VetMed: 3D Printed, Patient Specific Incline Plane For Management of Class II Malocclusions

FINAL REPORT

BME 200/300

Team Members:

Benjamin Smith, *Team Leader*

Lily Gallagher, *BWIG*

Giovanni Militello, *BSAC*

Daniel Konon, *BPAG*

Tony Pribnow, *Communicator*

Owen Kolnik, *Co-BWIG*

Client:
Dr. Graham Thatcher

Advisor:
Dr. John Puccinelli

December 15th, 2021

Abstract

Class II malocclusions are a common genetic skeletal deformity that affects 10% of purebred dogs [1]. The malocclusion occurs when the mandibular (lower) jaw is shorter than the maxillary (upper) jaw. This can result in the mandibular canine being situated directly under the palatal tissue of the upper mouth. This can lead to palatal trauma which can become infected overtime. To correct a Class II malocclusion, veterinarians use tipping orthodontics. Incline planes are common devices used in tipping orthodontics to provide a counter force at an angle to guide the malocclusion outside the mouth. A 3D printed incline plane allows for flexible design required for the intricate nature of an incline plane device. Current fabrication methods for these incline planes require intubation to scan the patient's jaw. A model of the patient's jaw is then constructed via the scan data, so the veterinarian can create a mold which they then send to a software engineer. The engineer creates a computer model of the mold to be 3D printed.

The incline plane prototype reduces the need to intubate and scan the patient's mouth. In addition, the design eliminates the need for a software engineer and puts the design process in the hands of the veterinarian. The design reduces the number of patient specific measurements to four, which allows the veterinarian to measure the patient's mouth. Reducing variables makes the computer design process simpler when paired with a step by step design guide. This design requires the use of titanium filament (Ti641A4V) due to its reduced nature. Computer simulated analysis was performed, and found that the incline plane device passed the stress and deformation tests. Therefore, the incline plane device conceivably reduces cost, increases treatment accessibility, and treats Class II malocclusions effectively.

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I. Introduction

a. Impact

Class II malocclusions are a common genetic skeletal deformity that affects 10% of purebred dogs; most commonly, Golden Retrievers, Labrador Retrievers, Standard Poodles, and German Shepherds [1][2]. With this condition, the dog's lower jaw is relatively shorter than the upper jaw, causing the lower canine teeth to be misaligned. This abnormal alignment diminishes the functionality of the bite. Not only is this painful, but if it is not corrected, it can lead to dental attrition, gum diseases, oronasal fistula, and the destruction of the gum pallet and tissue[2].

According to the Veterinary Medical Ethics of the American Veterinary Medical Association (AVMA), "Should the health of the patient require correction of such genetic defects, it is recommended that the patient be rendered incapable of reproduction," [3]. However, from a genetics perspective, malocclusion is an inherited condition that is an autosomal recessive mutation[4]. So as shown in Figure 1, even if the breeding of visibly affected dogs is stopped, this does not stop the carrier puppies from mating with another carrier puppy and passing the condition onto their offspring.

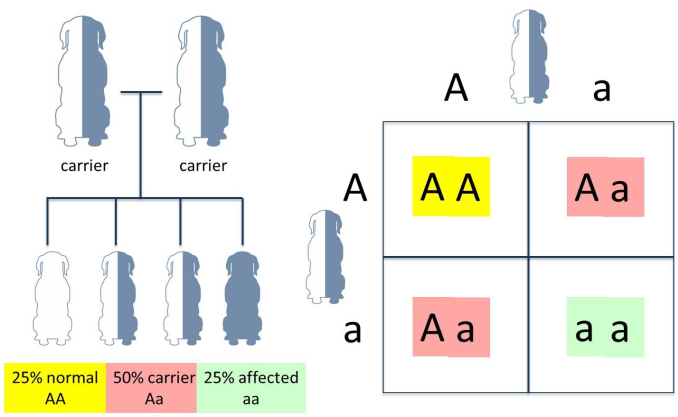


Figure [1]: *Punnett square that predicts the variation and probabilities of the offspring from a crossbreed of two heterozygous recessive parents [4]. Twenty-five percent of the puppies will visibly have malocclusions and if bred, they will pass the mutated information on. Fifty percent of the litter will carry one abnormal gene from one parent and a normal gene from the other, making them carriers. They will look normal, but have the chance of passing on malocclusions if bred with another carrier. The other 25% will be unaffected and will not pass the trait onto future generations [5].*

To stop the reproduction of affected dogs is an unrealistic solution due to the high chance a dog could be a carrier of the mutation. Additionally, the dogs affected, Golden Retrievers, Labradors, Poodles, and German Shepherds are among the most popular dog breeds in the US, making it even more difficult to stop the spread [6]. Overall, there needs to be an easily accessible and efficient veterinary treatment that works to correct class II malocclusions, so that every dog diagnosed has an opportunity for correction.

b. Existing Treatments

The position statement of the American Veterinary Dental College (AVDC) states that "the goal of veterinary orthodontic procedures of companion animals is to alleviate pain and provide a healthy and functional occlusion" [7]. The current treatments used to treat class II malocclusions utilize intrusive or tipping orthodontics.

Intrusive orthodontic procedures are focused on removing the painful contact point in class II malocclusions. Methods include either extracting, or shaving the problematic tooth. These procedures, however, do not provide a long-term solution, as they decrease the functionality of the teeth and bite. Dog's teeth are needed to serve as weapons and as tools for cutting or tearing food, so it is important that the teeth stay intact.

Tipping orthodontics uses an incline plane to guide the misaligned teeth to the correct position by utilizing controlled tipping mechanics. When the dog closes its mouth, the teeth will hit the incline plane with the force of a bite. Due to Newton's 3rd law, this force moves the crown in one direction, while the root of the tooth resists motion [8]. A moment force is created at the apex of the root, and over time repeated motion will slowly guide the canines into the desired position. In figure 2, the root of the tooth stays in the same place so there is no damage done to the buccal bony plate.

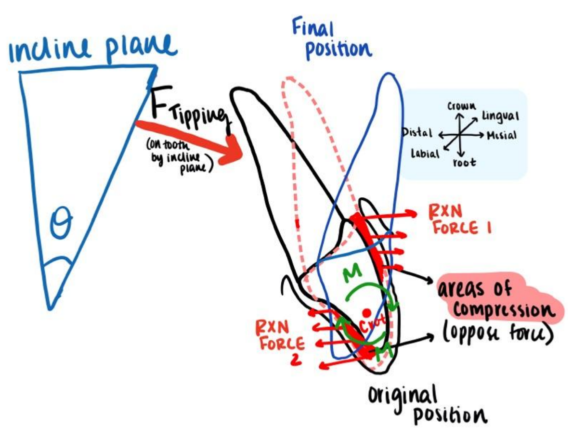


Figure [2]: *Controlled tipping mechanics combined with the incline plane. The moment force created at the apex of the tooth M = F x d.*

Dr. Graham Thatcher has been working to perfect an inclined plane device that is non-intrusive to the rest of the patient's mouth with a height, size and angle of incline that is patient-specific [2]. Figure 3 shows the incline plane device attached to two teeth of the mandibular jaw, with built-in incline plane ramps on the sides. In order to produce this device, Dr. Graham first takes a Computed Tomography (CT) scan of the canines' jaw. Then, this data is saved in the Digital Imaging and Communications in Medicine (DICOM) format, and the file is used to produce a 3D printed version of the patient's jaw. Using the printed jaw as a reference, Dr. Thatcher carves out an initial mold of the incline plane using a bis-acryl composite material. A software engineer then creates a 3D model of the hand carved incline plane with a series of adjustments to produce a final printable incline plane. The BME 2020 group printed this device in Dental LT resin, however, it was not able to withstand the bite force and this material broke after two weeks of treatment.

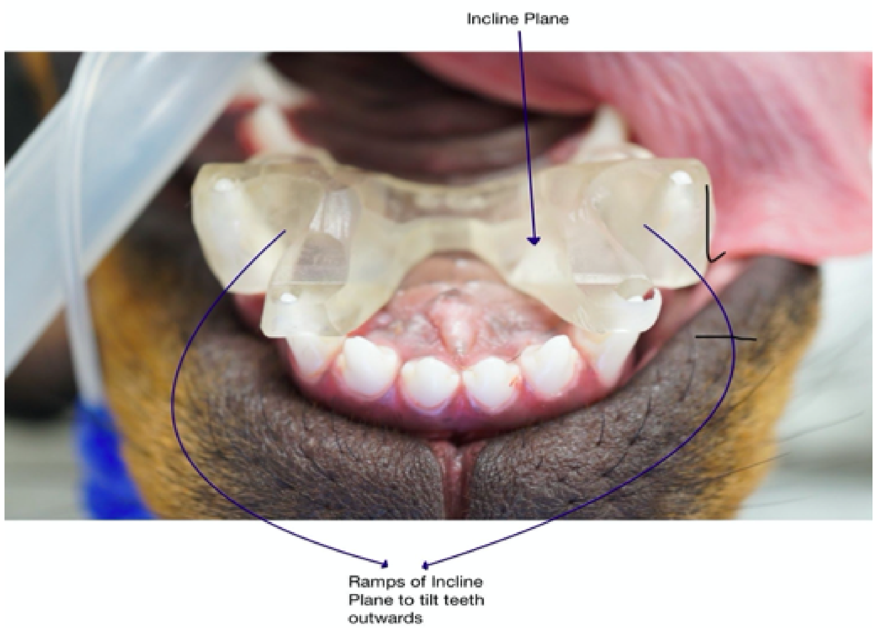


Figure [3]: *Incline plane device.*

To treat mild to moderate malocclusions, another form of an incline plane, a crown extension can be used. In figure 4, the semi-translucent blue core build-up material is formed around the mandibular canine so that the incisive tip no longer impacts tissue. The same tipping orthodontics are used, as the patient closes its mouth, the crown extension makes contact with the upper gum of the patient, reaction forces act upon the extension, tipping the canine into the desired position. Initially, the patient will not be able to fully close the mouth, the extension should be visible and pointing outwards [2].

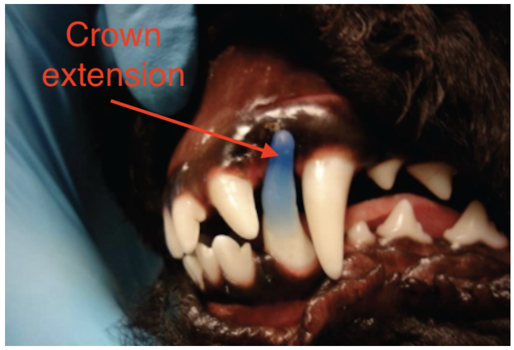


__Figure [4]:__ The blue piece is a crown extension composite in a patient. It acts as an extension of the lower mandibular canine, tilting the tooth into a correct position.

c. Problem Statement

Class II malocclusions negatively affect the quality of life of dogs and if left untreated, the dog is at risk for infections, tissue damage, and irreversible tooth damage. Dr. Graham Thatcher has produced a 3D printed patient-specific incline plane, which safely corrects class II malocclusion in dogs. However, the process is time-consuming and complex, making the procedure more expensive for pet owners. In addition, there is limited flexibility between patients, Dr. Graham has to restart the whole design process for each patient. To create an easily accessible and efficient veterinary treatment, there needs to be an improved workflow and design of the incline plane device.

II. Background

a. Research

Biology and Physiology

Normal Occlusion

An occlusion is the dental interlock between the maxillary (upper) and mandibular (lower) canines. Figure 5 displays a normal, functional occlusion. The mandibular canine fits in between the upper third incisor and the maxillary canine. In addition, the crown of the tooth is pointed outward allowing for the jaw to close without puncturing the gum. Abnormal alignment between one or many teeth is described as a malocclusion.

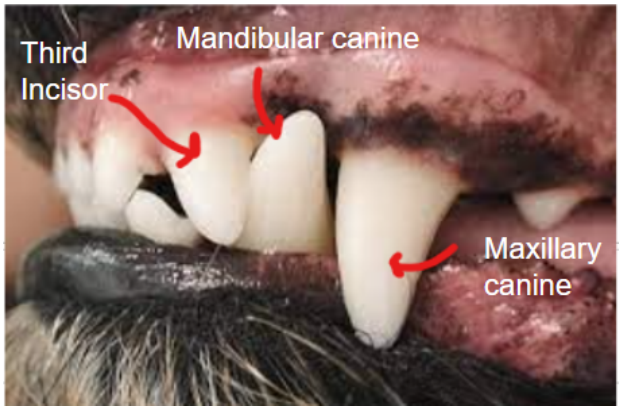


Figure [5]: *Normal occlusion in a dog with the mandibular canine correctly aligned, causing no damage to the gum tissue.*

Class II Malocclusion

Malocclusions are caused by discrepancies in the length of the mandibular or maxillary jaw with respect to normal jaw lengths. Specifically, a class II malocclusion is diagnosed when the mandibular (lower) jaw is shorter in length than the maxillary (upper) jaw, often referred to as an overbite. In figure 6, the mandibular canine is pointing inward and puncturing the roof of the mouth, causing damage to the gum and palatal tissue. In addition to pain, the jaw does not close correctly and normal jaw movement is inhibited. This often leads to poor quality of life for patients.

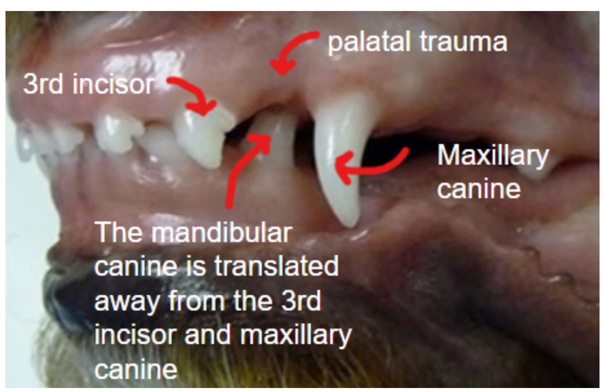


Figure [6]: *Class II Malocclusion in a dog.*

Design Research

Existing Patent

US5151027A is an expired patent for a veterinary orthodontic fixture useful in correcting lingual displacement of the mandibular canine teeth of an animal [8]. This device utilizes incline planes attached to the maxillary canine to tilt the mandibular canines into a normal position where they will not interfere with the gingival tissue of the maxilla (Figure 7). This device does not inhibit the normal growth of the patient's jaw, and it is cemented to the teeth to fit snugly on the maxillary canines.

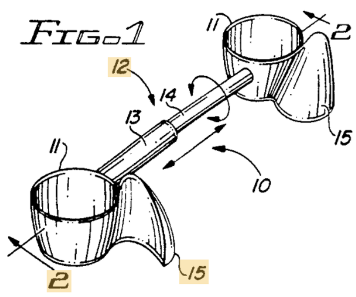


Figure [7]: *US5151027A Patent used to correct class II malocclusions in dogs. This expired in 2009.*

b. Client Information

Dr. Graham Thatcher is a Veterinary Orthodontist and an Assistant Professor of Dentistry and Oral Surgery at the University of Wisconsin-School of Veterinary Medicine. Dr. Graham has been working with tipping orthodontics and especially incline planes.

c. Design Specifications

Incline Plane and material

In Veterinary orthodontics, incline plane devices are attached directly to the patients teeth to gradually correct class II malocclusions by tipping orthodontic mechanics [2]. Thus, it is essential that the device's material must be able to last intraorally for 6 weeks. The incline plane will provide a force equal and opposite to the bite force of the dog that will create a moment force to tip the tooth. So material of the device has to withstand the potential maximum bite force of a dog, 1400 N with repeated and continual stress synonymous with eating [9]. In addition, the device should ideally withstand face traumas as these treatments are often implemented in puppies. Therefore, a strong biocompatible material needs to be considered to achieve these specifications.

The ability to 3D print an incline plane could potentially lower treatment cost and manufacturing time if it is possible to reduce the need for anesthetics and CT scans for each patient. Hence, the material chosen should be compatible with 3D printers while still being capable of withstanding the stresses applied. Lastly, the incline plane device must span the distance between both maxillary canines, fit around the mandibular canines, and have the proper incline plane angle to push the malocclusion out of the patient's mouth. All these dimensions would vary from patient to patient and vary over a broad range. The incline plane angle is determined from patient to patient based on the degree of malocclusion determined solely by the veterinarian [2]. The average tooth width for a dog's mandibular canine is 11mm, and the average distance in dogs from maxillary canine to maxillary canine is 38mm [9].

Software/workflow

Having software that is easily operated will be optimal for the design fabrication process. This allows for veterinarians with little computer-aided design skills to personally manipulate the device. Having the veterinarian able to manipulate a Standard Triangle Language (STL), such as a Solidworks file, will allow them to make each device patient-specific. In addition, this will eliminate the need for a software engineer, allowing fast fabrication periods. This can reduce cost and make this treatment more accessible for a greater number of patients. Eliminating the number of variables could potentially make the software more easily operated, while also reducing the need to intubate and scan each patient's mouth. Similarly, creating a step-by-step reference guide will aid in the operability of the software chosen to create the design, such as Solidworks. Finally, the software must be archived in a STL file to be compatible with 3D printers.

III. Preliminary Designs and Materials

Design 1: Ring Design

This design is inspired by an expired patent, US5151027A [10]. The design features two rings that will be secured to the upper maxillary canines of the patient. Attached to these two rings will be an incline plane which will be used to tilt the lower mandibular canines into place. Supporting the pressure experienced by the upper maxillary canines from the contact with the lower maxillary canines will be a supporting bridge running along the roof of the patient's mouth, connecting the upper canines. The goal of this design is to offer the most optimized design while also simplifying the workflow. There are four main variables in this design, being the two widths of the elliptical rings, the length of the supporting bridge, and the angle of tilt of the incline planes, all seen in figure 8. These variables are all patient-specific, and therefore will need to be measured and altered for each patient. Because of the simplification in design, the design will eliminate the need for costly CT scans and allow the client to simply take measurements in the patient’s mouth, alter a base 3D model of the design, and print the device.

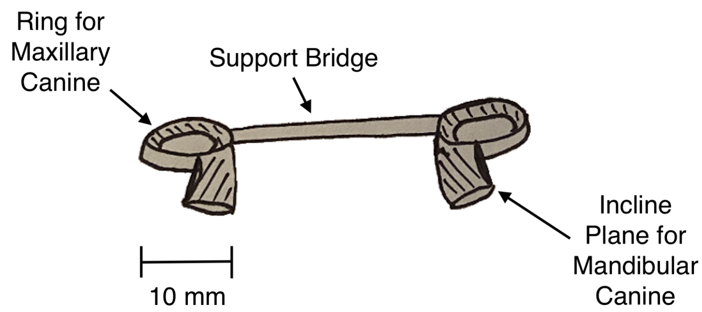


Figure [8]: *Ring design inspired by expired patent US5151027A .*

Design 2: Separate Incline Plane

The second design comes from the previous group that worked on this project [11]. This design excludes the supporting characteristics of design 1 by utilizing two separate pieces to be attached on either side of the patient's mouth (Figure 9). Eliminating the bridge component decreases the possibility of irritation on the upper palate of the patient's mouth and thus mitigates risks of discomfort. To offset the pressure from the tilting of the mandibular canines, this design will be attached to the maxillary canine, maxillary molar, and 3rd incisor.

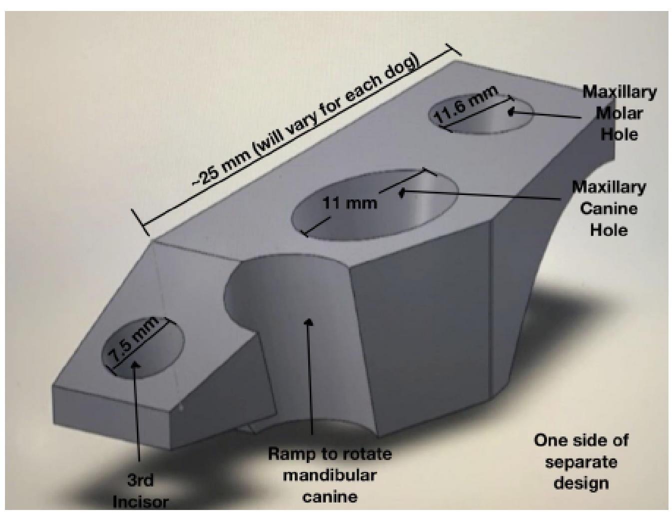


Figure [9]: *Separate incline plane design from the previous group [11].*

Design 3: Dental Retainer

The third design is a dental retainer mold mimicking the process used in human orthodontics (Figure 10). The goal of this design is to eliminate the need for computerized tomography (CT) scans of the patient, ultimately shortening the manufacturing time of the device. The process to create the mold is to put the patient under anesthesia, take a vinyl polysiloxane (VPS) dental impression of the upper palate and teeth of the patient, and vacuum thermoform a sheet of thermoplastic over the impression to create the dental retainer that would have incline planes built-in [12]. This process can be done quickly and would save the client the time it would take to typically take a CT scan and then communicate with a software engineer to create a device.

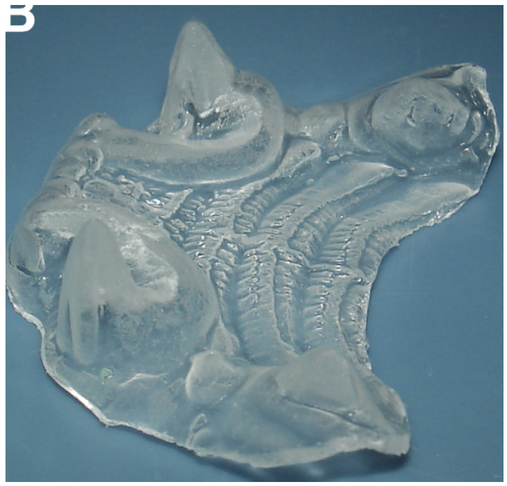


Figure [10]: *Example retainer to fix class II malocclusions.*
This would be put on the upper palate of the patient's mouth.

Material 1: Dental LT Resin

Dental LT Resin is a biocompatible photopolymer compatible as a 3D printer filament used in splints and occlusal guards (Figure 11). This filament has an elastic modulus of 2.41 GPa and a yield strength of 83.43 MPa [13]. This material is available via formlabs for $350 a liter for the Form 3B printer [13].

Figure [11]: *Dental Retainers printed in Dental LT Resin.*

Material 2: Polymethylmethacrylate (PMMA)

This material is often used in orthodontics to create fake teeth (Figure 12) and is therefore biocompatible. Polymethylmethacrylate (PMMA) has an elastic modulus of roughly 2.41-3.45 GPa and a yield strength of 82.73-117.21 MPa [14]. The price is roughly $49/kg at laminated plastics and works with the Form Labs Form 3B [14].

Figure [12]: *Model human teeth printed in PMMA*

Material 3: Titanium (Ti64A14V)

Titanium is a metal alloy often used in human orthodontics as wire for braces as it resists corrosion [15]. Ti64A14V is a 3D-printer filament and has an elastic modulus of 113.8 GPa and a yield strength of 830 MPa (Figure 13) [16]. Ti64 filament costs around $20 per gram used [17].

Figure [13]: *3D printed titanium.*

IV. Preliminary Design Evaluation

a. Design Matrices

Six different criteria were used when grading each of the three designs. These are listed in order of weight in the design matrix (Table 1). Effectiveness is the ability of the design to correct class II malocclusions by allowing the mandibular canines to come in contact with the incline plane of the device and be tipped outwards rather than impacting the upper palate of the patient's mouth. Durability is the ability of the design to withstand forces that are generated from a canine, such as biting forces, which can be up to 1400 N [9]. The effectiveness of the design correlates directly with how durable the design is which is why both are one category in the design matrix and why they were ranked the highest, given a score of 30. Designs 1 and 3 received the highest score in this criteria. Although designs 1 and 3 do not seem as durable based on their structural design and geometry, it is because design 2 broke upon usage during one of the client's treatments of a patient during last year's project that led to the decision to give design 1 and 3 higher scores. Additionally, since the client was not able to use design 2 as a possible treatment option, the design failed in its effectiveness to correct class II malocclusions, further leading to award design 1 and 3 higher scores. The ease of manufacturing is the next biggest priority, given a score of 20. The ability to easily 3D print the design allows for the client to have the incline plane sooner and start his treatment process right away. Design 1 scored the highest in this criteria as this design is the simplest out of all three designs which makes it possible to be 3D printed the fastest. Additionally, design 1 is also able to be modified more easily than the other two designs for each specific patient as this was a request from the client. The costs of the designs are equally important as current treatment costs need to be reduced so that the client can distribute and use the product in their treatment at a relatively low cost. Designs 1 and 2 ranked the highest in this criterion as both of these designs are smaller compared to design 3 making them not as costly to 3D print. Safety of the patient while using the incline plane for treatment is the next priority, with the given score of 15. Since all three designs are applied with similar dental procedures, such as sedating the patient and using dental glue to implant the device, all three designs received the same score. Compatibility is the ability of the design to work with the client's process to 3D print the design to be able to treat class II malocclusions, which was given a score of 10. Design 1 received the highest score in this criteria as it is the simplest design which allows for it to be easily modified for each patient and be 3D printed, which are specific requirements from the client. Finally, treatment time is the amount of time it would take for each design to correct class II malocclusions. Because all three designs are incline planes, the treatment time is the same for all three, therefore each design was based on how much time it takes to create each design. Design 1 was ranked the highest in this criteria as it would be able to be 3D printed and modified the quickest for the client. Design 1 (Ring Design) ranked the highest compared to the other two designs with a score of 93/100 points.

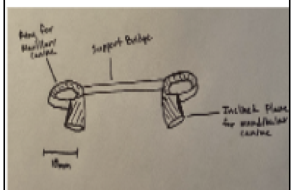
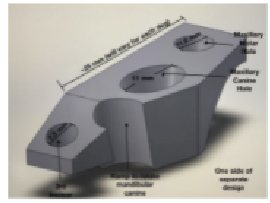
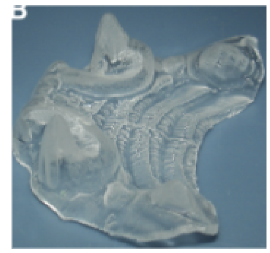
Criteria	Design 1 - Ring Design 	Design 2 - Separate Incline 	Design 3 - Dental retainer 
Effectiveness / Durability (30)	4/5 (24)	3/5 (18)	4/5 (24)
Ease of Manufacturing (20)	5/5 (20)	4/5 (16)	3/5 (12)
Cost (20)	5/5 (20)	5/5 (20)	4/5 (16)
Safety (15)	5/5 (15)	5/5 (15)	5/5 (15)
Compatibility (10)	5/5 (10)	3/5 (6)	1/5 (2)
Treatment time (5)	4/5 (4)	3/5 (3)	1/5 (1)
Total (100)	93	78	70

Table 1: *Design matrix detailing the scores of each three designs received. Individual criteria were graded on a scale of 1(Low) - 5(High), these scores were then multiplied by the predetermined weight of the criteria to calculate the weighted score. The highest scores for criteria are highlighted in blue and total scores are out of 100.*

Six different criteria were used when grading each of the three materials. These are listed in order of weight in the design matrix (Table 2), similarly to in the design matrix above (Table 1). Durability, or biofunction, is the most important criterion, given a score of 30, as the material needs mechanical and physical properties that enable the implanted device to perform its function under the stresses imposed in the oral cavity. Although all three designs have elastic modulus with the ability to withstand forces that are generated from a canine, such as biting forces that can be up to 1400 N [9], designs 2 and 3 were ranked higher in this criteria than dental LT resin (V2) as this material was used during last year's project but fractured when used during treatment. Safety (biocompatibility) is the next biggest priority, given a score of 25, as interactions between materials and the recipient tissues of the body are an important factor when selecting a material. Although there are no FDA safety regulations for canines, the same approach will be taken with canines as with humans by using standard FDA safety regulations [18]. Given that all three materials are biocompatible with humans, they were all ranked the same as these materials are safe for human use. The cost of the material is equally important as the treatment cost needs to be lowered so that the client can distribute and use the product in their treatment at a relatively low cost. Design 2 ranked the highest in this criteria as polymethyl methacrylate is lower in cost to 3D print compared to the other two materials looked at. Ease of fabrication in the next criteria, given a score of 10. This looks at the availability of the material for use during 3D printing. Both designs 1 and 2 are ranked the highest in this criteria as there are accessible 3D printers on campus that can print using dental LT resin V2 and Polymethylmethacrylate (PMMA). The last two criteria are weight and comfort, both given a score of 5. A material that is light in weight so as to not cause damage to the canine's mouth and therefore not cause discomfort in the canine is required. Designs 1 and 2 ranked the highest in both criteria as dental LT resin V2 and PMMA are lighter and feel smoother, as they have plastic texture, compared to the 3D printable titanium, as titanium is metal. This, therefore, makes dental LT resin V2 and PMMA more comfortable in the patient's mouth. Of the three materials, design 2 (PMMA) ranked the highest compared to the other two materials with a score of 92/100 points.

			
Criteria	Design 1 - Dental LT Resin (V2)	Design 2 - Polymethyl Methacrylate (PMMA)	Design 3 - 3D Printable Titanium
Durability (biofunction) (30)	4/5 (24)	5/5 (30)	5/5 (30)
Safety (biocompatibility) (25)	5/5 (25)	5/5 (25)	5/5 (25)
Cost (25)	3/5 (15)	4/5 (20)	1/5 (5)
Ease of Fabrication (availability) (10)	4/5 (8)	4/5 (8)	2/5 (4)
Weight (5)	4/5 (4)	4/5 (4)	2/5 (2)
Comfort (5)	5/5 (5)	5/5 (5)	3/5 (3)
Total Score (100)	80	92	69

Table [2]: *Design matrix detailing the scores of each three materials received. Individual criteria were graded on a scale of 1(Low) - 5(High), these scores were then multiplied by the predetermined weight of the criteria to calculate the weighted score. The highest scores for criteria are highlighted in blue and total scores are out of 100.*

Proposed Final Design

After evaluating the three designs in the design matrix, the Ring Design (design 1) was chosen. This design scored highest in all categories of the Incline Plane Design Matrix as it most efficiently optimizes the design specifications given by the client. The Ring Design will be made out of polymethylmethacrylate (PMMA), as chosen by the Materials Design Matrix. This material will satisfy the design specifications of the client.

V. Fabrication/Development Process

a. Materials

After further consideration of the preliminary material design matrix, the ultimate decision was made to use 3D Printable Titanium (Ti64A14V) rather than polymethylmethacrylate (PMMA). With the structure of the Ring Design being weaker than the other two options, a stronger material was needed to ensure that the product would not fail. Since PMMA has similar mechanical properties to dental LT resin (V2) and dental LT resin failed when undergoing canine forces during treatment of Class II Malocclusions for the previous project, the decision was made to not continue with PMMA. Ti64A14V is a 3D-printer filament and has an elastic modulus of 113.8 GPa and a yield strength of 830 MPa [16]. Ti64 filament costs around $20 per gram and takes around 3-4 weeks to be 3D printed [17]. Titanium (Ti) is an element from transition metal with lustrous silver color, high strength, and low density. Ti has high resistance to corrosion under different circumstances, and Ti has biocompatible and nontoxicity properties in humans [15]. Unfortunately with time constraints, a final prototype was not able to be 3D printed in Ti64 so an initial prototype of the final design was printed in PLA, as that was the cheapest option available at UW Makerspace.

b. Methods

To create the SolidWorks STL file, a simplistic set of two ellipsed rings connected by a straight support bridge was assembled. In order to make this design easily adjustable, the file was made so each of the variables referenced each other and would not cause overlapping of parts when measurements were changed. An incline plane was then added that referenced the ring and the support bridge measurements, which allowed for changes to any of the measurements to cause the others to adapt and form a final patient-specific model.

With the SolidWorks STL file, the client measures the four required variables of the ring design: the upper length of the maxillary canine and upper width of the maxillary canine (Figure 14), the distance between the insides of the maxillary canines (Figure 15), and the degree of tilt of the incline plane (Figure 16). The client uses the measurements in the SolidWorks Design Workflow to create a patient-specific model (see Appendix B). This model is then 3D printed in PLA in order to check the fit on the patient. If the fit is correct, the product is 3D printed in titanium (Ti64) and placed into the patient's mouth using dental cement.

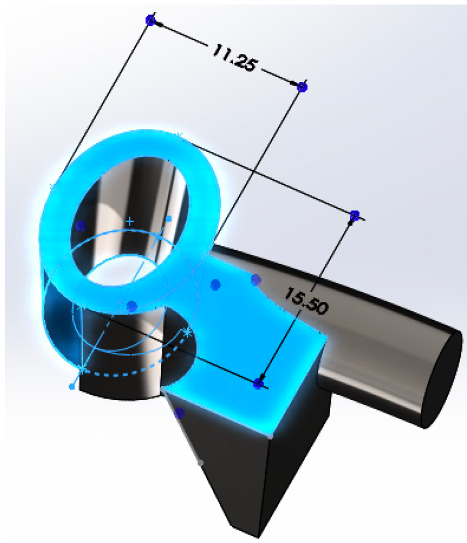


Figure [14]: *Patient-specific length and width dimensions of the maxillary canines.*

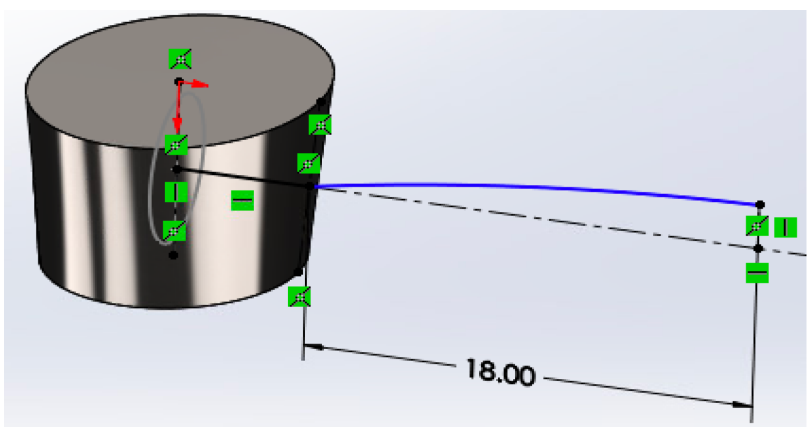


Figure [15]: *Patient-specific distance between the maxillary canine/ support bridge length input.*

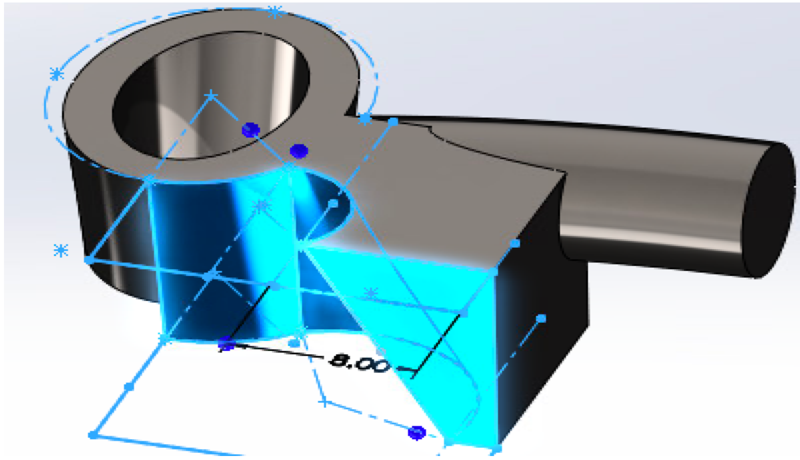


Figure [16]: *Patient-specific degree of tilt of the incline plane input.*

c. Final Prototype

The final design that was used was two ellipsed rings with a support bridge attaching both of them and an incline plane on the end where the ring and support bridge meet (Figure 17). The final design has four variables that the client will need to change (Figure 18), and these variables are all identified in the SolidWorks STL file feature tree that the client will receive (see Appendix B). Due to time constraints and procurement time of 3D printing in TI64A14V, the final prototype was printed in PLA.

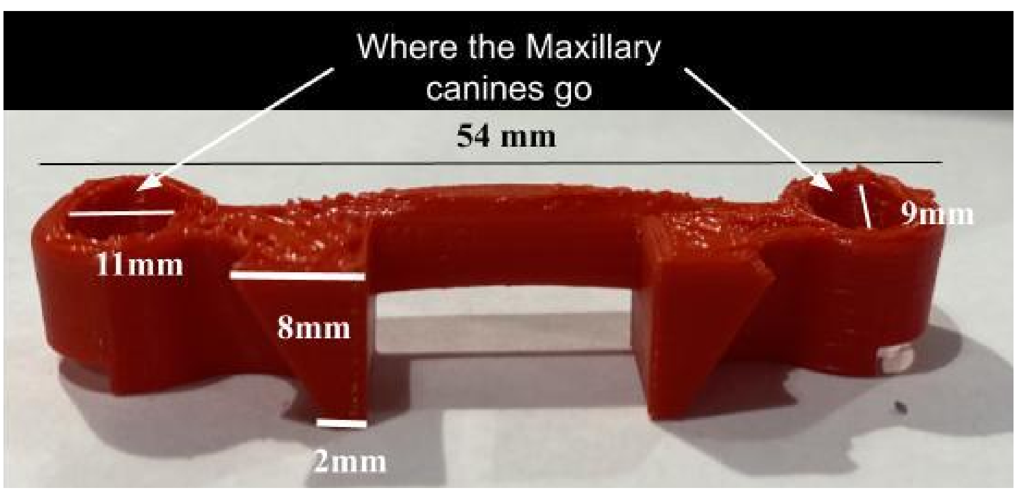


Figure [17]: *Front view of final prototype. This is the configuration for which it will be placed in the patient's mouth.*

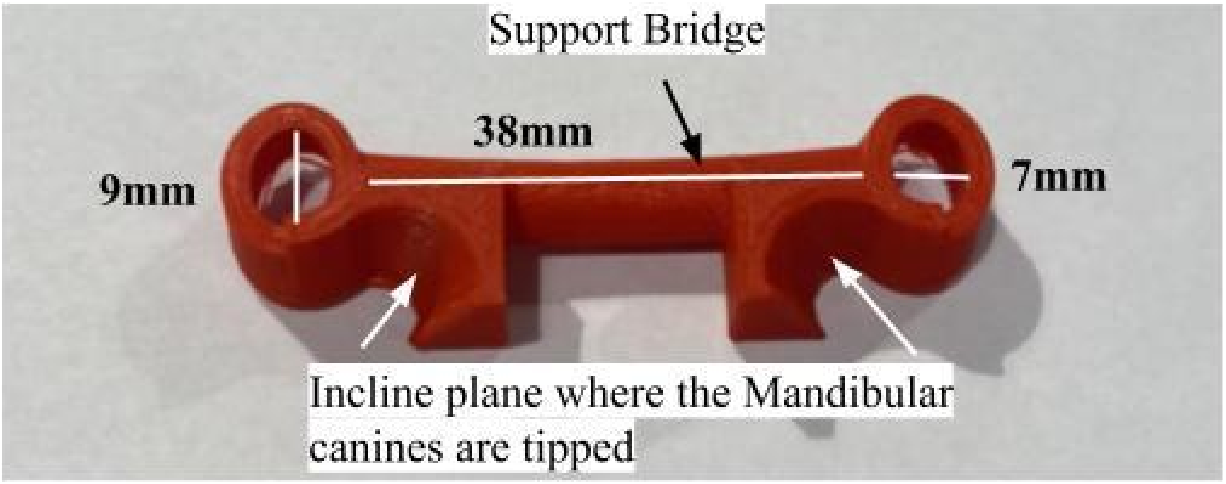


Figure [18]: *Bottom view of the final prototype.*

d. Testing

Once the final design was created and assembled in Solidworks, Solidworks SimulationXpress Analysis Wizard was used to test if the design would be able to withstand a max force of 1400 N. The SimulationXpress feature allows the user to apply forces to particular portions of a design and determine where deformation and von Mises stresses would occur. In the SimulationXpress, the user is also allowed to choose a material to simulate how the material would perform under the forces applied based on its mechanical properties. Titanium alloy Ti64 was an option to select in the SimulationXpress and was used as the material for the final design for testing. During the process of testing, the support bridge was chosen to be fixed together as when the final design is 3D printed, the part is printed as one piece rather than two separate pieces (Figure 19). The forces were applied directly onto the incline plane as that is where the mandibular canines of a patient would come in contact with the device (Figure 19). Expected outcomes from the Solidworks SimulationXpress testing were that the design would experience little to no deformation as well low values for von Mises stresses. Unfortunately due to time constraints, no mechanical testing was able to be performed for the design to gather more accurate data on the final design but will be considered for the future.

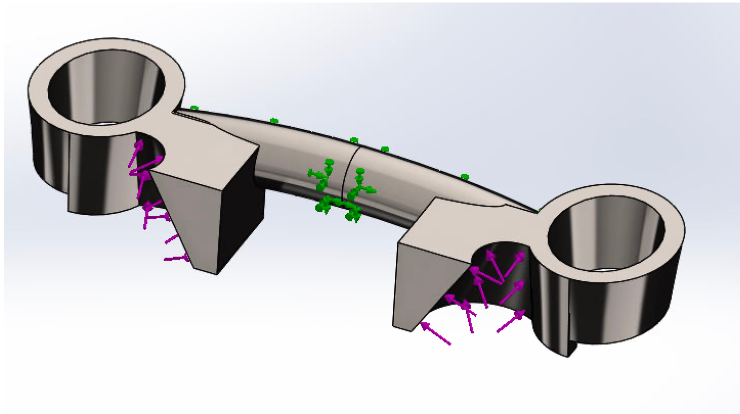


Figure [19]: *Final design in Solidworks SimulationXpress with the support bridge fixed together and 1400 N force applied to the incline plane. The green arrows show where the device is fixed, and the pink arrows show where the force is applied.*

VI. Results

Results shown from the Solidworks SimulationXpress test were as expected. Little to no deformation of the design occurred as a result of the 1400 N force applied. Maximum deformation occurred on the smaller edges of the incline plane, seen in the red regions, with the largest deformation being 7.12 µm. Deformation decreased significantly closer to the rings and support bridge as there is more material located in that portion of the design, with values of 0.71 µm in the blue regions (Figure 20). With little deformation being recorded, the assumption can be made that the design would not be distorted or change shape during clinical treatment. Von Mises stress values reported from the SimulationXpress test were relatively low. Maximum von Mises stress values were located on the corners of the incline plane attached to the support bridge, seen in the red regions, with the largest stress value being 88.6 MPa (Figure 21). Where the 1400 N force was applied on the incline plane, stress values ranged from 0.007 MPa, blue regions, to 44.3 MPa, green regions (Figure 22). With the yield strength of Ti64 being 830 MPa, the assumption can also be made that during clinical treatment, the design would not fracture at any location since under the 1400 N of force applied, the lowest factor of safety reported from the SimulationXpress test was 9.33.

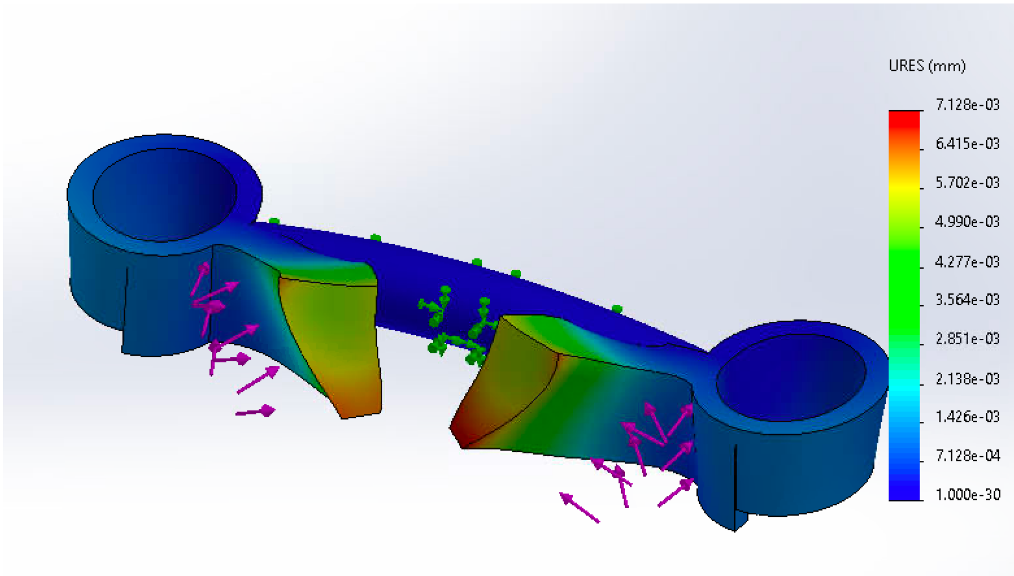


Figure [20]: *Deformation (µm) of the device under 1400 N force applied on the incline plane. Max deformation occurring in the red regions at 7.12 µm. Towards the middle of the incline plane, deformation decreases to 3.56 µm, in the green regions. Near the ring and support bridge, lower deformation was recorded at 0.71 µm, in the blue regions.*

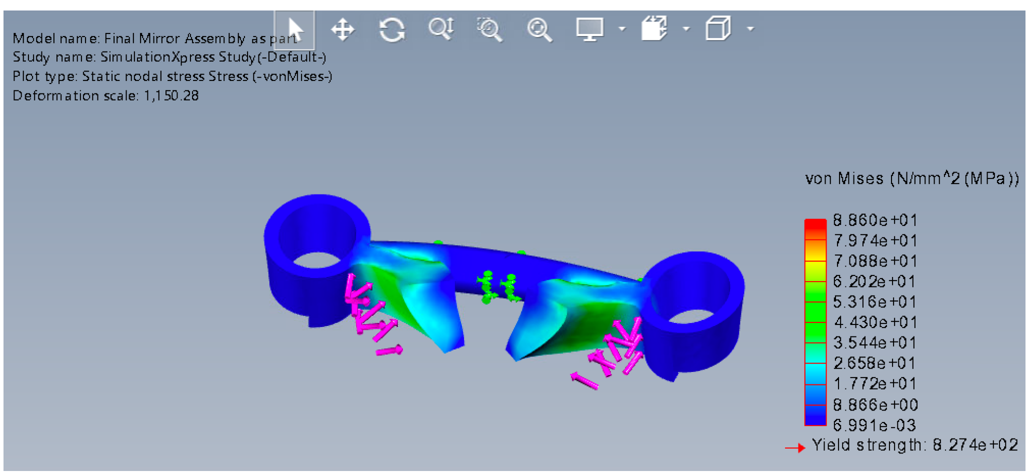


Figure [21]: *Von Mises stress (MPa) of the device under 1400 N force applied on the incline plane. The incline plane underwent 44.3 MPa of stress, in the green regions, where the force was applied.*

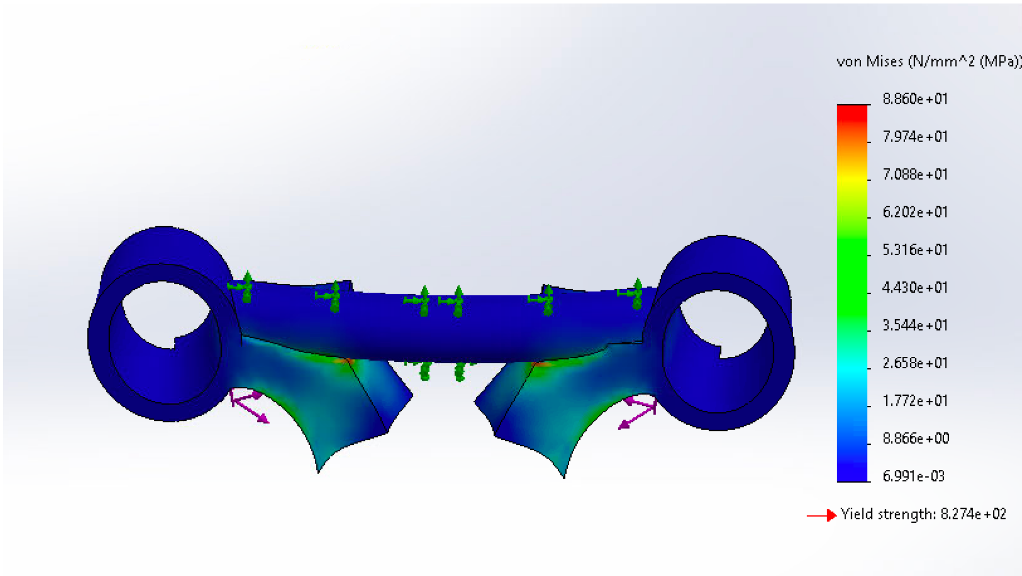


Figure [22]: *Von Mises stress (MPa) of the device under 1400 N force applied on the incline plane. The corners of the incline plane connected to the support bridge underwent a max of 88.6 MPa of stress, in the red regions.*

VII. Discussion

The goal of this project is to help the client optimize the workflow and improve the design to aid in the treatment of class II malocclusions. The final design first does this by significantly decreasing the workflow for the client. The process to create a patient specific model has been reduced from having to take a CT scan of the patient's mouth, print out a 3D model of the patient's skull, from the CT scan, make a carved mold of an incline plane, and then send the mold to a software engineer to make and print a 3D model to only having to adjust the required variables of the Solidworks STL file of the final design and then 3D print. The original process took over a week before the final product was ready to be printed whereas the improved process allows for the client to have the final product ready to print in under an hour. Additionally, this process eliminates the cost of CT scans and the cost to outsource work to a software engineer, which reduces the total cost of the product substantially. In addition, the final design has been improved to be a more simplistic incline plane, which allows for only four variables needing to be changed to make it patient specific. With the design being more simplistic, structural integrity was compromised which is why the decision was made to 3D print in titanium (Ti64). Throughout the Solidworks SimulationXpress testing, the results showed that the design made out of Ti64 would be able to withstand maximum forces generated from a dog bite from mandibular canines and therefore can assume that the design would not fracture during clinical treatment. Throughout the design process, it was also important to consider morals and ethics in the design and testing process. Patients will be treated as if they are human, using non-toxic materials and ethical test standards. The procedure and product of the design do follow the standard, “ISO 13504” Dentistry requirements and related accessories used in dental implant placement and treatment along with implant and implant materials following “ISO 13504” Dentistry requirements as the material used, Ti64, is a biocompatible material and the standard procedure to implant the incline plane by the client is similar to how braces are implanted in a human's mouth [19]. Also, the initial veterinary examination done by the client does follow the AAHA-AVMA canine preventive healthcare guidelines [3]. Any sources of error from the design process would have taken place during testing. Solidworks SimulationXpress testing is a simulation of stress testing so the result obtained from the test performed could differ from mechanical testing of the final design.

VIII. Conclusions

The goal is to create a streamlined, efficient process for correcting class II malocclusions in dogs, in a safe and harmless manner. Class II malocclusions stem from the misalignment of the mandibular, or the lower canine tooth, causing puncture wounds and issues in the upper gums of the patient. Currently, the process for fixing the malocclusions with an incline plane is crude and inefficient. The other processes that are currently used include removal or destruction of the mandibular canine, however, these can lead to future conflict in the patient. The design and process created last year also fell short in efficiency and durability. This year, the goal is to redesign the product in a way that significantly simplifies both the workflow and the design and in turn makes it cheaper and more efficient.

The final design involves a ring around each of the maxillary or upper canines connected by a support bridge that offsets the force of the incline plane. An incline plane is connected to the bottom of these rings and used to gradually reposition the mandibular canines. Due to the small nature of the design, 3D printable titanium (Ti64) is used to ensure the stability of the product. The simplicity of the design also meant that a computerized tomography (CT) scan was not necessary to determine the variables of the patient-specific product, and instead, a caliper can be used to measure the variables [20]. Dental glue is also used to fix any small errors around the circumference of the canines. This workflow saves a substantial amount of money and simplifies the workflow. The ring design significantly outperformed the other initial designs in every category of the design matrix. The other two designs fell short in efficiency, compatibility, and cost. Next time, further planning would be required in order to print the final design in titanium to ensure mechanical testing could be conducted.

In the future, the plan is to further optimize the final design. The inside of the rings and the incline plane will be fileted to ensure a sleek, compact, and safe design. The SolidWorks file will also be further simplified so creating a patient-specific model requires simply typing in four values and the product will print in the right size, with the measurement error eliminated. Then, the final design will be printed in 3D printable titanium (Ti64) and mechanically test the model. Finally, work will be done with the client to test the product in a variety of different-sized patients.

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X. Appendix

X. Appendix

a. PDS

Team Members:
Benjamin Smith, *Team Leader*
Lily Gallagher, *BWIG*
Giovanni Militello, *BSAC*
Daniel Konon, *BPAG*
Tony Pribnow, *Communicator*
Owen Kolnik, *Co-BWIG*

Client:
Dr. Graham Thatcher

Advisor:
Dr. John Puccinelli

Function:
Class II malocclusion is a common genetic skeletal deformity among a variety of animal breeds [1]. Specifically, in canines, this type of mandibular dissolution refers to the misalignment of the teeth; the canine's lower jaw is shorter than the upper jaw[1]. This condition leads to the destruction of the palate and gum tissue of the upper jaw. This negatively affects the canine's quality of life by inhibiting necessary instincts, such as eating and defense. The current design scope of our project is to further develop the current design, Dr. Thatcher's incline plane, by creating a design that is easier to manufacture and is more adaptable for each specific patient. In addition, to design a more efficient workflow by understanding how to more effectively flow through converting a DICOM file from a CT scan to a 3D printable STL file, or ultimately, eliminating the need for these steps.

Client Requirements:

- Incline plane device
- Device can be modified based on each specific patient based on their CT scan
- Device must be easy to create from CT scan using user-friendly software
- Device must be placed in the patient's mouth
- Simplified Software Workflow
- Withstand 6-8 weeks of use
- Reduce the 1-week fabrication timeline (using a software engineer)
- Eliminate the need to intubate in the case of the device breaking (cost $90 to $200)
- Reduce the need to take CT Scans ($100-$500) for each patient.

Design Requirements:

Physical and Operational Characteristics:

A. Performance requirements:

The goal of the incline plane is to slowly, over time guide the mandibular (lower) canines into the correct positioning. The incline plane will be positioned comfortably using dental glue on the maxillary palate (upper jaw) in the canine's mouth. It will need to withstand the bite force of the canine teeth ranging from 147-926 N [2]. In addition, the device will be interfaced with the chosen software and generated from patient-specific DICOM and STL files.

B. Safety:

The incline plane should not impede the canine's wellbeing. The device should adjust to the mouth without causing sores and pain. The device also must be made of a non-toxic material, it must follow the standard, "ISO 13504" Dentistry requirements and related accessories used in dental implant placement and treatment[3]. The device should be strong enough to withstand the force of the dog's bite, for 6-8 weeks without breakage. The initial veterinary examination should follow the AAHA-AVMA canine preventive healthcare guidelines[4]. In addition, the following implant and implant materials should follow, "ISO 13504"

C. Accuracy and Reliability:

The device will be patient-specific in order to minimize error. To get an accurate, personalized fit, a CT scan is required to generate DICOM and STL files. Information from the DICOM files will be interfaced with the software to create a model that fits around the patient's teeth. In human orthodontics dimensional errors for the incline plane must be under 300-500 micrometers to be considered acceptable for treatment use[3].

D. Life in Service:

The incline plane should last from 6-8 weeks, depending on the circumstances of the malocclusion. The device will be placed on the maxillary arches and therefore will need to last in the mouth of the patient for the stated amount of time.

E. Shelf Life:

The plane needs to have a shelf life of up to 10 weeks to consider the time between manufacturing the device and putting the device into the mouth of the patient. After the correction cycle is complete, the device will not need to operate anymore as it is specific to one patient and it is then removed and disposed of.

F. Operating Environment:

The incline plane will be worn 24 hours a day- 7 days a week and so the patient's day-to-day environment will be its operating conditions because the device will be attached to the patient's mouth, which is a moist environment and so the device needs to withstand the bacteria that is present in the mouth. For temperatures, the device will need to be able to withstand a range of -32℃ to 50℃ to accommodate extreme weather conditions the patient may encounter. The device will need to withstand the bite force of a dog bite that ranges from 147-926 N [3] so the device is not loosened from the mouth or is not cracked or fractured. The device should not interfere with the patient's food consumption, so it should not have food stick to it or cause the device to peel off. The device should also withstand normal interactions with toys and other objects. The software used should be accessible to the veterinary orthodontist to use. The software should also be easy to follow and can be used on most computers.

G. Ergonomics:

The plane will be placed on the mandibular canines of the patient. When the patient closes their mouth, the force from the mandibular canines will be applied to the incline plane. Over time, this repeating motion combined with the angle of the incline plane will slowly guide the canines into the desired position. The device should be non-intrusive to the rest of the patient's mouth with a height and size that is patient-specific. The angle of the incline plane will be patient-specific; it will be determined by the degree of dissolution, size of teeth, and time needed for correction, which typically falls into a range of 45-60 degrees.

H. ***Size:***

The general size of the incline plane will vary from patient to patient and therefore should be size adjustable to accommodate for each patient and the varying Class II Malocclusions. The typical canine width to consider in the design is an 11 mm width of the crown as a percentage compared with the widest crown The product will range from 5 mm to 22 mm width found within canines. The typical length between the maxillary canines is 38 mm and the product will fit a range of 18 mm to 58 mm length [2]. The degree of tilt of the incline plane will range from 45° to 60°.

I. Weight:

The incline plane should weigh 170 grams or less. This will ensure that the patient does not notice the device and is able to use it comfortably for 6-8 weeks. The optimum weight would be around 85-113 grams, depending on the size of the patient.

J. Material:

Current treatments use a self-curing temporary crown material (bisacodyl composite)[2], however, the material for this treatment must be available as a 3D printer filament.

K. Aesthetics:

Color is relatively unimportant for the functionality of the incline plane, and therefore this aspect of aesthetics is not the focus of the design. The shape of the incline plane will be that of the maxillary arches of the patient [2]. The devices will have 3 slots for the upper maxillary, upper canine, and upper incisor. As for texture the devices should be smooth to negate any lacerations and to maximize comfort for the patient.

Production Characteristics

A. Quantity:

Units are designed specifically for each individual patient, so quantity depends on the number of patients with Class II Malocclusions. One device is used per patient.

B. Target Product Cost:

The cost of production will be based on the specific material used for 3D printing the incline plane, which is around $10-15 [9], as well as the size of it as each incline plane will vary from each patient.

C. Standards and Specifications:

The incline plane would go under the category of Orthodontic appliance and accessories, in which the device is affixed on a tooth so that pressure can be exerted on teeth for orthodontic treatment, which is a Class 1 classification. This means the incline plane is low to moderate risk of injury [9].

D. Customer:

The client would like an incline plane that would be able to fit on any size canine with Class II Malocclusion. This would be achieved by having software that can take scans of the mouth of the patient and create a specific incline plane that fits the patient.

E. Patient-related concerns:

For each individual patient, a scan will be taken through software, an incline plane will be created specifically for that patient, resulting in no need for sterilization between uses. Additionally, the owner of the patient will be explained how the incline plane is supposed to work to fix the Class II Malocclusion. Furthermore, the owner of the patient will be explained how the incline plane should be monitored when the patient eats or plays as if the incline breaks, the owner of the patient needs to return to get another incline plane implanted.

F. Competition:

There exists a patent for an orthodontic fixture intended for use with animals to correct lingually displaced canine teeth [9]. This device uses non-toxic metal which can be costly and difficult to manufacture. This product can be improved by adding support, such as a thicker bridge and thicker crowns, to prevent this design from breaking upon usage.

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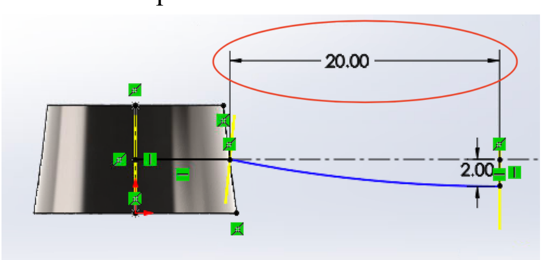
b. Solidworks Design Workflow

Creation of Patient Specific Part

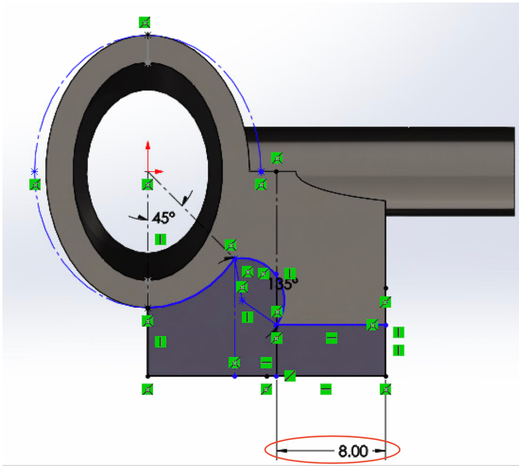
1. Open up the **Final Design** document
2. Measure the Upper Diameter of the maxillary canine
    a. Double click on the **Upper Tooth Diameter** tab in the feature tree under the tab **Tooth dimension**

b. Double click on the larger dimension and insert the number in millimeters of the longer width of the tooth, + 5 mm, to take account for the ring thickness along with giving the maxillary canine 0.5 mm space from the ring, on the plane closest to the base of the tooth
c. Double click on the smaller dimension and insert the number in millimeters of the smaller width of the tooth, + 5 mm, to take account for the ring thickness along with giving the maxillary canine 0.5 mm space from the ring, on the plane closest to the base of the tooth
d. Click exit sketch in top left corner of the screen

3. Measure the Lower Diameter of the maxillary canine
    a. Double click on the **Lower Tooth Diameter** tab in the feature tree under the tab **Tooth dimension**
    b. Double click on the larger dimension and insert the number in millimeters of the longer width of the tooth, + 5 mm, to take account for the ring thickness along with giving the maxillary canine 0.5 mm space from the ring, on the plane closest to the tip of the tooth
    c. Double click on the smaller dimension and insert the number in millimeters of the smaller width of the tooth, + 5 mm, to take account for the ring thickness along with giving the maxillary canine 0.5 mm space from the ring, on the plane closest to the tip of the tooth
    d. Click exit sketch in top left corner of the screen
4. At this point, the dimensions of the ring should be all set.
5. Now, edit the length of the support bridge.
6. Measure the distance between the maxillary canine
7. Subtract 4mm, to account for the ring thickness, and divide this value by 2. Remember this value.
8. Click on the **Support Bridge** tab in the feature tree, and double click on **Support Bridge Arc**
9. Double click on the dimension of the arc circled in red, and insert the value in millimeters found in step 7.



10. Now change the angle of the incline plane.
11. Determine the angle required for desired correction.
12. In the design tree, click on the **Incline Plane** tab and double click on the **Incline Plane Angle** tab
13. In this sketch, double click on the dimension circled in red below



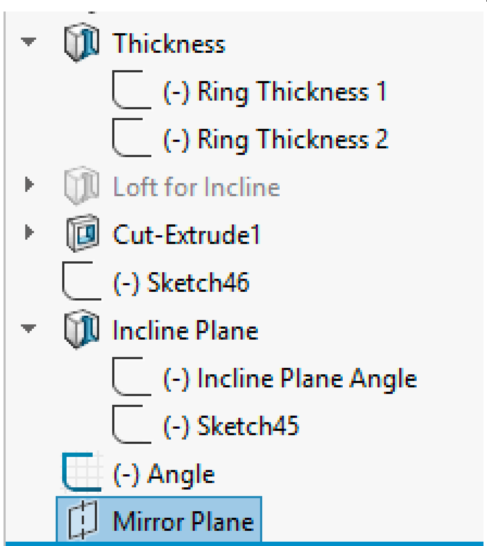
14. To find the desire dimension, solve for x in the equation and add 2, as the bottom of the incline plane stays at 2 mm:
    x= (10)/(tan(desired angle in degrees))

    For example, for a desired angle of 45 degrees, the equation is:
    x= (10)/(tan(45)) , where x=10, and thus x+2 = 12, so enter in 12mm for the circled dimension.

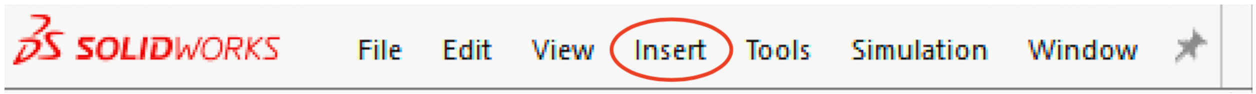
15. To verify the desired angle was obtained, exit this sketch, and click on the **Angle** tab in the design tree. In this sketch, the dimension shown is the angle of tilt for the incline plane.
16. At this point, the part should be fully dimensioned and patient specific. All that is left to do now is mirror the part, and create an assembly to make the piece.

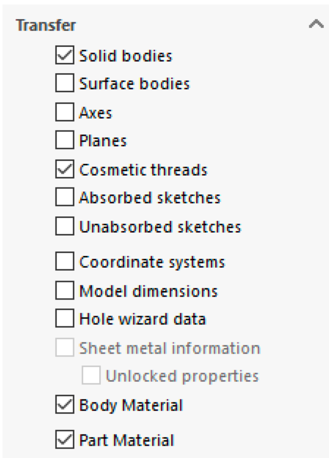
<u>Creation of Mirrored Part</u>

1. Now to mirror the part for the assembly.
2. Click on **Mirror Plane** at the very bottom of the feature tree

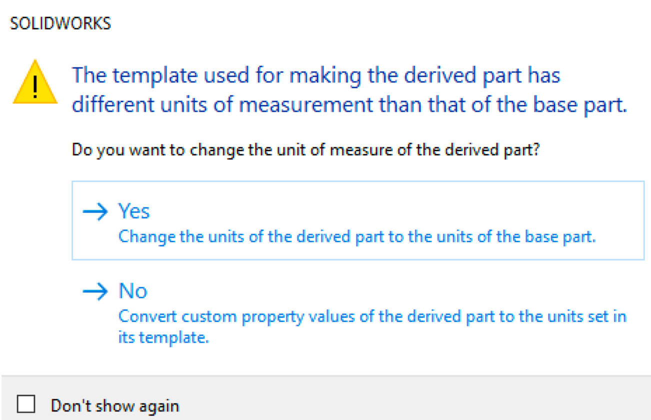


3. Next select **Insert → Mirror Part** found at the top of the screen, and make sure the boxes are checked as they are in the following picture





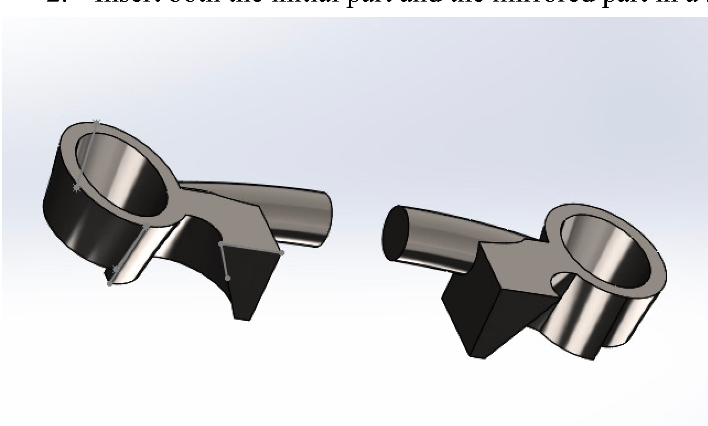
4. If the following message appears, click **yes**



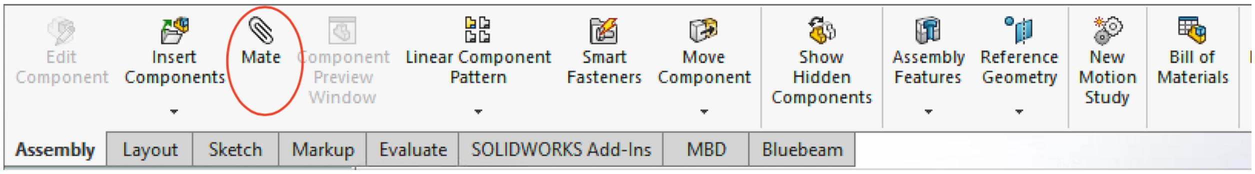
5. The mirrored part will appear, and you should now **Save As** a new part

Creation of Assembly

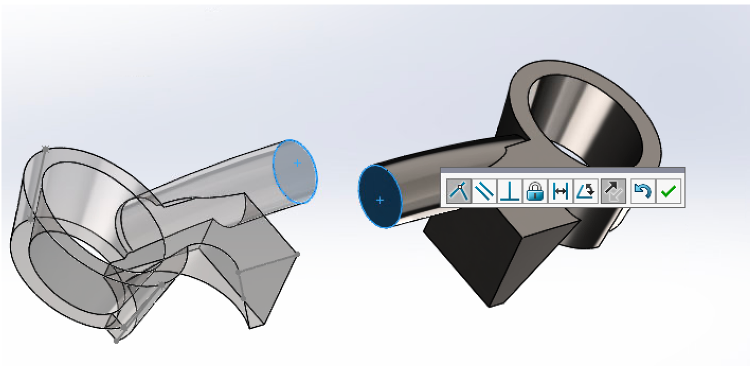
1. Open a new assembly in Solidworks
2. Insert both the initial part and the mirrored part in a similar configuration as shown below



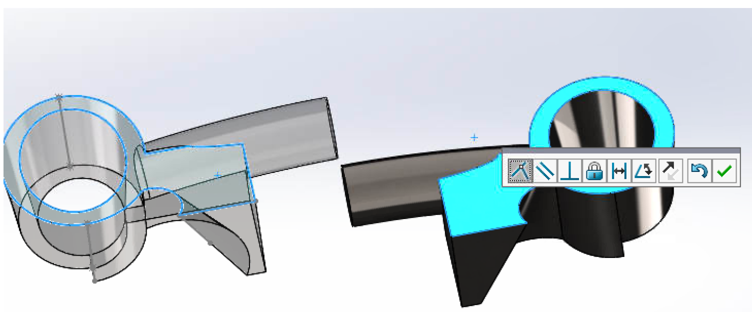
3. In the toolbar, select **Mate**



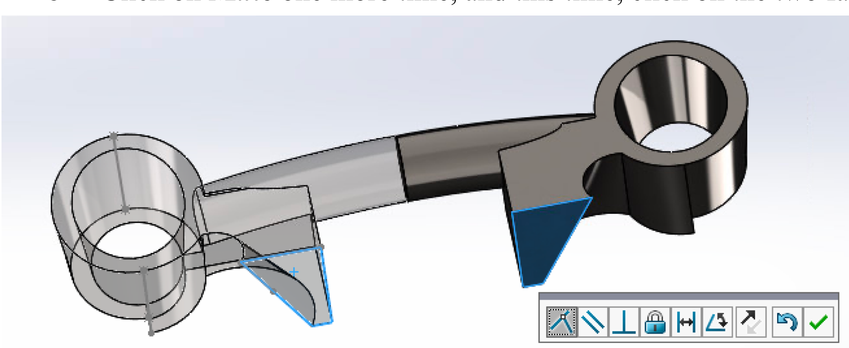
4. In the **Mate** tool, click on the two faces at the end of each support bar as shown below



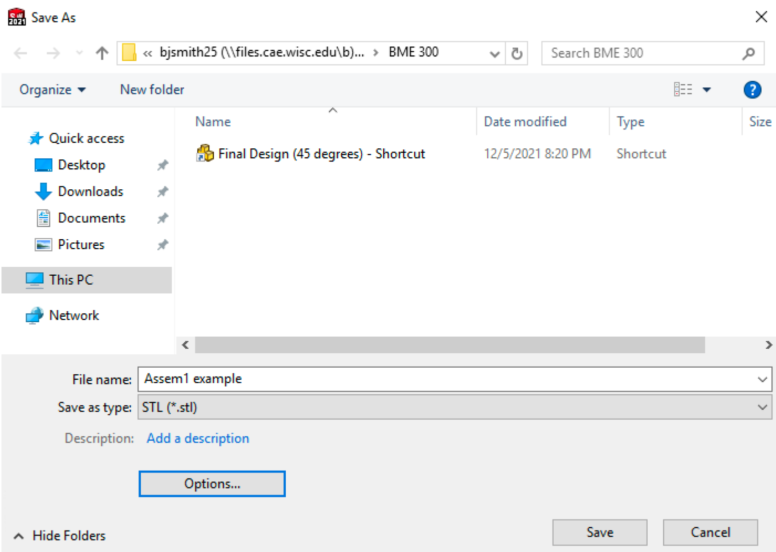
5. With these faces in the same place, click on **Mate** again, and this time click on the two faces in the image shown below.

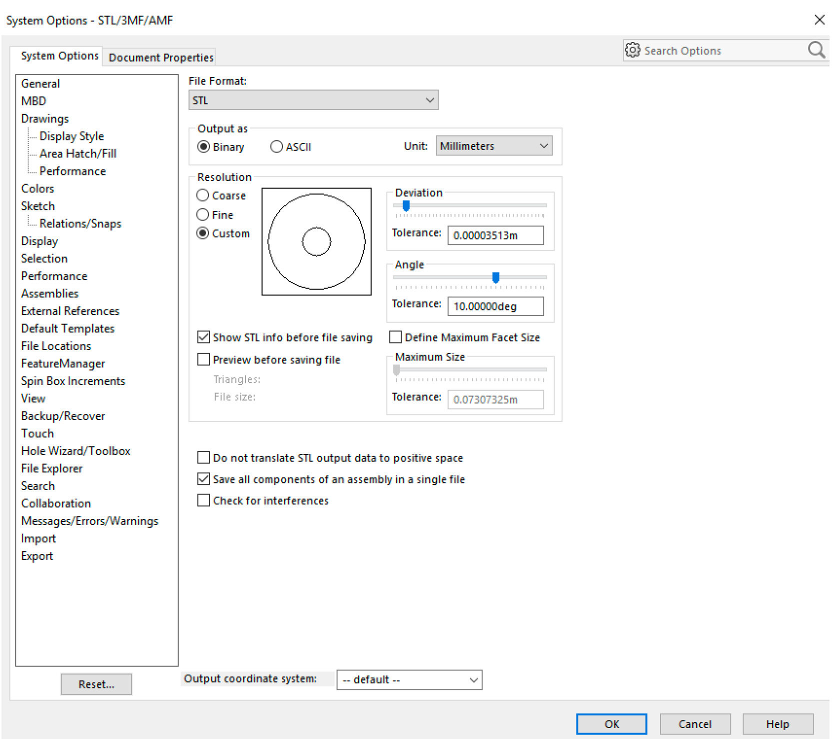


6. Click on **Mate** one more time, and this time, click on the two faces shown in the image below.



7. At this point, the piece is fully configured and ready to be printed.
8. Save the file as a .stl file
    a. Click options
    b. Check Save all components of an assembly in a single file


Save As
bjsmith25 (\\files.cae.wisc.edu\b)... › BME 300
Search BME 300
Organize
New folder
Name
Date modified
Type
Size
Quick access
Desktop
Downloads
Documents
Pictures
This PC
Network
Final Design (45 degrees) - Shortcut
12/5/2021 8:20 PM
Shortcut
File name:
Assem1 example
Save as type:
STL (*.stl)
Description:
Add a description
Options...
Hide Folders
Save
Cancel


System Options - STL/3MF/AMF
System Options
Document Properties
Search Options
General
MBD
Drawings
Display Style
Area Hatch/Fill
Performance
Colors
Sketch
Relations/Snaps
Display
Selection
Performance
Assemblies
External References
Default Templates
File Locations
FeatureManager
Spin Box Increments
View
Backup/Recover
Touch
Hole Wizard/Toolbox
File Explorer
Search
Collaboration
Messages/Errors/Warnings
Import
Export
File Format:
STL
Output as
Binary
ASCII
Unit:
Millimeters
Resolution
Coarse
Fine
Custom
Deviation
Tolerance:
0.00003513m
Angle
Tolerance:
10.00000deg
Show STL info before file saving
Preview before saving file
Triangles:
File size:
Define Maximum Facet Size
Maximum Size
Tolerance:
0.07307325m
Do not translate STL output data to positive space
Save all components of an assembly in a single file
Check for interferences
Reset...
Output coordinate system:
-- default --
OK
Cancel
Help

c. Expense Spreadsheet

Item	Description	Manufacturer	Part Number	Date	QTY	Cost Each	Total	Link
Category 1								
3D- Print	Printing of the initial design in PLA	Makespace		10/14/2021	1	$0.16	$0.16	
3D- Print	Printing of the final design in PLA	Makespace		12/6/2021	1	$0.32	$0.32	
3D- Print	Printing of the final design in PLA	Makespace		12/8/2021	1	$0.32	$0.32	
						TOTAL:	**$0.80**	