Simple-to-use Teleoperated 3D Printed Hand

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Abstract— **The aim of this project is to create a cheap teleoperated hand that can be easily controlled by its user. In order to reduce cost of prosthetics, we hope to eventually have this system be implemented in prosthesis. Three scenarios were present to 8 subjects from various ages where they tried to determine if a 3D printed hand was grasping or at least touching a stress ball, laying on top of the palm of the 3D printed hand. All subjects were right handed, except for the exception of one ambidextrous subject. The 3D printed hand contained two force sensors to enable tactile feedback on the fingertip of the thumb and index fingers. Only the thumbs and index fingers were operational, but operation of all 5 fingers can be achievable. We determined that we can indeed produce an affordable, working 3D printed hand that gives the user real time tactile information. Even with the lack of a few degrees of freedom in the thumb, the experiment were still successful, giving subjects who were not looking at the 3D printed hand the information needed to determine that they were indeed touching or grasping the stress ball with the movement of their hand. This can also give headway in humanoid robotics or virtual reality environments.**

I. Introduction

As many people know, robotic components can be expensive, especially if you want it to be accurate in any way. This is especially true in the field of prosthetics, where a leading prosthetic hand can cost up to $100,000. With DC motors, position and torque sensors, among other components, the price tag on some of these prosthetics can go up really fast.

Now, why a hand and not a robotic gripper? Sure, a gripper has a much simpler design, easier to manufacture, can exert a large amount of force, and is cheaper. But the main issue is that it lacks familiarity and adaptability. Familiarity is more of an issue that varies between users that can eventually be fixed with time and training, but will never achieve the same amount as one would have with their own hands. It is also dependent on the control system of the gripper, which are not always as intuitive as doing it yourself. By having a robotic hand that moves with your hand in the same motions, a fair amount of the familiarity is covered since you do not have to adapt to a new control system or mechanism. As far as adaptability goes, a hand is fairly adaptable to several situations in comparison to a gripper. A gripper is capable of grabbing an object, letting go of an object, and pushing an object. In contrast, a hand has a few other applications that cannot be done by a gripper, one of which is communicating to others (this can range from something as simple as numbers to using sign language).

Our aim is to prove that our 3D printed hand is practically and can be give more information about an object than grippers. Instead of position and torque sensors, and an expensive DC motor, we can try using a servo motor and take care a of all of these components, all while taking the price tag down much more. To start, we will try to determine if we actually provide the information needed to detect objects and give enough force to be able to move them or influence them in any way. This will be the objective of our study. If this is a success, we would move on to actually grasping different types of objects with different shapes and rigidness. The results of the second stage could lead to a second study to try to determine how to best determine different surfaces using force sensors in a 3D printed hand. At this point, we can safely assume that grippers, though practical, no longer have any the edge and we can go with the much more familiar human hand, opening the door to many tasks that could not be done by grippers.

II. Background

Multi-sensory prosthetic hand research has been around for a long time. With better and evolving technology, we are seeing a diversification of works done in the field. What once was just a plastic hand without any possible movement or grippers, we are now looking into using prosthetics with the brain and hands with 11 degrees of freedom, able to grasp multiple kinds of object with ease. It is no longer an impossible dream to provide those who have lost limbs with a replacement. The field of prosthetics is now moving into humanoid robotics, bringing the possibility to enhance one self. But, as stated earlier, costs of prosthetics are high. With higher complexity, comes more labor, difficult programming, and usually strong and durable materials. With the rise of 3D printing, prosthetics costs have gone down, but rehabilitation or enhancement is still not within the grasp of the public.

III. Constructing The Hand

A. *3D Printing the Hand*

First thing we need to do is build the hand itself. This was accomplished by modelling a hand in SolidWorks, using a model made by OpenBionics as a reference. After each of the fingers and the palm is modelled, the models are 3D printed in order to keep both weight and costs down. The type of filament used for this particular hand was PLA (Polyactic Acid). The printing time for the fingers averaged about 2.5 hours, while the palm was about 4 hours. Two pulleys were also printed, but these could be bought (they took a total of 30 minutes). In total, it would take about 17 hours to print all the parts that were used in order to make a hand. This is also good advantage to have, since it would normally take significantly longer (sometimes up to three weeks) for a clinic to provide a prosthetic to their patients. With that, we have the parts to build the hand itself.

B. Electrical components for the Hand

With the hand ready to be built, we have to add the components to make it work. Unfortunately, our project will not include the full functionality of all five fingers, we will only be using the thumb and index finger. This is primarily due to the spacing requirements of the components being used. On the other hand, we will be allowing the hand receive and send feedback back to the user. In order for the fingers to move, we will be using two high torque servos and nylon in order to simulate tendons. The feedback that was mentioned earlier will be from a force sensor that will be attached to the tips of the two active fingers. How the user will receive this feedback will be explained in the control system of the hand.

IV. Controlling The Hand

Finally, with the hand built and working, we need a way to control the hand. As stated earlier, we want to achieve a system that was easy to control, perhaps even intuitive if possible. The easiest way would be by having the system mimic your actual hands, which is what we did.

This was accomplished by making a haptic glove that would be connected to the hand through an Arduino Uno in order to communicate the motions between the user's hand and the printed system's hand. The haptic glove was made using an ordinary glove, two flex sensors, and two micro servos. The flex(ible) sensors are sensors that are used to measure the bending of the system it is attached to. These sensors are attached to the thumb and index fingers of the glove in order to measure how far the user's actual fingers are bending. With that data, we can send the measured amount to the Arduino which will then bend the finger of the printed hand. The micro servos that are attached to the tips of the thumb and index finger have some nylon wrapped around the finger. These servos are controlled by the force sensors on the tips of the printed hand's fingers, and, if activated, will tighten the nylon around the fingertips of the glove in order to simulate a force similar to the one being experienced by the printed hand. This will act as a form of tactile feedback for the user.

V. Limitations

Regrettably, there are a few limitations to the 3D printed hand that was made for this experiment. One of which that has already been mentioned is that the hand can currently only operate two of its five fingers. We hope to change that in the future and allow functionality to all of the fingers once a solution for the spacing has been determined.

Another is the loss of a few degrees of freedom in the hand. Most people can move their fingers inwards/outwards and sideways to a varying degree. We were able to successfully allow for the inwards/outwards motion, but were not able to allow for the limited sideways motion. Because of this, we were also forced to estimate a rotational angle for the thumb to imitate one of the degrees of freedom. This is a fairly common issue with robotic hands and prosthetics, and are usually ignored. Likewise, with the haptic glove, the feedback is limited to only the fingertips, which can provide issues if there are forces interacting with the hand at any other location.

Figure 1. The 3D printed hand, force sensors have not been installed.

VI. Experimental Procedures

How the experiment is set up is fairly simple. We will have four scenarios in which a volunteer will be tasked to do the same objective. The objective is to grab a stress ball by only using the index finger and the thumb of printed hand. This is a straightforward task if one were to do so with their own hand, but with the four scenarios it will add a small range in difficulty.

The four scenarios consist of two variables being changed. The first variable will be whether or not the user will be receiving the tactile feedback on their fingertips, while the second variable will be if the printed hand is in the direct line of sight of the user. The scenarios will be listed as Scenario A-D, where A will consist of the user having no tactile feedback but will have direct view of the printed hand as they attempt to grab the object. Scenario B will be when the user will have both tactile feedback from the glove and direct view of the hand. Scenario C will not have tactile feedback and the user will not be in direct view of the hand. Instead, a live video stream will be provided of the hand and the user will have to use that in order to ascertain if they are holding the object. And finally, Scenario D will have the tactile feedback and will not have the direct view of the hand.

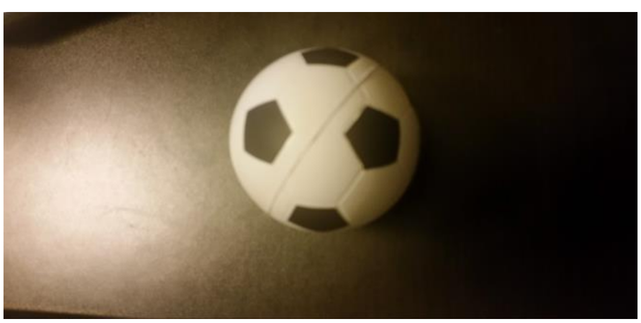
The live video stream will be done using a smartphone and a laptop. The laptop will provide the video for the user to see the printed hand while the smartphone will be sending the video using the free IP Webcam application. There is a small delay in videos that are streamed, but that is to be expected and will provide a proper real world example for teleoperated devices that also experience delays.

All subjects are to hold or touch a stress ball with the 3D printed hand. We allowed them to get familiarized with the hand operation, having them try to understand how to trigger the force feedback and how far they can take the fingers. We asked then asked them to let us know when they felt a finger touch the ball and when both fingers where touching or on the ball. They were allowed to take their time until both fingers were on the ball and the subject felt the ball.

Before the experiments, we asked the subjects to try the stress ball and get familiarized with how it felt using their whole hand and then with their thumb and index only. Either hand was used.

After the subjects complete all four scenarios, we asked them to fill out a small survey asking how comfortable they were with each of the methods as well as how easy they perceived each of the scenarios to be. As was stated earlier, we aim to make the hand both familiar and easy to control. The survey asked for their age, height, gender, ethnicity, and handedness, along with a scale of zero (0) to ten (10) asking to determine how easy it was to operate the hand, how difficult was it to touch the ball, how long it took the hand to copy their movement, and how natural it felt, the lower number being the most positive. We also asked them about the sensation on their fingertips where the glove with the feedback set up felt.

Figure 2. Stress Ball used for the experiment



VII. RESULTS

Many of the subjects got accustomed to the operation very fast, some taking more time than others, but nonetheless were able to operate the hand fairly easy. Some subjects were not able to move the thumb as far as others, but this may have been due to the code used. We asked one subject to try to determine if he could determine if the index finger and thumb was touching the ball without the force feedback sensor and without looking and it was determined impossible to tell whether or not the fingers were touching the ball when the force feedback was deactivated and the subject was not looking. This is natural as it would be very hard to determine if we were holding something while our hands were completely numb. This was the most successful subject, being able to determine when the fingers were touching on the second trying when not looking and on the first try when looking. He was also able to put a good amount of force on the ball, determined by the deformation on the ball. This made us consider other ways to produce feedback not involving force sensors or tactile senses.

Eight (8) participants were used for this experiment, all male, ages ranging from 19-34 years. All but one are right handed, having one individual claim he was ambidextrous. The subjects in question were not individually chosen, and participated based on interest of the project during it showcase. None of the subject had prior experience with prosthetics or using the setup we had. Except for Scenario B, all subject generally thought that the experience, whether they were looking or not looking, was about the same. Even though the visual feedback made it easier to know when the 3D printed hand actually touched the provided ball, they also described they paid much more attention to their fingers and how they were moving them, giving them a better sensation of where the ball is.

All subjects found it moderately easy to operate the hand, with the exception of one subject while doing Scenario D. They all used a similar technique where they would start with one finger and moving to the next. We noticed that when they started with the thumb only, they had more difficulty touching the ball with the index finger, as they ended up landing on top of the thumb instead of the ball. This never triggered the force sensor, but we noted this might be a problem that could give false feedback that could be easily addressed.

Out of all the Scenarios the subjects went through, they enjoyed being able to look and experience the feedback the best. According to the survey, it felt the most natural, saying that it almost felt like it was their own hand. Only those who had trouble with the thumb, specified that it did not quite feel right, but it was close enough to the movement of their hand. They all expressed that the hand almost moved instantly with theirs, noticing a delay but not that big. We can only hypothesis that in Scenario C, this response might have change to feel much longer, making the subjects uncomfortable, making the experience less natural.

Due to the small difficulties some of the subjects were having and similarity to Scenario B, Scenario A was dropped. Five (5) out of the eight (8) subjects merged the two scenarios, prompting us to eliminate Scenario A.

Subjects also noted that the response of the force sensors was slow, but not overall bad. They reported that, because it the sensation felt was all around the finger, it wasn’t quite as natural but it was understood was what trying to be done. They express that it is not the same sensation as actually touching the ball, comparing it to their previous experience when we asked them to get familiarized with the stress ball before the experiments were conducted.

VIII. Conclusion

In the end, only three scenarios were used to gather our data, dropping Scenario A because subjects, being able to see prompted to say that the fingers where on the ball even when they felt nothing. This is not necessarily a negative outcome, as the subject was still able to tell the fingers where doing what was intended, but force becomes a very important factor. Brittle materials might break due to the force exerted. Using our force sensors, they provide a tighter grip as more force is put on them.

A. Fixing False Data

We noticed that having set limiters in our code, used to simulate the best motion possible, may have hindered the facilitation of the operation of the hand from subject to subject. Updating the code to adjust to every persons hand and having a calibration period may produce much better results. Bigger force sensors or a larger amount installed of sensors on a single finger would definitely help with detection of objects. This might prevent giving false feedback when fingers touch one another instead of intended objects or the environment.

B. Possible Future Works

We determined that, even though there were complications and there is still room for vast improvements that we can indeed provide good tactile feedback and can be used for training in prosthetics. Since one hand is being used to operate the other, there are some complications when it comes to using both hands interactively. Unless the environment is configured to accommodate the limitations of our setup where both hands as being used in a mirrored manner, then this experiment was a complete success. One application to this mirrored environment is flying a plane, where both hands are mirroring each other and the user can push buttons on the yoke of the plane. We also determined that we could also use the hand to explore areas where no humans can get easy access to, subjects expressing interest in humanoid robot control. This expands on the importance of familiarity behind using a hand instead of a gripper.

There is also potential in the virtual reality realm for rehabilitation or gaming. Though there is no 3D printing, a hand is still created in the environment and the same application can be used. In fact, some of the challenges faced, like our lost degrees of freedom in the thumb, can be eliminated in a virtual reality environment with the opportunities graphic designing and physic engines provide in a virtual reality. More tests can be performed and research in the area can flourish, all while keeping costs very low and provide great efficiency.

C. Possible Improvements Needed

Improving the amount of degrees of freedom in at least the thumb can improve results drastically. All subjects expressed that having more freedom with the thumb would give them the control they need to more accurately be able to tell where the ball is and when the fingers are touching the ball. This design limitation is the most difficult to overcome but it is achievable. Multiple trials were done before a single finger was able to move as freely as they did during our experiment and, without a doubt, we can eventually get that extra degree of freedom in the thumb to make the best, much more affordable and accurate prosthetic hand.

In terms of the force feedback sensors response, faster, higher quality servo motors can eliminate this problem. The subjects noticed it took a little bit for the servo motor to move the string around the tips of the finger, even though it responded or started to turn as soon as a force was detected on the force sensors. A better system can also improve the response time of the set up and create a more natural feeling or a the very least, more accurate feeling. This would be crucial when trying to avoid over exerting the hand or wanting to produce taps. Seeing as taps are only felt or a fraction of a second, motors might have trouble replicating the force when they have to move the circumference of a string around a finger. The programming code and also be improved to be more sensitive to force changes, though the sensors might also need to be upgraded.

When tapping is considered and successfully implemented, we have to remember that we are engaging the whole circumference of the finger when there is tactile feedback. While this set up is very practical and goes over many of the difficulties encountered when trying to simulated tactile senses in the hand, it could still be improved. Having a fully integrated glove might help make the sensation much more accurate. By this we mean having a glove the contracts itself in a similar manner. Instead of exploiting the circumference of the finger and some string, using the length of the hand can be something to explore in order to recreate a real tactile feeling.

D. Success

We considered our hand to be a success with room for improvement. It has amazing potential, seeing as our total cost for two operational finger was under $200. The programming done (provided in appendix) is very short and straight forward with the flexibility to incorporate new ideas. All of the subjects enjoyed using our hand and believe that it has a lot of room for improvement, prompting us to move on to the next stage by making the experiment harder and gathering more quantitative data.

The intent is for prosthetics to drop in cost and provide a new aspect tactile aspect to them. The code used and SolidWorks drawings are provided in the appendix to further develop this idea and make it better. There is much room for improvement but it is definitely attainable.

Figure 3. Working Prototype

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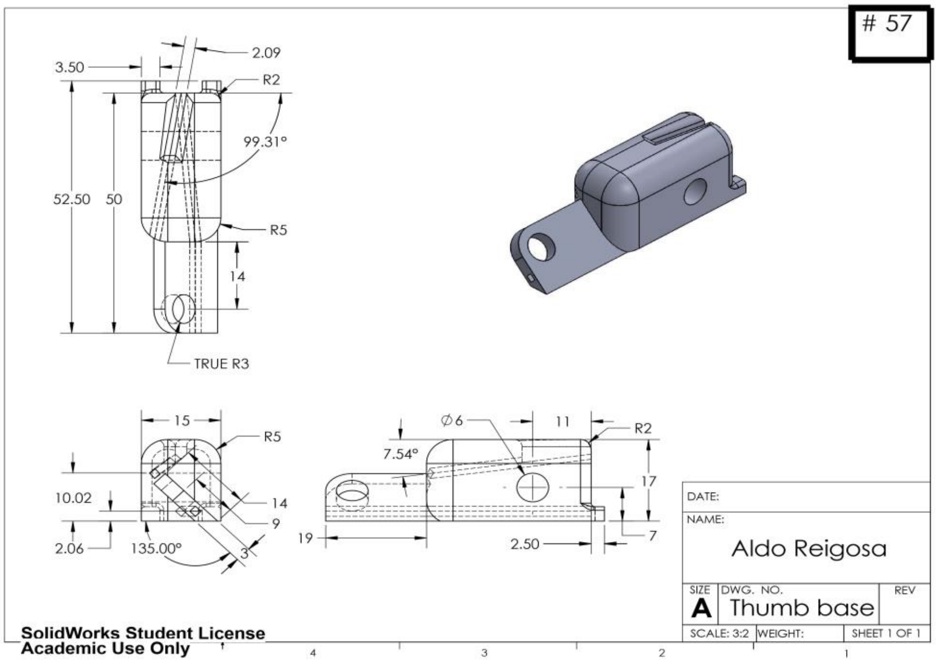
Appendix

Arduino C++ Code

```
#include <Servo.h>
Servo indservo;            // Servos for the index finger (Hand)
Servo thuservo;            // Thumb (Hand)
Servo itipservo;           // Index fingertip (Glove)
Servo ttipservo;           // Thumb fingertip (Glove)

int intip = 0;             // Analog Inputs: Index fingertip
int thtip = 1;             // Thumb tip
int index = 2;             // Index finger
int thumb = 3;             // Thumb

int vali;                  // Bending value of index finger
int valt;                  // Of thumb

int valitip;               // Force value of index fingertip
int valttip;               // Of thumb tip
void setup()
{
 Serial.begin(9600);
 indservo.attach(7);       // Attaching servos to designated pins
 thuservo.attach(8);
 itipservo.attach(9);
 ttipservo.attach(10);
}
void loop()
{
 vali = analogRead(index);          // Assigning vals for their assigned fingers
 valt = analogRead(thumb);
 valitip = analogRead(intip);
 valttip = analogRead(thtip);

 vali = map(vali, 500, 650, 1, 179);    // Adjusts values to be proportional to the 180
 valt = map(valt, 560, 700, 1, 179);    // degrees of a servo
 valitip = map(valitip, 150, 900, 0, 179);
 valttip = map(valttip, 150, 900, 0, 179);

 constrain(vali, 0, 180);           // Limits values to be between 0 and 180
 constrain(valt, 0, 180);
 constrain(valitip, 0, 180);
 constrain(valttip, 0, 180);

 indservo.write(180 - vali);        // Values being written to servo according to
 thuservo.write(valt);              // servo according to orientation
 itipservo.write(valitip);
 ttipservo.write(180 - valttip);
 delay(15);
}
```



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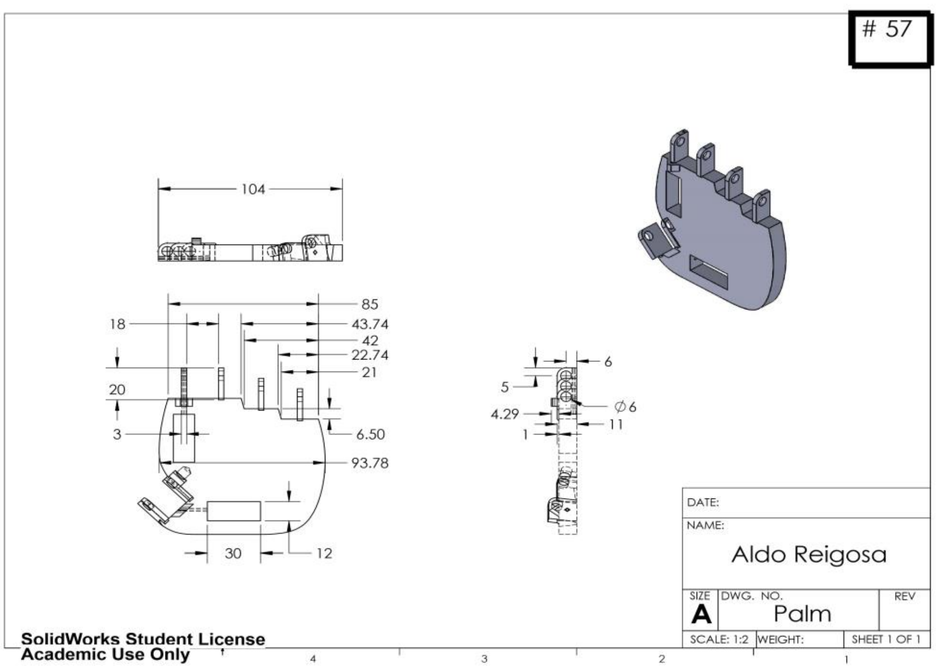

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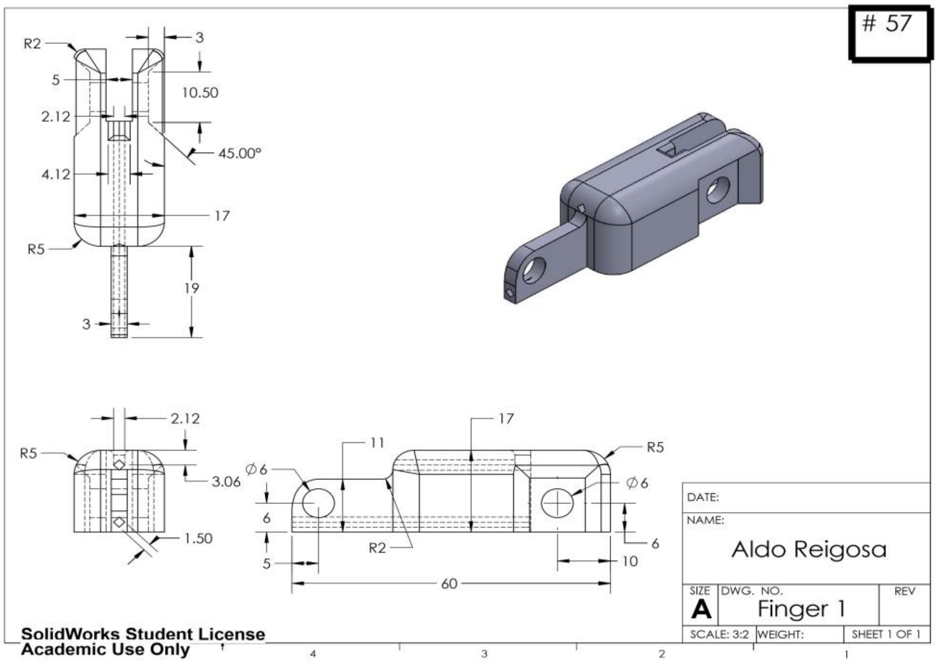

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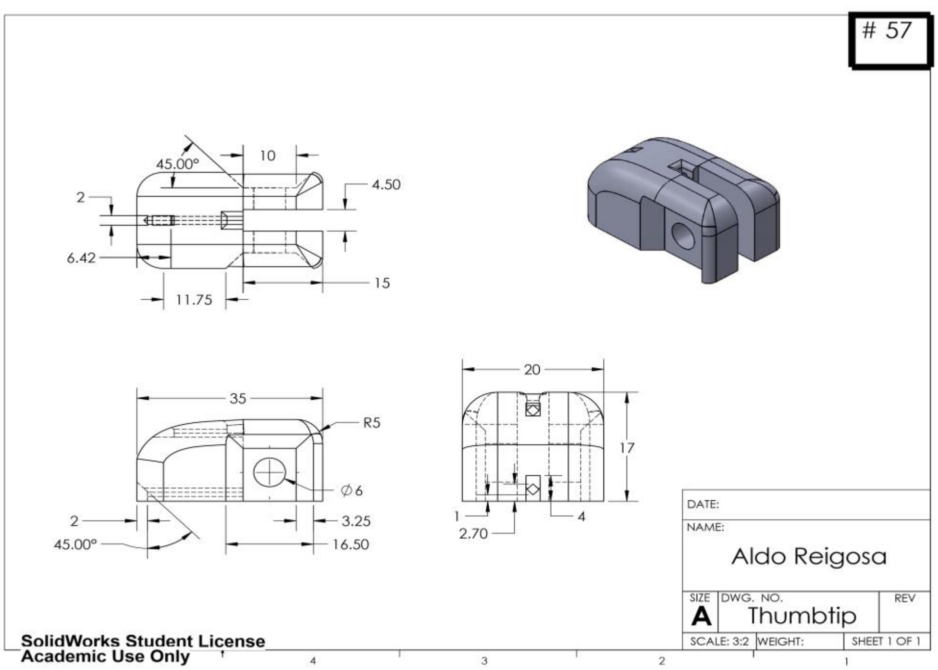

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