspend the lower jaw at rest parallel to the upper jaw (typical jaw rest position). However, without iterative calibration (tightening) of the elastic, the supports will sag as gravity pulls them down, weakening the elastic force over time. To address this weakness, the elastic supports will either need to be periodically tightened or replaced with tension springs that would retain their elastic support for longer.

18.3 Future Improvements on Design

Given the limitations of the project, specifically the project timeline and budget, we are pleased with the outcome of the design process. However, being the first design team to address the posed problem of creating an educational tool for dental professors, we wanted to leave our design open to further development by anyone wanting to improve on our foundation. The following sections will highlight many of the improvements to our design that would add additional value to the existing design.

18.3.1 ***Virtual Model Integration***

The scale of the prototype is large enough to be utilized in a lecture hall setting. However, looking toward the future, there could additional educational value by integrating our physical model with a virtual model. In addition to being able to be projected on a screen in a classroom, a virtual model could help integrate sensors that could limit ranges of motion or measure contact forces between teeth. Though there are practical limitations to the applicability of additional technology, the prototype and proposed final design leave these options open for the future.

18.3.2 ***Open-Source Programming***

Currently the prototype takes advantage of the microcontroller and accompanying program language simplicity. Given the wide range of possibilities afforded by open-source technology, it would be possible to adjust actuation speed as well as program more complex simulations once there is a foundation of existing programs on which to build.

18.3.3 *Integrated Limitation of Motion*

As previously highlighted in Section 7, the prototype and proposed final design do not address the design problem of modeling condylar inclination. Though the design does not provide an accurate physical model of the condylar joint, it would be possible to integrate limitations to the jaw motions that effectively limit jaw motion the same way the condylar joint does. Looking forward, integrating these limitations to motion would be an effective way of modeling condylar inclination without any significant changes to the design.

19. RECOMMENDATIONS

Though we have proposed several improvements to the design that could improve its utility in the future, there are also several recommendations we would urge being taken immediately to maximize prototype use and as a result project success.

19.1 User Familiarity with Computer and Manual Controls

Despite the simplicity of the computer interface and manual controls they will require some practice to develop a comfort level required by the user to effectively teach dental concepts using the prototype.

19.1.1 Using Arduino Computer Interface

The microcontroller and programs utilize Arduino open-source computer code which is not relatively commonplace, especially in the dental industry. As such a detailed description of the computer interface will be provided to our sponsor upon prototype delivery. This description will include accessing/downloading controller interface, creating programs, and uploading programs onto the microcontroller. The simplicity of the program provides the user(s) with the ability to create and test their own programs. We recommend this be done as a means of learning more about the programming interface and capabilities obtainable by the prototype.

19.1.2 Using Manual Controls

The actuator switches are simple to use but may require practice to integrate into an educational setting. This practice would allow the user to seamlessly integrate the prototype into the framework of existing lectures and maximize the educational opportunities created by the model. In addition, familiarity with the manual controls can avoid producing high forces resulting from the strength of actuation and interconnected nature of jaw motion. For example, when protruding the lower palate translates forward. To do so the upper actuator must extend to account for the increased distance of the lower palate to the upper vertical actuator support. Without accounting for this vertical displacement, the lower palate will be forced to rise toward the upper jaw which could result in excessive contact forces between teeth sections. By growing comfortable with the controls, situations that threaten prototype integrity can be avoided.

19.2 Quantify Prototype Effectiveness

Many of the goals of the project can be definitively tested. The prototype's ability to replicate the human jaw and move the specified distances have been validated. However, qualitative specifications such as the overarching 'is the design an effective teaching tool?' is impossible to determine without actually using the prototype. As such, we recommend that the first uses of the prototype be accompanied by a series of surveys for the lecturer (user) and students being taught. These surveys would ask a series of questions to both teacher and student inquiring into their ease of concept comprehension, proclivity toward using the model in class, and general design acceptance. Surveys such as these, called Likert surveys, prompt survey takers with intentionally leading questions to determine their true inclination toward a concept. A draft Likert survey was compiled to question a professor using the prototype in lecture for the first time after limited exposure to its uses. See Appendix M for sample survey. Until the prototype is proven to be an effective educational tool, it is impossible to truly know the extent of success of the design.

19.3 Organization During Disassembly

In the event that the prototype needs to be disassembled, we would recommend that each part be categorically labeled indicating its specific location on the prototype so that reassembly will be as simple as possible. As a result of the quantity of parts fabricated for the prototype there are locations where close fits were necessary for complete assembly. Similarly, disassembly of the electrical componentry should be accompanied by a detailed labeling of wires, connections, etc. in order to reassemble the model quickly and correctly. For assembly of the physical and electrical systems, please refer to the Fabrication Plan (Section 15).

19.4 Account for Storage of Prototype

Though we are excited about the future use of the prototype in an academic setting, we would also recommend that the user take care to store the prototype when not in use. Given the size of the model, storage locations may be limited to excess shelf or floor space in a classroom or office setting. With this, there may be a tendency to stack the prototype on top of other material in storage or even worse, store things on top of the prototype. In this respect, we recommend that the user keep in mind the intended function of the prototype and limit its use to these functions.

20. ACKNOWLEDGEMENTS

The success of our senior design project would not have been possible without the help from many esteemed professionals and advisors. We appreciate all the time you have spent helping us.

The sponsor of our project, Dr. Geoffrey Gerstner, was an incredible resource in many aspects. Not only did he teach us occlusion, to which we knew nothing about in September, he also gave us creative and helpful ideas in the design process as well. He was a pleasure to work with and was always willing to help us in any way he could. Thank you! Good luck with the electric eel energy source!

Professor Nikos Chronis, our faculty advisor, was an amazing resource and advisor throughout this semester. Our weekly meetings were constructive, productive, and enjoyable. Prof. Chronis' amiable attitude lightened the mood and definitely calmed us down when we were on the verge of panic. Prof. Chronis always greeted us with a smile and was a tremendous support in our endeavors. We developed a strong relationship with Prof. Chronis and we will miss the Greek life in our weekly meetings.

Bamal Fastener Corp donated the three linear actuators of Jaws: The Educator. These actuators were the arms and the legs of our prototype. Without this very generous donation, we would not have been able to actuate the jaw as we had hoped. Thank you, Bamal, for your support in Mechanical Engineering education.

Mr. Dan Johnson is the superhero of engineers. There were countless times where Dan rescued us from possible failure. From the start, Dan advised us on the design and encouraged us to order supplies right away. He was always willing to dedicate any time he had to helping us and other 450 teams. Without his help, we would have not finished on time or as completely. Dan was also a tremendous support who lifted our spirits whenever we saw him. His love for mechanical engineering and design was inspiring and definitely had a positive influence on us throughout the term. Dan always cheered us up with an appropriate South Park quote for every occasion.

Words cannot express the gratitude we feel for Bob Coury and Marv Cressey. Some of us felt as though we were walking into the shop for the first time this semester and were clueless on where to start. Bob and Marv were always ready to help and chat it up whenever we needed them. They were very patient with us, even when they were explaining a certain process for the second or third time. Time in the shop was very limited and we were extremely worried that we wouldn't finish manufacturing all of our parts. They managed all of the teams in the short amount of time and paid special attention to everyone. Thanks to them, we have manufactured a successful prototype and still have all of our fingers.

Professor Kathleen Sienko was enormously helpful towards the end of our project. As the second professor in DR #3 and #4, she provided a new and fresh way of approaching the validation of our prototype that we had not considered. Thank you for your advice!

21. CONCLUSIONS

This report is the cumulative result of our senior design project, Jaws: The Educator. The project goal was to improve upon existing dental teaching tools, and assist professors in demonstrating several fundamental but difficult to comprehend dental concepts (collectively known as 'occlusion') to large classes of students. We have accomplished this goal.

There are four main issues with the existing methods used by dental professors. First, they do not perform the actual motions of the human jaw. A physical, manually manipulated device known as an articulator mimics jaw motions through movement of the upper jaw, which in reality is fixed. Secondly, supplemental virtual models attempt to teach the 3-dimensional jaw motion using 2-dimensional visuals (via Powerpoint® slides). Even when used in conjunction, these tools neither demonstrate true jaw motion nor allow for variation in teeth and jaw structures. Thirdly, the real human jaw has significant variability from person to person, but there is no way of showing this with the existing tools because altering how the teeth lie in the articulator is virtually impossible. Finally, teaching the concepts with good visual clarity is also virtually impossible due to the complex interrelations of the teeth concepts and the small size of the articulator relative to the normal class size.

Our prototype hits these teaching issues right in the jaw. The final product is an 8X scaled up prototype of the human jaw that is electronically actuated to simulate actual motions of the lower jaw. The prototype motion is accomplished with 3 linear actuators that are controlled either via computer programming or manual operation of electrical switches. The teeth are attached with Velcro to the upper and lower palates, allowing for easy removal and adjustment within the jaw. Extra teeth components were also fabricated to vary the teeth angles and sizes. Overall, the product is a user and viewer friendly prototype that is electronically controlled and anatomically variable.

As in all products, our design has its strength and weaknesses. It has the variability to be applicable in the presentation of many dental concepts, and the physical size to show them clearly. The prototype can be fully automated or manually actuated per the user's desire, while the teeth can be placed in various jaw positions to exaggerate concepts and facilitate lecturing. However, each individually automated motion and teeth arrangement requires its own individual program using the current technology. Also, the prototype lacks feedback control to prevent the prototype from damaging itself if it is used improperly. This requires the user to familiarize himself/herself with the equipment before attempting a demonstration. Despite these drawbacks, the design was left as open to future improvement and variation as possible.

Overall, Team Jaws is incredibly proud of the project achievements. The final prototype was presented to our sponsor and the engineering community at the University of Michigan Design Expo on 10 December 2009. It will be delivered to our sponsor by 22 December 2009, and we look forward to the possibilities for further research using the design, and anticipate integration of the prototype into the dental curriculum in the near future.

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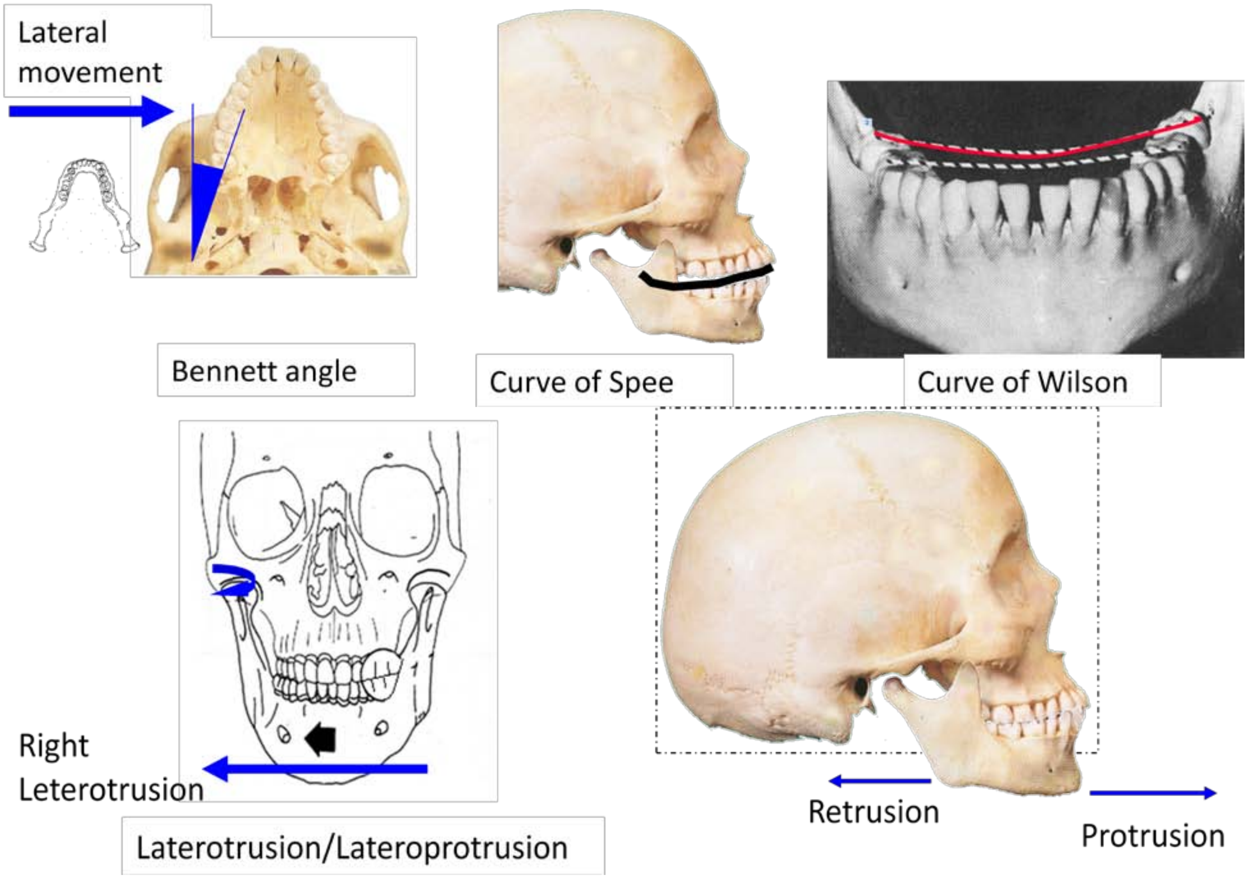
APPENDIX A. Illustrative Figures of Dental Concepts [1]



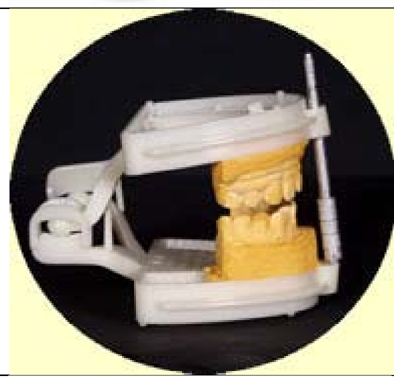
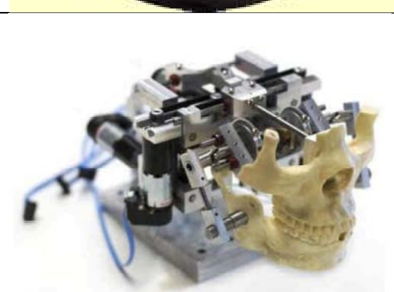
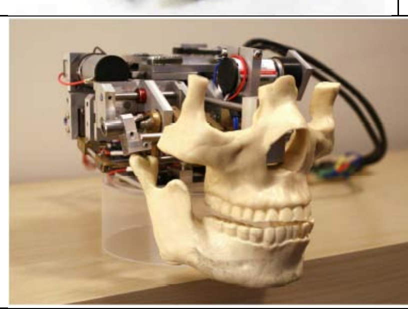
APPENDIX B. Literature Review

APPENDIX B.1 Patents and papers regarding models simulating occlusion movement of the jaws.

Patent #	Date	Inventor(s)	Title	Highlighted Claims
3896550	July 29, 1975	Robert L. Lee [15]	Jaw Movement Simulator	-mandibular frame and hinge axis of human mandible -upper jaw movement with respect to lower jaw -spherical styluses used to simulate horizontal or hinge axis condyles
4969820	Nov. 13, 1990	Gerd Oestreich [16]	Jaw model	-rotatable and removable teeth to simulate different configurations
6120290	Sept. 19, 2000	Susumu Fukushima et al. [17]	Jaw movement simulator, jaw movement simulation system, and jaw movement simulation method	-lower jaw fixed position relative to lower jaw -image pick-up apparatus for imaging movement -many cameras
US/2005/0089815A1	Oct. 24, 2003	Wan Ki Lee [18]	Dental device for modeling system with articulator adjustable, articulator stand, classified label and protective cover	-3D articulator model having upper & lower base members -upper and lower bases have an arch-shape for casting dentures on pins

Date	Authors	Title	Abstract
2005	Dr. John Bronlund [19]	Robotic Human Jaw	-3D model accurate simulation of chewing -mathematical model of human jaw muscles to reproduce jaw movement through muscle contraction
2009	Jakstat & Ahlers [20]	Development of a computer-assisted system for model-based condylar position analysis	-ability to take measurements with electronic measuring instruments applied directly to patient -computerization of imaging condylar position in 3D

APPENDIX B.2. Relevant existing technology.

Model	Picture	Description	Source
Whip Mix 8500 Series Articulator		• Standard articulator • movable upper jaw and stationary lower jaw • 6 DOF joint • Condylar inclination track • Incisal pen	www.whipmix.com [21]
Viade Model 2072		• Anatomical jaw model • Epoxy removable teeth • Memory-like material gums • Flexible plastic hinge	www.viade.com [12]
All Stone II Full Arch Articulator		• Standard hand held clamping device for any mold • Incisal pen • Ball-and-socket hinge allows for flexibility and easy to use	http://www.cbite.com /products/viper.htm
6 DOF Robotic Jaw Design 1		• Simulates movement in facial expression • Uses 4 DC gearmotors, motorized cross roller sliders, torsional springs	(Flores, et. Al. Design 1) [11]
6 DOF Robotic Jaw Design 2		• Simulates movement in facial expression • Electronic controller design • 6 DC Motors	(Flores, et.al. Design 2) [11]

APPENDIX C. How the current teaching methods fail/succeed as an effective education tool

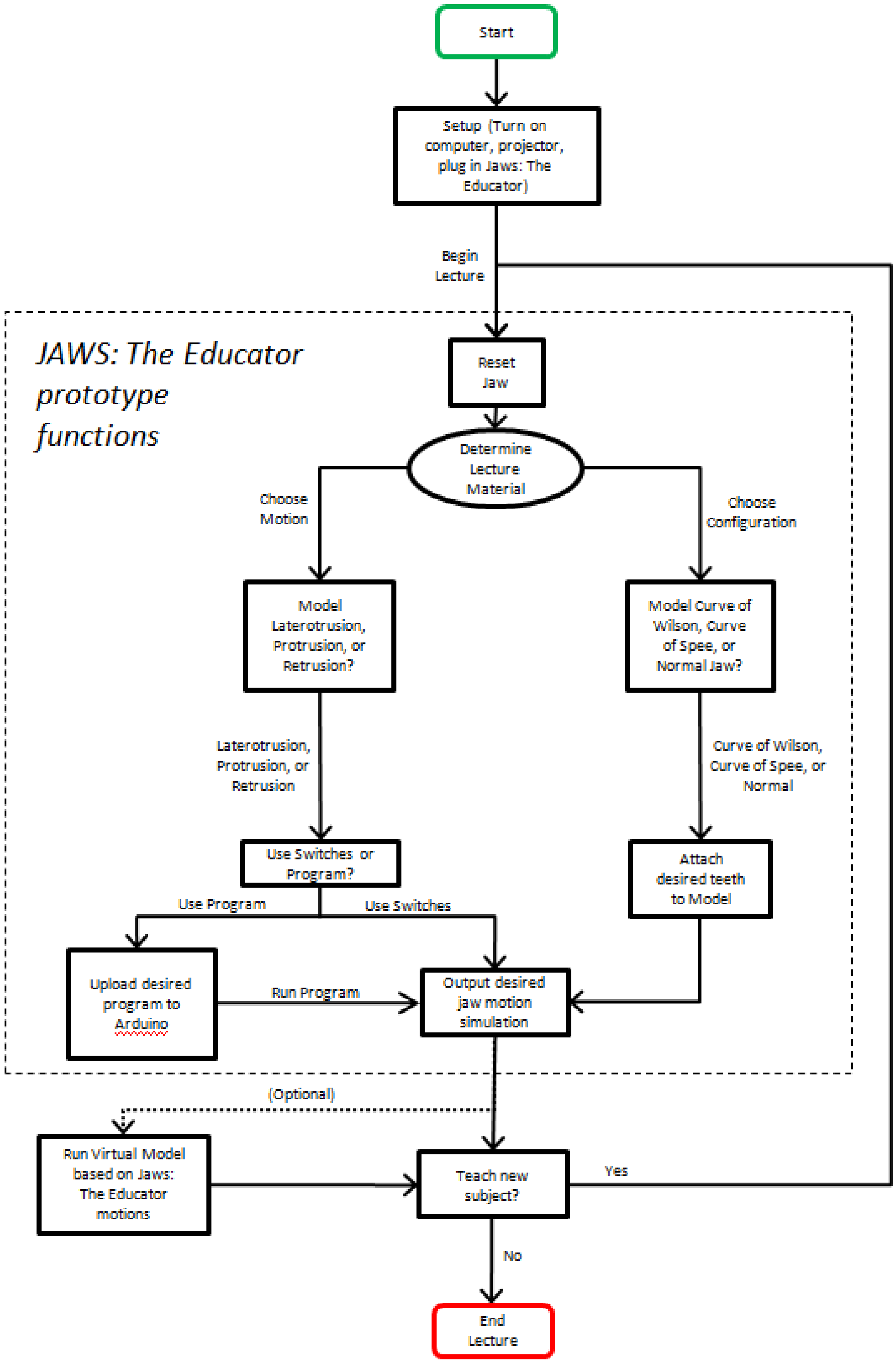
Design Theme	#	Required Functionality	Most Effective Tool (Articulator, PPT Slides, N/A)	Capability of Current System (High, Med, Low, N/A)	Capability for Improvement (High, Med, Low, N/A)	Comments
Educational Topics / Concepts	1	Model Concept of Protrusion	Articulator	High	Low	Articulator jaw joint is easy to set up to model the concept of protrusion
	2	Model Concept of Retrusion	Articulator	High	Low	Articulator jaw joint is easy to set up to model the concept of retrusion
	3	Model Concept of Right Laterotrusion	Articulator	Med	Med	Articulator jaw joint is moderately difficult to set up to model right laterotrusion
	4	Model Concept of Left Laterotrusion	Articulator	Med	Med	Articulator jaw joint is moderately difficult to set up to model left laterotrusion
Educational Topic / Concept Variables	5	Model Variable Condylar Inclination	Articulator	Med	Med	Articulator jaw joint able to model various condylar inclinations, but not easy to visualize
	6	Model Variable Curve of Wilson	Articulator	Low	High	If the articulator teeth are made movable then this can be modeled well
	7	Model Variable Curve of Spee	Articulator	Low	High	If the articulator teeth are made movable then this can be modeled well
	8	Model Variable Intrusion/Extrusion of Teeth	Articulator	Low	High	If the articulator teeth are made movable then this can be modeled well
Educational Effectiveness	9	Effectively Illustrate Concepts	Articulator	High	Med	The ability to model laterotrusion might be able to be increased by remodeling the jaw joint dynamics
	10	Quickly Illustrate Concepts	PPT Slides	High	Med	Rethinking how to illustrate the concepts can increase presentation speed, possibly by integrating software with the articulator
	11	Effectively Illustrate Concept Variables	PPT Slides	Low	High	Making the teeth of the articulator movable and integrating this with the powerpoint presentation can make illustrating the variables more effective
	12	Quickly Illustrate Concept Variables	PPT Slides	High	Med	Integrating the powerpoint with the articulator might be able to increase speed by being more effective
	13	Effectively Illustrate Concepts While Simultaneously Varying the Concept Variables	Articulator	Low	High	Integrating the powerpoint with the articulator can more effectively display how jaw motion dynamics vary when the concept variables are varied
	14	Quickly Illustrate Concepts While Simultaneously Varying the Concept Variables	PPT Slides	Low	High	Integrating the powerpoint with the articulator can more quickly display how jaw motion dynamics vary when the concept variables are varied
	15	Effectively Illustrate Concepts and Concept Variables to Larger Audiences	PPT Slides	Low	High	Integrating the high capability of the articulator to model the concepts with the ability of powerpoint slides to be seen by large audiences can help more people understand the concepts at once
	16	Quickly Illustrate Concepts and Concept Variables to Larger Audiences	PPT Slides	High	Med	Integrating the high capability of the articulator to model the concepts with the ability of powerpoint slides to be seen by large audiences can increase the speed of understanding for larger audiences
	17	Switch from lecture topic to lecture topic in a non-linear fashion	Articulator	Med	High	It takes a very long time to set/reset the articulator. Interfacing with software can increase the speed of transition.
	18	Switch from lecture topic to lecture topic in a non-linear fashion easily and effectively	PPT Slides	Low	High	The powerpoint slides are difficult to understand.
	19	Effectively provide several view angles to reinforce visualization of concepts	Articulator	Low	High	The articulator is very small and compact. Integration with software that is easily projected to large audiences and has manipulatable 3D view capability could make it more effective.
	20	Quickly Provide Several View Angles to Reinforce Visualization of Concepts	PPT Slides	High	Low	It's quick to rotate 3D images. The key is finding the angle you want, not just being able to show different angles.

APPENDIX D. QFD, tool to compare technical requirements with customer needs. Customer needs are weighted based on importance and then compared to each project requirement. The raw scores and rankings serve as a means of determining the most significant focuses of the project.

			Technical Requirements							
	Customer Needs	Customer Weights	6 degree of freedom jaw joint (with capability for fixing joint positions) limited to mimicking human-capable motions	Anthropomorphic , anatomically accurate model parts	2 degree of freedom ±30° variable posterior tooth angles	1 degree of freedom ±5mm variable tooth extrusion levels	1 degree of freedom ±30° variable condylar inclination	Hardware/software interface using CAD models	Grounded, stable physical upper jaw model support structure	Able to fit through 1mx2.3m doorway
1	Large-scale Model	8	1	9	1	1	1	9	3	9
2	Clear Views during Simulation	8	9	3	3	3	3	9	1	1
3	Easy to use	6	9	3	9	9	9	3	1	3
4	Shows Protrusion & Retrusion of Teeth	9	9	9	3	1	3	9	1	1
5	Shows Laterotrusion	9	9	9	3	3	3	9	1	1
6	Shows Condylar Inclination	9	9	9	1	1	9	9	1	1
7	Variable Angles of Posterior Teeth (Curve of Wilson)	9	1	9	9	1	1	9	1	1
8	Intrude and Extrude Anterior Teeth	9	1	9	1	9	1	9	1	1
9	Open Jaw completely	7	9	1	1	1	1	3	1	1
10	Suspended lower jaw	7	9	3	1	1	1	3	9	1
11	Adjustable and fixable parts	9	9	1	9	9	9	1	1	1
12	Educational Tool	9	9	9	9	9	9	9	3	1
13	Durable to withstand forces of actual human jaw	5	9	1	9	9	9	1	9	1
14	Additional Visual Model	4	1	1	1	1	1	9	1	1
15	Variable Curves of Spee	9	1	3	9	1	1	1	1	1
17	Ability to demonstrate motions of different jaw and teeth configurations	9	9	9	9	9	9	9	3	1
18	6 degrees of freedom	9	9	1	3	3	3	1	1	1
		Raw score	903	763	653	563	581	839	283	211
		Scaled	1	0.845	0.723	0.623	0.643	0.929	0.313	0.234
		Relative Weight	19%	16%	14%	12%	12%	17%	6%	4%
		Rank	1	3	4	6	5	2	7	8

APPENDIX E. Concept Generation

APPENDIX E.1. Functional Decomposition using Jaws: The Educator



APPENDIX E.2. Jaw Motion

JAW CONCEPTS	DESCRIPTION
Ball and Channel	Condyle ball in a channel to show incline
Bike wheel jaw joint	Tighten to lock in place like a bike tire
Braces Jaw	Hooks and rubber bands to latch or clasp for storage
Bunjee Condylar Joint	Rubber/Elastic joint connected to condyles to move lower jaw
Chapstick Knob	Like a chapstick rotational knob, condylar incline with change curvature
Condylar track	Manually- moved through track
Electromagnet Condylar Channel	Electromagnet- turn on, condyle ball will move up channel due to attractive forces, move down when electromagnet is off
Improved articulator	Suspended lower jaw, adjustable knob
Jaw Channel	Channel enables teeth to slide to any position
Jaws in half	Jaws cut down the middle, swing on hinge, connect with magnet/velcro
Linear Actuator Jaw	2 on each side- replace 6 DOF joint
Motorized Jaw	Using 4 motors to move mechanical arms for x,y,z, dir and tilt
Spring Condylar Joint	Using springs to manually adjust the lower jaw
Torsional Spring Joint	Prevent motion due to gravity of lower jaw

APPENDIX E.3. Teeth Adjustability

TEETH CONCEPTS	DESCRIPTION
2-screw tilt	Change tilt with two screws for each tooth
Ball and clamp tooth	Change angle and tighten with a clamping nut
Individual Teeth vs Groups of teeth	Teeth grouped in sections to save materials/cost
Magnetic Teeth caps	Tooth attached to a round magnet, allowing for angular adjustment
Teeth screws	Screw in or out of jaw to adjust height, nut will keep in place
X-Mas Tree Stand	Use three screws to clamp teeth in
Rubber/Mesh Mouthgaurd and pins	Teeth on pins stick into hard rubber and adjusted to desired height/angle
Friction Fit	Teeth fit snuggly into cavity in gums
Velcro teeth	Velcro allows for adjustment in cavity
Cup-holder teeth	Four rubber flaps keep tooth in place
Fixing teeth clamp	Clamp around perimeter of gums to clamp teeth in place
Tab Slots	Push in tab, with many holes at different heights, allow for fixing
Denture pins	Ball and socket snap in
Spacers	Crowded teeth- allow for adjustment w.o interference

APPENDIX F. Pugh chart comparisons for jaw motion and teeth variability

APPENDIX F.1. Pugh Chart for jaw joint/condylar motion compares different design concepts with one another with respect to weighted design criteria. Resultant total points serves as a reference as to which concepts best satisfy the design criteria. (28 October, 2009)

Jaw Joint/Condylar Motion Designs	Weight	Linear Actuators and Elastic Jaw Joint	Rubber Condylar Joint	Modified Articulator	Motorized jaw	Flexible Neck
Design Criteria						
Effectively incorporates a large scale model	8	0	2	DATUM	-1	0
Allows for clear view of parts during motion	8	2	-1		2	0
Easy for dental professors to use	6	2	1		2	1
Able to show protrusion/retrusion of jaw	9	2	0		2	0
Able to show laterotrusion of jaw	9	2	0		2	0
Able to vary condylar inclination	9	-1	-1		0	2
Able to open jaw to at least 90deg angle	7	-2	0		2	0
Incorporates a suspended lower jaw	7	0	0		0	0
Serves as effective educational tool	9	2	-1		2	0
Durable to withstand normal forces of human jaw	5	-1	0		-1	-1
Incorporates additional software	4	3	0		3	0
Able to vary both teeth and jaw configurations	9	0	0		0	0
Able to mimic human-like 6 DOF jaw joint	9	2	1		2	0
Low estimated cost	9	-1	2		-2	1
Is feasible to make	9	2	-1		-2	1
Total Points		93	14	-	77	37

APPENDIX F.2. Pugh Chart for teeth/lower jaw designs compares different design concepts with one another with respect to weighted design criteria. Resultant total points serves as a reference as to which concepts best satisfy the design criteria. (28 October 2009)

Teeth/Lower Jaw Designs	Weight	Flexible Epoxy Mesh Mouthguard	Magnets and Linear Actuators	Rigidly Attached Removable Teeth	Ball/Socket, Compressive Tightener, Screw Adjusted	Rigid, Removable & Variable Sets of Teeth
Design Criteria						
Able to tip posterior teeth	9	2	0	DATUM	2	2
Able to intrude/extrude anterior teeth	9	-3	2		2	1
Teeth can mimic curves of Wilson/Spee	9	-1	2		2	2
Allows for clear view of parts during motion	8	1	1		1	1
Easy for dental professors to use	6	2	2		-2	1
Serves as effective educational tool	9	0	1		1	2
Teeth are removable, replaceable	5	1	0		0	0
Teeth are fixable	9	-2	-1		0	0
Low estimated cost	9	2	-2		-1	0
Total Points		7	38	-	50	77

APPENDIX F.3 Reference Figure: Rating Scale

Design Rating Scale	Rating Scale Meaning in Comparison to Datum Design	Comments
3	Can do much better than Datum	
2	Can do better than Datum	
1	Can do a little better than Datum	Positive Points
0	Can do equally as good as Datum	Neutral Points
-1	Datum can do a little better	
-2	Datum can do much better	
-3	Can't do	Negative Points

APPENDIX G. Parts List and Bill of Materials

APPENDIX G.1 Parts List

Part #	Part Name	Qty	Material	Engineering Drawing (APPENDIX J)	Mass [lb]
1	6" Stroke, 150lb Linear Actuator	2	Composite	N/A	2
2	9" Stroke, 150lb Act	1	Composite	N/A	2
3	Right Angle Joint	2	Steel	N/A	0.06
4	Inline Joint	2	Steel	N/A	0.07
5	Threaded Ball	2	Aluminum	N/A	0.33
6	Threaded Rod	2	Steel	N/A	0.09
7	Actuator Fastener (1/4")	4	Aluminum	L4	0.31
8	Actuator Fastener (3/8")	2	Aluminum	L11	0.31
9	Elastic	5	Elastic	N/A	N/A
10	Ball Enclosures	4	Aluminum	L6	0.48
11	Upper Ball Plate	1	Aluminum	L7	2
12	Upper Support Bars	4	Aluminum	L8	1
13	Rear Support Columns	2	Wood	L3	0.78
14	Jaw Support Columns	2	Aluminum	L10	1.72
15	Upper Palate	1	Wood	L9	5.34
16	Lower Palate	1	Wood	L5	5.6
17	Mounting Board	1	Wood	L2	18.9
18	Base Peg	4	Wood	L1	0.36
19	Front Angle Bracket	6	Aluminum	L13	0.1
20	Side Angle Bracket	6	Aluminum	L13	0.1
21	Wood Screws (1-1/2")	4	Steel	N/A	0.02
22	Tee Nut	2	Steel	N/A	0
23	1/4" x 20, 2.5" length bolt	8	Steel	N/A	0.05
24	1/4" x 20, 2" length bolt	22	Steel	N/A	0.04
25	1/4" x 20, 1.5" length bolt	20	Steel	N/A	0.03

26	3/8" x 16, 2.75" length bolt	4	Steel	N/A	0.12
27	1/4" Nut	42	Steel	N/A	0
28	3/8" Nut	4	Steel	N/A	0
29	Velcro	1	Velcro	N/A	0.01
30	Upper Molars	4	Balsa Wood	L17	0.2916
31	Upper Premolars	2	Balsa Wood	L18	0.3888
32	Upper Front Incisals	1	Balsa Wood	L20	0.432
33	Upper Canines	2	Balsa Wood	L19	0.162
34	Lower Molars	4	Balsa Wood	L14	0.3402
35	Lower Premolars	2	Balsa Wood	L15	0.3888
36	Lower Incisals	1	Balsa Wood	L16	0.3024
37	Big Canine	2	Balsa Wood	L21	-
38	Big Upper Incisals	2	Balsa Wood	L22	-
39	Lower Spee	2	Balsa Wood	L23	-
40	Lower Wilson	2	Balsa Wood	L24	-
41	Upper Spee	2	Balsa Wood	L25	-
42	Arduino	1		N/A	-
43	55V H-Bridge	2		N/A	-
44	ScrewShield	1		N/A	-
45	Breakout Board H Bridge	4		N/A	-
46	Breadboard Small Self-Adhesive	1		N/A	-
47	Electrical Box	1		L12	
	Final				
48	Extension Spring	1		N/A	

APPENDIX G.2 Bill of Materials

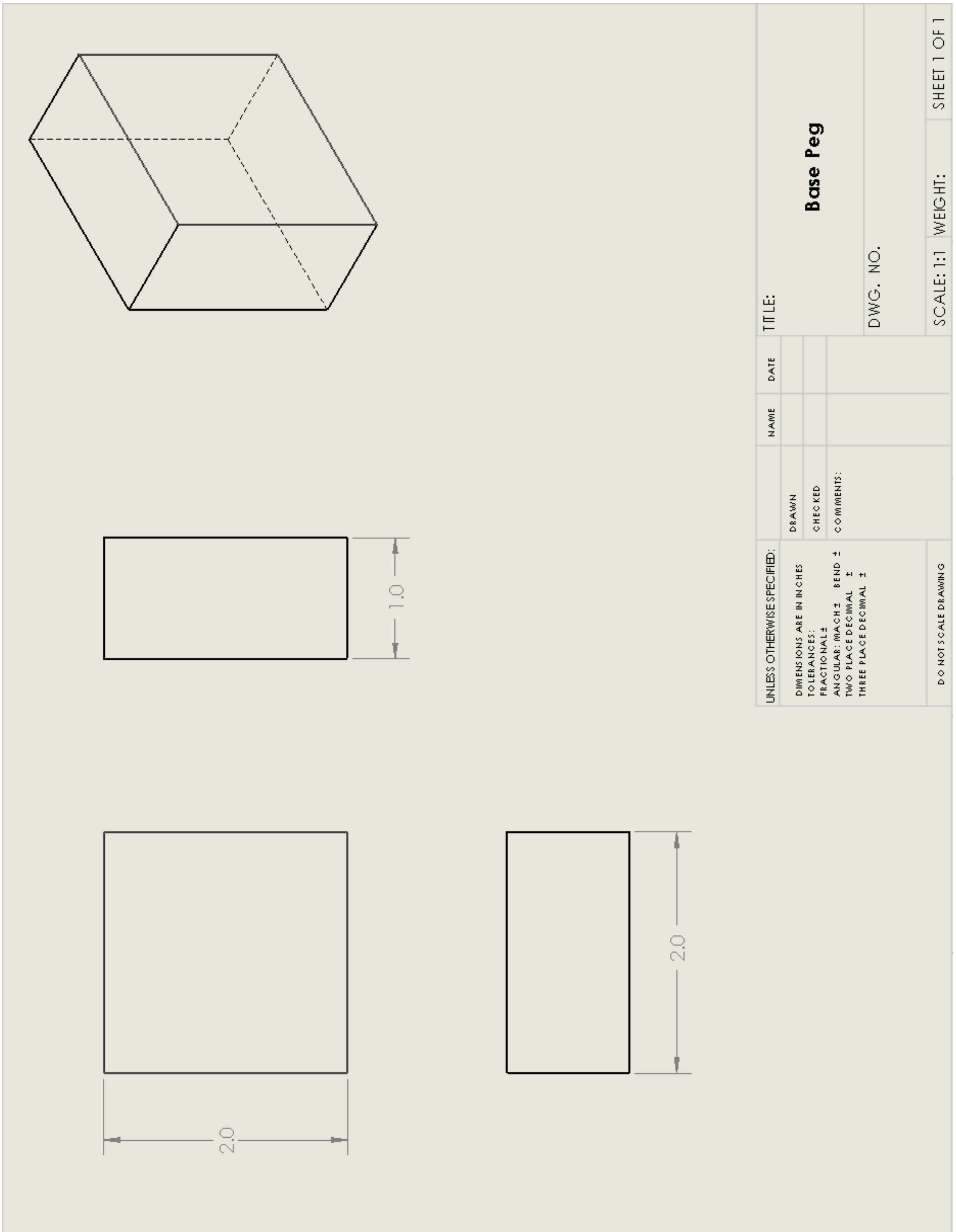
Part #	Part Name	Qty	Source	Catalog Number	Material	Cost/Unit	Cost	Contact	Shipping	Tax	Ins.
1	6" Stroke, 150lb Linear Actuator	2	Progressive Automations		Composite	$118.99	$237.98				
2	9" Stroke, 150lb Act	1	Progressive Automations		Composite	$118.99	$118.99				
3	Right Angle Ball Joint	2	McMaster-Carr	60645K221	Steel	$5.05	$10.10	mcmaster.com			
4	Inline Ball Joint	2	McMaster-Carr	8412K41	Steel	$5.34	$10.68	mcmaster.com			
5	Threaded Ball	2	McMaster-Carr	6940K52	Aluminum	$10.22	$20.44	mcmaster.com			
6	Threaded Rod	2	McMaster-Carr	98750A058	Steel	$1.31	$2.62	mcmaster.com			
7	Actuator Connection Adaptor (1/4")	4	Stock	-	Aluminum		-				
8	Actuator Connection Adaptor (3/8")	2	Stock	-	Aluminum		-				
9	Ball Cap	4	Stock	-	PVC		-				
10	Top Actuator Plate	1	Stock	-	PVC		-				
11	Top Actuator Plate Supports	4	Stock	-	Aluminum		-				
12	Right Angle Joint Support (2"x2")	2	Stock	-	Wood		-				
13	Aluminum Alloy (6061) Rect tube, 3'	2	McMaster-Carr	6546K223	Aluminum 6061	$19.86	$39.72	mcmaster.com			
14	Upper Palate	1	Stock	-	Wood	-	-				
15	Lower Palate	1	Stock	-	Wood	-	-				
16	Base Board	1	Home Depot		Wood		-	734-375-1029			
17	Base Board Legs	4	Stock	-	Wood	-	-				
18	Angle Brackets	14	Stock	-	Aluminum	-	-				
19	Tee Nut	2	Stock	-	Steel	-	-				
20	All-Purpose Nylon Hook and Loop 2" x 10', Velcro	1	McMaster-Carr	9273K231	Velcro	$28.16	$28.16	mcmaster.com	$9.50		
21	BW 3x3x6 block	2	Balsa USA	599	Balsa Wood	$1.85	$3.70	balsausa.com			
22	BW 2x4x12	4	Balsa USA	254	Balsa Wood	$3.85	$15.40	balsausa.com			
23	BW 3x4x12	2	Balsa USA	255	Balsa Wood	$5.75	$11.50	balsausa.com			
24	BW 3x3x36	1	Balsa USA	256	Balsa Wood	$11.99	$11.99	balsausa.com	$9.95		
25	Arduino	1	Sparkfun Electronics	-	-	$29.95	$29.95	sparkfun.com			
26	55V H-Bridges Electric Bipolar CMOS Control Circuit	2	Virtual Village	-	-	$9.99	$19.98	VirtualVillage.com	$7.98		$2
27	ScrewShield	1	Sparkfun Electronics	-	-	$9.95	$9.95	sparkfun.com			
28	Breakout Board for H Bridge	4	Sparkfun Electronics	-	-	$1.95	$7.80	sparkfun.com			
29	Breadboard Small Self-Adhesive	1	Sparkfun Electronics	-	-	$5.95	$5.95	sparkfun.com	$8.38		
30	SPST ON-OFF Blk Rockert Switch 16A	1	RS Electronics	35-693	-	$2.38	$2.38	734-525-1155		$0.14	
31	22 Gauge 25' Spool Yellow Hookup Wire	1	RS Electronics	14-422-1M18	-	$9.52	$9.52	734-525-1156			
32	Solid Hookup 22G 25' Black	1	RS Electronics	14-422-1M11	-	$9.52	$9.52	734-525-1157			
33	Adjustable Wire and Jacket Str	1	RS Electronics	1161	-	$8.82	$8.82	734-525-1158			
34	SPDT ON-OFF-ON Min Bat Tog-5A	3	RS Electronics	35-005	-	$3.16	$9.48	734-525-1159		$2.24	
35	3/4 " 2x4 MDF Base Wood	1	Home Depot	99167678085	Boise Wood	$9.88	$9.88	734-375-1029			
36	2X Flat Black Spray Paint	1	Home Depot	20066187811	-	$3.44	$3.44	734-375-1030			
37	2X Berry Pink Spray Paint	1	Home Depot	20066187774	-	$3.44	$3.44	734-375-1031			
38	White Epoxy Spray Paint	1	Home Depot	20066788186	-	$4.98	$4.98	734-375-1032		$1.30	
39	Dowel Pin Fluted 5/16"33	1	Ace Hardware	5013008	Wood	$2.29	$2.29	734-971-4555			
40	Cord Stretch	1	Ace Hardware	8063976	-	$2.99	$2.99	734-971-4556			

41	Rubber Bands	1	Ace Hardware	91234	Rubber	$0.49	$0.49	734-971-4557			
42	1/8" Fasteners	16	Ace Hardware	56	Rubber	$0.17	$2.72	734-971-4558			
43	1/4 "Fasteners	6	Ace Hardware	56	Rubber	$0.15	$0.90	734-971-4559			
44	3/8" Fasteners	4	Ace Hardware	56	Rubber	$0.25	$1.00	734-971-4560		$0.62	
45	PLASTBAGGDS - Large Hooks	1	Home Depot	30699157112	-	$0.98	$0.98	734-375-1032			
46	PLASTBAGGDS - Small Hooks	1	Home Depot	30699157310	-	$0.98	$0.98	734-375-1033			
47	4 *1.24" Woodscrews	2	Home Depot	30699198214	Steel	$0.98	$1.96	734-375-1034			
48	Washers	1	Home Depot	30699210411	Steel	$0.98	$0.98	734-375-1035			
49	3/8" X3HEXBOLT	4	Home Depot	AWF	Steel	$0.38	$1.52	734-375-1036			
50	HEX BOLT	16	Home Depot	AGG	Steel	$0.19	$3.04	734-375-1037			
51	5/16 HXNUTUSS (nuts)	16	Home Depot	655430	Steel	$0.10	$1.60	734-375-1038			
52	CUTWSHR1/4" (washers)	10	Home Depot	655554	Steel	$0.10	$1.00	734-375-1039		$0.78	
53	Flat Black Spray	1	Jack's Hardware	-	-	$3.49	$3.49	734-995-0078			
54	Flat White Spray	2	Jack's Hardware	-	-	$4.99	$9.98	734-995-0079		$0.81	
55	Cable 7" UV20P Tie	1	Jack's Hardware	-	-	$1.29	$1.29				
56	4 1/4" D Bolts	2	Jack's Hardware	-	-	$0.77	$1.54				
57	Cable 4" UV8PC	1	Jack's Hardware	-	-	$1.49	$1.49			$0.26	
58	THRD.ZP 3/8"X24	1	Jack's Hardware	-	-	$2.79	$2.79			$0.17	
						Subtotal	**$332.43**		**$35.81**	**$6.32**	**$2**
						Total	$376.56				

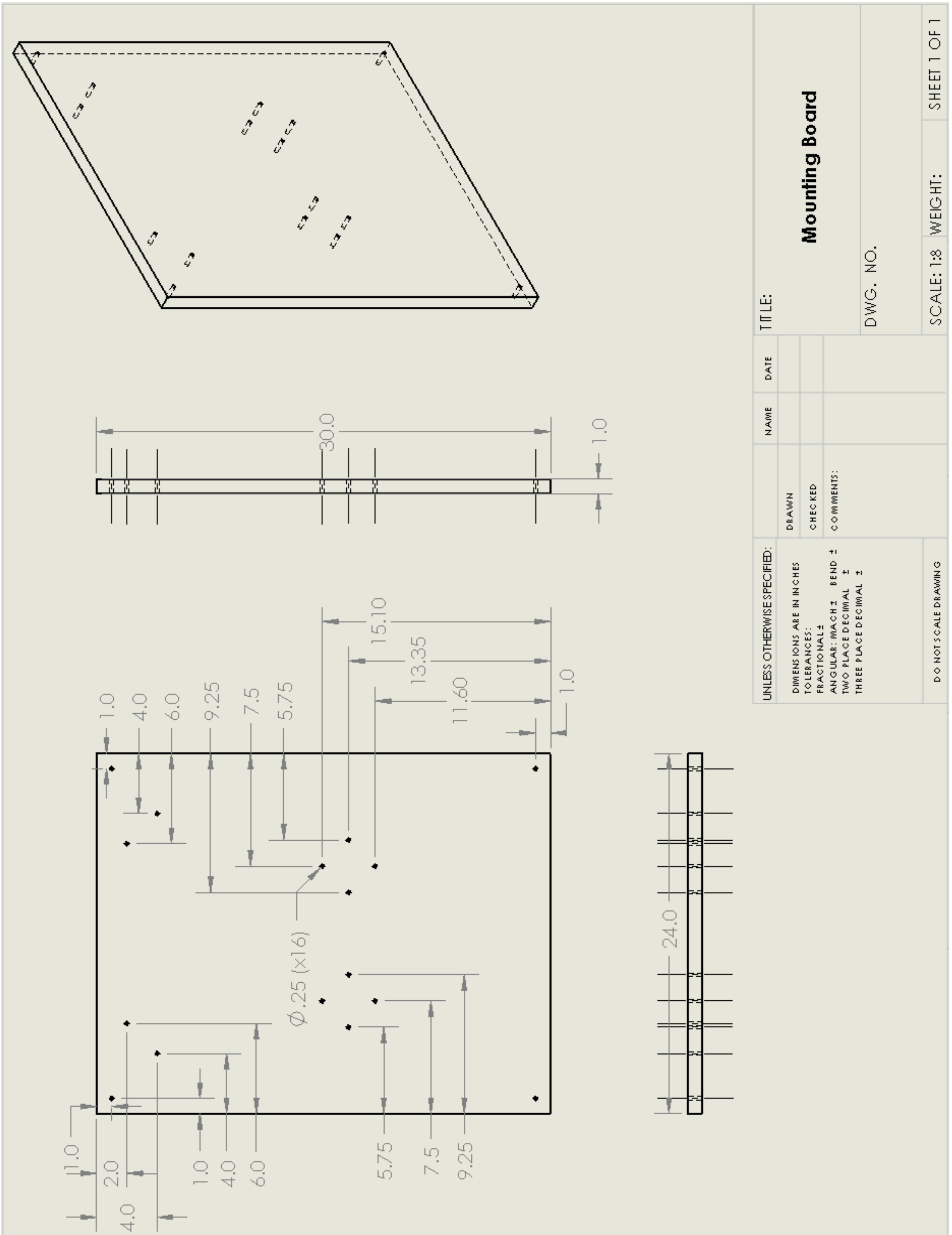
- Nuts/Bolts/Other hardware was provided in the shop
- Actuators are NOT included in this pricing

APPENDIX H. Engineering Drawings of Parts to be Fabricated

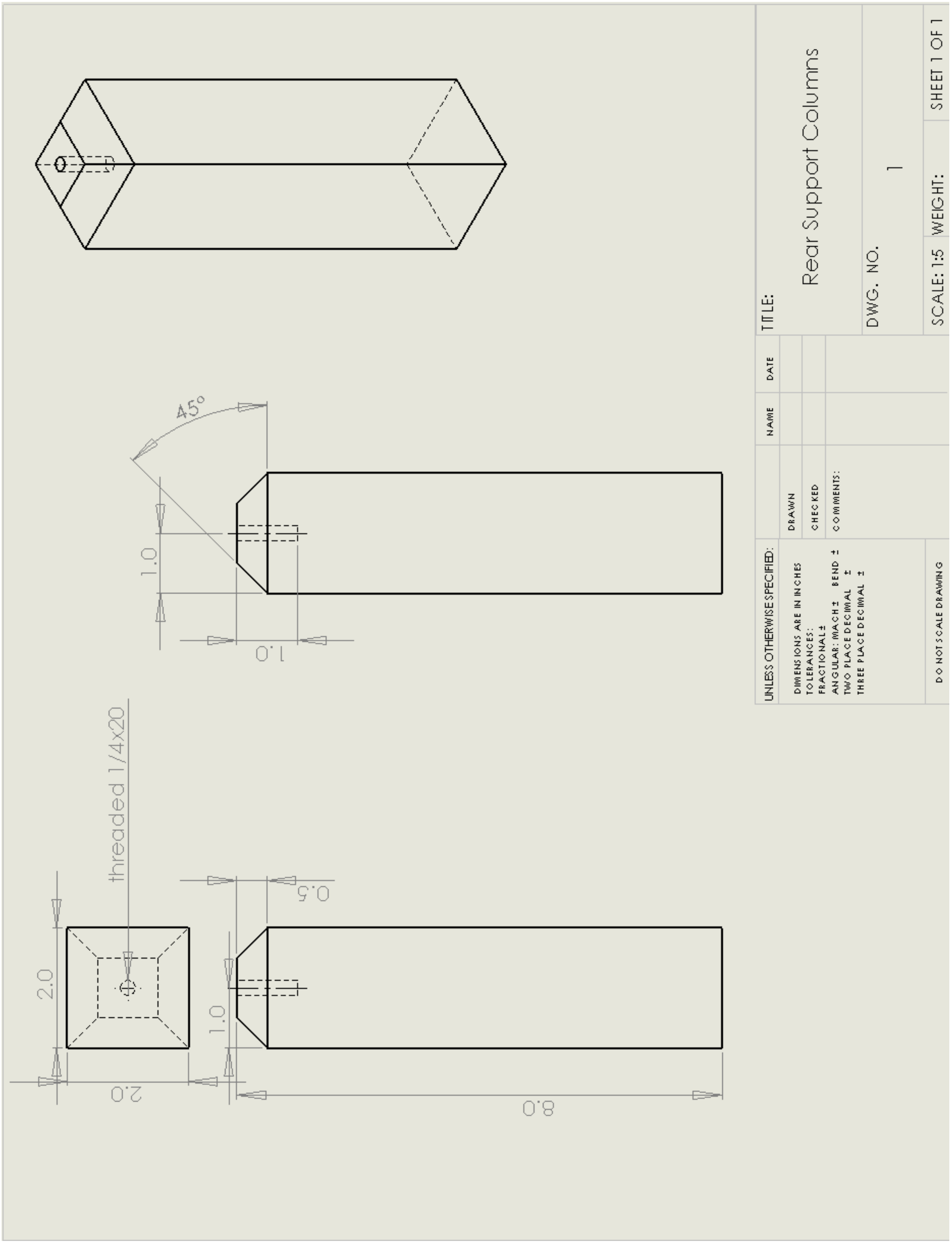
APPENDIX H.1 Base Pegs



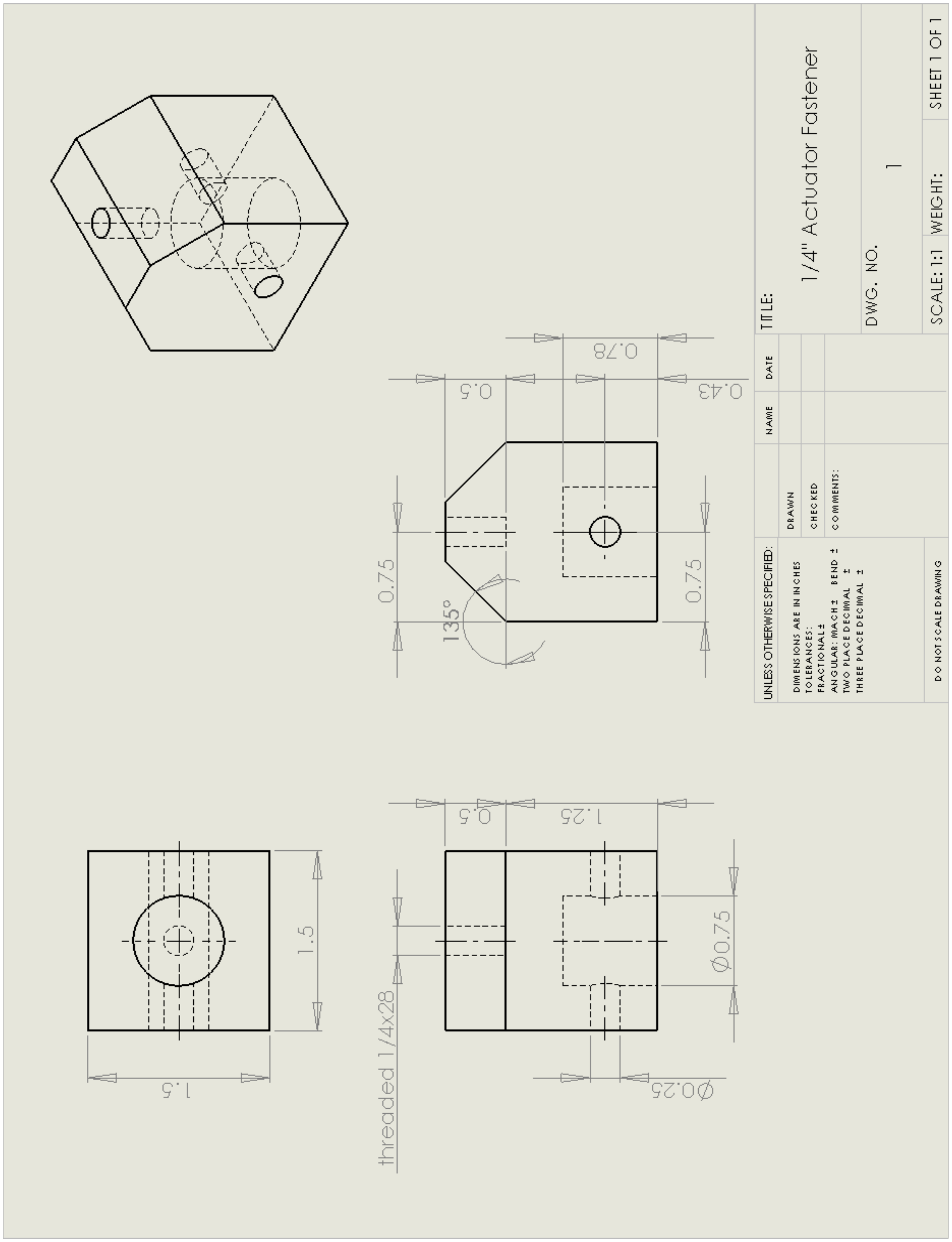
APPENDIX H.2 Mounting Board



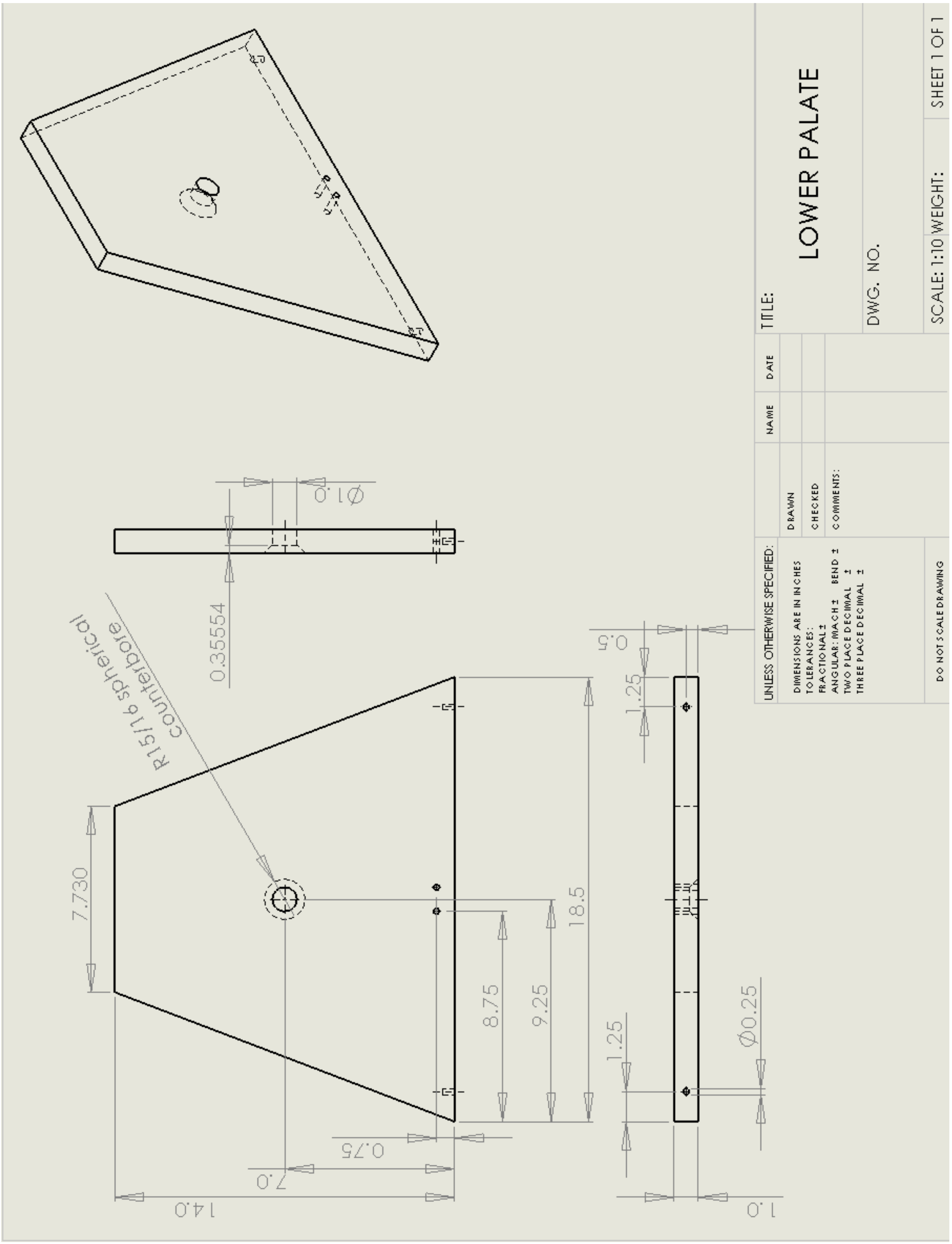
APPENDIX H.3 Rear Support Columns



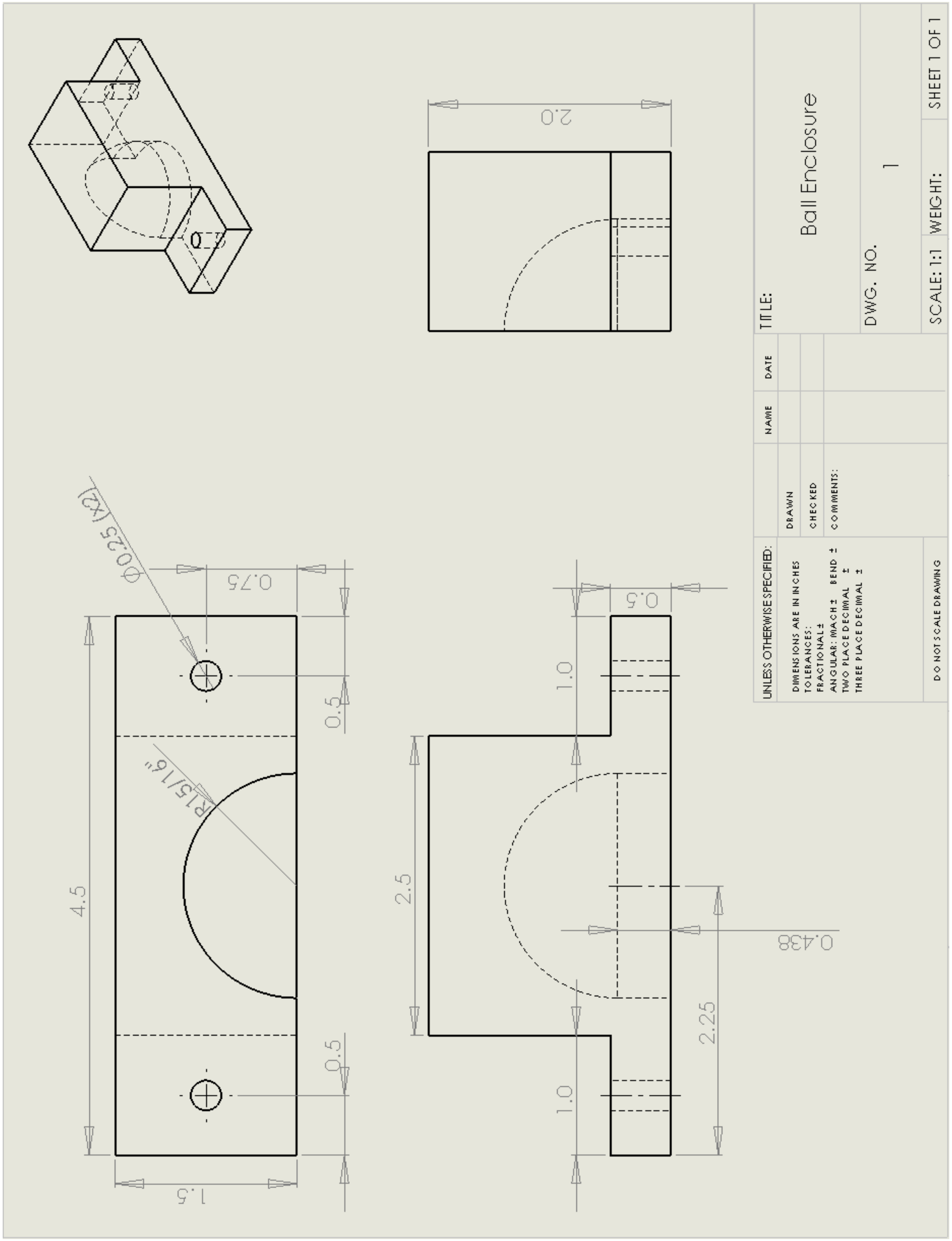
APPENDIX H.4 1/4” Actuator Fasteners



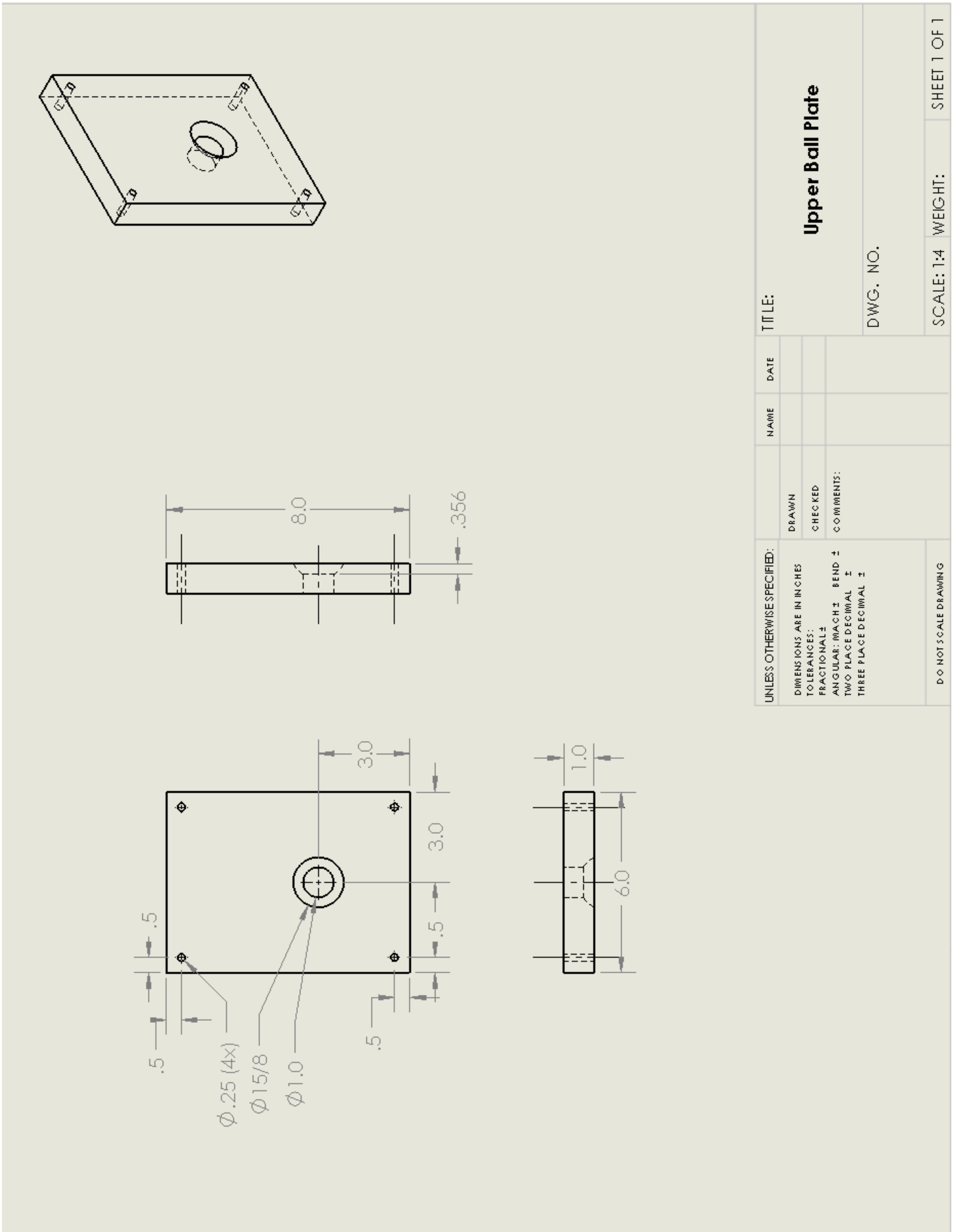
APPENDIX H.5 Lower Palate



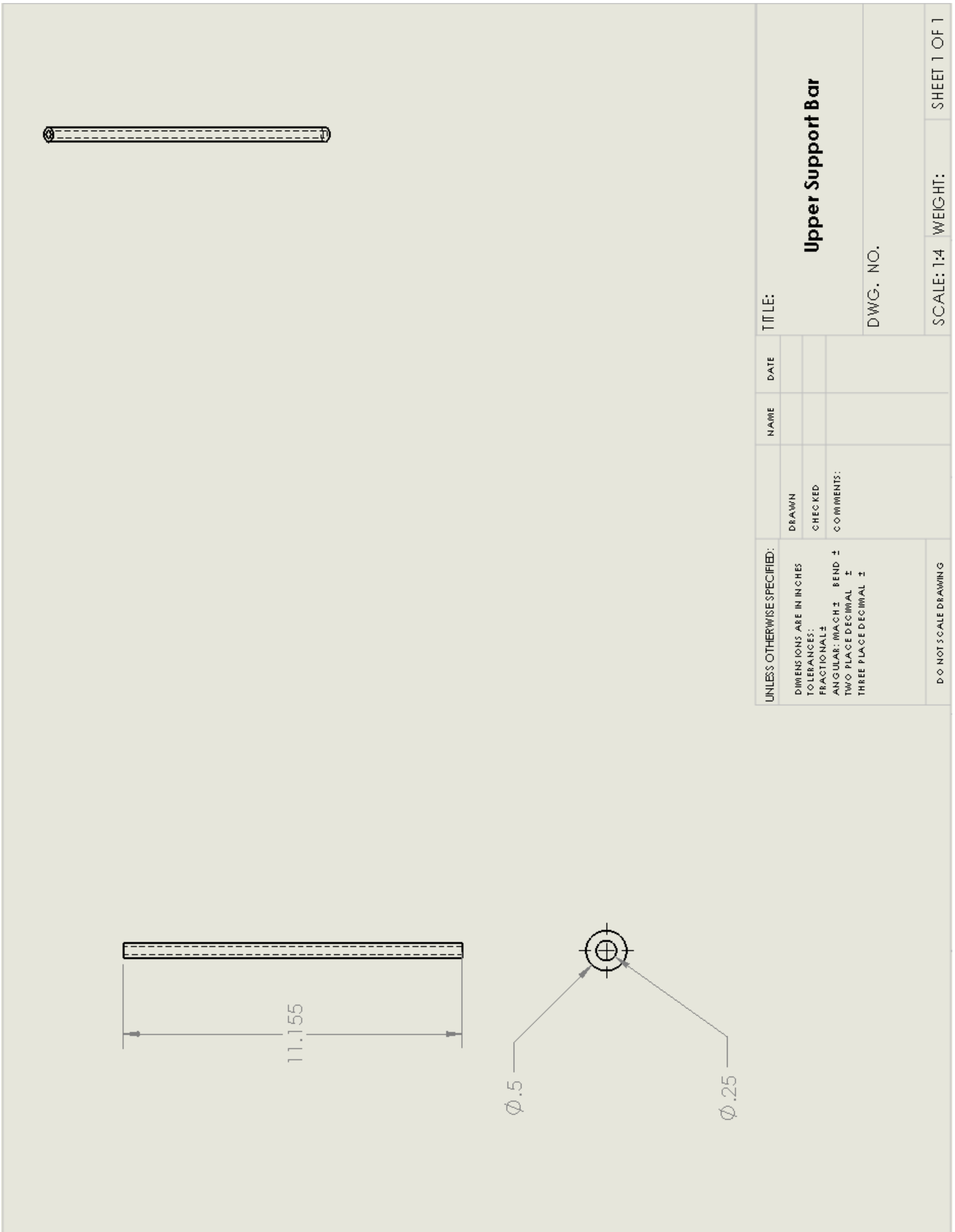
APPENDIX H.6 Ball Enclosures



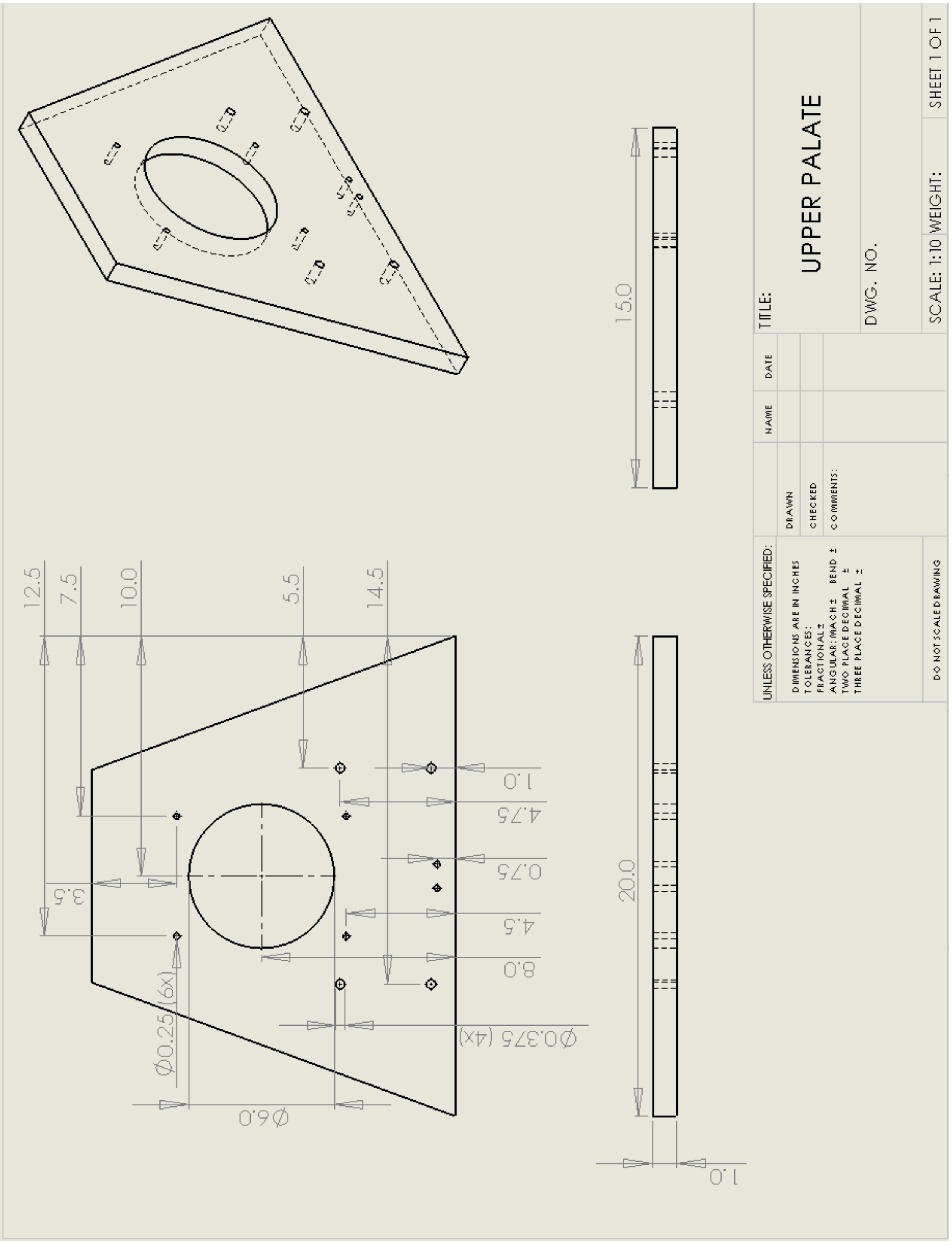
APPENDIX H.7 Upper Ball Plate



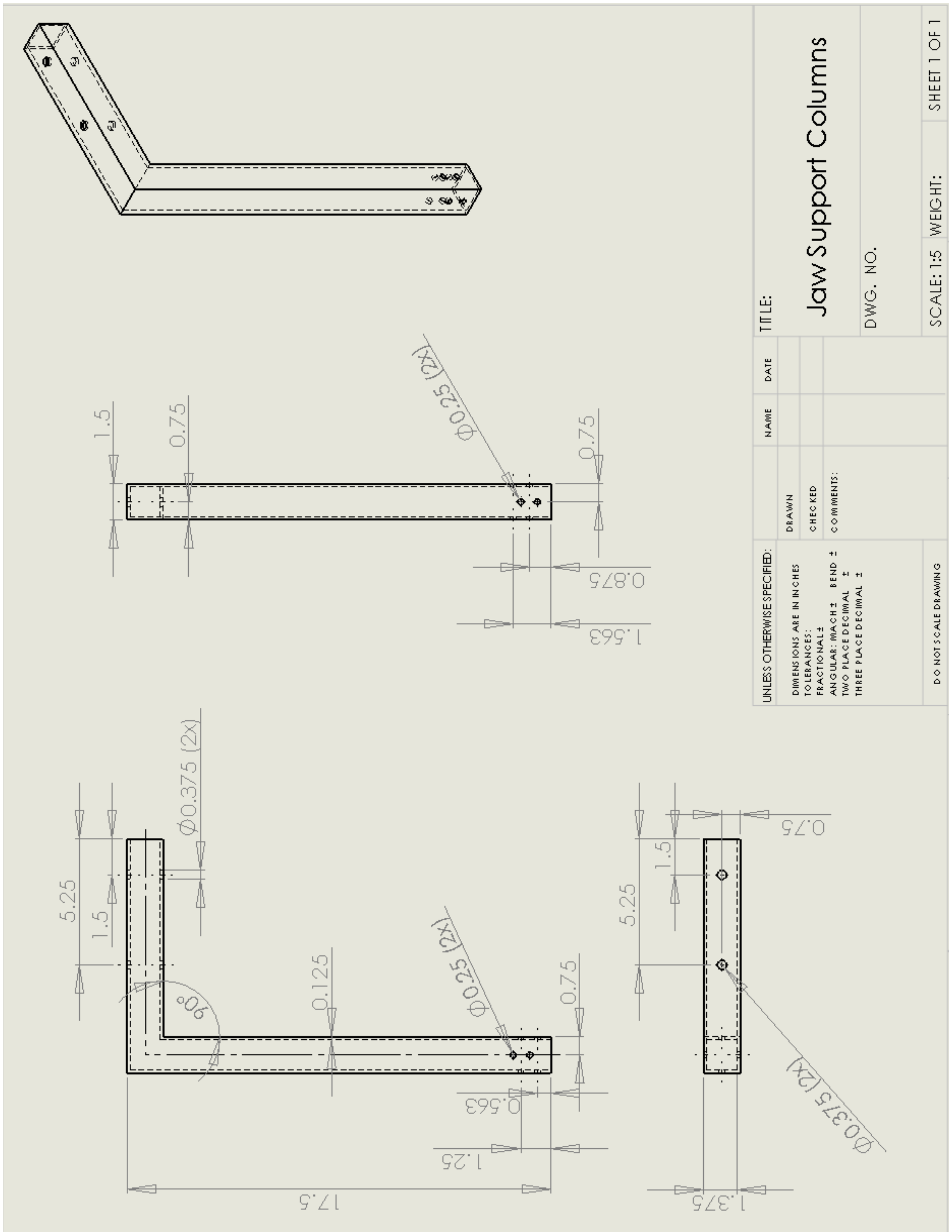
APPENDIX H.8 Upper Support Bars



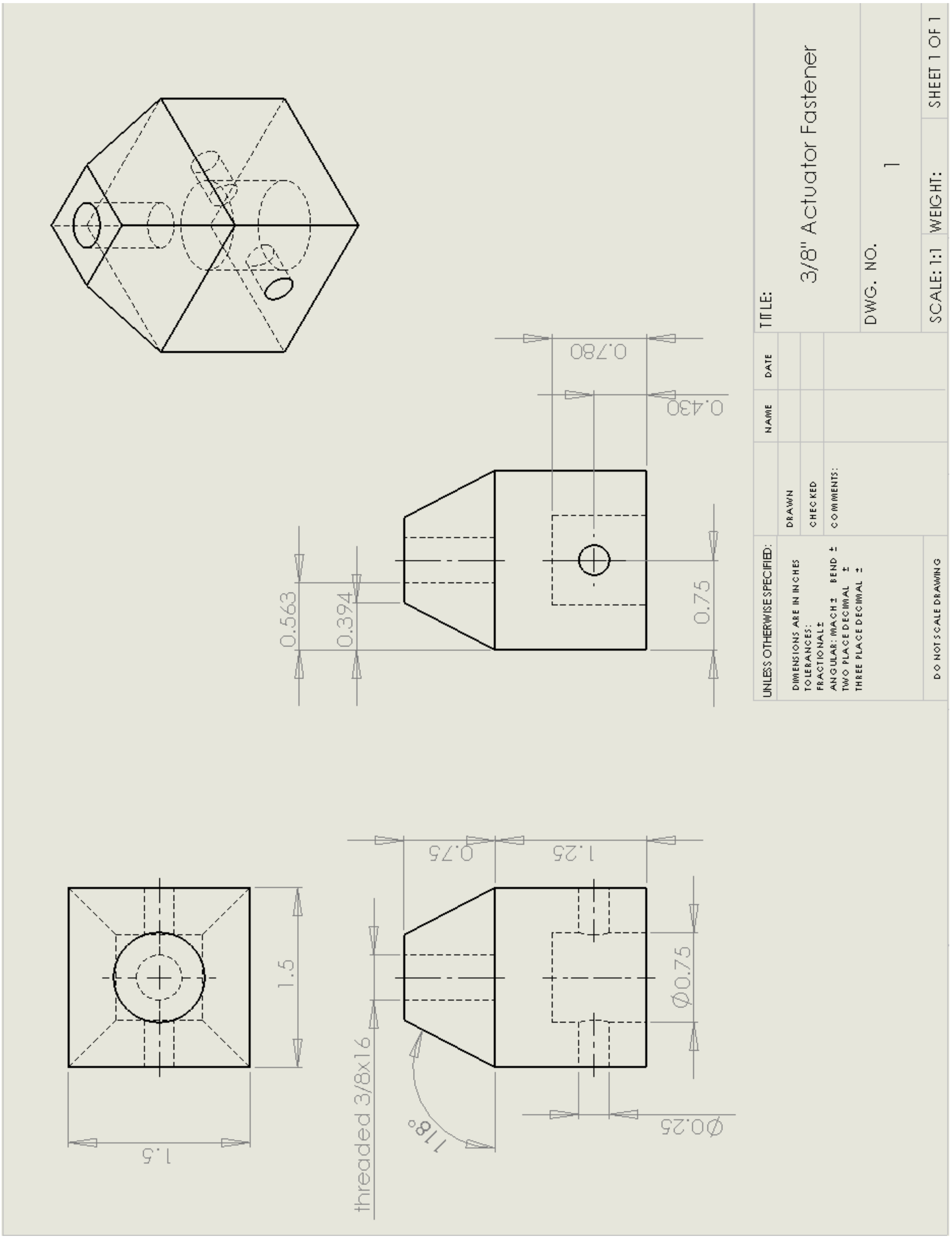
APPENDIX H.9 Upper Palate



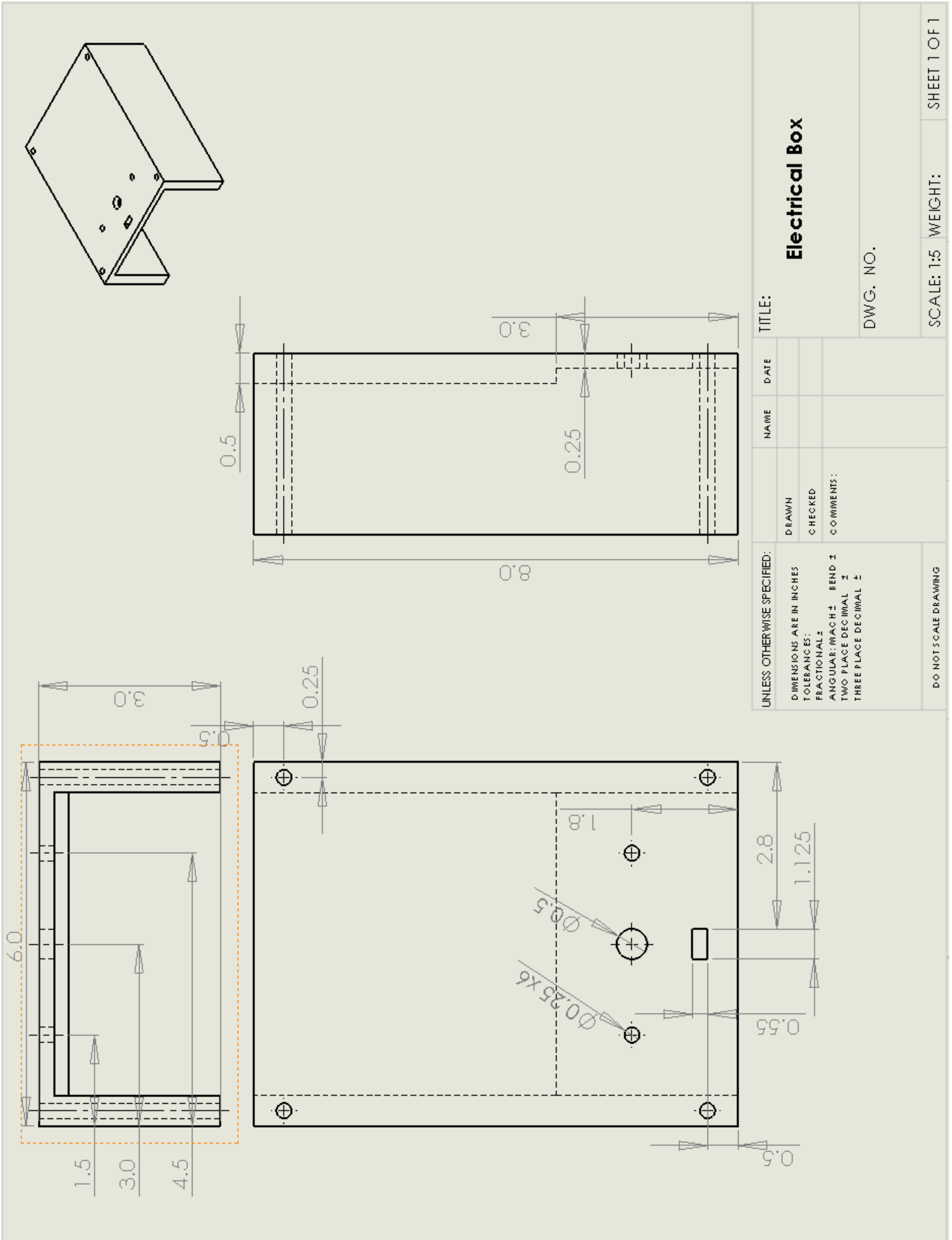
APPENDIX H.10 Jaw Support Columns



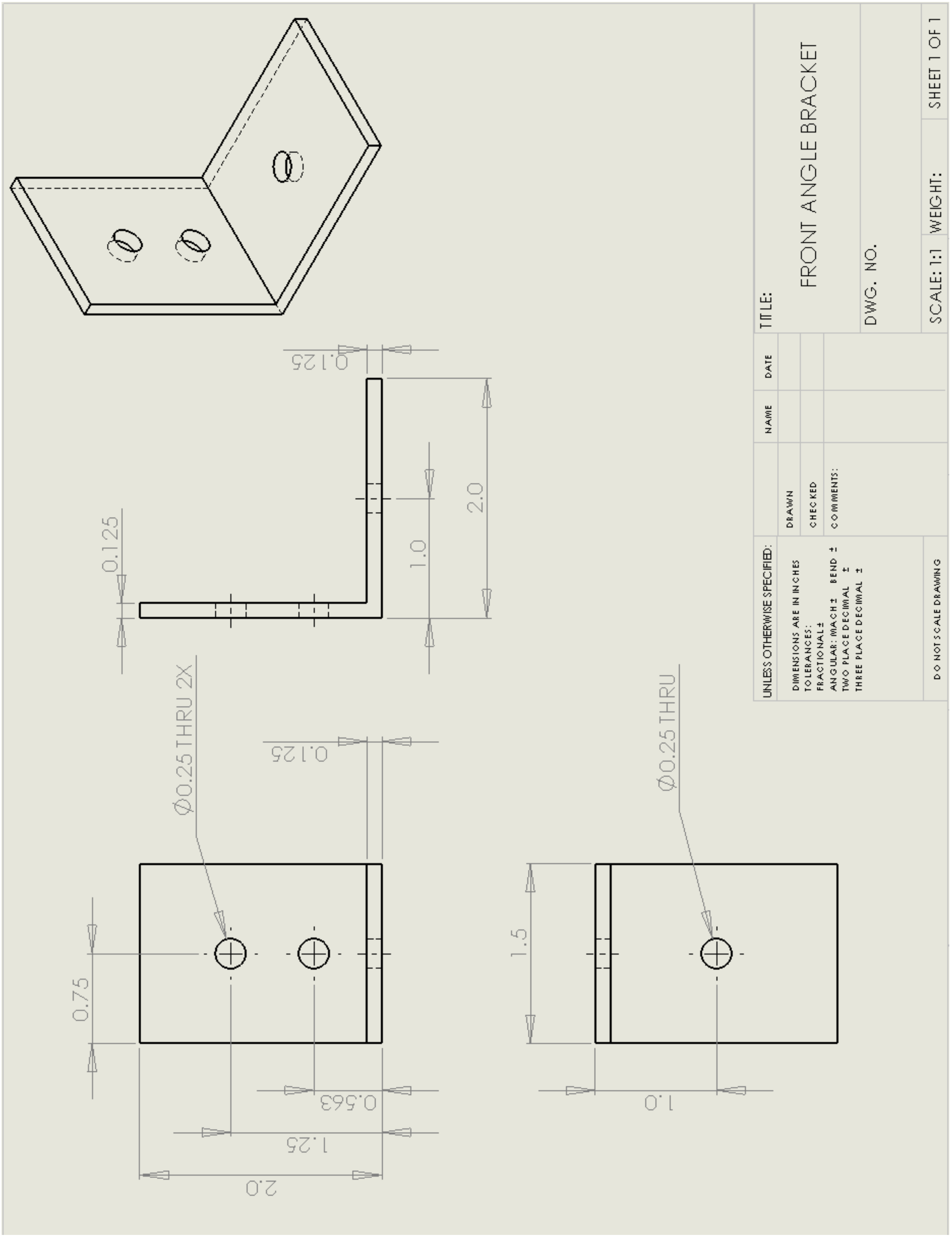
APPENDIX H.11 3/8" Actuator Fasteners



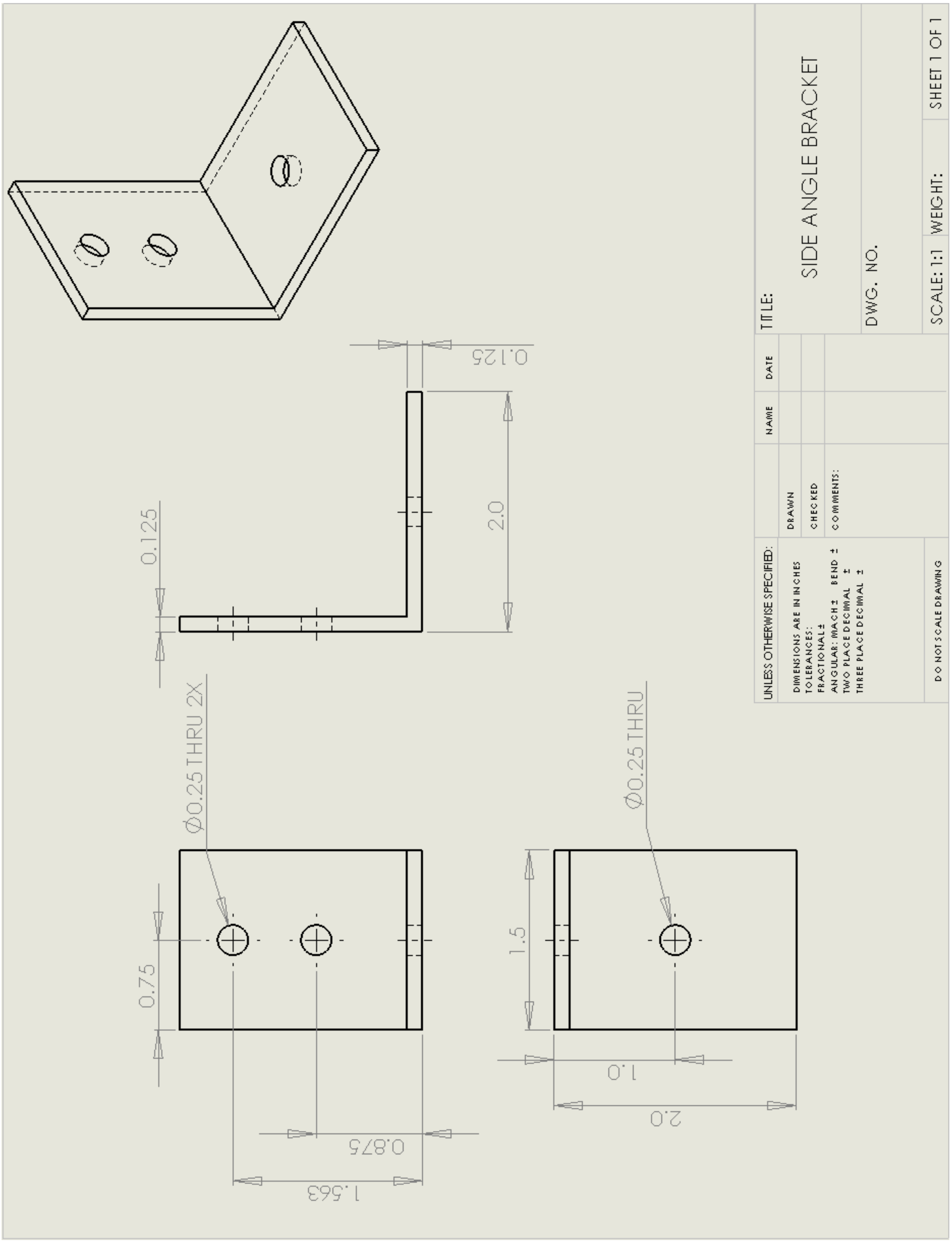
APPENDIX H.12 Electrical Box



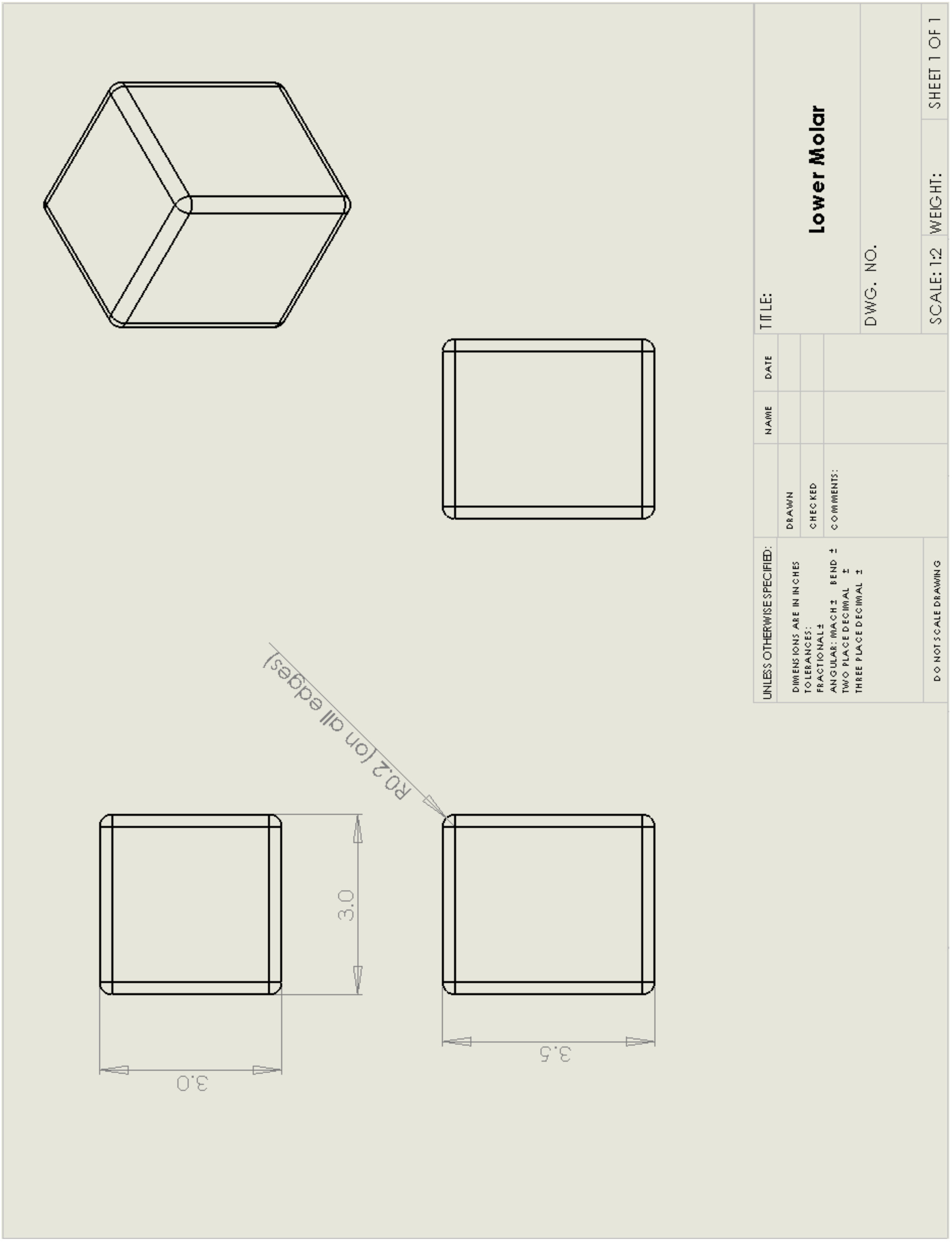
APPENDIX H.13.1 Mounting Brackets (1)



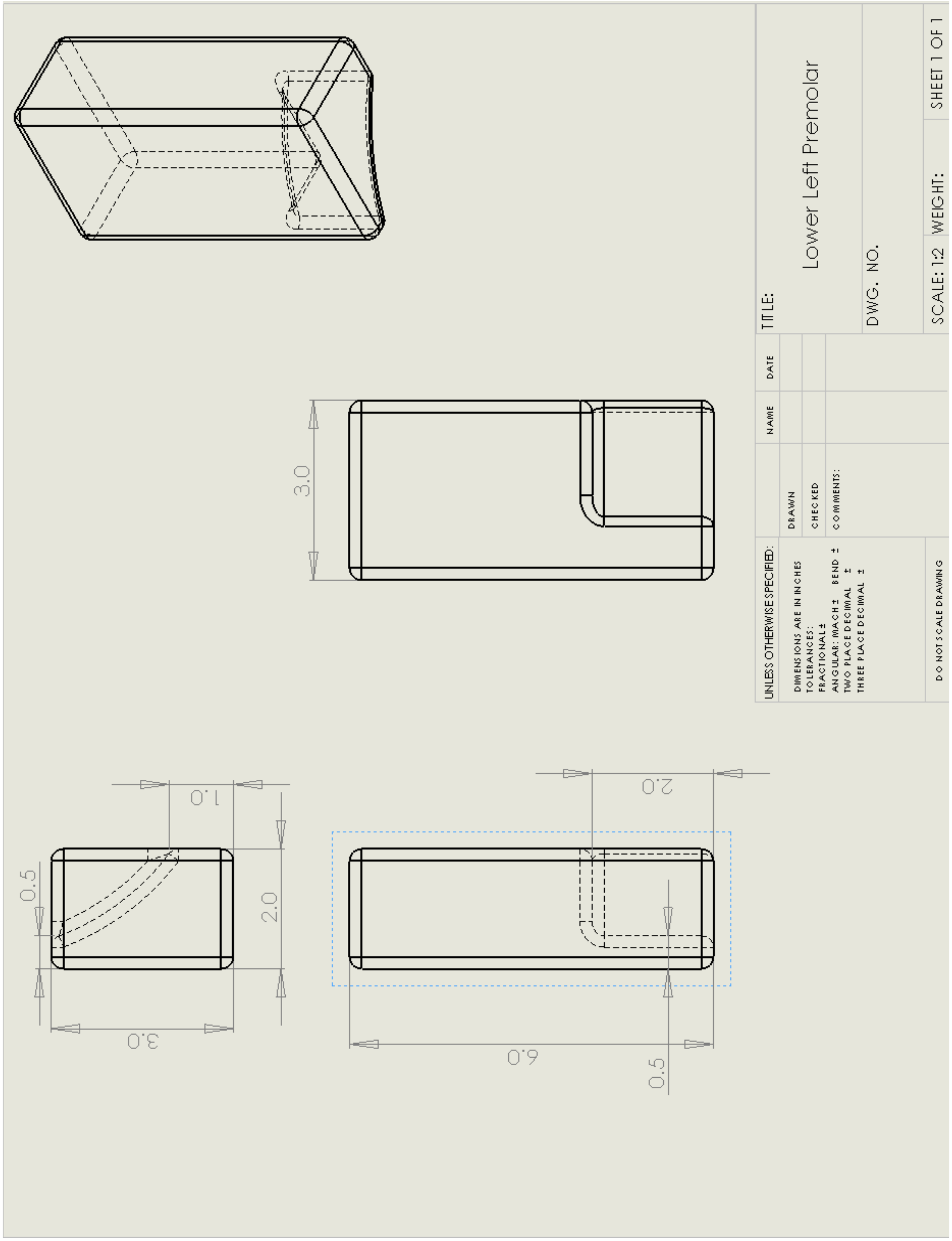
APPENDIX H.13.2 Mounting Brackets (2)



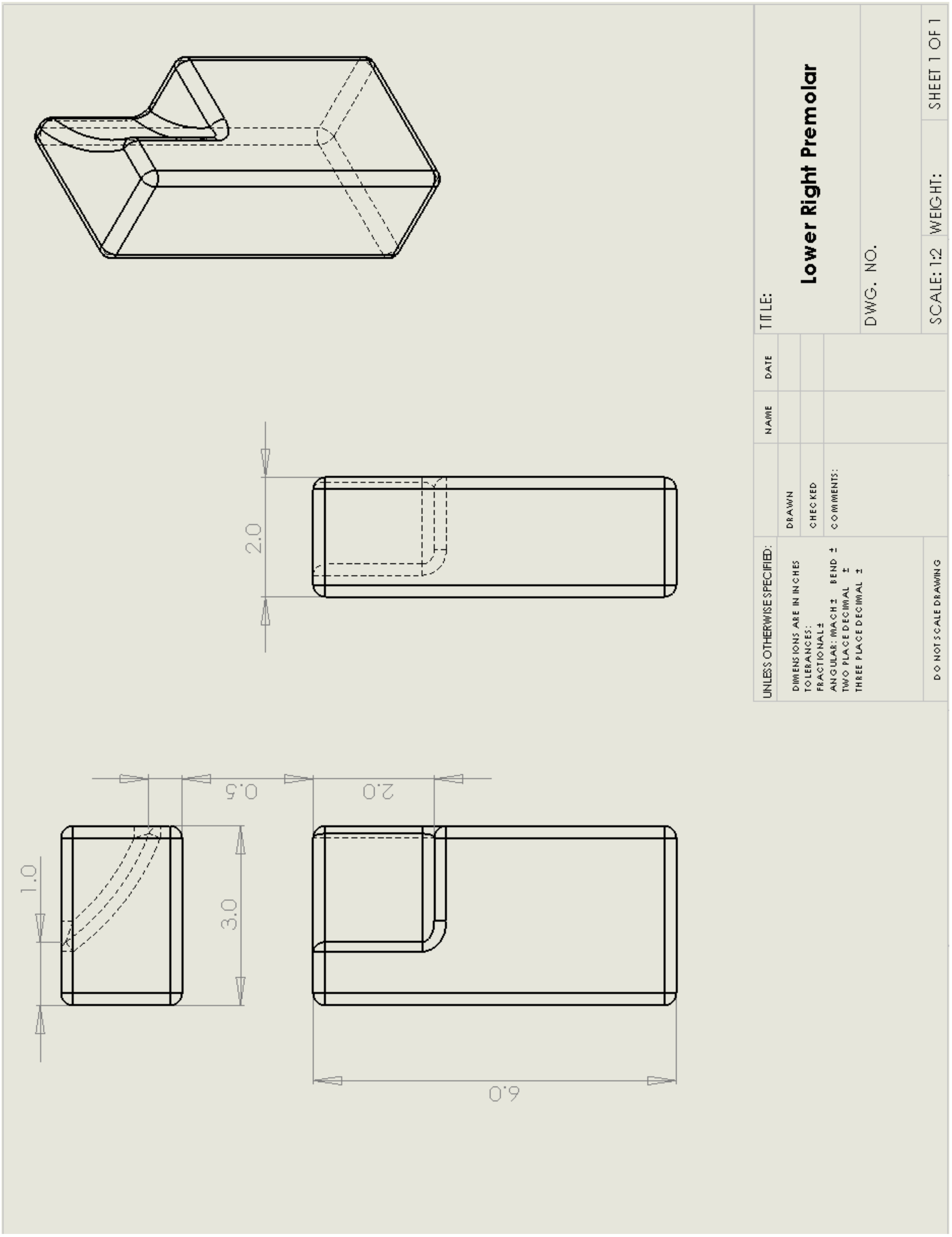
APPENDIX H.14 Lower Molars



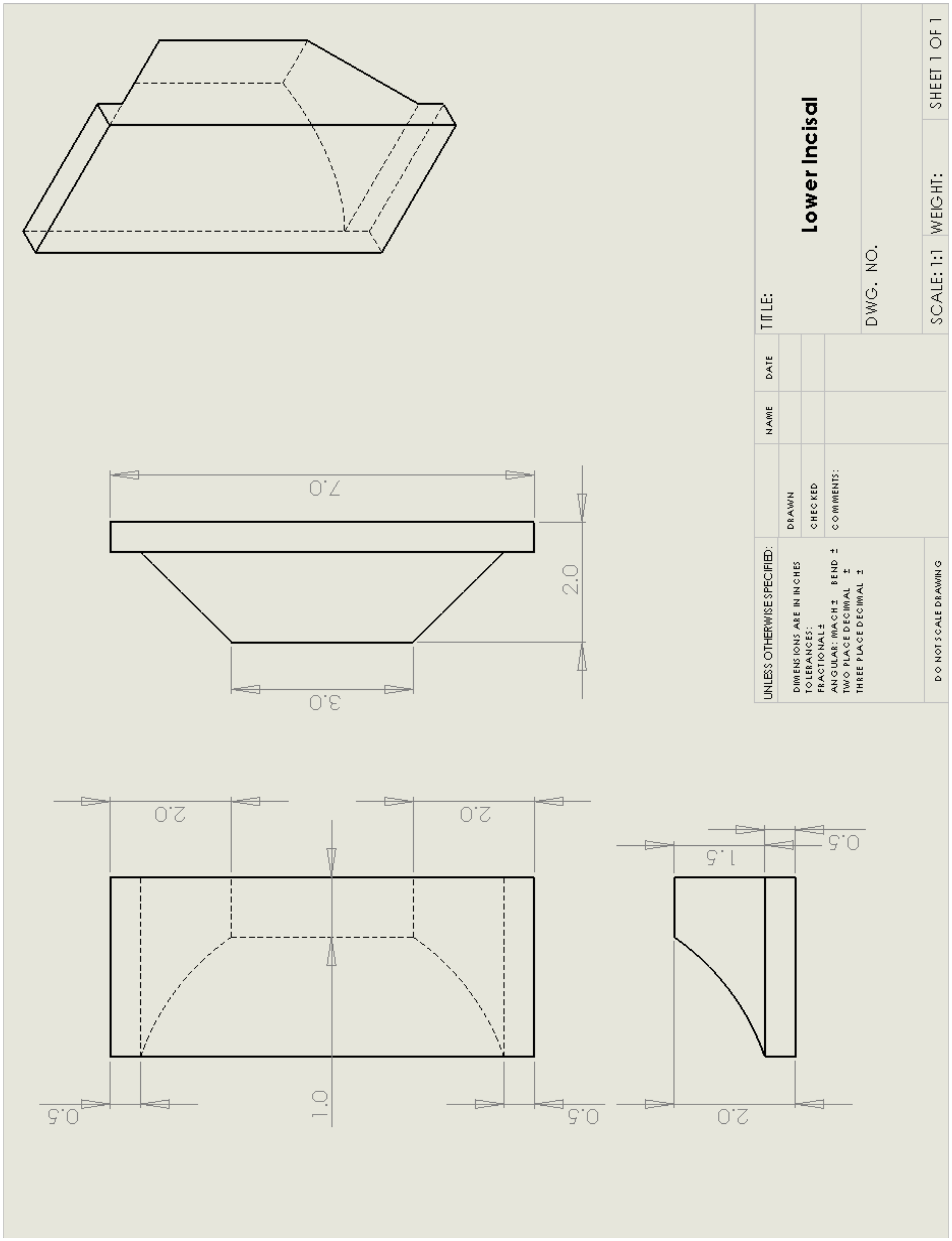
APPENDIX H.15.1 Lower Premolars (L)



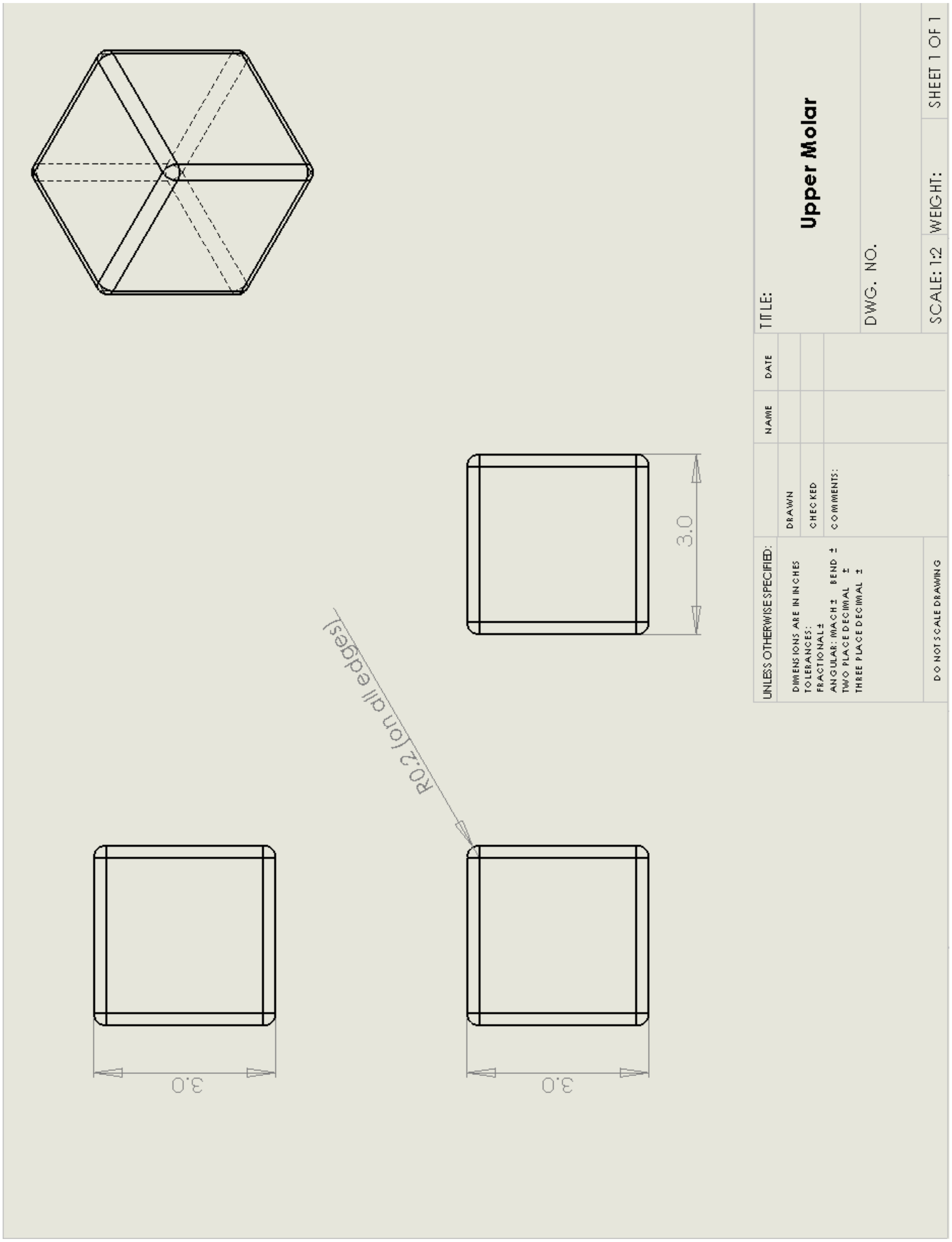
APPENDIX H.15.2 Lower Premolars (R)



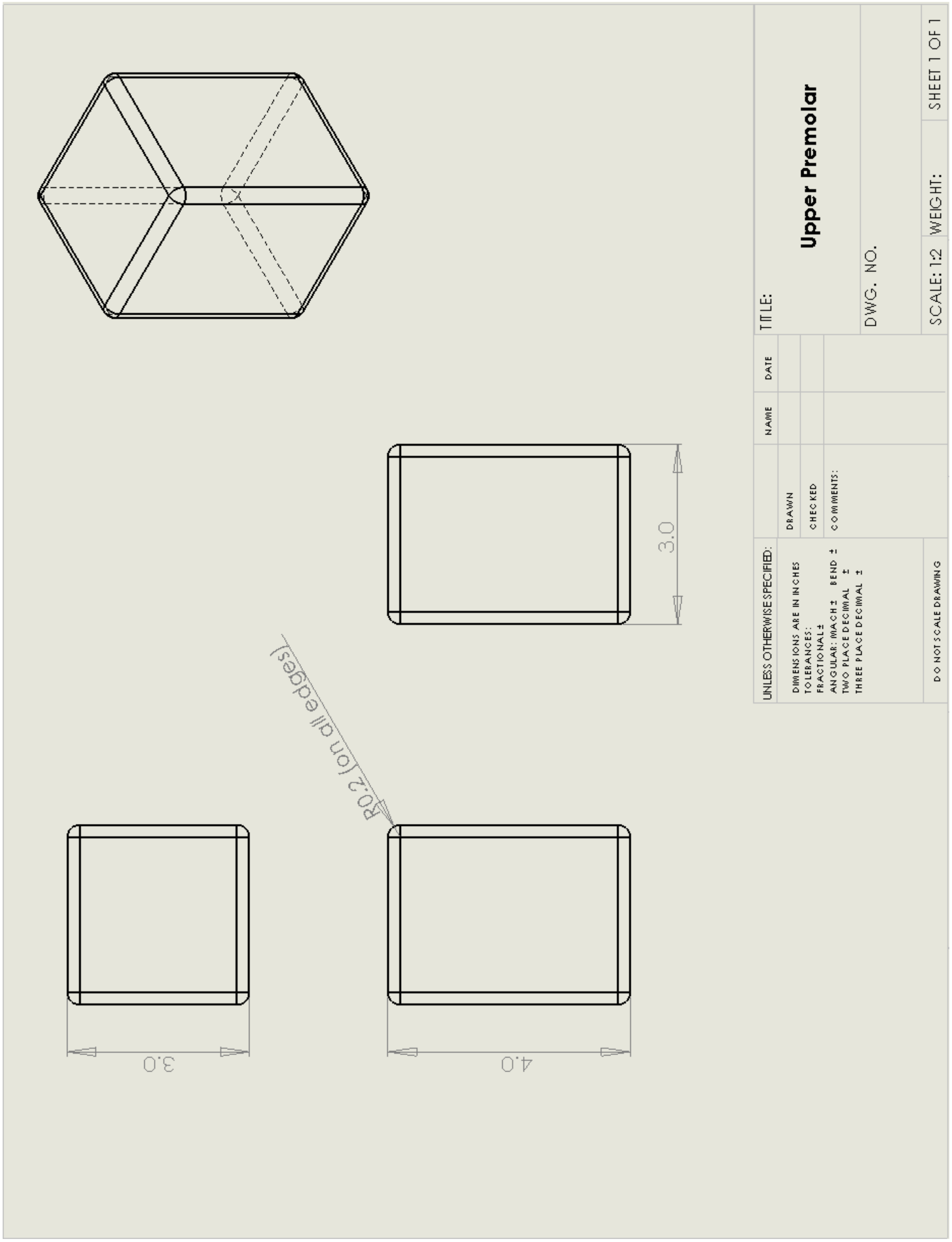
APPENDIX H.16 Lower Incisors



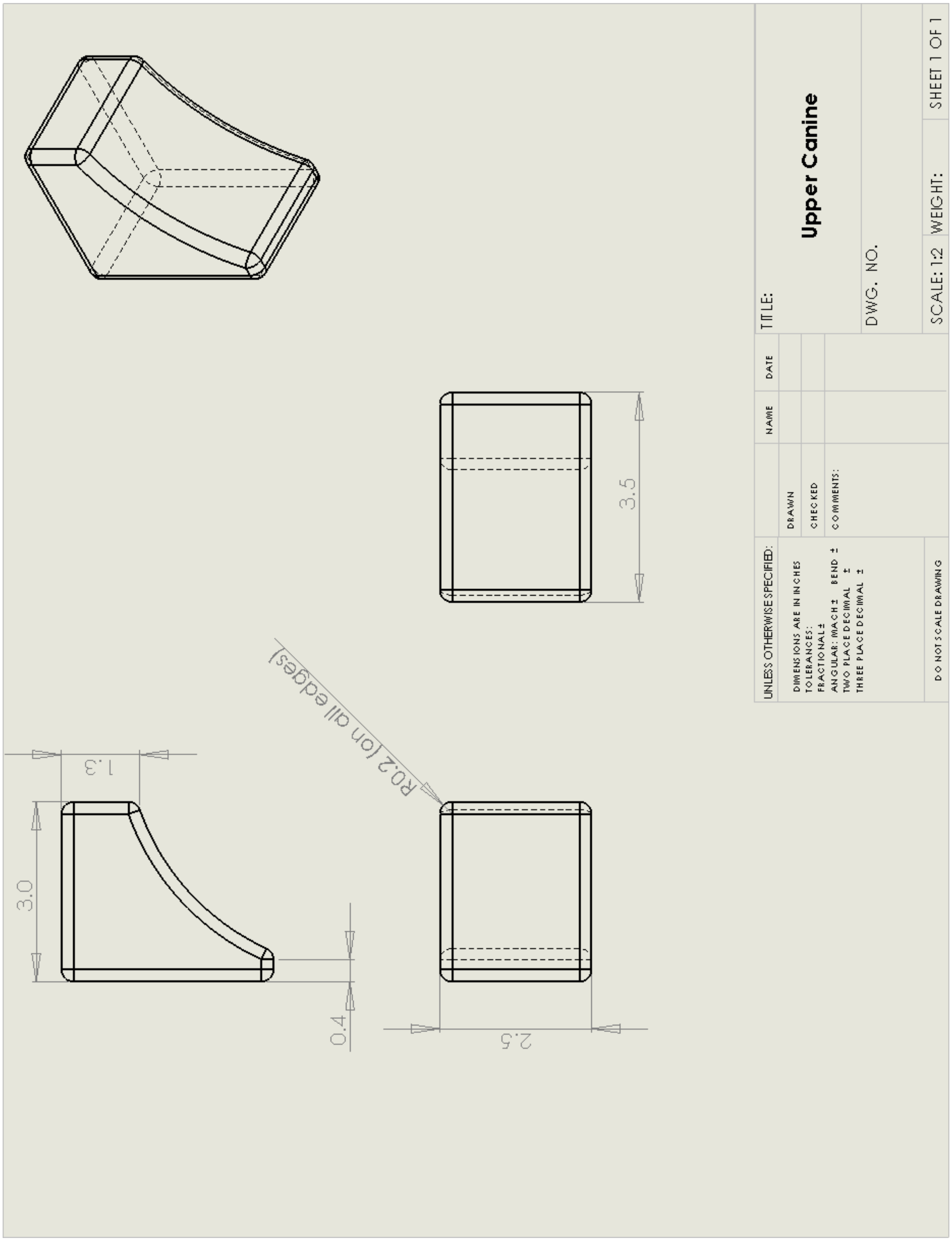
APPENDIX H.17 Upper Molars



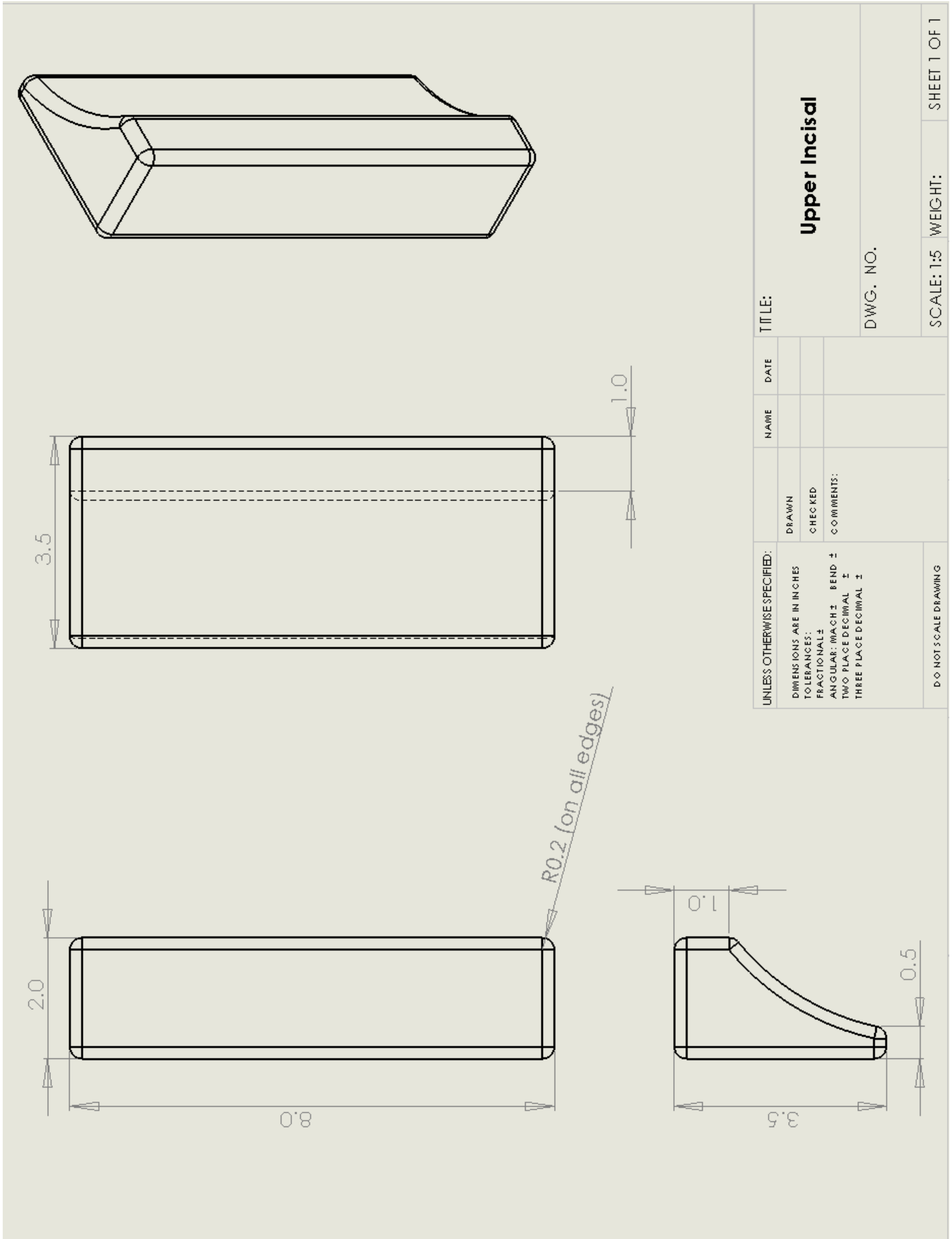
APPENDIX H.18 Upper Premolars



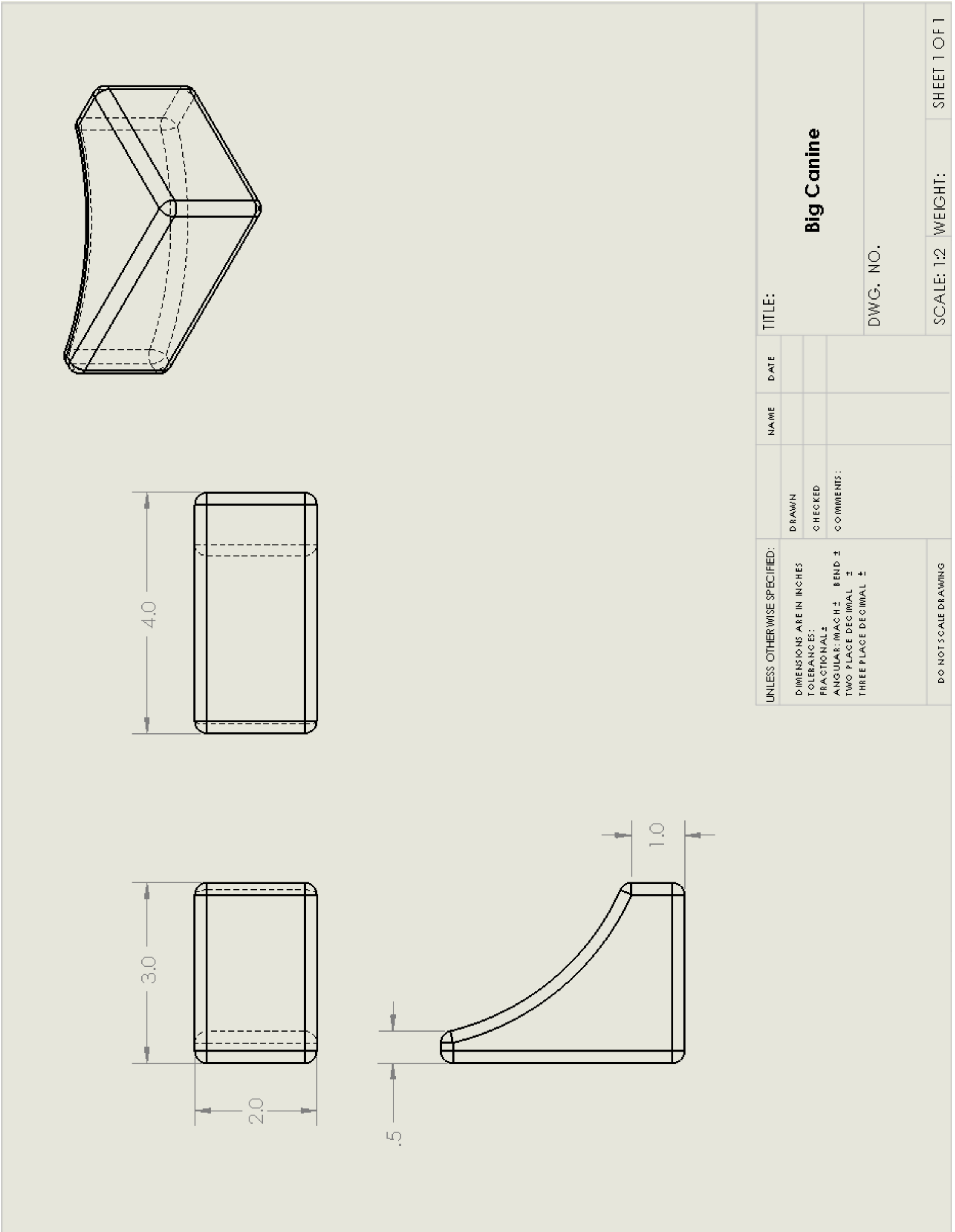
APPENDIX H.19 Upper Canines



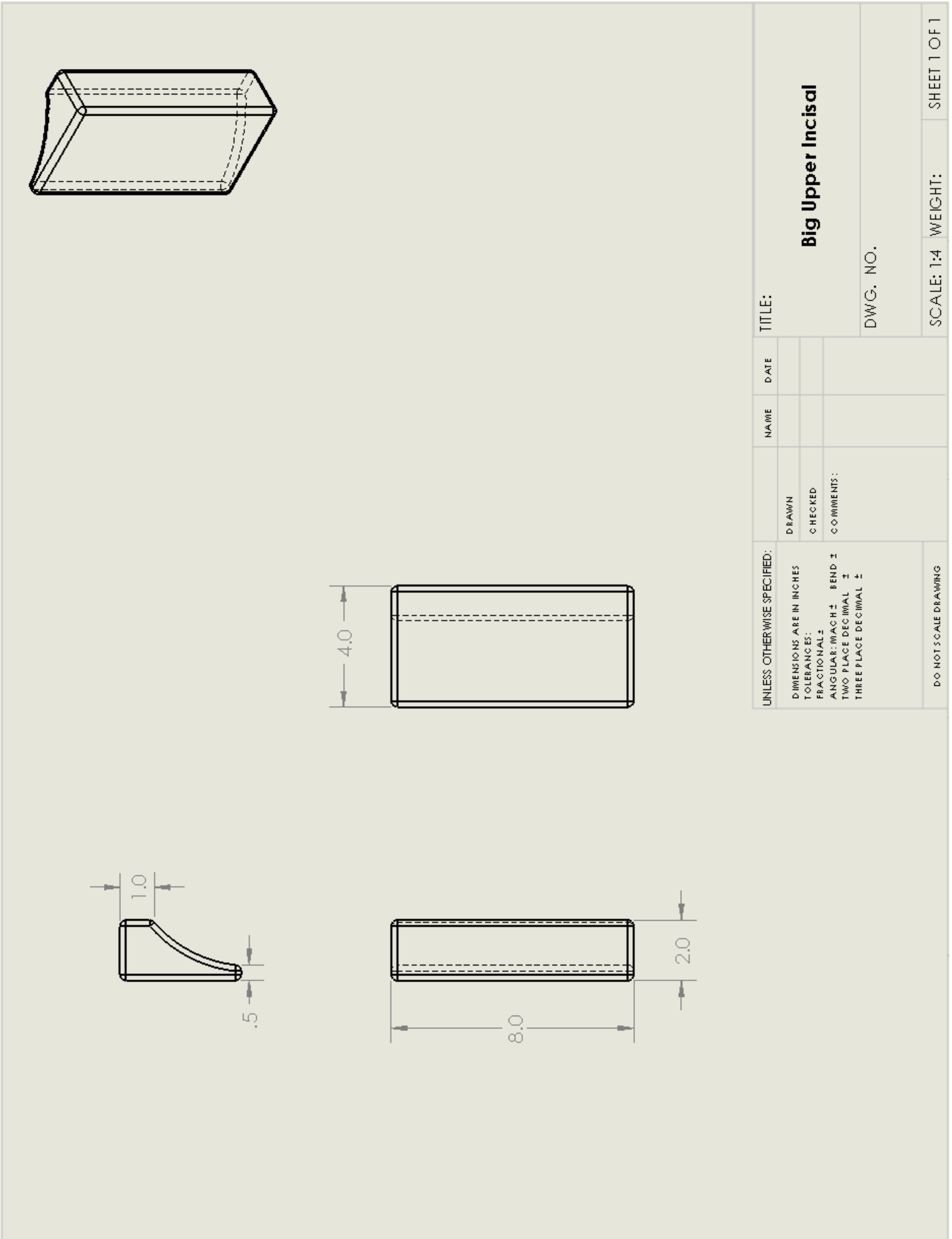
APPENDIX H.20 Upper Incisors



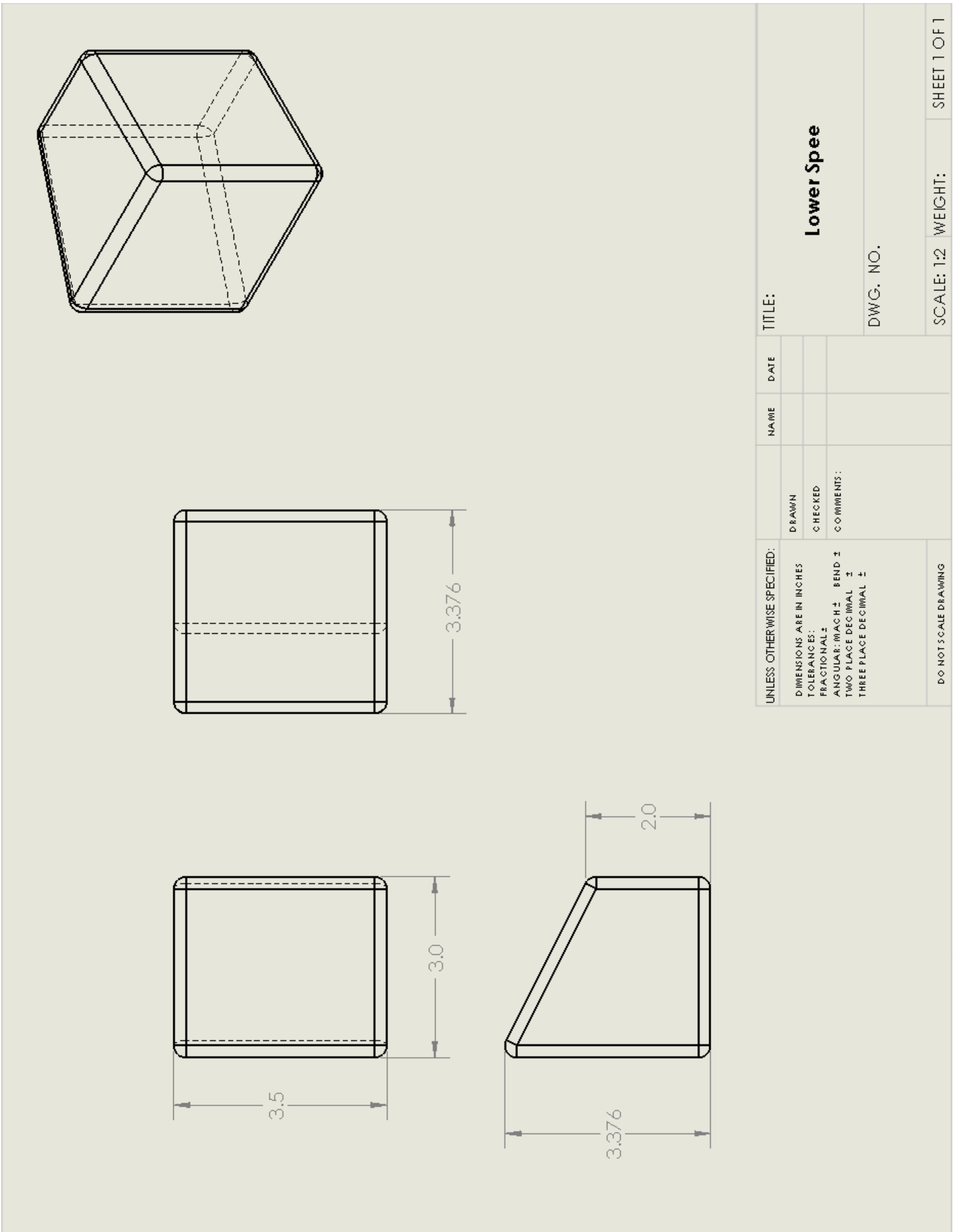
APPENDIX H.21 Big Canine



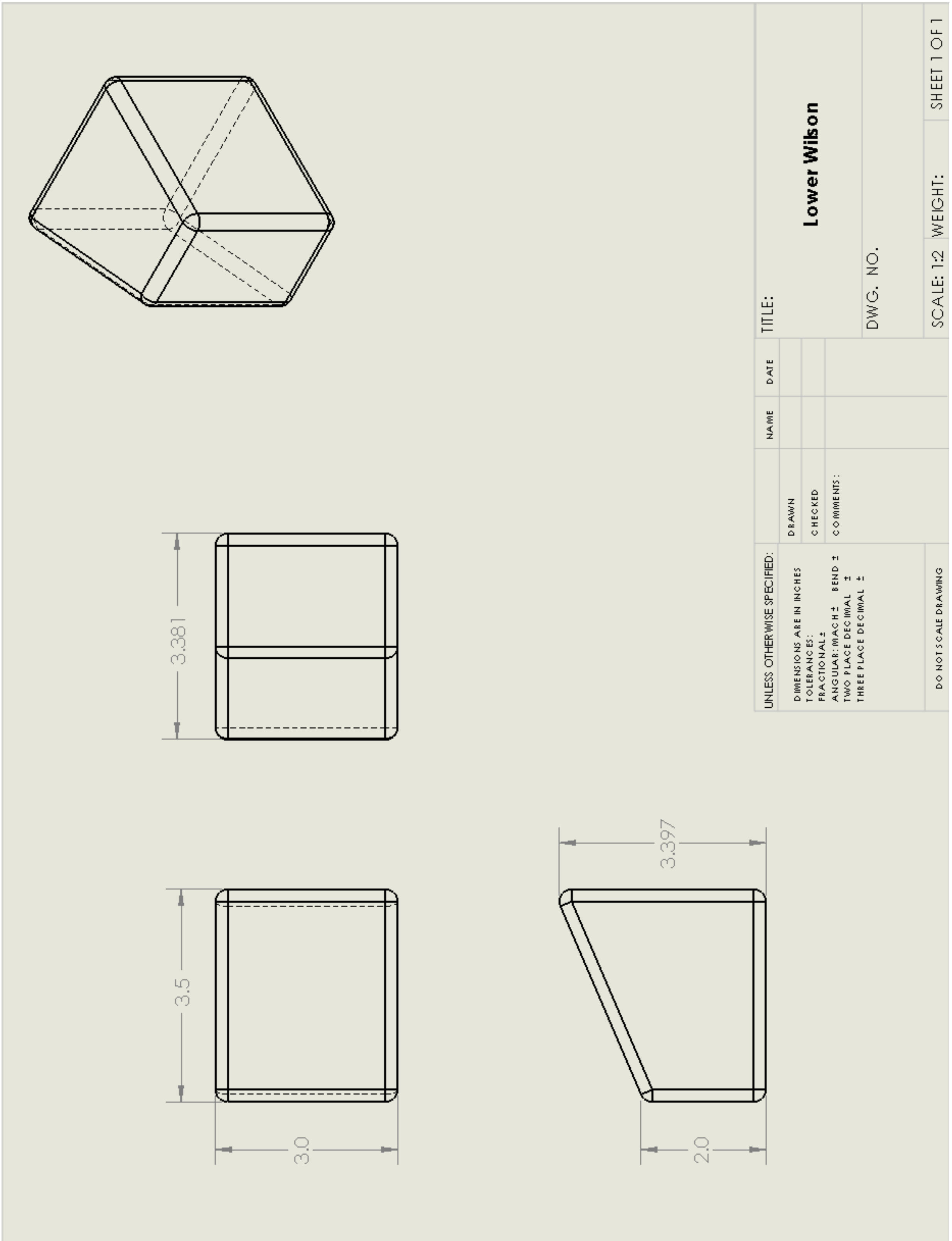
APPENDIX H.22 Big Upper Incisors



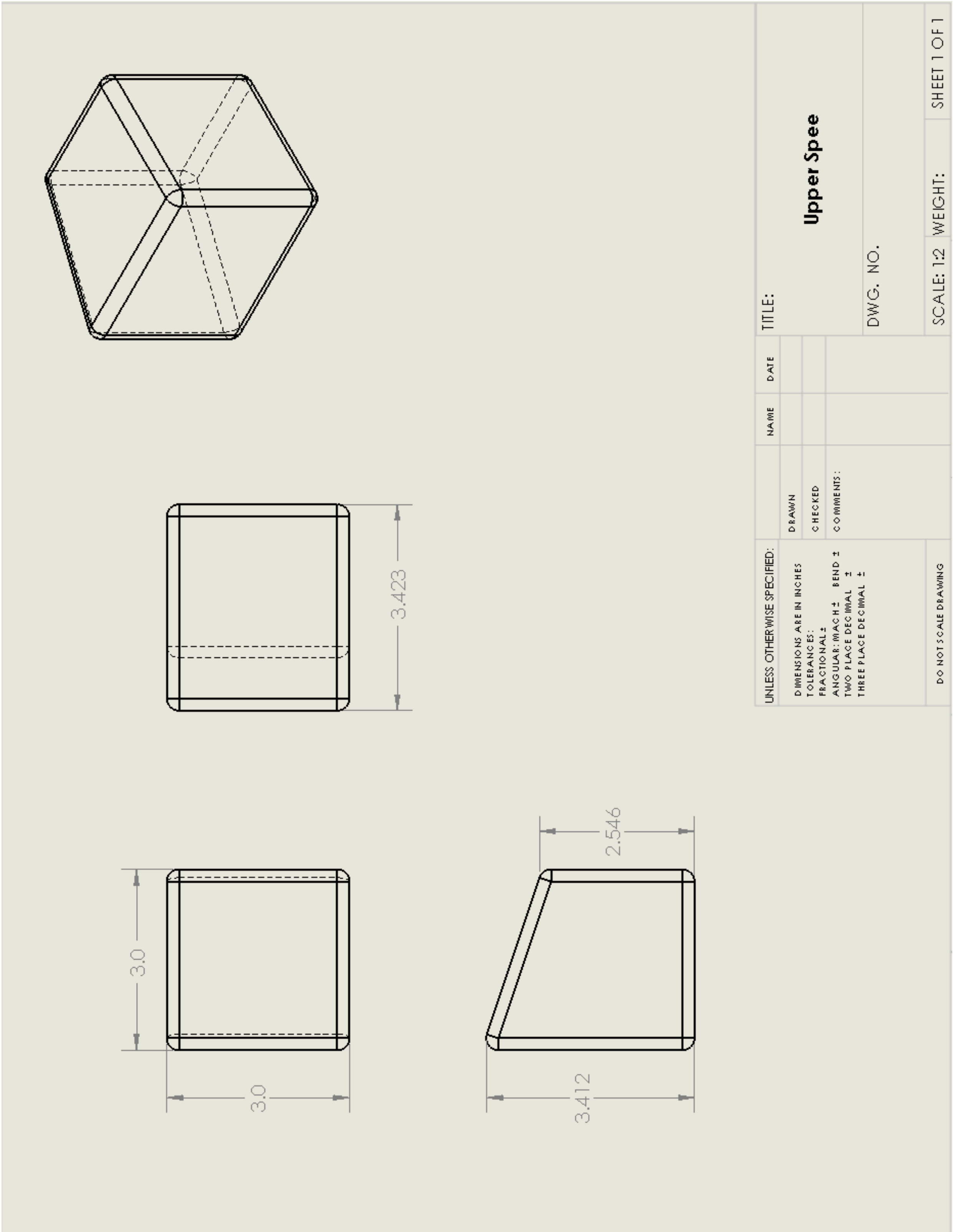
APPENDIX H.23 Lower Spee



APPENDIX H.24 Lower Wilson



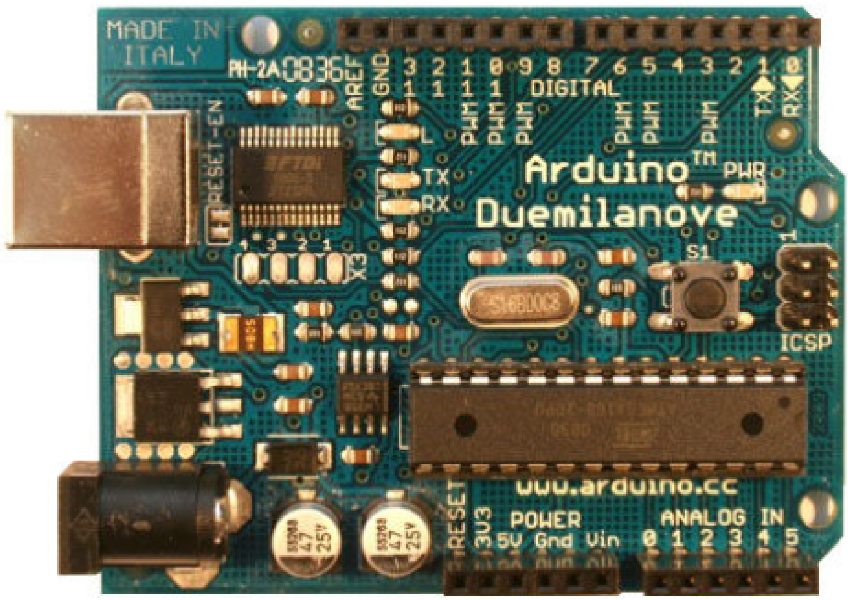
APPENDIX H.25 Upper Spee



APPENDIX I. Electrical Datasheets

APPENDIX I.1. Product Data for Arduino Duemilanove Microcontroller

Arduino Duemilanove



Overview

The Arduino Duemilanove ("2009") is a microcontroller board based on the ATmega168 (datasheet) or ATmega328 (datasheet). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.

"Duemilanove" means 2009 in Italian and is named after the year of its release. The Duemilanove is the latest in a series of USB Arduino boards; for a comparison with previous versions, see the index of Arduino boards.

Schematic & Reference Design

EAGLE files: arduino-duemilanove-reference-design.zip

Schematic: arduino-duemilanove-schematic.pdf

Summary

Microcontroller	ATmega168
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA

Flash Memory	16 KB (ATmega168) or 32 KB (ATmega328) of which 2 KB used by bootloader
SRAM	1 KB (ATmega168) or 2 KB (ATmega328)
EEPROM	512 bytes (ATmega168) or 1 KB (ATmega328)
Clock Speed	16 MHz

Power

The Arduino Duemilanove can be powered via the USB connection or with an external power supply. The power source is selected automatically.

External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector.

The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.

The power pins are as follows:

- **VIN.** The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
- **5V.** The regulated power supply used to power the microcontroller and other components on the board. This can come either from VIN via an on-board regulator, or be supplied by USB or another regulated 5V supply.
- **3V3.** A 3.3 volt supply generated by the on-board FTDI chip. Maximum current draw is 50 mA.
- **GND.** Ground pins.

Memory

The ATmega168 has 16 KB of flash memory for storing code (of which 2 KB is used for the bootloader); the ATmega328 has 32 KB, (also with 2 KB used for the bootloader). The ATmega168 has 1 KB of SRAM and 512 bytes of EEPROM (which can be read and written with the EEPROM library); the ATmega328 has 2 KB of SRAM and 1 KB of EEPROM.

Input and Output

Each of the 14 digital pins on the Duemilanove can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms. In addition, some pins have specialized functions:

- **Serial: 0 (RX) and 1 (TX).** Used to receive (RX) and transmit (TX) TTL serial data. These pins are connected to the corresponding pins of the FTDI USB-to-TTL Serial chip.
- **External Interrupts: 2 and 3.** These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.
- **PWM: 3, 5, 6, 9, 10, and 11.** Provide 8-bit PWM output with the analogWrite() function.
- **SPI: 10 (SS), 11 (MOSI), 12 (MISO), 13 (SCK).** These pins support SPI communication, which, although provided by the underlying hardware, is not currently included in the Arduino language.
- **LED: 13.** There is a built-in LED connected to digital pin 13. When the pin is HIGH value, the LED is on, when the pin is LOW, it's off.

The Duemilanove has 6 analog inputs, each of which provide 10 bits of resolution (i.e. 1024 different values). By default they measure from ground to 5 volts, though is it possible to change the upper end of their range using the AREF pin and the analogReference() function. Additionally, some pins have specialized functionality:

- **I^2C: 4 (SDA) and 5 (SCL).** Support I^2C (TWI) communication using the Wire library.

There are a couple of other pins on the board:

- **AREF.** Reference voltage for the analog inputs. Used with analogReference().
- **Reset.** Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

Communication

The Arduino Duemilanove has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega168 and ATmega328 provide UART TTL (5V) serial communication, which is available on digital pins 0 (RX) and 1 (TX). An FTDI FT232RL on the board channels this serial communication over USB and the FTDI drivers (included with the Arduino software) provide a virtual com port to software on the computer. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the Arduino board. The RX and TX LEDs on the board will flash when data is being transmitted via the FTDI chip and USB connection to the computer (but not for serial communication on pins 0 and 1).

A SoftwareSerial library allows for serial communication on any of the Duemilanove's digital pins.

The ATmega168 and ATmega328 also support I2C (TWI) and SPI communication. The Arduino software includes a Wire library to simplify use of the I2C bus; see the documentation for details. To use the SPI communication, please see the ATmega168 or ATmega328 datasheet.

Programming

The Arduino Duemilanove can be programmed with the Arduino software (download). For details, see the reference and tutorials.

The ATmega168 or ATmega328 on the Arduino Duemilanove comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol (reference, C header files).

You can also bypass the bootloader and program the microcontroller through the ICSP (In-Circuit Serial Programming) header; see these instructions for details.

Automatic (Software) Reset

Rather then requiring a physical press of the reset button before an upload, the Arduino Duemilanove is designed in a way that allows it to be reset by software running on a connected computer. One of the hardware flow control lines (DTR) of the FT232RL is connected to the reset line of the ATmega168 or ATmega328 via a 100 nanofarad capacitor. When this line is asserted (taken low), the reset line drops long enough to reset the chip. The Arduino software uses this capability to allow you to upload code by simply pressing the upload button in the Arduino environment. This means that the bootloader can have a shorter timeout, as the lowering of DTR can be well-coordinated with the start of the upload.

This setup has other implications. When the Duemilanove is connected to either a computer running Mac OS X or Linux, it resets each time a connection is made to it from software (via USB). For the following half-second or so, the bootloader is running on the Duemilanove. While it is programmed to ignore malformed data (i.e. anything besides an upload of new code), it will intercept the first few bytes of data sent to the board after a connection is opened. If a sketch running on the board receives one-time configuration or other data when it first starts, make sure that the software with which it communicates waits a second after opening the connection and before sending this data.

The Duemilanove contains a trace that can be cut to disable the auto-reset. The pads on either side of the trace can be soldered together to re-enable it. It's labeled "RESET-EN". You may also be able to disable the auto-reset by connecting a 110 ohm resistor from 5V to the reset line; see this forum thread for details.

USB Overcurrent Protection

The Arduino Duemilanove has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500 mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

Physical Characteristics

The maximum length and width of the Duemilanove PCB are 2.7 and 2.1 inches respectively, with the USB connector and power jack extending beyond the former dimension. Three screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.

Listen to the name

This is how you can pronounce the board's name in proper Italian, download the sound file in the format that better suits you: WAV, OGG, MP3, FLAC, WMA

National Semiconductor

April 2005

LMD18200
3A, 55V H-Bridge

General Description

The LMD18200 is a 3A H-Bridge designed for motion control applications. The device is built using a multi-technology process which combines bipolar and CMOS control circuitry with DMOS power devices on the same monolithic structure. Ideal for driving DC and stepper motors; the LMD18200 accommodates peak output currents up to 6A. An innovative circuit which facilitates low-loss sensing of the output current has been implemented.

Features

- Delivers up to 3A continuous output
- Operates at supply voltages up to 55V
- Low R_{DS}(ON) typically 0.3Ω per switch
- TTL and CMOS compatible inputs
- No "shoot-through" current
- Thermal warning flag output at 145°C
- Thermal shutdown (outputs off) at 170°C
- Internal clamp diodes
- Shorted load protection
- Internal charge pump with external bootstrap capability

Applications

- DC and stepper motor drives
- Position and velocity servomechanisms
- Factory automation robots
- Numerically controlled machinery
- Computer printers and plotters

Functional Diagram

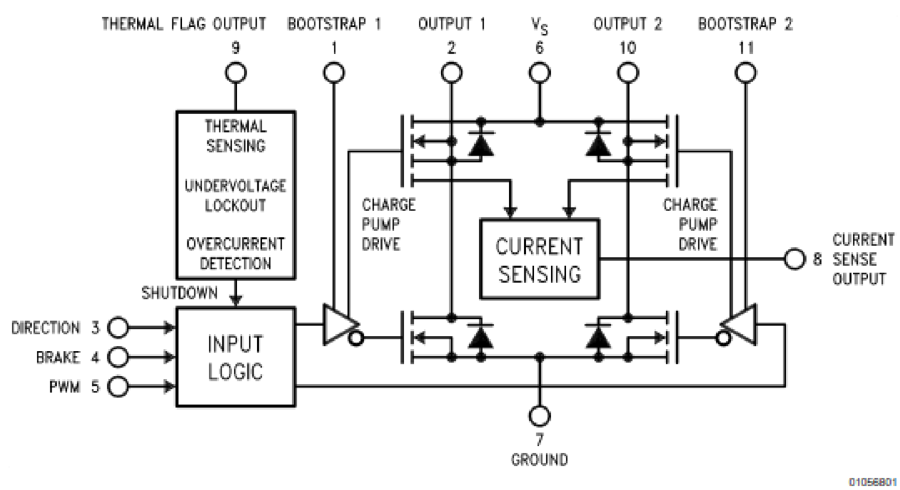
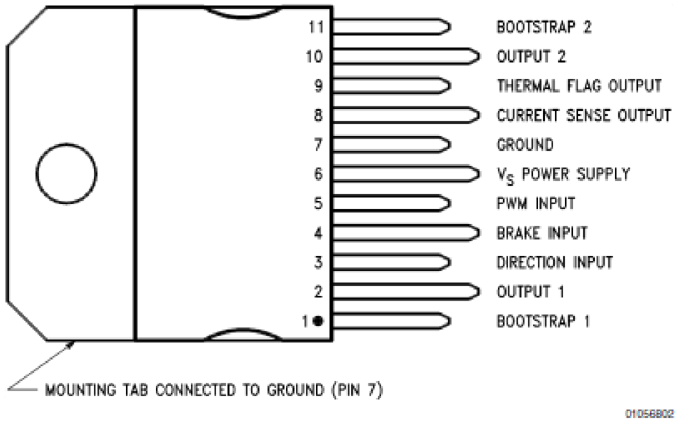


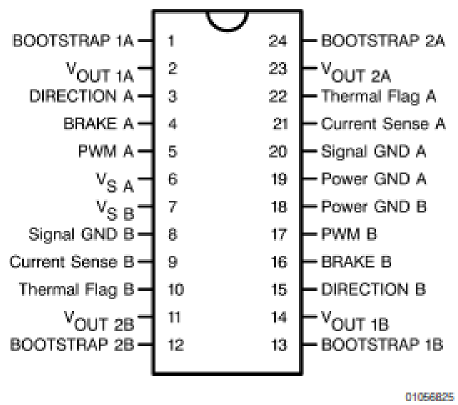
FIGURE 1. Functional Block Diagram of LMD18200

 DS010568 www.national.com

Connection Diagrams and Ordering Information



11-Lead TO-220 Package
Top View
Order Number LMD18200T
See NS Package TA11B



24-Lead Dual-in-Line Package
Top View
Order Number LMD18200-2D-QV
5962-9232501VXA
LMD18200-2D/883
5962-9232501MXA
See NS Package DA24B

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Total Supply Voltage (V_S, Pin 6)	60V
Voltage at Pins 3, 4, 5, 8 and 9	12V
Voltage at Bootstrap Pins	
(Pins 1 and 11)	V_{OUT} +16V
Peak Output Current (200 ms)	6A
Continuous Output Current (Note 2)	3A
Power Dissipation (Note 3)	25W
Power Dissipation (T_A = 25˚C, Free Air)	3W
Junction Temperature, $T_{J(max)}$	150˚C
ESD Susceptibility (Note 4)	1500V
Storage Temperature, T_{STG}	−40˚C to +150˚C
Lead Temperature (Soldering, 10 sec.)	300˚C

Operating Ratings (Note 1)

Junction Temperature, T_J	−40˚C to +125˚C
V_S Supply Voltage	+12V to +55V

Electrical Characteristics (Note 5)

The following specifications apply for V_S = 42V, unless otherwise specified. **Boldface** limits apply over the entire operating temperature range, −40˚C ≤ T_J ≤ +125˚C, all other limits are for T_A = T_J = 25˚C.

Symbol	Parameter	Conditions	Typ	Limit	Units
R_{DS}(ON)	Switch ON Resistance	Output Current = 3A (Note 6)	0.33	0.4/**0.6**	Ω (max)
R_{DS}(ON)	Switch ON Resistance	Output Current = 6A (Note 6)	0.33	0.4/**0.6**	Ω (max)
V_{CLAMP}	Clamp Diode Forward Drop	Clamp Current = 3A (Note 6)	1.2	1.5	V (max)
V_{IL}	Logic Low Input Voltage	Pins 3, 4, 5		**−0.1**	V (min)
				0.8	V (max)
I_{IL}	Logic Low Input Current	V_{IN} = −0.1V, Pins = 3, 4, 5		**−10**	μA (max)
V_{IH}	Logic High Input Voltage	Pins 3, 4, 5		**2**	V (min)
				12	V (max)
I_{IH}	Logic High Input Current	V_{IN} = 12V, Pins = 3, 4, 5		**10**	μA (max)
	Current Sense Output	I_{OUT} = 1A (Note 8)	377	325/**300**	μA (min)
				425/**450**	μA (max)
	Current Sense Linearity	1A ≤ I_{OUT} ≤ 3A (Note 7)	±6	±9	%
	Undervoltage Lockout	Outputs turn OFF		9	V (min)
				11	V (max)
T_{JW}	Warning Flag Temperature	Pin 9 ≤ 0.8V, I_L = 2 mA	145		˚C
V_F(ON)	Flag Output Saturation Voltage	T_J = T_{JW}, I_L = 2 mA	0.15		V
I_F(OFF)	Flag Output Leakage	V_F = 12V	0.2	10	μA (max)
T_{JSD}	Shutdown Temperature	Outputs Turn OFF	170		˚C
I_S	Quiescent Supply Current	All Logic Inputs Low	13	25	mA (max)
t_{Don}	Output Turn-On Delay Time	Sourcing Outputs, I_{OUT} = 3A	300		ns
		Sinking Outputs, I_{OUT} = 3A	300		ns
t_{on}	Output Turn-On Switching Time	Bootstrap Capacitor = 10 nF			
		Sourcing Outputs, I_{OUT} = 3A	100		ns
		Sinking Outputs, I_{OUT} = 3A	80		ns
t_{Doff}	Output Turn-Off Delay Times	Sourcing Outputs, I_{OUT} = 3A	200		ns
		Sinking Outputs, I_{OUT} = 3A	200		ns
t_{off}	Output Turn-Off Switching Times	Bootstrap Capacitor = 10 nF			
		Sourcing Outputs, I_{OUT} = 3A	75		ns
		Sinking Outputs, I_{OUT} = 3A	70		ns
t_{pw}	Minimum Input Pulse Width	Pins 3, 4 and 5	1		μs
t_{cpr}	Charge Pump Rise Time	No Bootstrap Capacitor	20		μs

Appendix I.3. Selected Product Data for Linear Actuators

PROGRESSIVE AUTOMATIONS

Custom Orders:

PA-14 Mini Linear Actuator

Voltage: 24V DC **or** 12V DC
Load Capacity: 8, 15, 35, 70, 150 lbs
Type of Duty: 25%
Operation Temperature: -25ºC~+65ºC
Protection class: IP54
Low Noise Design: db<45 (A)
Certification: CE

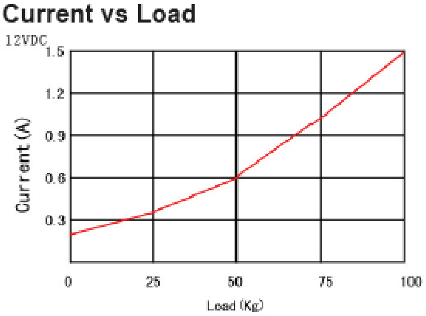
Made from aluminum alloy

Speed in mm per Second

Forces (N)	No Load	Full Load
36	25	22
68	20	17
126	20	17
158	20	17
225	20	17
315	25	22
675	15	13

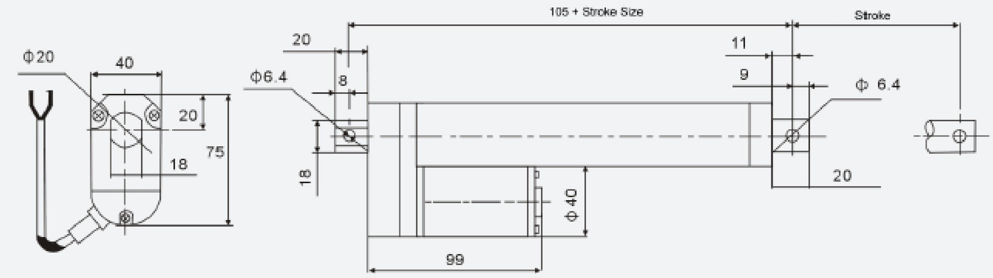
Standard Stroke (mm)	<50	100	150	200	250	300
Minimum Dimension	158	209	260	311	362	413

Current vs Load



TYPE	Amp at Full Load (24V) A	Amp at Full Load (12V) A
675 N	3.0	0.45 - 1.5
125 N	2.8	1.4

Dimensions in mm



WWW.PROGRESSIVEAUTOMATIONS.COM

APPENDIX J. Arduino Programming

During the assembly of the electrical circuit, it was determined that two of the three H-Bridges used were defect. We were able to procure one more LMD18200T H-Bridge, bringing our total for working H-Bridges to two, but in order to complete the programming of all three actuators, a third is needed. During the Design Expo, we were only able to write a program to move the lower two actuators. The used program is given in Figure J.1 below. At time of printing, a third LMD18200T H-Bridge has been ordered, and will be installed for the sponsor (Dr. Gerstner) before final prototype delivery.

```
// 'pwm' outputs send the driving signal to the controller
// 'dir' outputs control the direction that the motors turn
// 'brk' controls stopping the motor
//  all three of these controls are needed for each motor because of the LMD18200T h-bridge logic tables

#define YLA_pwm 3
#define YLA_dir 4
#define YLA_brk 5
#define BRA_pwm 6
#define BRA_dir 7
#define BRA_brk 8

int endprog=0;                     // need this to control that the program operates only once, and
                                   // doesn't continuously loop

void setup()                       // this is always run first to set up the Arduino
{
  pinMode(YLA_pwm, OUTPUT);        // these lines set all the defined pins above as outputs
  pinMode(YLA_dir, OUTPUT);
  pinMode(YLA_brk, OUTPUT);
  pinMode(BRA_pwm, OUTPUT);
  pinMode(BRA_dir, OUTPUT);
  pinMode(BRA_brk, OUTPUT);
}

void loop()                        // this is the loop that executes the motor motions
{
  if(endprog==0){
    digitalWrite(YLA_pwm, HIGH);    //}
    digitalWrite(YLA_dir, LOW);     //} these three lines run the left actuator 'forward'
    digitalWrite(YLA_brk, LOW);     //}
    digitalWrite(BRA_pwm, HIGH);     //}
    digitalWrite(BRA_dir, LOW);      //} these three lines run the left actuator 'forward'
    digitalWrite(BRA_brk, LOW);      //}
    delay(6000);                    //  this line lets the motors run for 6 seconds

    digitalWrite(YLA_dir, HIGH);    //}
    digitalWrite(BRA_dir, HIGH);     //} this and the previous line change the motor directions
    delay(6000);                    // this lets the motors run in the changed direction for 6 seconds

    digitalWrite(YLA_pwm, LOW);     //  these four lines stop the actuators
    digitalWrite(YLA_brk, HIGH);
    digitalWrite(BRA_pwm, LOW);
    digitalWrite(BRA_brk, HIGH);
    endprog++;                      // this increments 'endprog' so the previous 'if' statement
                                    // won't run after the loop
  }
}
```

Figure J.1 The Arduino Program used during the Design Expo.

The H-Bridge logic table can be found in section 13.5 of the Prototype Description.

As seen in the Figure, the main commands used to operate the actuators are ‘digitalWrite()’ and ‘delay()’. A third command, ‘analogWrite()’ should be used if the motors are to be operated at different speeds with PWM (pulse width modulation). The descriptions of these functions are provided in Table J.1, below, as reproduced from http://www.arduino.cc.

Table J.1 Description and proper syntax for the main commands used to control the actuators.

Syntax	Parameters	Description
delay(ms)	ms - number of milliseconds to pause	Pauses the program for the amount of time (in miliseconds) specified as parameter.
digitalWrite(pin, value)	pin - the pin number; value HIGH or LOW	Write a HIGH or a LOW value to a digital pin. If the pin has been configured as an OUPUT with pinMode(), its voltage will be set to the corresponding value: 5V (or 3.3V on 3.3V boards) for HIGH, 0V (ground) for LOW.
analogWrite(pin, value)	pin - the pin number; value - the duty cycle, between 0 (always off) and 255 (always on)	Writes an analog value (PWM wave) to a pin. Can be used to light a LED at varying brightnesses or drive a motor at various speeds. After a call to analogWrite(), the pin will generate a steady square wave of the specified duty cycle until the next call to analogWrite() (or a call to digitalRead() or digitalWrite() on the same pin). The frequency of the PWM signal is approximately 490 Hz.

APPENDIX K. Ranges and Limitations of Motion

APPENDIX K.1. Opening Jaw – Exclusively Vertical Actuator.

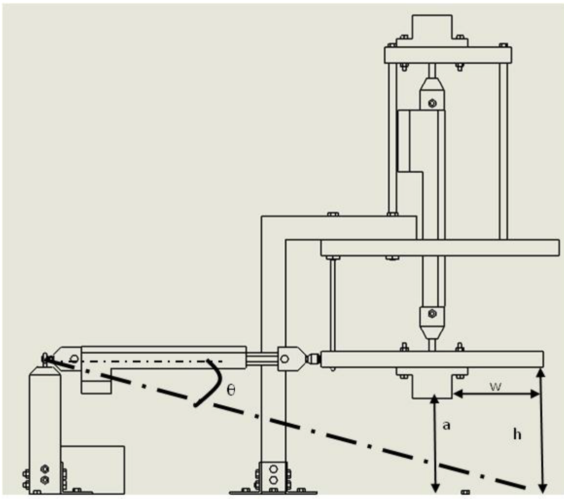


Figure K.1: Assembly side view. Available motion of right angle ball and socket joint.

Table K.1: **Summary of limiting factors to open/close motion. The motion is limited by the ball cap part contacting the baseboard after the vertical actuator extends 6 inches.**

Range of Motion lower palate - open jaw, (*ignore elastic)		
h [in]	8	
a [in]	6	
w [in]	5.75	
theta_joint [deg]	18	
theta_front [deg]	14.45243	
theta_ballcap [deg]	13.34655	*Limiting angle measure. First contact will be when Ball Cap touches base board. Right angle joint 13.3deg off horizontal.

APPENDIX K.2. Pro-/Retrusion – Exclusively Horizontal Actuators.

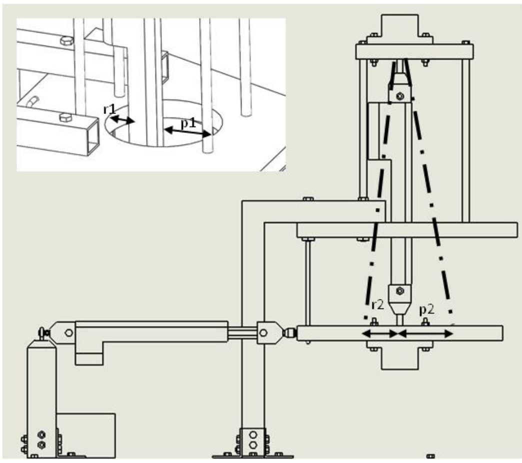


Figure K.2: Assembly side view, upper palate isometric view. Available motion for lower palate given horizontally actuated motion.

Table K.2: Summary of pro-/retrusion limiting clearances. This motion is limited by the stroke length (6 inches) of the horizontal linear actuators.

Range of Motion vertical actuator in upper palate (pro- & retrusion)			
	6" hole in upper palate		
	p1 [in]	3.21	
	r1 [in]	1.41	
	theta_p1 [deg]	16.05	0 deg pointing downward, positive
	theta_r1 [deg]	-7.2	angles counterclockwise
	6" stroke length of horizontal actuators		
	p2 [in]	4	
	r2 [in]	2	
*	theta_p2 [deg]	12.43	0 deg pointing downward, positive
	theta_r2 [deg]	-6.28	angles counterclockwise
	* Stroke length of horizontal actuators limits motion		

APPENDIX K.3. Laterotrusion – Simultaneous Vertical and Horizontal Actuation (Asymmetrical)
Dental concepts regarding laterotrusion are highly dependent on teeth anatomy. Programs relating to laterotrusion will vary with respect to the concept being taught. One such position of the lower palate in laterotrusion is shown below. The linear actuators have enough clearance so as to not interfere with the stand in all motions.

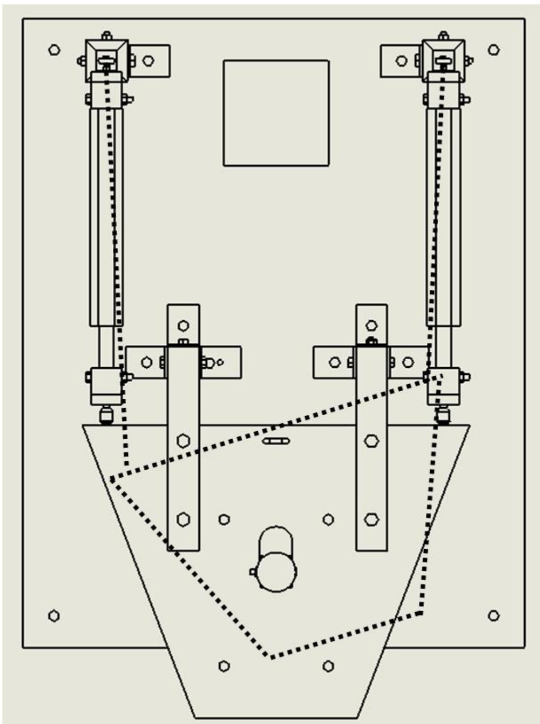


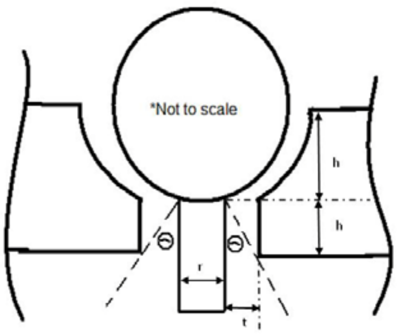
Figure K.3. Assembly top view, several parts hidden to show lower palate. Sample jaw motion to demonstrate laterotrusion.

Table K.3: Summary of sample motion provided above.

Laterotrusion - sample motion, additional motions programmed as time allows
Top View
Right actuator retrudes 2 inches
Left actuator protrudes 2 inches
Top actuator adjusts for teeth interference depending on attatched teeth size.
Elastic provides constant vertical support (approx. 4.5 lbs)
*Dotted line represents final lower palate location at end of motion

Appendix K.4. Vertical Actuator Ball and Socket

Vertical actuator ball and socket joint provides for 32 degrees of motion in either direction measured from vertical. All other ball and socket joints purchased and shown separately in provided engineering drawings.



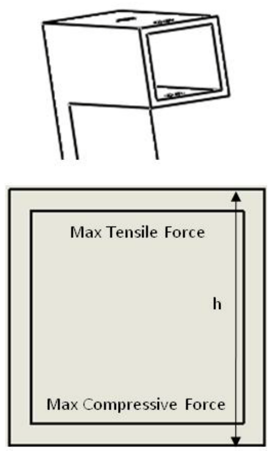
(a)

Range of Motion vertical actuator at 1 7/8" D Threaded ball (3/8" x 16)	
h [in]	0.5
r [in]	0.375
t [in]	0.3125
theta [deg]	32.01

(b)

Figure K.4 (a) & Table K.4 (b): Motion potential of fabricated ball and socket joint connected to vertical linear actuator.

Appendix K.5 Deflection Analysis



(a)

Area - deflection/buckeling		
A_tube (in^2)	0.36	Area of material (1.5x1.5x1/8)
Deflection - hanging mass on stand		
Moment of Inertia (I) square tube = (1/12)*(D^4 - d^4)		
I [in^4]	0.22	
h [in]	1.375	
M_y [lb*in]	252.00	Moment at base of stand
M_y_max [lb*in]	1875.00	Moment if load at end of stand
Stress [lb/in^2]	793.1803	Shear stress on square tube due to hanging mass
Stress_max [lb/in^2]	5901.639	
Stress_vonMises [lb/in^2]	8346.178	*both worst case scenario, mass hanging at end of palate
Stress_yield [lb/in^2]	3770848	Yield stress of aluminum (~26 Gpa [Dowling]) [21])
Safety Factor_normal	4754.086	SF for typical weight
Safety Factor_MAX	451.8053	SF for max weight

(b)

Figure K.5 (a) and Table K.5 (b): The cantilever support was analyzed to determine that deflections for a length of tubing with this cross section and length are negligible and can be ignored.

APPENDIX K.6. Kinematic Analysis

The table below was created by converting the given data for the linear actuators to English units. See Appendix I.3 for detail.

Table K.6: Actuation Speed Conversion

	Speed [in/s]	
Force [lbs]	No Load	Full Load
8	6.4	5.6
15	5.1	4.3
28	5.1	4.3
36	5.1	4.3
51	5.1	4.3
71	6.4	5.6
152	3.8	3.3

Using the data above in combination with the prescribed motions of the jaw (actuators) it is possible to calculate the time each actuator will take to perform the desired displacement. The table below describes one motion (laterotrusion) by the time required for actuator to move to their final position.

Table K.7: Sample analysis of time to perform single motion, double proposed time for cyclic motion.

	Laterotrusion								
	Horizontal Actuator (1)			Horizontal Actuator (2)			Vertical Actuator		
		Time Required			Time Required			Time Required	
Force	Displacement	No Load	Full Load	Displacement	No Load	Full Load	Displacement	No Load	Full Load
[lbs]	[in]	[s]	[s]	[in]	[s]	[s]	[in]	[s]	[s]
8	4.0	0.63	0.72	2.0	0.31	0.36	0.5	0.08	0.09
15	4.0	0.79	0.93	2.0	0.39	0.46	0.5	0.10	0.12
28	4.0	0.79	0.93	2.0	0.39	0.46	0.5	0.10	0.12
36	4.0	0.79	0.93	2.0	0.39	0.46	0.5	0.10	0.12
51	4.0	0.79	0.93	2.0	0.39	0.46	0.5	0.10	0.12
71	4.0	0.63	0.72	2.0	0.31	0.36	0.5	0.08	0.09
152	4.0	1.05	1.21	2.0	0.52	0.61	0.5	0.13	0.15

The table below summarizes all of the actuation speeds in as much detail as is available on the given data sheet (Appendix I.3). The table describes these speeds by detailing the amount of time required for each actuator to move a prescribed displacement. Actuation speeds in practice can be interpolated from the data below using the applied force and load to each actuator.

Table K.8: Detailed analysis of actuation speed, described as specific time required for prescribed actuator displacement. Specific speeds for desired forces and loads can be determined through interpolation.

Actuator Displacement [in]	Force = 8 lbs Time Required for Displacement [s]		Force = 15, 28, 36 or 51 lbs Time Required for Displacement [s]		Force = 71 lbs Time Required for Displacement [s]		Force = 152 lbs Time Required for Displacement [s]	
	No Load	Full Load	No Load	Full Load	No Load	Full Load	No Load	Full Load
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.04	0.04	0.05	0.06	0.04	0.04	0.07	0.08
0.50	0.08	0.09	0.10	0.12	0.08	0.09	0.13	0.15
0.75	0.12	0.13	0.15	0.17	0.12	0.13	0.20	0.23
1.00	0.16	0.18	0.20	0.23	0.16	0.18	0.26	0.30
1.25	0.20	0.22	0.25	0.29	0.20	0.22	0.33	0.38
1.50	0.24	0.27	0.30	0.35	0.24	0.27	0.39	0.45
1.75	0.28	0.31	0.34	0.41	0.28	0.31	0.46	0.53
2.00	0.31	0.36	0.39	0.46	0.31	0.36	0.52	0.61
2.25	0.35	0.40	0.44	0.52	0.35	0.40	0.59	0.68
2.50	0.39	0.45	0.49	0.58	0.39	0.45	0.66	0.76
2.75	0.43	0.49	0.54	0.64	0.43	0.49	0.72	0.83
3.00	0.47	0.54	0.59	0.69	0.47	0.54	0.79	0.91
3.25	0.51	0.58	0.64	0.75	0.51	0.58	0.85	0.98
3.50	0.55	0.63	0.69	0.81	0.55	0.63	0.92	1.06
3.75	0.59	0.67	0.74	0.87	0.59	0.67	0.98	1.14
4.00	0.63	0.72	0.79	0.93	0.63	0.72	1.05	1.21
4.25	0.67	0.76	0.84	0.98	0.67	0.76	1.12	1.29
4.50	0.71	0.81	0.89	1.04	0.71	0.81	1.18	1.36
4.75	0.75	0.85	0.94	1.10	0.75	0.85	1.25	1.44
5.00	0.79	0.89	0.98	1.16	0.79	0.89	1.31	1.51
5.25	0.83	0.94	1.03	1.22	0.83	0.94	1.38	1.59
5.50	0.87	0.98	1.08	1.27	0.87	0.98	1.44	1.67
5.75	0.91	1.03	1.13	1.33	0.91	1.03	1.51	1.74
6.00	0.94	1.07	1.18	1.39	0.94	1.07	1.57	1.82
6.25	0.98	1.12	1.23	1.45	0.98	1.12	1.64	1.89
6.50	1.02	1.16	1.28	1.51	1.02	1.16	1.71	1.97
6.75	1.06	1.21	1.33	1.56	1.06	1.21	1.77	2.04
7.00	1.10	1.25	1.38	1.62	1.10	1.25	1.84	2.12
7.25	1.14	1.30	1.43	1.68	1.14	1.30	1.90	2.20
7.50	1.18	1.34	1.48	1.74	1.18	1.34	1.97	2.27
7.75	1.22	1.39	1.53	1.79	1.22	1.39	2.03	2.35
8.00	1.26	1.43	1.57	1.85	1.26	1.43	2.10	2.42

APPENDIX L. Material Selection

APPENDIX L.1 Functional Performance

CES material selection software was used to determine the material for the teeth and to adequately confirm the material for the main stands for Jaws: The Educator. In order to use CES properly, each component was analyzed for function, objective, and constraint requirements. During the material selection process, the teeth were approached as columns in compression and the stand as a beam in bending. The following table includes the definition of each requirement, and descriptions for each requirement corresponding to the teeth and the stand [lecture slides by Dan Johnson].

Table L.1: Method to determine Function, Objective, and Constrains for teeth and stand

	Function	Objective	Constraints	Material Chosen
Description	What does the component do?	What is to be maximized or minimized?	What non-negotiable conditions must be met? What negotiable but desirable …	
Teeth	Withstand frictional and other forces (5lbf); can't buckle or deform; replaceable	Minimize mass and cost; maximize compressive strength; 8x the size of normal teeth	Cost(budget); weigh; fixed volume; max load for one tooth around 5lbf; durability	Balsa Wood
Stand	Must hold 50lbf; withstand bending	Minimize mass; maximize modulus of elasticity	Fixed length; must hold 50lbf; can control cross sectional area	Aluminum 6061

Teeth: From the table above, the functional, geometry, and material properties of the teeth were cost, volume, and compressive strength respectively. In equation, the requirements must be a function of F=functional, G=geometrical, and M=material properties, which is $p = f(F, G, M)$. To find a material in CES that incorporated all of these properties, each property must be a function of each other, like in the equation $p = f_1(F)f_2(G)f_3\,(M)$. The material must ensure that each tooth will not fail functionally, geometrically, or materially. The functional index corresponds to the cost for the tooth. This index relates cost/kg of a material multiplied by the mass; $C = C_m V\rho$. The geometry index corresponds to the fixed volume of the tooth; $m = V\rho$. The material index corresponds to the compressive strength of a material so the tooth will not buckle; $\sigma_{UT} = \frac{F}{A}$. These parameters are used to make sure that the material chosen will not fail in any of the required aspects. The following work shows how certain material properties were chosen to determine the best material for the teeth.

$$m = AL\rho;\ \frac{F}{A} = \sigma_{UT} \longrightarrow\ m = FL\frac{\rho}{\sigma}$$

The max load for one tooth was set at 5lbf or 22.24 N. With the $\frac{\rho}{\sigma}$ for the material index, density was plotted against compressive strength. We also placed a cost restraint on the results as well as an index of -2. With these parameters and constraints, CES narrowed the list to the following: polystyrene foam closed cell, polyethylene foam, carbon foam, phenolic foam, and balsa wood. The following table includes the top 5 choices and the corresponding properties of density, cost, compressive strength, primary material processing carbon footprint and primary production energy.

Table L.2: Properties of different materials for teeth of the prototype.

Material	Density (kg/m3)	Cost (USD/kg)	Compressive Strength (Pa)	CO_2 footprint (kg/kg)	Primary Production Energy (J/kg)
Polystyrene foam	**28**	**2.5**	2E5-2.5E5	3.55-3.93	1.05E8
Polyethylene foam	27-30	3.11	1E5	4.16-4.6	1.04E8-1.15E8
Carbon foam	49-51	20.7	2.8E5	4.62-5.1	8.56E7-9.5E7
Phenolic foam	32-38	8.3-10.4	**8.4E4**	3.55	1.05E8-1.15E8
Balsa Wood	90	7.06	3.2E5-6E5	**0.47**	**7.2E6**

As you can see from the table, Balsa wood was the best overall. Balsa was more expensive than some of the other top 5 choices, but the price was reasonable for project. The main factor for choosing balsa wood over the foams was its high compressive strength and low primary material processing energy consumption and carbon footprint.

Stand: We repeated the same strategy as the teeth to confirm that Aluminum would be an adequate choice for the stands. The main stands of the prototype must support the weight of the upper jaw palate, as well as the support structure for the weight bearing actuator. Thus, the stand was approached as a beam in bending.Table K.1 led to the functional, geometry, and material properties of deflection, fixed length, and modulus of elasticity respectively. The following are some calculations to determine the material index, and to narrow down the search.

$$M = \frac{\sigma_{UT}}{\rho}\ (A\ high\ material\ index, high\ performance)$$

$$S = \frac{F}{\delta}(Critical\ deflection); S = \frac{F}{\delta} \leq \frac{CEI}{L^3}(E = Young's\ modulus, I = 2nd\ moment\ of\ inertia)$$

Free variables: A b/c must be certain length

$$S = \frac{F}{\delta} = \frac{CEI}{L^3} = \frac{CEA^2}{12L^3}$$

$$m = \frac{12S^{\frac{1}{2}}}{CL} L^3 \frac{\rho}{E^{\frac{1}{2}}} -\!\!\to\!= \frac{E^{\frac{1}{2}}}{\rho} (inverse\ because \max performance\ is\ minimum\ function)$$

$$logE = 2log\rho + 2logM$$

A log plot of young's Modulus plotted against density narrowed down our search. A 1.0E8 Pa yield strength limitation as well as a cost constraint narrowed down the results even more. Al6061 was right in the narrowed search along withZn-50% SiC, Al8090, Chromic oxide, and silicon nitride.

Table L.3 Properties of different materials for stand of prototype

Material	Density (kg/m3)	Yield Strength (USD/kg)	Young's Modulus (Pa)	CO_2 footprint (kg/kg)	Primary Production Energy (J/kg)
Al 6061	2.7E3	1.03E8	6.8E10	11.4	1.97E8-2.18
Zn-50% SiC	4.1E3	3.1E8	**2.2E11**	15.6	2.08E8-2.3E8
Al8090	2.52E3	**4.35E8**	8E10	11.4	1.97E8-2.18E8
Titanium alloy	4.51E3	2.76E8	1E11	39.5	6.27E8-6.93E8
Silicon Nitride	**2.43E3**	1.4E8	1.17E11	**6.56**	1.22E8-1.34E8

Table L.3 shows that Al6061 falls pretty average in comparison to the other materials. However, this data shows that Al6061 would be an excellent material for its purpose. We also found Al6061 more available than other materials and much cheaper.

L.2 Environmental Performance

There can be many improvements to Jaws: the Educator with respect to environmental processes. Balsa wood was specifically chosen over other materials, as mentioned above, because of the significantly small carbon footprint and processing energy in comparison. To analyze environmental impacts in more depth, we used SimaPro to analyze and compare the environmental impact of Balsa wood and Al6061. For the final prototype, about 1 kg of Balsa wood for the teeth and about 2kg of Al6061 for the stand were used. Although Al6061 was not available in SimaPro, Al6060 was compared to balsa wood instead. SimaPro analyzes the environmental impact of materials in many aspects. For our purpose, we used SimaPro to calculate the masses of emissions and to determine which material has a greater impact on the environment using the EcoIndicator 99 damage classifications.

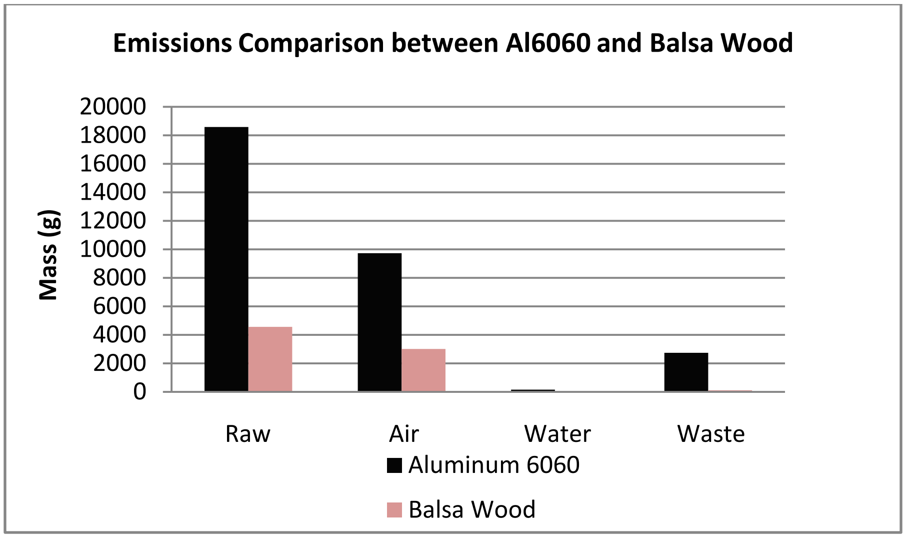


Figure L.1: Comparison emissions (g) of Al6060 and Balsa Wood

The figure above compares the masses of raw, air, water, and waste emissions of Al6060 and Balsa wood. From this graph, it is clear that Al6060 has a greater environmental impact with respect to emissions. Al6060 produces more emissions in each category with 185779.4 g of raw emissions, 9726.72 g of air emissions, 146.25 g of water emissions, and 2744.86 g of waste emissions. This is not surprising since Al6060 went through a more energy-intensive process from mining to the finished product as opposed to balsa wood which is found naturally in parts of South America. The mass emissions for balsa were 4567.28g of raw emissions, 3017.33 g of air emissions, 0.0754 g of water emissions, and 102.203 g of waste emissions.

Other data representations are available through SimaPro. This software analyzes the relative impacts in disaggregated damage categories such as carcinogens, resp. organis, resp. inorganics, climate change, acidification/eutrophication, ozone layer, exotoxicity, land use and minerals. Figure L.2 compares the relative impacts of these categories of balsa wood and Al6060. This data is shown in percentages, but at least one material at 100% to make a clear comparison.

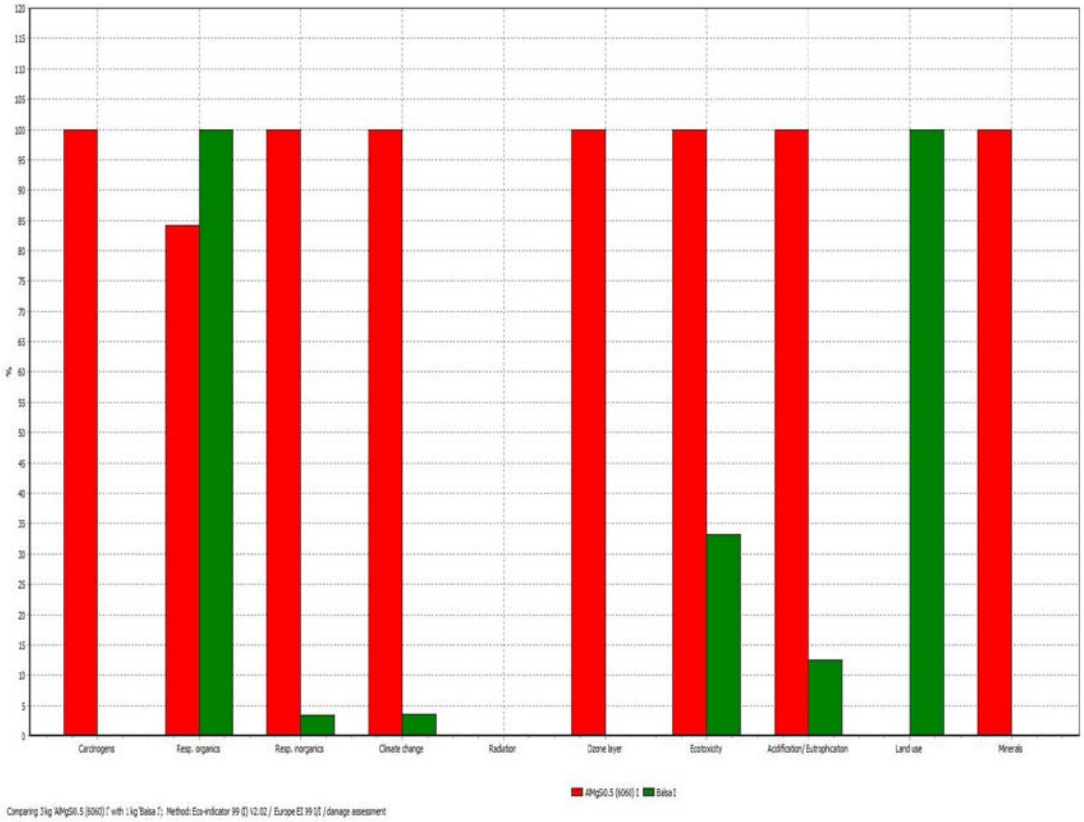


Figure L.2: Relative Impacts in % in Disaggregated Damage Categories of balsa wood and Al6060

Figure L.2 clearly shows that Al6060 has a greater impact on the environment in these categories as well. Al6060 significantly outweights balsa wood in impact of carcinogens, ozone layer, and mineral damages. Balsa wood virtually has 0% impact in these categories comparatively. Al6060 also outweighs balsa wood in impact in resp. inorganics, ecotoxicity, and acidification/eutrophication. The impacts of resp. organics and land-use damages of balsa wood outweigh impact of those damages by Al6060. Overall, Figure L.2 shows that Al6060 has a greater environmental damage impact than balsa wood.

Taking a closer look on the impact of balsa wood and Al6060, Figure L.3 shows the normalized score in human health, ecosystem quality, and resources of the two materials.

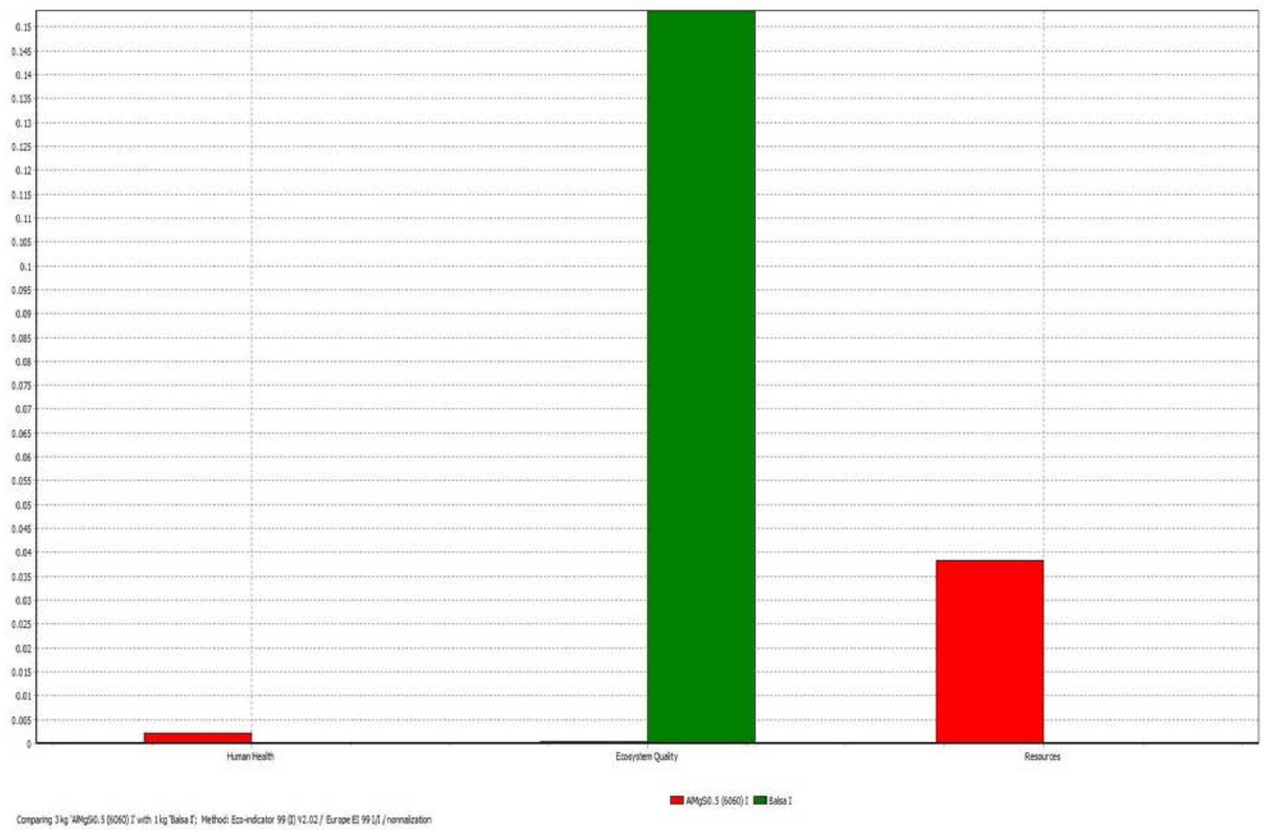


Figure L.3. Normalized Score in Human Health, Ecosystem Quality, and Resource Categories of balsa wood and AL606

Similarly, Figure L.4 relates the normalized score of impact on the same categories in Figure L.3 to EI99 points on the following page.

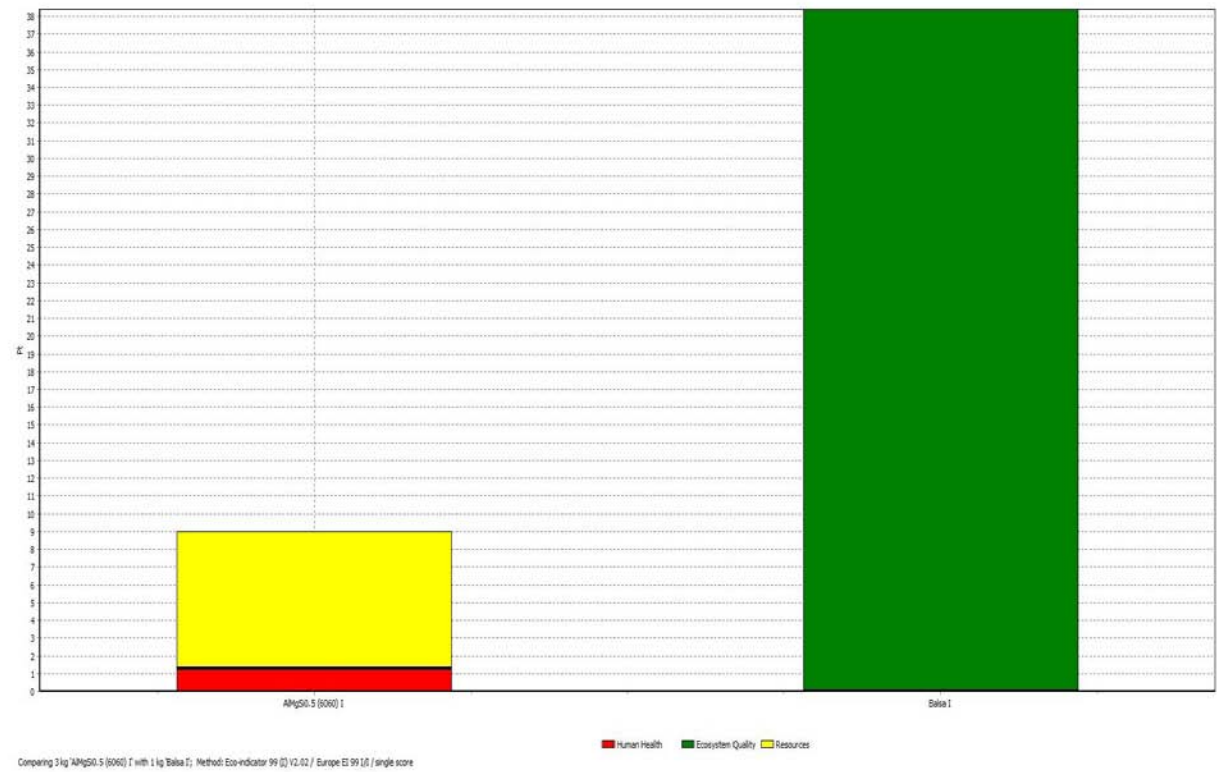


Figure L.4. Single Score EI99 Point Values of balsa wood and Al6060 on Damage Meta-Categories.

From both figures L.3 and L.4, balsa wood has the largest impact on ecosystem quality than the impacts of Al6060 combined. As seen in figure L.4, balsa wood has the most cumulative EI99 point score of around 39 points compared to Al6060. When comparing the single-stand alone scores, balsa wood clearly has a much higher EI99 score. This score, however, does not mean that balsa wood is worse for the environment than Al6060. On the contrary, not only do the previous figures show that Al6060 has the most emissions (g) and damage impacts, but also the life cycle of Al6060 is much worse for the environment than balsa wood. The carbon footprint, from CES software, in Tables L.2 and L.3 of balsa wood and Al6061 respectively, also support this conclusion. Al6061 has a much higher CO2 footprint as well as processing energy consumption.

Extensive research using CES and SimaPro software has been informative and has inspired new ideas on how to improve Jaws: The Educator to be more environmentally friendly. We believe balsa wood was a good choice in that respect, especially when comparing the CO_2 footprint and primary processing energy numbers from Table L.2. Al6061 was very damaging, comparatively, to the environment. The CES analysis has introduced many other materials that could replace Al6061 and have less of an impact on the environment. Other aspects of our prototype could also change to waste less energy; have less impact on the environment, and save materials. Some of these ideas were created upon completion of the Design for the Environment Handout. Below is a list of improvements to make Jaws: The Educator more eco-friendly.

Table L.4 DFE improvement strategies

DFE Strategies	Improvement Options
1. New Concept Development	
(effective teaching tool)	1. Virtual model
2. Physical Optimization	
(make 8x the size of normal jaw)	1. Energy efficient Actuators 2. Auto-power off
3. Optimize Material Use	
(recycled ME 450 projects)	1. Recycled parts steel, aluminum, etc. 2. Epoxy- from CES/ SimaPro has less environmental impact than balsa wood 3. Non-toxic paints instead of spray paint 4. Electronic copies of reports instead of printed copies
4. Optimize Production	
(recycled parts, used scrap, little mistakes to prevent waste)	1. Using battery-powered machines 2. Whittle by hand 3. Plant a tree for every 100 pages printed/ kg of wood used
5. Reduce Impact During Use	
	1. Optimize energy use for actuators 2. Zero-watt principles to reduce energy use 3. Implement clean energy- solar powered jaw actuator (class must be taught outside)
6. Optimize End-of Life Systems	
	1. Design for disassembly 2. Recyclable parts 3. Biodegradable 4. Long life materials

APPENDIX L.4. Manufacturing for Mass Production

According to the Bureau of Labor Statistics, about 145,000 people were employed in 2006 as postsecondary (or collegiate level) health specialties teachers (http://www.bls.gov/OCO/ocos066.htm#projections_data). Assuming that 145,000 are still employed today, that 5% teach dentistry, that 50% of that 5% teach to large classes of about 100 students that would benefit from using the prototype, and that initial yearly market penetration of our prototype for that demographic is 1%, then the initial total number of production units needed comes to 36. Additionally, this means that in an ideal world with a projected 100% market penetration, a maximum of 3,625 units would be needed.

For all units, the CES Materials Selector has determined that the optimal material to be used for the teeth is balsa wood, and that all machined parts should be made of 6061 Aluminum alloy. Tables L.5 and L.6 below show the best manufacturing methods determined for these components as researched with the CES Manufacturing Process Selector

Table L.5 Optimal manufacturing methods for large scale production

Components	Material	Optimal Manufacturing Process
Teeth	Balsa Wood	Band Sawing, Slab Milling
Rear Support Columns	6061 Al	Slab Milling, Drilling
1/4" Actuator Fasteners	6062 Al	Slab Milling, Drilling
3/8" Actuator Fasteners	6063 Al	Slab Milling, Drilling
Upper Support Bars	6064 Al	Drilling
Jaw Support Columns	6065 Al	TIG Welding, Slab Milling, Drilling
Mounting Brackets	6066 Al	Band Sawing, Drilling

Table L.6 Cost characteristics of the manufacturing processes listed in Table L.5.

Process	Rel. Tooling Cost	Rel. Equipment Cost	Labor Intensity	Economic Batch Size
Band Sawing	low	med	med	1-1e4 units
Slab Milling	low	high	med	1-1e7
Drilling	low	med	high	1-1e7
TIG Welding	low	med	low	n/a

The first order factor in determining the optimal manufacturing processes is the estimated production run size. We estimated a needed production of 36 units, which is not enough to justify the high investment required to make a die for casting of the metal parts. Secondly, as was demonstrated by the manufacturing of our prototype, standard milling and drilling operations are perfectly adequate, and the reusability of these machines for various parts is good justification for investing in a mill. The wood parts cannot be made fluid to be formed at all, so conventional machining techniques were necessary to begin with. Finally, labor costs are high only for the drilling operations, but the tapping of holes would be necessary even if we had cast the parts. Ultimately, the low production run estimated is best served with the processes as given in Table L.6 above.

In the case where production increases to the estimated maximum of 3,625 units per year, the revenue from these sales might justify die casting a majority of the parts, but that is not determinable at this time, since profit margins and unit costs have not been discussed.

APPENDIX M. Likert Survery for Professor

1. It is easy to work Jaws: The Educator in lecture.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

2. I can use Jaws to show protrusion/retrusion.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

3. I can use Jaws to show laterotrusion.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

4. I can use Jaws to show Curve of Wilson.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

5. I can use Jaws to show Curve of Spee.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

6. It is difficult for students to understand concepts using Jaws.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

7. I like the old teaching methods more than using Jaws.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

8. I cannot vary the teeth to show different concepts.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

9. I cannot incorporate Jaws into lecture easily.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

10. I waste time during class when changing the teeth or programs.

Strongly Agree Agree Neither Agree or Disagree Disagree Strongly Disagree

1-5 Points: Strongly Agree (4), Agree (3), Neither (0), Disagree (2), Strongly Disagree (1)

6-10 Points: Strongly Agree (1), Agree (2), Neither (0), Disagree (3), Strongly Disagree (4)

Highest score = 40, Lowest score = 10, 0 = no effect. High score = efficient teaching tool (success!)