FINAL TECHNICAL REPORT FOR THE DESIGN AND PROCESS PLANNING OF A DRAGON ASSEMBLY

Prepared for:

Stephen McMillan, MEng, Peng

And

Darlene Webb

BCIT Mechanical Engineering Technology

Prepared by:

Angel Zeth Tolod

A01014727

Set 4C

BCIT Mechanical Engineering Technology Program

Submitted on

May 8,2020

EXECUTIVE SUMMARY

The purpose of this report is to present and discuss the manufacturing process of a 3D dragon puzzle assembly. The parts are cut from cold-rolled steel sheet by waterjet. The head of the dragon will be made from aluminum by casting either by lost PLA casting, investment casting, or die casting depending on the total cost. Then project is brazed, sandblasted and powder coated.

The report includes the model design, manufacturing plan, cost estimate, break-even point and conclusion.

The final deliverables of the project are the prototype, concept sketches, SolidWorks models, final written report and final presentation which is submitted on May 8, 2020.

The final manufacturing cost of the project can be viewed at Table 27. The total numbers of hours committed to this project is around 350 hours. Future work for the project is to fully manufacture the dragon assembly using lost PLA casting.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to all the people that helped in the creation of this project. Their experience and knowledge were a great help in the progress of this report.

To Stephen McMillan for the knowledge about manufacturing processes and the recommendation on how to improve the project.

To Darlene Webb for the guidance and encouragement throughout the semester.

To Adam Marciniak for the time on helping me for lost PLA casting and giving feedback on the status of the report.

To Brian Ennis for the input regarding writing comprehensive technical reports.

1. INTRODUCTION

The purpose of this report is to present information relating to the manufacturing plan for a dragon assembly, a type of 3D puzzle. The purpose of the project was to design and manufacture the parts and then to assemble it.

A proof of concept prototype is made using laser cutting to better visualize the project as shown in Fig. 9. The final project itself is to be made of cold-rolled steel sheet which is cut by waterjet. The dragon head is to be made of aluminum and manufactured by using either lost wax PLA casting, investment casting, or die casting depending on the total cost. The assembly will then be brazed, sandblasted and powder coated.

The inspiration of this project is due to an interest in 3D puzzle assembly. I was fascinated in the art and complexity of such puzzles which prompted me to design and manufacture my own puzzle. This project will apply the skills learned from mechanical engineering technology at BCIT.

The report includes the model design, manufacturing plan, cost estimate, break-even point and conclusion.

The deliverables for this project include: a 3D solid model, a proof-of-concept prototype, a final technical report, a final technical presentation.

2. BACKGROUND

Unlike 2D jigsaw puzzles that only portray an image, 3D puzzles portray various kinds of objects in a 3D view. Each 3D puzzle is unique, and can represent an architectural landmark, mythical creatures, or sci-fi vehicles. The puzzle can be made from different materials such as cardboard, wood or steel (Fig. 1 to 3). The challenge of building a 3D puzzle depends on the number of parts and complexity of the shape.

3D puzzles can be found on the market with varying prices depending on the material, complexity and overall aesthetic. 3D puzzles can also be purchased by using just their digital data and then customized by scaling the size. 3D puzzles can be manufactured by lasercut if made of wood and waterjet if made of steel.

Figure 1: Carboard 3D puzzle

Source: https://dynamic.indigoimages.ca/gifts/665541020193_hi.jpg?altimages=true&scaleup=true&width=614&maxheight=614

Figure 2: Wood 3D puzzle

Source: https://cdn.shopify.com/s/files/1/1402/8033/products/U-9_Grand_Prix_Car_Ugears_1__DSC6595_copy_700x700.jpg?v=1528012875

Figure 3: Steel 3D puzzle

Source: https://alexnld.com/wp-content/uploads/2019/08/f467ad07-b18c-48fc-b110-c2c6bc571dc6.jpg

When I was young, I played with a metal assembly toy with interchangeable parts. The metal parts could be made into objects and this toy sparked my interest for engineering. So, for my project, I wanted to make a 3D puzzle as shown in fig. 4-6.

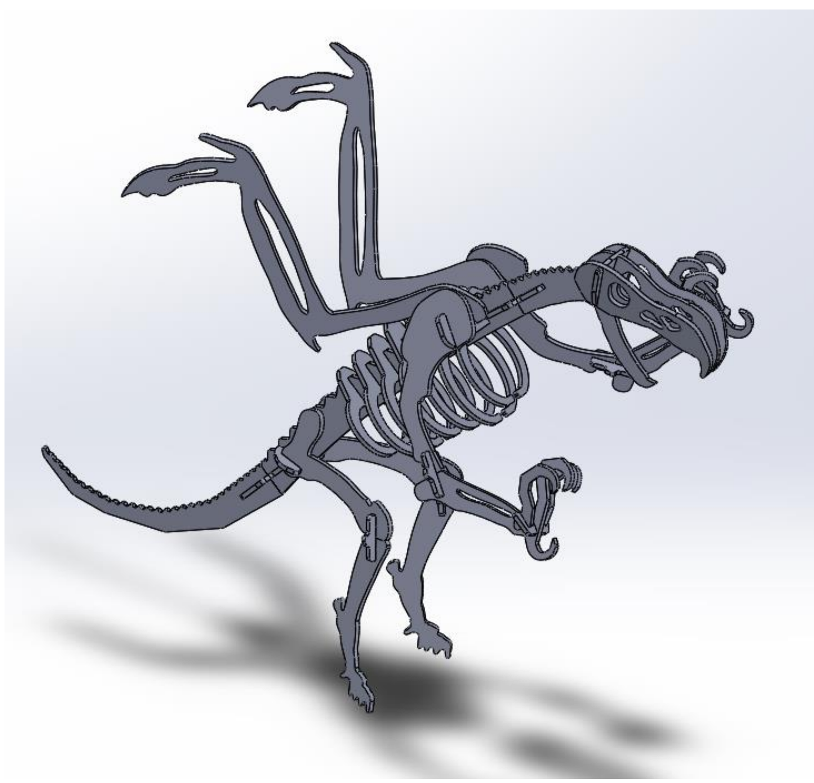

Figure 4: Griffin Isometric View

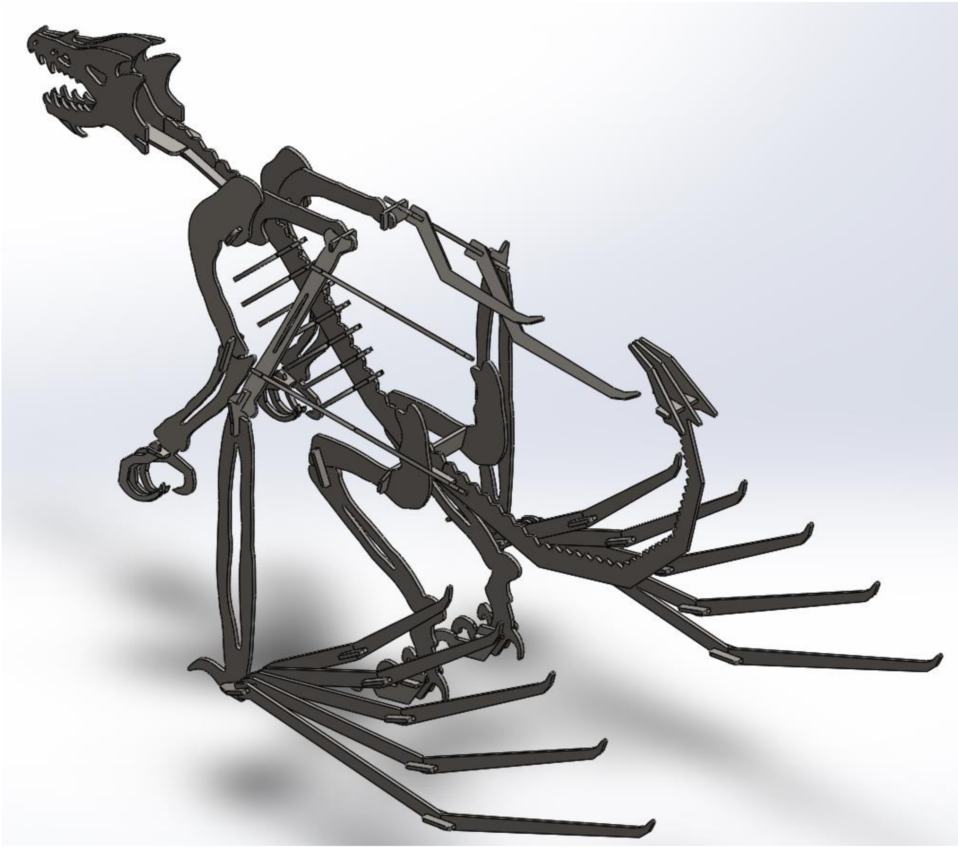

Figure 5: Dragon Prototype Isometric View

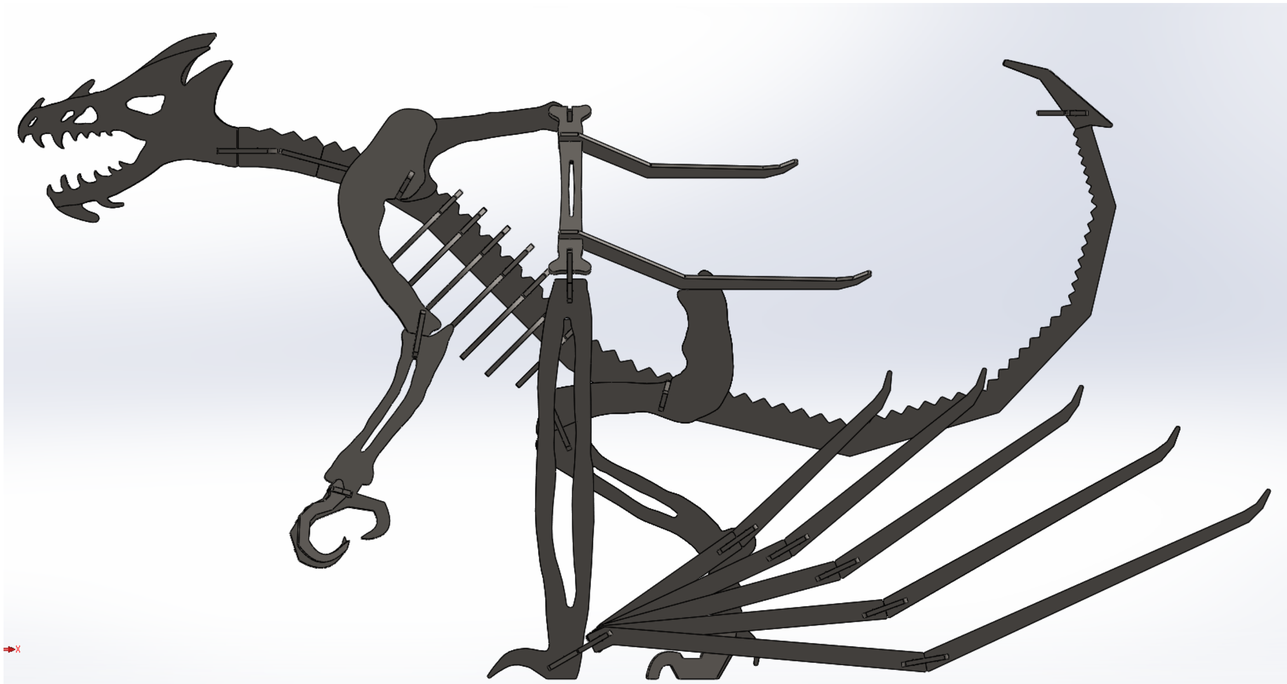

Figure 6: Dragon Prototype Side View

Two assemblies were made in SolidWorks; the first one was a griffin (Fig. 4) which took 27 hours to model, and the second one was a dragon (Fig. 5 & 6), which took 45 hours to model. The griffin has a total of 37 parts while the dragon has a total of 88 parts. The griffin will be considered as the project research since the lessons learned from the previous experience in designing made modeling the dragon easier.

3. TEAM MEMBER PROFILE

Angel Zeth Tolod is a student at BCIT mechanical manufacturing option. The original design and manufacturing of the project was solely done by him. He is passionate and gave his all to finish the project.

Zeth knows various software used in engineering including AutoCAD, SolidWorks, Mastercam, and Microsoft Excel. After BCIT, Zeth will pursue a career in manufacturing, using AutoCAD and SolidWorks.

4. PROJECT OBJECTIVES

The objectives of this project were to:

- sketch concept designs and model the chosen design using Solid Works.
- laser print a prototype of the whole assembly.
- cut the parts using waterjet and join the assembly by brazing.
- cast the dragon head with lost PLA process.
- sandblast and powder coat the assembly.
- create a cost estimate of manufacturing process.

5. DISCUSSION OF CAD/CAM MODEL

The item used for project researched study is the griffin which was the first 3D assembly. The griffin's research, concept sketch and CAD modelling was done during the winter break. Concept sketches was made before modelling the designs in SolidWorks which is shown in the appendix. When all the parts are modelled, it will be assembled in SolidWorks.

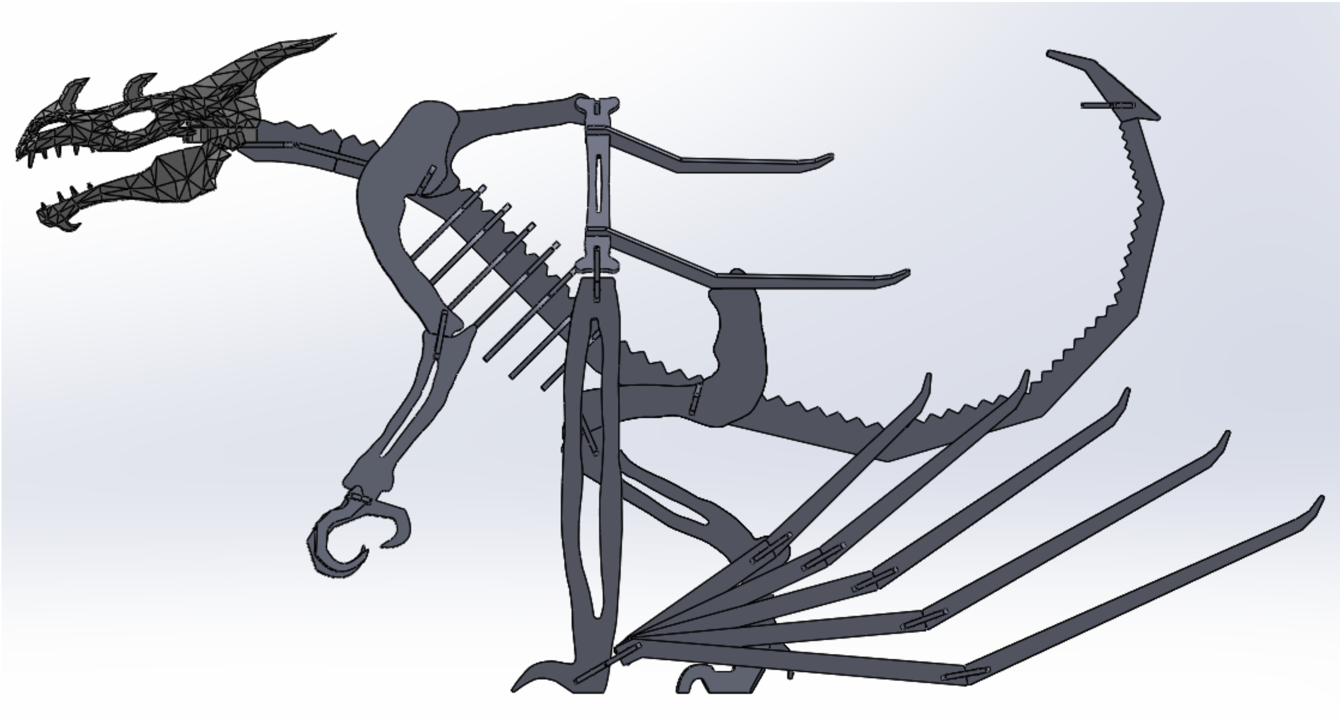

Figure 7: Final Manufacturing Project Side View

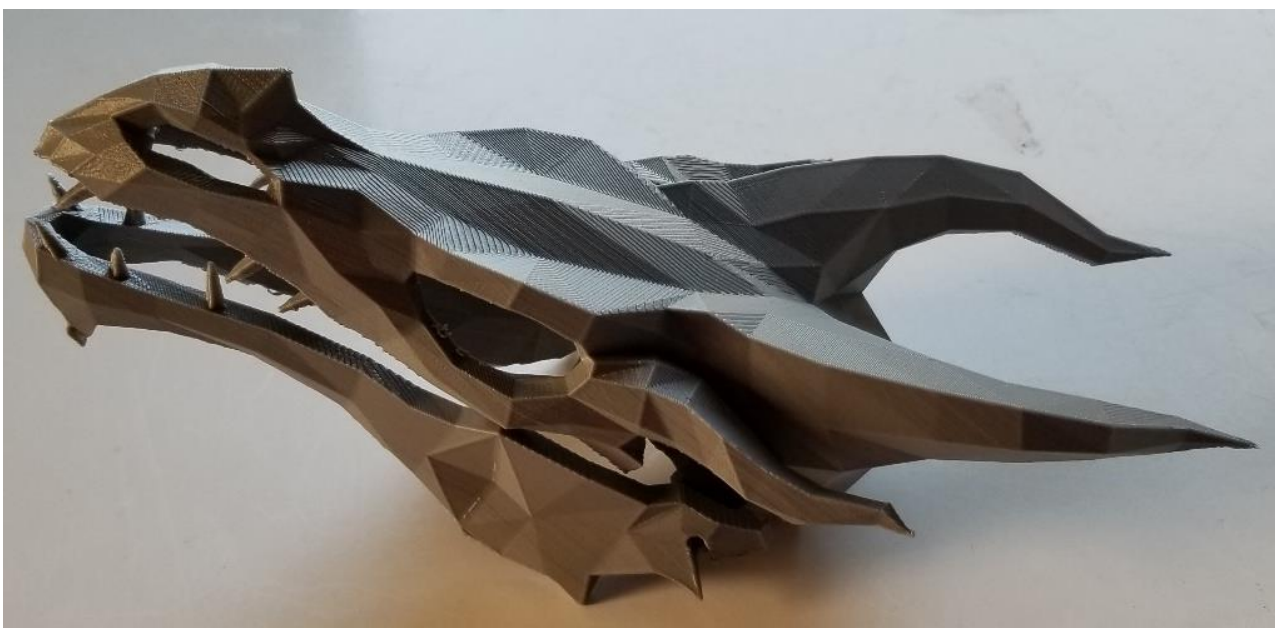

Figure 8: Dragon Skull – Proof of Concept

Fig. 7 is the CAD model of the final manufacturing project, after the sketches were converted to models and then assembled. The final manufacturing project assembly has a height of 16.1 in., length of 31.9 in., and width of 12.5 in..

The dragon skull is manufactured by lost PLA casting of aluminium. Figure 8 shows the proof of concept of the dragon skull made by 3D printing the skull and the jaw. The total weight of the project is 9.06 lbs. by using the mass properties function on SolidWorks.

The appendix will show further information about the dimensions of the assembly.

6. MANUFACTURING PROCESS PLANS

This section of the report presents various manufacturing process plans for the dragon assembly.

6.1 Production of Prototype

A prototype of the assembly is generated through laser cutting a 1/8 in. hardwood to further visualize the project as shown in Figure 9.

Figure 9: Dragon Assembly Prototype

6.2 Waterjet Manufacturing Method Process Plan

The parts are then cut using a 24 in.x24 in. 11 gauge (0.1196 in) cold-rolled steel sheet by waterjet. One steel sheet is needed to cut all the parts of the assembly.

It is better to cut the steel sheet individually rather than stacking the sheets (see table 1 for more info).The total perimeter of all the parts is 1340.00 in..

The steps for waterjet cutting are as follows:

1. Set up the needed materials before starting.

WARNING: Wear safety googles, steel toe boots, and ear plugs when operating the waterjet.

2. Turn on the waterjet machine and make sure that the pressure and water temperature are within operating range. Check the amount of abrasive and fill if necessary.
3. Turn on the operating system and transfer the STL file needed for manufacture.
4. Choose the quality no. 4 for the cut quality and put tabs for smaller parts if necessary. Then set the type and thickness of the material.
5. Place the steel sheet on the waterjet and apply weighs to weigh down the steel sheet.
6. Move the nozzle to the starting point and use the go/no go gauge to set up the nozzle height.
7. Raise the water level to an acceptable amount and run the waterjet.
8. Let the waterjet run for a few moments and then stop the machine to check if the waterjet is cutting the steel sheet. Don't lower the water level when the waterjet is running.
9. Periodically check the abrasive and water level of the waterjet.
10. Use a magnet to prevent parts from falling to the water.
11. Inspect the parts for defects.

6.3 Lost PLA Casting Manufacturing Method Process Plan

Lost PLA [1] casting is a manufacturing process similar to lost wax casting. Lost PLA casting have three processes: 3D printing, molding and casting. Lost PLA casting implements 3D printed parts made of PLA instead of wax. The model [2] of the dragon head was remodelled to allow jaw movement.

The progress of manufacturing the dragon head at BCIT only reached to the molding stage out of the three stages.

The steps for lost PLA casting are as follows:

1. 3D print the two models, the skull and jaw, on Ultimaker S5. The settings for 3D printing are: fine setting, 10% infill, PLA for material and ABS for support. 3D printing the models would take 2 days, 11 hours and 7 minutes to print and weighs 179 grams.
2. Remove the ABS support by submerging the 3D printed parts in water.
3. Add wax sprues to the printed part as shown in Figure 10. When designing the model on SolidWorks, it is better to add sprues before 3D printing the part as shown in Figure 11 and 12.

4. Create mold containers for both the 3D printed parts. The minimum dimension of the mold container for the skull is 4.5 in.x3.6 in.x8.9 in., and for the jaw it is 4.2 in.x2.2 in.x6.7 in.. The mold container can be made of cardboard for easier removal.

WARNING: Wear safety googles, steel toe boots and dust mask for the next operations.

5. Mix the investment plaster and water. The plaster mixture is composed of 1:2.6 water/plaster ratio. An example of plaster mixture for the skull is 4.1 lb of water to 10.5 lb of plaster. An example of plaster mixture for the jaw is 2.5 lb of water to 6.5 lb of plaster. Calculate the correct ratio before mixing the plaster and water.
6. Mix the plaster mixture, weigh the correct amount of water to a container, then slowly mix the plaster and water. Make sure that clumps of plaster are broken down. This task should take 3 minutes to complete since the plaster mixture hardens in 10 minutes.
7. Move the mixture to a vacuum chamber to vacuum the air bubbles trapped in the mixture as shown in Figure 13. Make sure that the vacuum chamber is sealed, then operate the vacuum pump to vacuum the plaster mixture for two minutes.
8. Slowly pour the plaster mixture to the mold container while holding the 3D printed part. The 3D printed part will be buoyant, so hold the part until the plaster mixture hardens.
9. Wait for two hours until the plaster mixture completely hardens and remove the mold container. The mold is now ready for drying as shown in Figure 14.

WARNING: Wear heat-resistant gloves when removing the mold from the oven.

10. Place the mold inside an oven with a temperature of 50℃ for 30 minutes, then increased every 30 minutes to 75℃, then 100℃, until the temperature is 150℃, then the mold is dried for another 4 hours. The process will take $5\frac{1}{2}$ hours.
11. Place the mold upside down inside an oven to melt the PLA. The temperature is set to 50℃ for 30 minutes, then increased by 50℃ every 30 minutes until the temperature is 500℃, then the mold will be left inside for another 5 hours to completely melt the PLA. The process will take $9\frac{1}{2}$ hours.

WARNING: Wear a visor, heat resistant gloves, leggings and suit before proceeding for the next operation.

12. Melt the aluminium to be used for casting. The skull needs 0.93 lb of aluminium while the jaw needs 0.18 lb of aluminium.
13. Slowly pour the molten aluminium to the mold. Let the aluminium hardens for one day.
14. Submerge the mold in water to dissolve the plaster.
15. Cut the sprue from the casted parts and inspect the parts.

Figure 10: Wax Sprues on the Skull

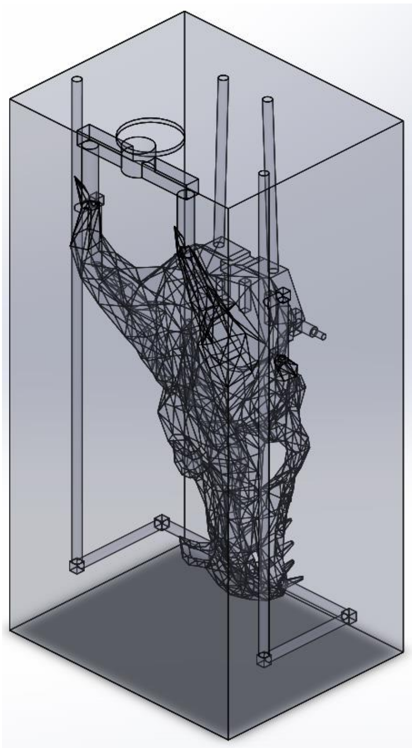

Figure 11: Lost PLA Casting – Skull

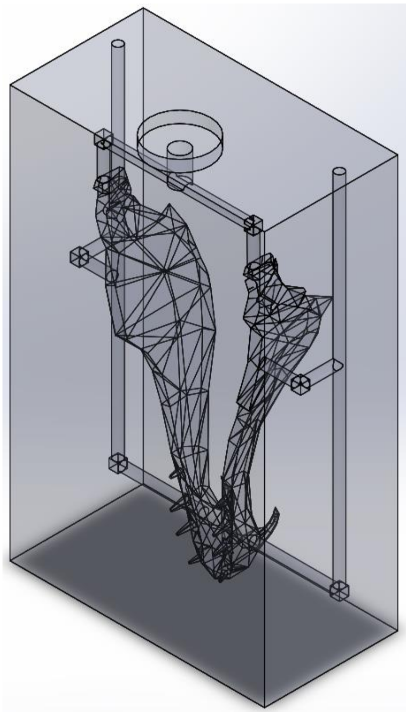

Figure 12: Lost PLA Casting – Jaw

Figure 13: Plaster Mixture inside a Vacuum Chamber

Figure 14: Mold of the Jaw

6.4 Investment Casting Manufacturing Method

Investment casting [3] is a manufacturing process which utilizes wax patterns and ceramic shell to cast, this process is based on lost wax casting. Investment casting is implemented for complex parts since it produces parts that are near net shape and have excellent surface finish.

It is not feasible to make a die pattern of the dragon head unless the dragon head is redesigned to a simpler model. The die pattern has two parts, but the geometry of the dragon head prevents the wax from being ejected from the die. A parting line and shrinkage should be considered when redesigning the dragon head.

6.5 Cold-Chamber Die Casting Manufacturing Method

Cold-chamber die casting [4] is a manufacturing process ideal for aluminum since it has a high melting point. The aluminum is set inside a furnace until it is melted. Then the molten aluminum is injected to the die by a hydraulic plunger under high pressure.

It is not feasible to make a die pattern of the dragon head unless the dragon head is redesigned to a simpler model. The die pattern has two parts, but the geometry of the dragon head prevents the casted part from being ejected from the die. A parting line and shrinkage should be considered when redesigning the dragon head.

6.6 Direct Metal Laser Sintering Manufacturing Method

Direct metal laser sintering (DMLS) [5] is another name of selective laser melting (SLM), is an additive manufacturing process using a high-powered laser to melt and fuse powdered metals. The DMLS printer raises the temperature to the sintering range of the metal and prints layer by layer. Inert gas is applied to protect the powder and the 3D printed part.

3DHub [6] and Xometry [7] is quoted for the prices of 3D printing the jaw and the skull. DMLS is the most expensive manufacturing process compared to the other casting processes.

6.7 Brazing Manufacturing Method

The parts cut by the waterjet and the casted dragon head are joined together by torch brazing [8] the parts. The smaller parts of the assembly are the first to be brazed before the larger parts. The quality of the brazing is tested before sandblasting the assembly. The filler metal applied is silver brazing alloy.

6.8 Sandblasting Manufacturing Method

The whole assembly is then sandblasted [9] to smoothen the surface. Sandblasting blasts abrasive material with high pressure to a rough surface to smoothen the surface. The media is applied to expand the abrasive material, which can be compressed air, pressurized fluid, or centrifugal wheel. Sandblasting removes any dirt or substances on the surface of the assembly which will prepare it for powder coating.

6.9 Powder Coat Manufacturing Method Process Plan

The assembly is powder coated [10] to give a durable quality finish. Powder coating will give the surface resistance to chipping, wearing, scratching and rusting.

The steps for powder coating are as follows:

WARNING: Wear safety googles, dust mask, and steel toe boots before starting.

1. Prepare the materials needed for powder coating.
2. Attach the ground clamp to the rack where the assembly are going to be hanged.
3. Hang the assembly to be powder coated.
4. Thoroughly spray the surface area of the assembly.
5. Inspect the part to make sure that the assembly is thoroughly powder coated before setting it in the oven.

WARNING: Wear heat-resistant gloves when removing the assembly from the oven.

6. Leave the assembly in the oven for 20 minutes.

7. COMPARISON AND ANALYSIS OF MANUFACTURING METHODS

7.1 Waterjet vs Plasma cut

The parts can either be cut by waterjet or plasma cut. Ideally the best process to cut the parts are with the waterjet rather than the plasma cut. The table below shows the comparison of the two process.

Table 1: Waterjet vs Plasma Comparison

Waterjet	Plasma cut
No heat is generated, better edge quality	Faster cutting speed, shorter lead time
No fumes are generated when cutting	Lower operating cost
Able to cut thick materials with reasonable quality	
Higher accuracy and precision	

As shown on Table 1, it is better to operate a waterjet than a plasma cut when cutting steel sheet. The important characteristic of the waterjet is that there is no heat generated when cutting which leads to a better edge quality. The material utilised is a 0.1196 in. steel sheet, which will warp if plasma cut.

7.2 Lost PLA Casting vs CNC Milling vs Direct Metal Laster Sintering

The head of the dragon can be manufactured by lost PLA casting, CNC milling or by direct metal laser sintering. The table below shows the comparison of the three processes.

Table 2: Lost PLA casting vs CNC milling vs Direct metal laser sintering

Lost PLA casting	CNC Milling	Direct metal laser sintering
Can manufacture complex part geometry, but sprues must be correctly placed	Unable to machine the cavities and undercuts for some complex part geometry	Highest manufacturing cost pert
Three processes, 3D printing, molding and casting	Needs jigs or fixtures for parts	Can manufacture complex part geometry
Quality of the finished product depends on experience and skill	Best surface finish	Wide variety of metals can be manufactured
Needs extensive PPE when casting	Most material waste	Porous surface finish
Needs multiple materials and equipment, i.e. plaster, 3D printer, oven, furnace	Reliable and reduced human error	Reliable and reduced human error

As shown on Table 2, lost PLA casting is the best process to manufacture the dragon head since BCIT have the materials and equipment needed. CNC milling is not feasible due to the geometry of the dragon head.

Table 19 shows that lost PLA casting is the best option when manufacturing low volume batches. Investment casting is for medium volume production and is between lost PLA casting and die casting in regards to cost. Die casting has the most initial cost and only viable for mass production. Direct metal laser sintering is the most expensive out of the four processes.

7.3 Brazing vs Welding

The joining process can either be torch brazed or shield metal arc welded. Shield metal arc welding is also known as stick welding. Table below shows the comparison of the two processes

Table 3: Brazing vs Welding

Torch brazing	Stick welding
The filler metal is melted to fuse the base metals	The base metals are melted to achieve fusion
Lower temperature, uses less energy	Stronger joints
Can join dissimilar metals	Not suitable for thin sheet metals
Better appearance	

As shown on table 3, brazing is a better process than welding when joining steel sheets. The steel sheet utilised for this project are thin, which is 0.1196 in., and using welding will cause defects such as:

1. Warping-welding melts two metal together to achieve fusion, but heat will be focused on one area for a long time, the sheet metal will warp due to heat
2. Distortion-the sheet metal will bend due to the welded area being heated while the other areas of the parts are cool, which will bend when the welded area start to cool
3. Over penetration-the sheet metal is thin and will cause bumps on the other side which is an aesthetic problem. This bump will be expensive to remove.

8. LESSONS LEARNED

8.1 Waterjet

There were a couple of problems that I encountered when operating the waterjet. The list below shows the lessons learned when operating the waterjet:

1. Make sure that the correct material thickness and material type is set up when cutting the part. The previous operator might have inputted a different material thickness and material type.
2. When setting up the material to be cut and using the go/no go gauge make sure that the nozzle height is correct. The height of the nozzle might be fine for that point, but when moving to a different point, the nozzle will be closer to the material. Applying sufficient weights when setting up will force the material down to be flat. When the waterjet is cutting and the nozzle is too close to the material, then the hose from the abrasive material will eject. The abrasive will start leaking and water will go up the abrasive hose.
3. Return the material to the designated place after the job is done. Other people will also want to operate the waterjet and nobody will use the waterjet when the material is still on the waterjet.

8.2 Lost PLA Casting

There were a couple of problems that I encountered when working on lost PLA casting. The list below shows the lessons learned when working on lost PLA casting:

1. Add sprues on the 3D models before 3D printing the parts. Adding the sprues through SolidWorks will have better outcome rather than manually adding wax sprues.
2. When drying the mold or burning out the PLA, heat the oven gradually. Turning the oven to a high temperature without pre heating will crack the mold which makes the mold unusable as

shown if Figure 15. Start from 50^{O}C for the first 30 minutes, and add 50^{O}C every 30 minutes. The drying temperature of the mold is 150^{O}C while its burnout time is 500^{O}C.

3. When burning out the PLA, use an oven with an open ventilation. The exhaust fan will not be sufficient to siphon the fumes of the PLA.

Figure 15: Mold Cracks due to High Temperature

8.3 Investment Casting and Die Casting

Investment casting and die casting utilizes a die patterns in order to form the part. The die pattern has two parts, but the geometry of the dragon head prevents the casted part from being ejected from the die. A parting line and shrinkage should be considered when redesigning the dragon head. The horns and other miscellaneous parts of the dragon can be removed to make the model simpler.

9. COST ESTIMATES AND ANALYSIS

This section presents the cost estimates of the various manufacturing processes including lost PLA casting, investment casting, and die casting for the production of the dragon assembly. The data values on this section are just estimates which include the cost, time and power consumption.

The cost of electricity [11] is $0.1403 $/kwh and the cost of water [12] is $4.297/unit, where 1 unit is 623 gallons. Each manufacturing process have a setup time every day (every 8 hours), cycle time, transition time and quality inspection time. The overhead cost includes rent, utilities, etc.

9.1 Waterjet Manufacturing Method Cost Analysis

The parts are to be cut using a waterjet using a 24 in.x24 in. 11 gauge (0.1198 in.) cold – rolled steel sheet. The quality of the cut is on good setting and an abrasive flow of 0.9 lb/min.The total perimeter of all the parts is 1340.0 in.. A simulator [13] was used to find the cut rate of the sheet thickness in table 1.

Table 4: Waterjet Cut time

Thickness [in]	Stacked amount	Cut Rate [ipm]	Cut Rate [iph]	Cut Time per stack [hr]	Cut+transition time for multiple sheets [hr]	Sheets to be cut	Total time [hr]
0.1196	1	23.00	1380.0	0.97	1004.35	1000	1035.73
0.2392	2	9.30	558.0	2.40	1217.38	500	1255.43
0.3588	3	5.40	324.0	4.14	1389.71	333	1433.14
0.4784	4	3.60	216.0	6.20	1559.26	250	1607.99
0.5980	5	2.70	162.0	8.27	1660.99	200	1712.89

Table 4 shows that it is faster to cut individual sheets rather than stacking the sheets together. The cut rate of cutting one sheet is faster than cutting multiple sheets.

Table 5: Waterjet Operating Cost

Electricity [$/hr]	Abrasive [$/hr]	Water [$/hr]	Pump replacement parts [$/hr]	Head replacement parts [$/hr]	Waterjet Operating Cost [$/hr]
$ 3.51	$ 10.80	$ 0.41	$ 3.00	$ 2.00	$ 19.72

Table 5 shows the operating cost of the waterjet. Electricity cost $0.1403/kWh and the waterjet have a power requirement of 25 kW leading to $3.51/hr. Water cost $4.297/unit where one unit is 623 gallons, and the waterjet needs 60 gallons/hr leading to $0.41/hr.

Table 6: Waterjet Cost Estimate

Quantity	Cut Rate [ipm]	Cut time [hr]	Total time [hr]	Labor [$17/hr]	Overhead [$5/hr]	Waterjet Operating Cost [19.72/hr]	Sheet metal cost	Total cost
1	23.0	1.00	**1.59**	$ 26.99	$ 7.94	$ 19.72	$ 54.06	**$ 108.71**
10	23.0	10.04	**11.50**	$ 195.58	$ 57.52	$ 197.20	$ 321.76	**$ 772.06**
100	23.0	100.43	**115.05**	$ 1,955.77	$ 575.23	$ 1,972.00	$ 2,838.25	**$ 7,341.25**
1,000	23.0	1,004.35	**1,150.45**	$ 19,557.70	$ 5,752.26	$ 19,720.00	$ 26,275.44	**$ 71,305.40**
10,000	23.0	10,043.48	**11,504.53**	$ 195,576.99	$ 57,522.64	$ 197,200.00	$ 193,762.90	**$ 644,062.54**
100,000	23.0	100,434.78	**115,045.29**	$ 1,955,769.93	$ 575,226.45	$ 1,972,000.00	$ 1,937,000.00	**$ 6,439,996.38**
1,000,000	23.0	1,004,347.83	**1,150,452.90**	$ 19,557,699.28	$ 5,752,264.49	$ 19,720,000.00	$ 19,370,000.00	**$ 64,399,963.77**

Table 6 shows the cost estimate of the waterjet process. The waterjet hasa a setup time of 30 minutes per day and transition time of 2 minutes per finished sheet, and a quality inspection time of 5 minutes per sheet. The price for the sheet metal was based from the Metalsupermarket [14] .

9.2 Lost PLA Casting Manufacturing Method Cost Analysis

Table 7: 3D print Cost Estimate

Quantity (skull and jaw)	Print time [hr]	Total time [hr]	Weight [kg]	Price per gram [0.1 $/g]	Labor - price per hour [$0.25/hr]	Overhead [0.1/hr]	Electricity [$0.007015/hr]	Filament [30 $/kg]	Total cost
1	59.117	**59.32**	0.18	$ 17.90	$ 14.83	$ 5.93	$ 0.41	$ 5.37	**$ 44.45**
10	591.17	**593.17**	1.79	$ 179.00	$ 148.29	$ 59.32	$ 4.15	$ 53.70	**$ 444.46**
100	5,911.67	**5,931.67**	17.90	$ 1,790.00	$ 1,482.92	$ 593.17	$ 41.47	$ 537.00	**$ 4,444.55**
1,000	59,116.67	**59,316.67**	179.00	$ 17,900.00	$ 14,829.17	$ 5,931.67	$ 414.70	$ 5,370.00	**$ 44,445.54**
10,000	591,166.67	**593,166.67**	1,790.00	$ 179,000.00	$ 148,291.67	$ 59,316.67	$ 4,147.03	$ 53,700.00	**$ 444,455.37**
100,000	5,911,666.67	**5,931,666.67**	17,900.00	$ 1,790,000.00	$ 1,482,916.67	$ 593,166.67	$ 41,470.34	$ 537,000.00	**$ 4,444,553.68**
1,000,000	59,116,666.67	**59,316,666.67**	179,000.00	$17,900,000.00	$14,829,166.67	$5,931,666.67	$414,703.42	$5,370,000.00	**$44,445,536.75**

Table 7 shows the cost estimate of the 3D print process. The 3D print has a setup time of 10 minutes for every print and a transition time of 1 minute per part and quality inspection of 1 minute per part. Electricity cost $0.1403/kWh and a 3D printer have a power requirement of 50 W or 0.05 kWh leading to $0.00702/hr.

Table 8: Lost PLA Molding Cost Estimate

Quantity (skull and jaw)	Mixing time [hr]	Total time [hr]	Plaster Used [kg]	Water Used [Gallon]	Labor cost [20/hr]	Plaster cost [$3.6/kg]	Overhead Cost [5/hr]	Water [$0.006897 /gallon]	Total Cost
1	0.33	**0.87**	7.70	0.79	$ 17.33	$ 27.72	$ 4.33	$ 0.01	**$ 49.39**
10	3.33	**4.17**	77.00	7.91	$ 83.33	$ 277.20	$ 20.83	$ 0.05	**$ 381.42**
100	33.33	**38.75**	770.00	79.09	$ 775.00	$ 2,772.00	$ 193.75	$ 0.55	**$ 3,741.30**
1,000	333.33	**387.50**	7,700.00	790.90	$ 7,750.00	$ 27,720.00	$ 1,937.50	$ 5.46	**$ 37,412.96**
10,000	3,333.33	**3,875.00**	77,000.00	7,909.00	$ 77,500.00	$ 277,200.00	$ 19,375.00	$ 54.55	**$ 374,129.55**
100,000	33,333.33	**38,750.00**	770,000.00	79,090.00	$ 775,000.00	$ 2,772,000.00	$ 193,750.00	$ 545.51	**$ 3,741,295.51**
1,000,000	333,333.33	**387,500.00**	7,700,000.00	790,900.00	$ 7,750,000.00	$ 27,720,000.00	$ 1,937,500.00	$ 5,455.05	**$ 37,412,955.05**

Table 8 shows the cost estimate for the lost PLA molding process. The setup time is 30 minutes every day with a mixing and pouring time of 20 minutes per part and quality inspection of 2 minute per part. The water/plaster ratio is 1:2.6. For every mold, both the skull and jaw need 7.7 kg of plaster and 0.79 gallons of water. Water cost $4.297/unit where one unit is 623 gallons, leading to $0.006987/gallon.

Table 9: Lost PLA Casting Cost Estimate

Quantity (skull and jaw)	Drying and Burnout Time [hr]	Casting time [hr]	Total time [hr]	Weight for skull and jaw [lb]	Labor [$23/hr]	Electricity for oven [$42.09/hr]	Electricity for furnace [$112.24/hr]	Overhead [$5/hr]	Material Cost [0.9/lb]	Total cost
1	15.00	0.05	**15.60**	1.09	$ 13.80	$ 631.35	$ 67.34	$ 78.00	$ 0.98	**$ 791.47**
10	15.00	0.50	**16.50**	10.87	$ 34.50	$ 631.35	$ 168.36	$ 82.50	$ 9.79	**$ 926.50**
100	30.00	5.00	**40.31**	108.75	$ 237.19	$ 1,262.70	$ 1,157.48	$ 201.56	$ 97.87	**$ 2,956.80**
1,000	300.00	50.00	**403.13**	1,087.45	$ 2,371.88	$ 12,627.00	$ 11,574.75	$ 2,015.63	$ 978.71	**$ 29,567.96**
10,000	3,000.00	500.00	**4,031.25**	10,874.50	$ 23,718.75	$ 126,270.00	$ 115,747.50	$ 20,156.25	$ 9,787.05	**$ 295,679.55**
100,000	30,000.00	5,000.00	**40,312.50**	108,745.00	$ 237,187.50	$ 1,262,700.00	$ 1,157,475.00	$ 201,562.50	$ 97,870.50	**$ 2,956,795.50**
1,000,000	300,000.00	50,000.00	**403,125.00**	1,087,450.00	$2,371,875.00	$12,627,000.00	$11,574,750.00	$2,015,625.00	$ 978,705.00	**$ 29,567,955.00**

Table 9 shows the cost estimate for the lost PLA casting process. The setup time is 30 minutes every day with a pouring time of 3 minutes every part and quality inspection of 3 minute for every part. In one setup 50 molds can fit inside one oven and 50 molds are casted. The weight of both the skull and jaw is 1.09 lb, and the material is aluminium.

Electricity costs $0.1403/kWh, the oven has a power requirement of 300 kWh, while the furnace have a power requirement of 800 kWh. The electricity cost of the part while still inside the oven is $42.09 hr. Since the aluminium needs to be molten when casting, the electricity cost of the furnace is $112.24/hr.

Table 10: Lost PLA Casting Grand Total Cost

Quantity (skull and jaw)	Concept Sketch [$20/hr for 5 hours]	CAD Model [$25/hr for 45 hours]	3D print total cost	Mold total cost	Cast total cost	Grand total cost
1	$ 100.00	$ 1,125.00	$ 44.45	$ 49.39	$ 791.47	**$ 2,110.31**
10	$ 100.00	$ 1,125.00	$ 444.46	$ 381.42	$ 926.50	**$ 2,977.37**
100	$ 100.00	$ 1,125.00	$ 4,444.55	$ 3,741.30	$ 2,956.80	**$ 12,367.64**
1,000	$ 100.00	$ 1,125.00	$ 44,445.54	$ 37,412.96	$ 29,567.96	**$ 112,651.45**
10,000	$ 100.00	$ 1,125.00	$ 444,455.37	$ 374,129.55	$ 295,679.55	**$ 1,115,489.47**
100,000	$ 100.00	$ 1,125.00	$ 4,444,553.68	$ 3,741,295.51	$ 2,956,795.50	**$ 11,143,869.68**
1,000,000	$ 100.00	$ 1,125.00	$ 44,445,536.75	$ 37,412,955.05	$ 29,567,955.00	**$ 111,427,671.80**

Table 10 is the total cost of the lost PLA process which includes the concept sketches, CAD modelling, 3D printing, molding and casting.

Table 11: Lost PLA Casting Grand Total Time

Quantity (skull and jaw)	Concept Sketch [hr]	CAD Model [hr]	3D print total time [hr]	Mold total time [hr]	Cast total time [hr]	Grand total time [hr]
1	5.00	45.00	59.32	0.87	15.60	**125.78**
10	5.00	45.00	593.17	4.17	16.50	**663.83**
100	5.00	45.00	5,931.67	38.75	40.31	**6,060.73**
1,000	5.00	45.00	59,316.67	387.50	403.13	**60,157.29**
10,000	5.00	45.00	593,166.67	3,875.00	4,031.25	**601,122.92**
100,000	5.00	45.00	5,931,666.67	38,750.00	40,312.50	**6,010,779.17**
1,000,000	5.00	45.00	59,316,666.67	387,500.00	403,125.00	**60,107,341.67**

Table 11 is the total time for the lost PLA process which includes concept sketching, CAD modelling, 3D printing, molding and casting.

9.3 Investment Casting Manufacturing Method Cost Analysis

Table 12: Investment Casting Cost Estimate

Quantity (skull and jaw)	Cycle Time [hr]	Total time [hr]	Weight for skull and part [lb]	Labor cost [$23/hr]	Overhead cost [$15/hr]	Electricity cost for casting [$140.3/hr]	Electricity cost for furnace [$112.24/hr]	Electricity cost for oven [$42.09/hr]	Material Cost [0.9/lb]	Tooling cost	Total cost
1	0.0250	**13.63**	1.09	$ 313.38	$ 204.38	$ 3.51	$ 2.81	$ 21.05	$ 0.98	$ 4,200.00	**$ 4,746.09**
10	0.2500	**14.75**	10.87	$ 339.25	$ 221.25	$ 35.08	$ 28.06	$ 21.05	$ 9.79	$ 4,200.00	**$ 4,854.47**
100	2.5000	**43.39**	108.75	$ 997.86	$ 650.78	$ 350.75	$ 280.60	$ 42.09	$ 97.87	$ 4,200.00	**$ 6,619.96**
1,000	25.0000	**433.85**	1,087.45	$ 9,978.65	$ 6,507.81	$ 3,507.50	$ 2,806.00	$ 420.90	$ 978.71	$ 4,200.00	**$ 28,399.56**
10,000	250.0000	**4,338.54**	10,874.50	$ 99,786.46	$ 65,078.13	$ 35,075.00	$ 28,060.00	$ 4,209.00	$ 9,787.05	$ 4,200.00	**$ 246,195.63**
100,000	2,500.0000	**43,385.42**	108,745.00	$ 997,864.58	$ 650,781.25	$ 350,750.00	$ 280,600.00	$ 42,090.00	$ 97,870.50	$ 4,200.00	**$ 2,424,156.33**
1,000,000	25,000.0000	**433,854.17**	1,087,450.00	$ 9,978,645.83	$6,507,812.50	$ 3,507,500.00	$ 2,806,000.00	$ 420,900.00	$ 978,705.00	$42,000.00	**$24,241,563.33**

Table 12 shows the cost estimate for the investment casting process. The setup time is 30 minutes every day, casting one part takes 90 seconds, it takes 30 minutes to make a family sprue consisting of 10 parts and the pouring time is 3 minutes for each part. The part needs to be dried after the ceramic slurry which would take 12 hours, 50 parts can be dried at the same time. The part needs to be put into the oven before casting which would take 30 minutes, 50 parts can be put in the oven at the same time. The quality inspection for each part takes 3 minutes each. The weight of both the skull and jaw is 1.09 lb, and the material is aluminium.

Investment casting is not available until the redesign of the dragon head.

Electricity costs $0.1403/kWh, the casting machine has a power requirement of 1000 kWh, the oven has a power requirement of 300 kwh and the furnace has a power requirement of 800 kWh. Since the aluminium needs to be molten when casting, the electricity cost of the furnace is $112.24/hr. The electricity cost of the part while still inside the oven is $42.09 hr. The electricity cost for the casting machine is $140.3/hr. The tooling cost [15] for the custom die is $4,200 and can be applied for 100,000 parts.

Table 13: Investment Casting Grand Total Cost

Quantity (skull and jaw)	Concept Sketch [$20/hr for 5 hours]	CAD Model [$25/hr for 45 hours]	Investment casting total cost	Grand total cost
1	$ 100.00	$ 1,125.00	$ 4,746.09	**$ 5,971.09**
10	$ 100.00	$ 1,125.00	$ 4,854.47	**$ 6,079.47**
100	$ 100.00	$ 1,125.00	$ 6,619.96	**$ 7,844.96**
1,000	$ 100.00	$ 1,125.00	$ 28,399.56	**$ 29,624.56**
10,000	$ 100.00	$ 1,125.00	$ 246,195.63	**$ 247,420.63**
100,000	$ 100.00	$ 1,125.00	$ 2,424,156.33	**$ 2,425,381.33**
1,000,000	$ 100.00	$ 1,125.00	$ 24,241,563.33	**$ 24,242,788.33**

Table 13 is the total cost of the investment casting process which includes the concept sketches, CAD modelling, and investment casting.

Table 14: Investment Casting Grand Total Time

Quantity (skull and jaw)	Concept Sketch [hr]	CAD Model [hr]	Tooling die manufacturing time [4 weeks][hr]	Investment casting total time [hr]	Grand total time [hr]
1	5.00	45.00	672.00	13.63	**735.63**
10	5.00	45.00	672.00	14.75	**736.75**
100	5.00	45.00	672.00	61.09	**783.09**
1,000	5.00	45.00	672.00	610.94	**1,332.94**
10,000	5.00	45.00	672.00	6,109.38	**6,831.38**
100,000	5.00	45.00	672.00	61,093.75	**61,815.75**
1,000,000	5.00	45.00	6,720.00	610,937.50	**617,707.50**

Table 14 is the total time for the investment casting process which includes concept sketching, CAD modelling, and investment casting.

9.4 Die Casting Manufacturing Method Cost Analysis

Table 15: Die Casting Cost Estimate

Quantity (skull and jaw)	Cycle time [hr]	Total time [hr]	Weight for skull and part [lb]	Labor cost [$23/hr]	Overhead cost [$15/hr]	Electricity cost for casting [$140.3/hr]	Electricity cost for furnace [$112.24/hr]	Material Cost [0.9/lb]	Tooling cost	Total cost
1	0.0278	**0.58**	1.09	$ 13.29	$ 8.67	$ 3.90	$ 3.12	$ 0.98	$ 36,400.00	**$ 36,429.95**
10	0.2778	**1.28**	10.87	$ 29.39	$ 19.17	$ 38.97	$ 31.18	$ 9.79	$ 36,400.00	**$ 36,528.49**
100	2.7778	**8.28**	108.75	$ 190.39	$ 124.17	$ 389.72	$ 311.78	$ 97.87	$ 36,400.00	**$ 37,513.93**
1,000	27.7778	**82.64**	1,087.45	$ 1,900.69	$ 1,239.58	$ 3,897.22	$ 3,117.78	$ 978.71	$ 36,400.00	**$ 47,533.98**
10,000	277.7778	**826.39**	10,874.50	$ 19,006.94	$ 12,395.83	$ 38,972.22	$ 31,177.78	$ 9,787.05	$ 36,400.00	**$ 147,739.83**
100,000	2,777.7778	**8,263.89**	108,745.00	$ 190,069.44	$ 123,958.33	$ 389,722.22	$ 311,777.78	$ 97,870.50	$ 36,400.00	**$ 1,149,798.28**
1,000,000	27,777.7778	**82,638.89**	1,087,450.00	$1,900,694.44	$1,239,583.33	$ 3,897,222.22	$ 3,117,777.78	$978,705.00	$364,000.00	**$11,497,982.78**

Table 15 shows the cost estimate for the die casting process. The setup time is 30 minutes every day, casting one part takes 100 seconds and quality inspection is 3 minutes for every part. The weight of both the skull and jaw is 1.09 lb, and the material used is aluminium.

Die casting is not available until the redesign of the dragon head.

Electricity costs \$0.1403/kWh, the casting machine has a power requirement of 1000 kWh, while the furnace has a power requirement of 800 kWh. Since the aluminium needs to be molten when casting, the electricity cost of the furnace is \$112.24/hr. The electricity cost for the casting machine is \$140.3/hr. The tooling cost [15] for the custom die is \$26,000 and can be applied for 100,000 parts.

Table 16: Die Casting Grand Total Cost

Quantity (skull and jaw)	Concept Sketch [$20/hr for 5 hours]	CAD Model [$25/hr for 45 hours]	Investment casting total cost	Grand total cost
1	$ 100.00	$ 1,125.00	$ 36,429.95	**$ 37,654.95**
10	$ 100.00	$ 1,125.00	$ 36,528.49	**$ 37,753.49**
100	$ 100.00	$ 1,125.00	$ 37,513.93	**$ 38,738.93**
1,000	$ 100.00	$ 1,125.00	$ 47,533.98	**$ 48,758.98**
10,000	$ 100.00	$ 1,125.00	$ 147,739.83	**$ 148,964.83**
100,000	$ 100.00	$ 1,125.00	$ 1,149,798.28	**$ 1,151,023.28**
1,000,000	$ 100.00	$ 1,125.00	$ 11,497,982.78	**$ 11,499,207.78**

Table 16 is the total cost of the die casting process which includes the concept sketches, CAD modelling, and die casting.

Table 17: Die Casting Grand Total Time

Amount to be manufactured	Concept Sketch [hr]	CAD Model [hr]	Tooling die manufacturing time [6 weeks][hr]	Investment casting total time [hr]	Grand total time [hr]
1	5.00	45.00	1,008.00	0.58	**1,058.58**
10	5.00	45.00	1,008.00	1.28	**1,059.28**
100	5.00	45.00	1,008.00	8.28	**1,066.28**
1,000	5.00	45.00	1,008.00	82.64	**1,140.64**
10,000	5.00	45.00	1,008.00	826.39	**1,884.39**
100,000	5.00	45.00	1,008.00	8,263.89	**9,321.89**
1,000,000	5.00	45.00	10,080.00	82,638.89	**92,768.89**

Table 17 is the total time for the die casting process which includes concept sketching, CAD modelling, and die casting.

9.5 Direct Metal Laser Sintering

Table 18: Direct Metal Laser Sintering Cost and Lead Time

Company	Quantity	Skull Cost	Jaw Cost	Concept Sketch [$20/hr for 5 hours]	CAD Model [$25/hr for 45 hours]	Total Cost	Lead time [days]
3DHub	1	$ 2,055.08	$ 697.71	$ 100.00	$ 1,125.00	**$ 3,977.79**	10
	10	$ 5,743.50	$ 1,913.20	$ 100.00	$ 1,125.00	**$ 8,891.70**	11
	100	$ 41,246.00	$ 12,862.00	$ 100.00	$ 1,125.00	**$ 55,433.00**	16
	1,000	$ 320,600.00	$ 105,920.00	$ 100.00	$ 1,125.00	**$ 428,745.00**	41
Xometry	1	$1,237.71	$ 395.63	$ 100.00	$ 1,125.00	**$ 2,859.34**	9
	10	$7,530.00	$2,292.70	$ 100.00	$ 1,125.00	**$ 11,057.70**	15
	100	$73,482.00	$22,372.00	$ 100.00	$ 1,125.00	**$ 97,179.00**	17
	1,000	$692,410.00	$222,430.00	$ 100.00	$ 1,125.00	**$ 917,065.00**	17

Table 18 shows the quotes from the company 3DHub and Xometry for manufacturing the skull and the jaw by direct metal laser sintering. The total cost includes concept sketching. CAD modelling and 3D printing of the skull and jaw.

9.6 Dragon Head Manufacturing Cost Comparison

Table 19: Dragon Head Manufacturing Cost

Quantity	Lost PLA casting	Investment casting	Die casting	Direct metal laser sintering
1	$ 2,110.31	$ 5,971.09	$ 37,654.95	$ 2,859.34
10	$ 2,977.37	$ 6,079.47	$ 37,753.49	$ 8,891.70
100	$ 12,367.64	$ 7,912.25	$ 38,738.93	$ 55,433.00
1,000	$ 112,651.45	$ 30,297.48	$ 48,758.98	$ 428,745.00
10,000	$ 1,115,489.47	$ 254,149.80	$ 148,964.83	-
100,000	$ 11,143,869.68	$ 2,492,673.00	$ 1,151,023.28	-
1,000,000	$ 111,427,671.80	$ 24,915,705.00	$ 11,499,207.78	-

Table 19 shows that lost PLA casting is the best option when manufacturing low volume batches. Investment casting is for medium volume production and is between lost PLA casting and die casting in regards to cost. Die casting has the most initial cost and only viable for mass production. Direct metal laser sintering is the most expensive out of the four processes.

9.7 Brazing Manufacturing Method Cost Analysis

Table 20: Brazing Cost Estimate

Quantity of assembly	Cycle Time [hr]	Total Time [hr]	Labor cost [$27/hr]	Overhead cost [$15/hr]	Total Cost
1	2.00	**2.43**	$ 65.70	$ 36.50	**$ 102.20**
10	20.00	**21.88**	$ 590.63	$ 328.13	**$ 918.75**
100	200.00	**218.75**	$ 5,906.25	$ 3,281.25	**$ 9,187.50**
1,000	2,000.00	**2,187.50**	$ 59,062.50	$ 32,812.50	**$ 91,875.00**
10,000	20,000.00	**21,875.00**	$ 590,625.00	$ 328,125.00	**$ 918,750.00**
100,000	200,000.00	**218,750.00**	$ 5,906,250.00	$ 3,281,250.00	**$ 9,187,500.00**
1,000,000	2,000,000.00	**2,187,500.00**	$ 59,062,500.00	$ 32,812,500.00	**$ 91,875,000.00**

Table 20 shows the cost estimate for the brazing process. Brazing has a setup time of 20 minutes per day, transition time of 3 minutes per assembly, cycle time of 2 hours per assembly, and a quality inspection time of 3 minutes per assembly.

9.8 Sandblast Manufacturing Method Cost Analysis

Table 21: Sandblasting Cost Estimate

Quantity of assembly	Cycle time [hr]	Total time [hr]	Labor cost [$19/hr]	Overhead cost [$10/hr]	Total Cost
1	0.07	**0.62**	$ 11.72	$ 6.17	**$ 17.88**
10	0.67	**1.67**	$ 31.67	$ 16.67	**$ 48.33**
100	6.67	**12.40**	$ 235.52	$ 123.96	**$ 359.48**
1,000	66.67	**123.96**	$ 2,355.21	$ 1,239.58	**$ 3,594.79**
10,000	666.67	**1,239.58**	$ 23,552.08	$ 12,395.83	**$ 35,947.92**
100,000	6,666.67	**12,395.83**	$ 235,520.83	$ 123,958.33	**$ 359,479.17**
1,000,000	66,666.67	**123,958.33**	$ 2,355,208.33	$ 1,239,583.33	**$ 3,594,791.67**

Table 21 shows the cost estimate for the sandblasting process. Sandblasting has a setup time of 30 minutes per day, transition time of 1 minute per assembly, duration of 3 minutes per assembly, and a quality inspection time of 3 minutes per part.

The total surface area of all the parts is 693.78 in².

9.9 Powder Coat Manufacturing Method Cost Analysis

Table 22: Powder Coating Cost Estimate

Quantity of assembly	Cycle time [hr]	Total time [hr]	Labor cost [$23/hr]	Overhead cost [$15/hr]	Electricity for oven [$42.09/hr]	Total Cost
1	0.45	**0.95**	$ 21.85	$ 14.25	$ 14.03	**$ 50.13**
10	1.50	**2.00**	$ 46.00	$ 30.00	$ 14.03	**$ 90.03**
100	15.00	**15.94**	$ 366.56	$ 239.06	$ 28.06	**$ 633.69**
1,000	150.00	**159.38**	$ 3,665.63	$ 2,390.63	$ 280.60	**$ 6,336.85**
10,000	1,500.00	**1,593.75**	$ 36,656.25	$ 23,906.25	$ 2,806.00	**$ 63,368.50**
100,000	15,000.00	**15,937.50**	$ 366,562.50	$ 239,062.50	$ 28,060.00	**$ 633,685.00**
1,000,000	150,000.00	**159,375.00**	$ 3,665,625.00	$ 2,390,625.00	$ 280,600.00	**$ 6,336,850.00**

Table 22 shows the cost estimate for the powder coating process. Powdercoating has a setup time of 30 minutes per day, duration of 2 minutes per assembly, transition time of 1 minute per assembly, and a quality inspection time of 2 minutes per assembly.

Electricity costs $0.1403/kWh, the oven has a power requirement of 300 kWh. The electricity cost of the part while still inside the oven is $42.09 hr. One oven can fit 10 assembly.

The total surface area of all the parts is 693.78 in².

10. BREAK-EVEN POINT COST ANALYSIS

The break-even point is the quantity which a manufacturing process is more economically viable compared to another manufacturing process.

Investment casting and die casting are included, assuming that the dragon head was redesigned to a simpler model where it can be easily ejected from the die.

Lost PLA casting is compared to investment casting, and investment casting is compared to die casting.

10.1 Lost PLA Casting vs Investment Casting

Tables 23 to 26 are the break-even quantity for lost PLA casting and investment casting regarding the total cost and total manufacturing time.

Table 23: Lost PLA Casting vs Investment Casting Cost Comparison

Lost PLA Casting						
Quantity	Concept Sketch [$20/hr for 5 hours]	CAD Model [$25/hr for 45 hours]	3D print total	Mold total cost	Casting total cost	Grand total cost
46	$ 100.00	$ 1,125.00	$ 2,044.49	$ 1,709.54	$ 1,466.59	**$ 6,445.63**

Investment Casting				
Quantity	Concept Sketch [$20/hr for 5 hours]	CAD Model [$25/hr for 45 hours]	Investment casting total cost	Grand total cost
46	$ 100.00	$ 1,125.00	$ 5,240.27	**$ 6,465.27**

Table 24: Lost PLA Casting vs Investment Casting Time Comparison

Lost PLA Casting						
Quantity	Concept Sketch [hr]	CAD Model [hr]	3D print total time [hr]	Mold total time [hr]	Cast total time [hr]	Grand total time [hr]
46	5.00	45.00	59.32	17.37	20.10	**146.78**
Investment Casting						
Quantity	Concept Sketch [hr]	CAD Model [hr]	Investment casting total time [hr]	Tooling die manufacturing time [4 weeks][hr]		Grand total time [hr]
46	5.00	45.00	20.77	672.00		**742.77**

The break-even point for lost PLA casting and investment casting is 46 units. Manufacturing 46 units by lost PLA casting will cost $6,445.63 which is less expensive than manufacturing using investment casting which will cost $6,465.27.

It is advantageous to manufacture using lost PLA casting when the quantity of units is 46 or less.

The total time of lost PLA casting is 146.78 hours which is faster than investment casting which has a total time of 742.77 hours. Lost PLA casting is ideal for low volume production.

10.2 Investment Casting vs Die Casting

Tables 20 and 21 are the break-even quantity for lost PLA casting and investment casting regarding the total cost and total manufacturing time.

Table 25: Investment Casting vs Die Casting Cost Comparison

Investment Casting				
Quantity	Concept Sketch [$20/hr for 5 hours]	CAD Model [$25/hr for 45 hours]	Investment casting total cost	Grand total cost
2,343	$ 100.00	$ 1,125.00	$ 63,701.22	**$ 64,926.22**

Die Casting				
Quantity	Concept Sketch [$20/hr for 5 hours]	CAD Model [$25/hr for 45 hours]	Die casting total cost	Grand total cost
2,343	$ 100.00	$ 1,125.00	$ 63,711.92	**$ 64,936.92**

Table 26: Investment Casting vs Die Casting Time Comparison

Investment Casting					
Quantity	Concept Sketch [hr]	CAD Model [hr]	Tooling die manufacturing time [4 weeks][hr]	Investment casting total time [hr]	Grand total time [hr]
2,343	5.00	45.00	672.00	1058.01	**1,780.01**

Die Casting					
Quantity	Concept Sketch [hr]	CAD Model [hr]	Tooling die manufacturing time [6 weeks][hr]	Die casting total time [hr]	Grand total time [hr]
2,343	5.00	45.00	1008.00	193.62	**1,251.62**

The break-even point for investment casting and die casting are 2,343 units. Manufacturing 2,343 units by investment casting will cost $64,926.22 which is less expensive than manufacturing using investment casting which will cost $64,936.92.

It is advantageous to manufacture using die casting when the quantity of units is more than 2,343.

The advantage of manufacturing by die casting is the total time is 1,251.62 hours which is faster than investment casting which has a total time of 1,780.01 hours. Die casting is ideal for high volume production.

11. TOTAL MANUFACTURING COST AND TIME

Table 27: Total Manufacturing Cost and Average Cost

Casting Process	Quantity of assembly	Waterjet Cost	Casting Process Cost	Brazing Cost	Sandblast Cost	Powder Coat Cost	Total Cost	Average cost of manufacturing one assembly
Lost PLA Casting	1	$ 108.71	$ 2,110.31	$ 102.20	$ 17.88	$ 50.13	**$ 2,389.23**	**$ 2,389.23**
	10	$ 772.06	$ 2,977.37	$ 918.75	$ 48.33	$ 90.03	**$ 4,806.55**	**$ 480.65**
Investment Casting	100	$ 7,341.25	$ 7,912.25	$ 9,187.50	$ 359.48	$ 633.69	**$ 25,434.16**	**$ 254.34**
	1,000	$ 71,305.40	$ 30,297.48	$ 91,875.00	$ 3,594.79	$ 6,336.85	**$ 203,409.53**	**$ 203.41**
Die Casting	10,000	$ 644,062.54	$ 148,964.83	$ 918,750.00	$ 35,947.92	$ 63,368.50	**$ 1,811,093.78**	**$ 181.11**
	100,000	$ 6,439,996.38	$ 1,151,023.28	$ 9,187,500.00	$ 359,479.17	$ 633,685.00	**$ 17,771,683.82**	**$ 177.72**
	1,000,000	$ 64,399,963.77	$ 11,499,207.78	$ 91,875,000.00	$ 3,594,791.67	$ 6,336,850.00	**$177,705,813.21**	**$ 177.71**

Table 27 shows the recommended manufacturing procedure, the total manufacturing cost for producing each corresponding quantity and average cost of manufacturing one assembly. The average cost of manufacturing an assembly decreases as the quantity increases.

Table 28: Total Manufacturing Time and Average Time

Casting Process	Quantity of assembly	Waterjet Time [hr]	Casting Process Time [hr]	Brazing Time [hr]	Sandblast Time [hr]	Powder Coat Time [hr]	Total Time [hr]	Average time of manufacturing one assembly [hr]
Lost PLA Casting	1	1.59	125.78	2.43	0.62	0.95	**131.37**	**131.37**
	10	11.50	663.83	21.88	1.67	2.00	**700.88**	**70.09**
Investment Casting	100	115.05	767.16	218.75	12.40	15.94	**1,129.28**	**11.29**
	1,000	1,150.45	1,173.56	2,187.50	123.96	159.38	**4,794.85**	**4.79**
Die Casting	10,000	11,504.53	1,884.39	21,875.00	1,239.58	1,593.75	**38,097.25**	**3.81**
	100,000	115,045.29	9,321.89	218,750.00	12,395.83	15,937.50	**371,450.51**	**3.71**
	1,000,000	1,150,452.90	92,768.89	2,187,500.00	123,958.33	159,375.00	**3,714,055.12**	**3.71**

Table 28 shows the recommended manufacturing procedure, the total manufacturing time for producing each corresponding quantity and average time of manufacturing one assembly. The average time of manufacturing an assembly decreases as the quantity increases.

12. FAILURE MODE EFFECT ANALYSIS

Table 29: Failure Mode Effect Analysis for the Dragon Assembly

Dragon Assembly FMEA

Process	Potential Failure Mode	Potential Failure Effect	Severity	Potential Cause of Failure	Occurrence	Current Process Control	Detection	Risk Priority Number	Recommended Action
Waterjet cutting	Waterjet malfunctions	Lost time and resources	7	Too much sand in waterjet	3	Observe if the water is dirty	1	21	Clean waterjet every 3 months
			7	Not enough pressure	5	Check pressure gauge	2	70	Regularly check system pressure
Lost PLA Casting	Mold cracks	Unusable mold	8	Rapid heating when drying	3	Check oven temperature	3	72	Gradual increase of the oven temperature
	Rough Casting	Lost time and resources	9	Incorrect water/plaster ratio	5	Weigh the water and plaster for the correct ratio	2	90	Check the recommended water/plaster ratio
	Incomplete fill/Misrun	Lost time and resources	9	Metal too cold	3	Check metal temperature before pouring	1	27	Immediately pour the molten metal to the mold since metal might turn cold
	Porosity	Lost time and resources	9	Vacuum pump not working properly	4	Check the vaccum chamber for any leak	3	108	Seal the vacuum chamber with sealing tape when using
Investment Casting	Mold cracks	Unusable mold	7	Ceramic got into the cracks of the wax mold	2	Check mold quality	5	70	Check every wax mold
	Rough Casting	Lost time and resources	9	Incorrect water/plaster ratio	5	Weigh the water and plaster for the correct ratio	1	45	Machine needs maintenance or new mold cavity is needed
	Incomplete fill/misrun	Lost time and resources	8	Metal too cold	4	Check metal temperature before pouring	2	64	Immediately pour the molten metal to the mold since metal might turn cold
	Porosity	Lost time and resources	7	Trapped air bubbles	5	Air bubbles on the surface	3	105	Melt the aluminum in a vacuum
Die Casting	Rough Casting	Lost time and resources	9	Incorrect water/plaster ratio	4	Weigh the water and plaster for the correct ratio	1	36	Machine needs maintenance or new mold cavity is needed
	Incomplete fill/misrun	Lost time and resources	7	Metal too cold	4	Check metal temperature before pouring	1	28	Immediately pour the molten metal to the mold since metal might turn cold
	Porosity	Lost time and resources	7	Trapped air bubbles	4	Air bubbles on the surface	4	112	Melt the aluminum in a vacuum
Sand Blast	Sandblaster won't pressurize or maintain	Lost time and resources	5	Malfunctioning air inlet or air exhaust valve	2	Regular sandblaster maintenance	1	10	Immediately replace the broken valve
Powder Coat	Poor powder penetration	Powder would not coat holes, grooves, inside corners	5	Powder delivery too low	3	Visual inspection of the part	1	15	Increase powder delivery setting or use barrel extension

Severity is the seriousness of the failure mode, the higher the rating then the severity is more significant. The occurrence is the chance that the failure will happen, the higher the rating then the failure is more likely to happen. The detection is the chance to detect the failure mode, the lower the rating then the failure mode is easier to identify.

Table 29 shows that the greatest risk is porosity on casting the dragon head. The solution for this failure mode is utilizing a vacuum chamber to release the trapped air bubbles.

13. CONCLUSION

The dragon assembly will be manufactured at BCIT using waterjet, lost PLA casting, sandblasting, and powder coating. The dragon head can be manufactured by investment casting and die casting, but the dragon head have to be redesigned to a simpler model by removing the horns and other miscellaneous parts. Direct metal laser sintering can also be applicable to manufacture the dragon head, but it is too expensive.

Lost PLA casting is ideal when the quantity to be manufactured is 46 units or less. Investment casting should be used when manufacturing from 47 to 2,342 units. Die casting is recommended for high production of more than 2,343 units. The manufacturing cost and time for the production of an assembly decreases as the number of quantity increases.

14. RECOMMENDATION

To manufacture the assembly using lost PLA casting:

1. Order the parts needed for the project which are:
   a. PPE equipment: steel-toe shoes, safety glasses, hearing protection, etc.
   b. 24 in.x24 in. 11 gauge (0.1196 in) cold-rolled steel sheet
   c. Investment plaster
2. Redesign the dragon head to a simpler model.
3. Start the lost PLA casting immediately since failure rate is high for inexperience casters.
4. Plan when to operate the waterjet since a lot of people will operate the machine.

15. REFERENCES

[1] Tailortech, "https://www.instructables.com/workshop/," 14 October 2017. [Online]. Available: https://www.instructables.com/id/3D-Printed-Lost-PLA-Investment-Casting-Aluminium/. [Accessed 23 February 2020].

[2] dmaccallum, "https://www.thingiverse.com/," 2 March 2016. [Online]. Available: https://www.thingiverse.com/thing:1386439. [Accessed 16 February 2020].

[3] D. Olsen, "https://www.metaltek.com/," MetalTek, 15 January 2020. [Online]. Available: https://marketing.metaltek.com/smart-blog/what_is_investment_casting_and_how_does_it_work. [Accessed 18 April 2020].

[4] "https://www.dynacast.com/en," Dynacast, 14 April 2020. [Online]. Available: https://www.dynacast.com/en/specialty-die-casting/die-cast-process/cold-chamber-die-casting. [Accessed 22 April 2020].

[5] "https://all3dp.com/," 2020. [Online]. Available: https://all3dp.com/2/direct-metal-laser-sintering-dmls-simply-explained/. [Accessed 2 May 2020].

[6] "https://www.3dhubs.com/," 3DHubs, 2020. [Online]. Available: https://www.3dhubs.com/. [Accessed 1 May 2020].

[7] "https://www.xometry.com/," Xometry, 2020. [Online]. Available: https://www.xometry.com/. [Accessed 1 May 2020].

[8] "https://www.bernzomatic.com/," Bernzomatic, 2020. [Online]. Available: https://www.bernzomatic.com/Projects/DIY/Braze-Metal-Together. [Accessed 22 April 2020].

[9] "https://www.princeton.edu/," [Online]. Available: https://www.princeton.edu/~timeteam/sandblasting.html. [Accessed 22 April 2020].

[10] newdetroiter, "https://www.instructables.com/workshop/," 2015. [Online]. Available: https://www.instructables.com/id/Powder-Coating-Basics/. [Accessed 22 April 2020].

[11] "https://vancouver.ca/default.aspx," 2020. [Online]. Available: https://vancouver.ca/home-property-development/metered-rates.aspx. [Accessed 11 April 2020].

[12] "https://www.bchydro.com/index.html," BC Hydro, 2020. [Online]. Available: https://app.bchydro.com/accounts-billing/rates-energy-use/electricity-rates/residential-rates.html. [Accessed 11 April 2020].

[13] "https://my.wardjet.com/," Ward Jet, 2020. [Online]. Available: https://wardjet.com/products/waterjet/software/waterjet-feedrate-calculator. [Accessed 12 April 2020].

[14] "https://ecommerce.metalsupermarkets.com/msc-home.aspx?Country=CA," METAL Supermarkets, 2020. [Online]. Available: https://ecommerce.metalsupermarkets.com/catalog/STEEL-COLD_ROLLED/SHEET/A1008_-_CQ. [Accessed 16 February 2020].

[15] "http://www.iron-foundry.com/index.html," Dandong Foundry, [Online]. Available: http://www.iron-foundry.com/mould-pattern-cost-cast-iron-sand-castings-steel-castings.html. [Accessed 12 April 2020].

[16] R. Taylor, "https://drawingref.com/," [Online]. Available: https://drawingref.com/dragon-head/. [Accessed 23 December 2019].

[17] J.-M. Tsang, "http://blogs.bu.edu/biolocomotion/," 16 October 2011. [Online]. Available: http://blogs.bu.edu/biolocomotion/2011/10/16/bats-the-only-flying-mammal/. [Accessed 23 December 2019].

[18] R. Lydekker, "https://commons.wikimedia.org/wiki/Main_Page," 1879. [Online]. Available: https://commons.wikimedia.org/wiki/File:Crocodilelyd5.png. [Accessed 23 December 2019].

[19] T. Camehl, "https://www.artstation.com/," 2016. [Online]. Available: https://www.artstation.com/artwork/aDOm2. [Accessed December 23 2019].

[20] "https://www.custompartnet.com/," 2020. [Online]. Available: https://www.custompartnet.com/wu/die-casting. [Accessed 12 April 2020].

16. APPENDIX

16.1 Ribs 1-7

To begin this project, hand sketches of the design were generated. The hand sketches are shown below in Figures 16 through to 38.

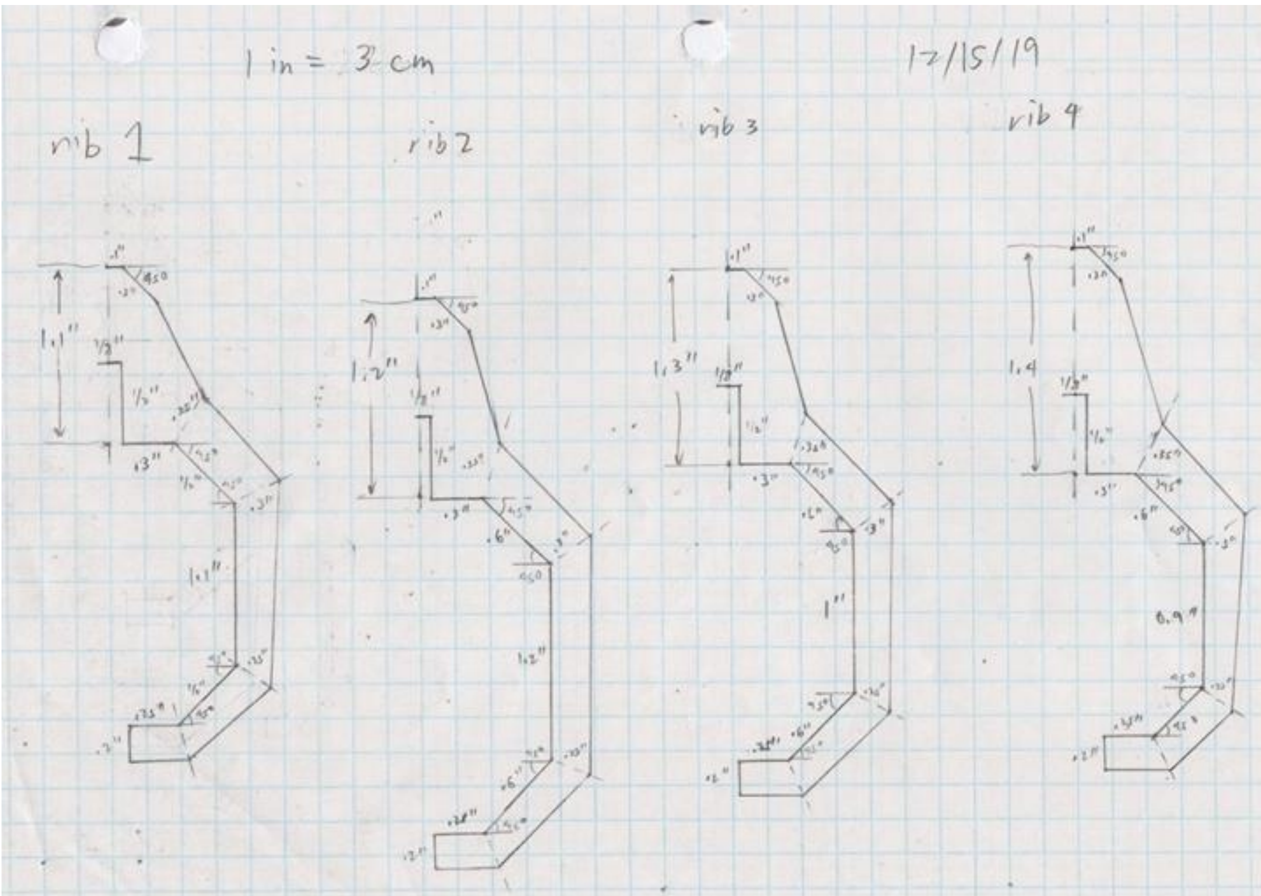

Figure 16: Ribs 1-4

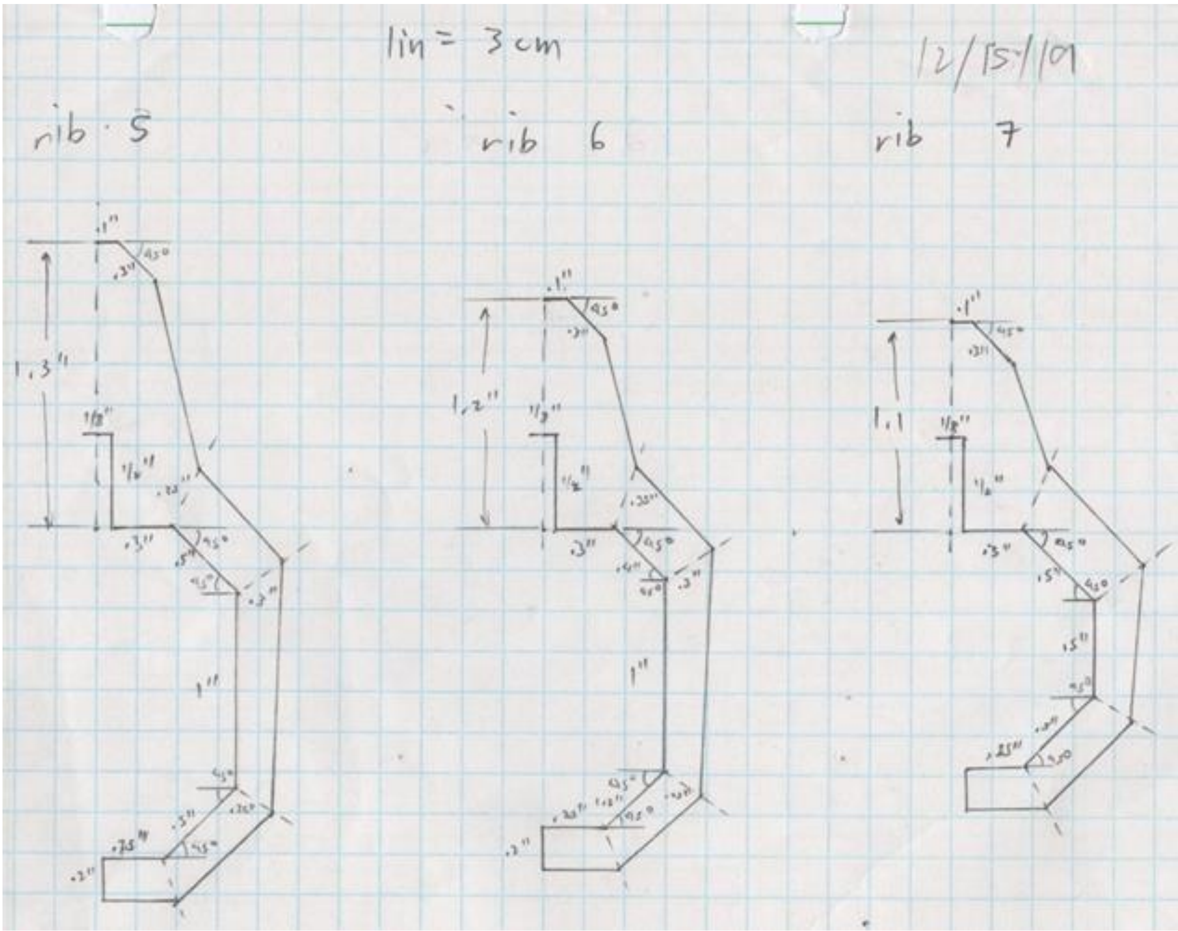

Figure 17: Ribs 5-7

Figure 16 and 17 are the very first sketch that I drew for the project. I only sketched half of it since the model will be mirrored in SolidWorks.

16.2 Dragon Head

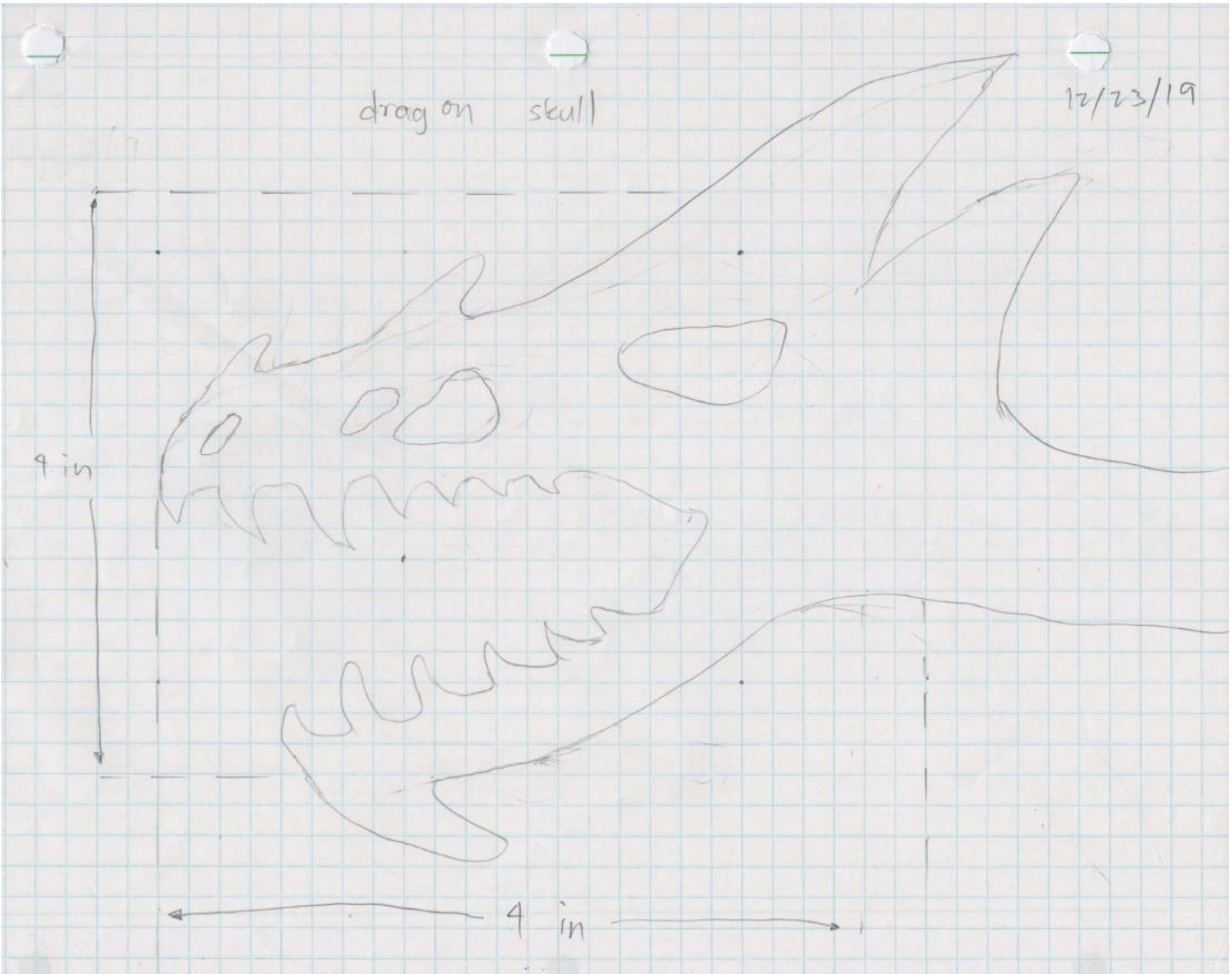

Figure 18: Dragon Head

Figure 18 only shows height and length since the dragon head is traced in SolidWorks. I tried dimensioning when sketching, but it looked blocky. After many attempts, I decided to sketch the head by looking at images of dragons [16] and then used lines to spline the dragon head.

The slots for the joints are made after modeling the parts.

Three parts for the head which are derived from this sketch. The plans for manufacturing the assembly was changed, so a new model will be casted with a lost PLA process.

16.3 Wings Part 1,2 & 3

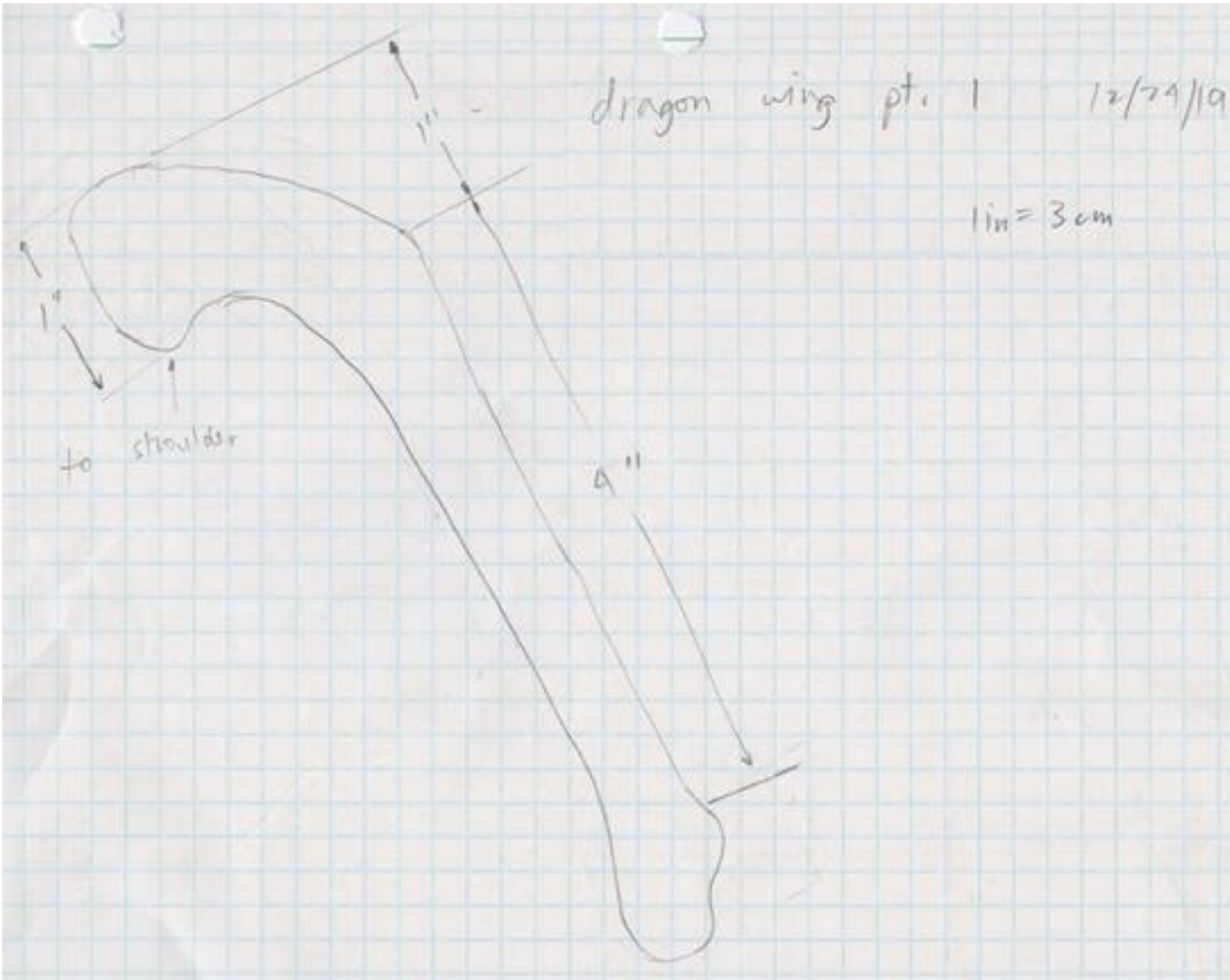

Figure 19: Dragon Wing part 1

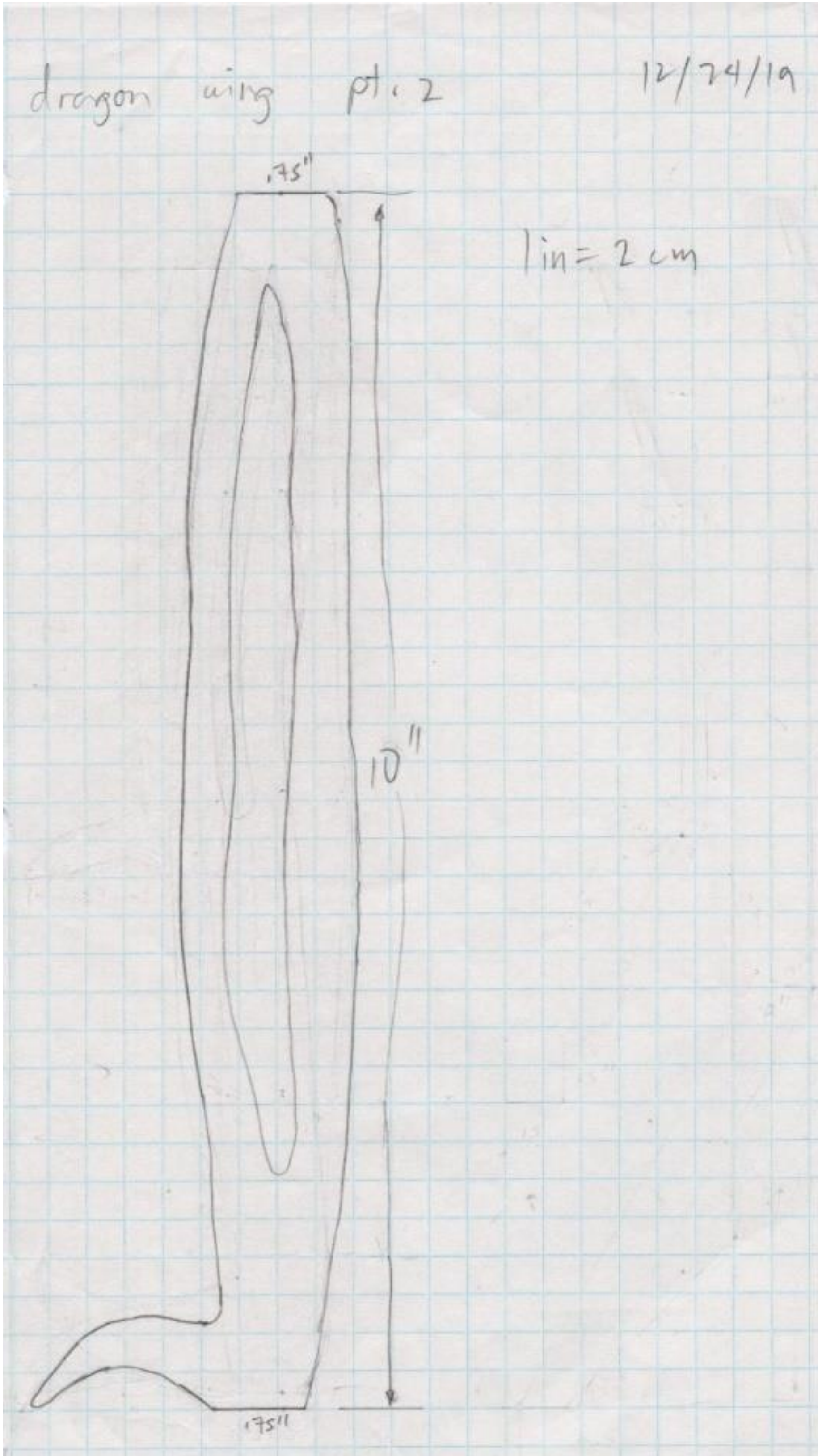

Figure 20: Dragon Wing part 2

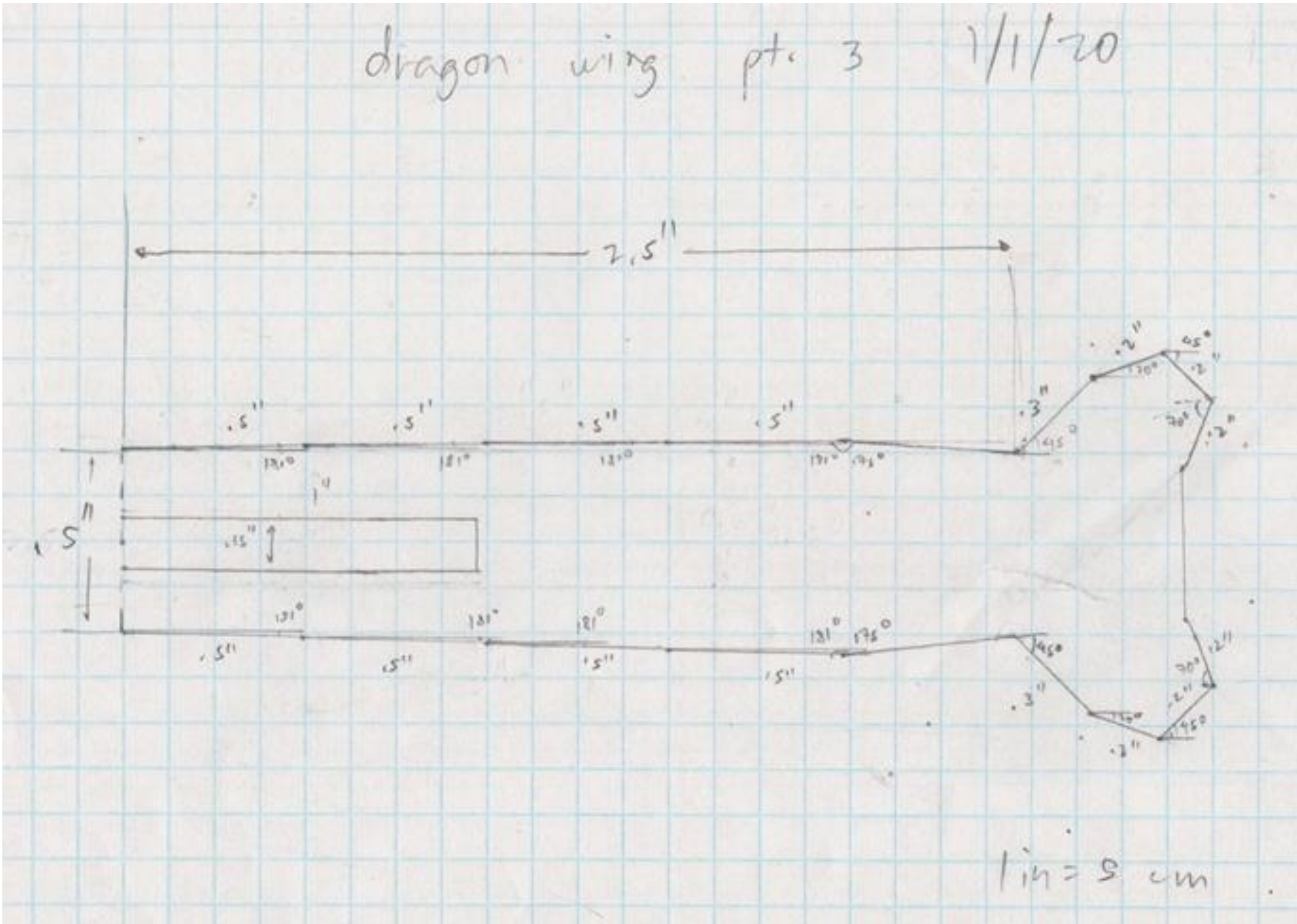

Figure 21: Dragon Wing part 3

The reference for the dragon wings for Figure 19 to 21 are images of bat wings [17].The first and second parts of dragon wings are traced using lines and splines.

Unlike the first and second part which was sketched free hand, the third part was dimensioned. The only downside is that the third part looked different from the rest.

Each part is manufactured twice both for the left and right side for symmetry.

16.4 Spine v1 & v2

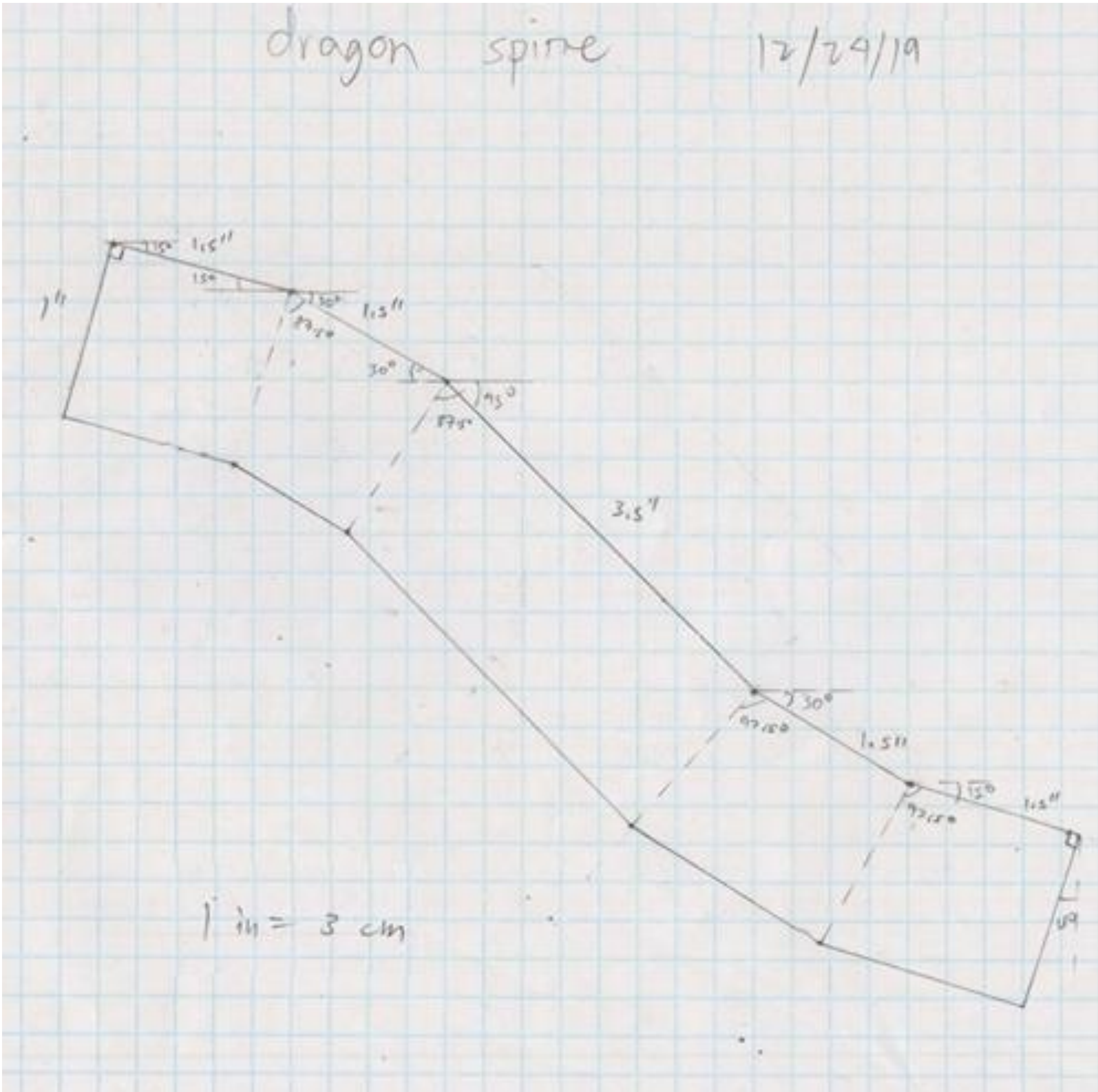

Figure 22: Dragon Spine – v1

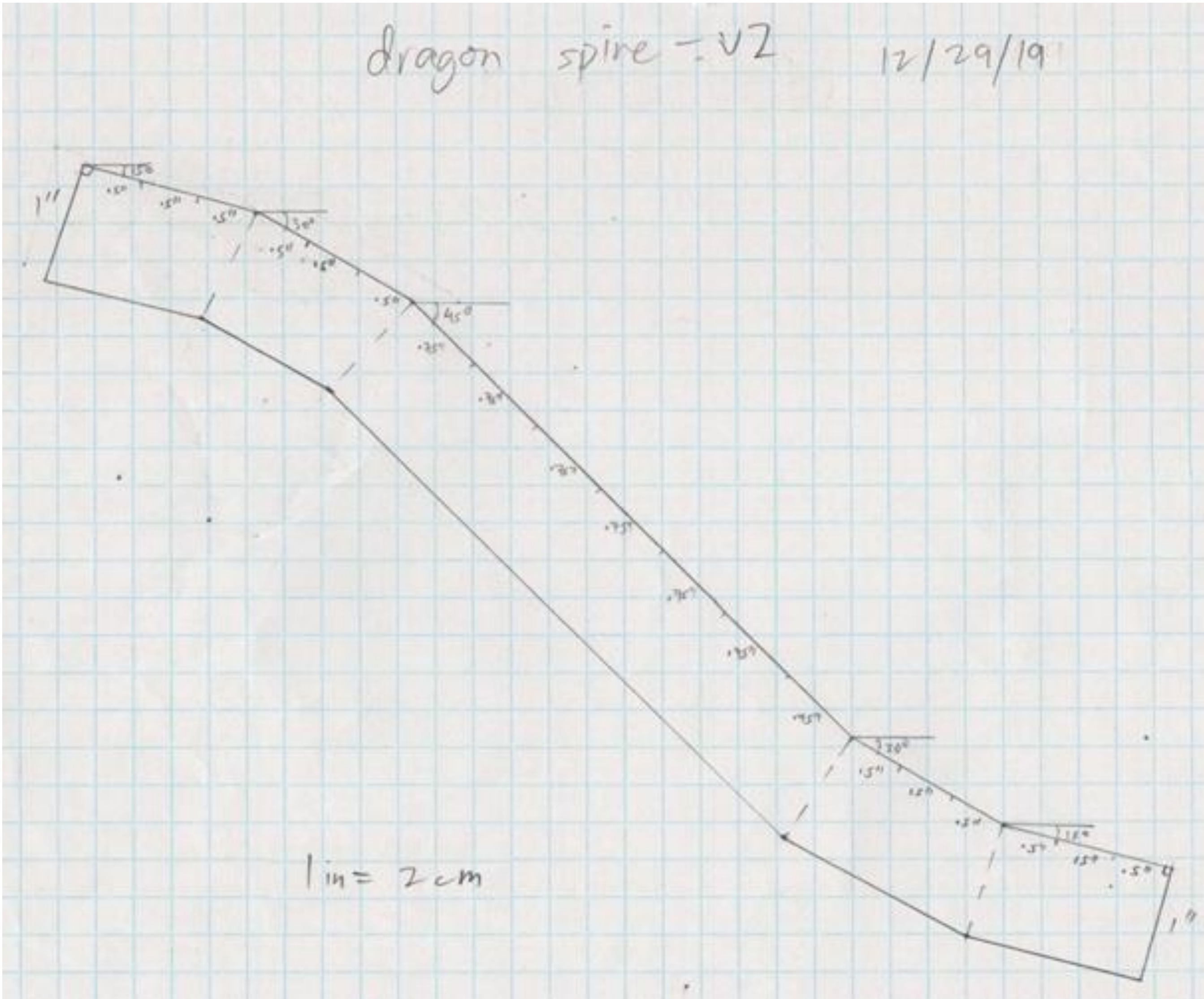

Figure 23: Dragon Spine – v2

Two sketches were made for the spine since the first sketch, Figure 22 was short so I made Figure 23 longer. I didn't realize this mistake until I was modeling the first version. The middle part of the spine is 3.5 in. for the first version and 5.25 in.for the second version.

16.5 Tail

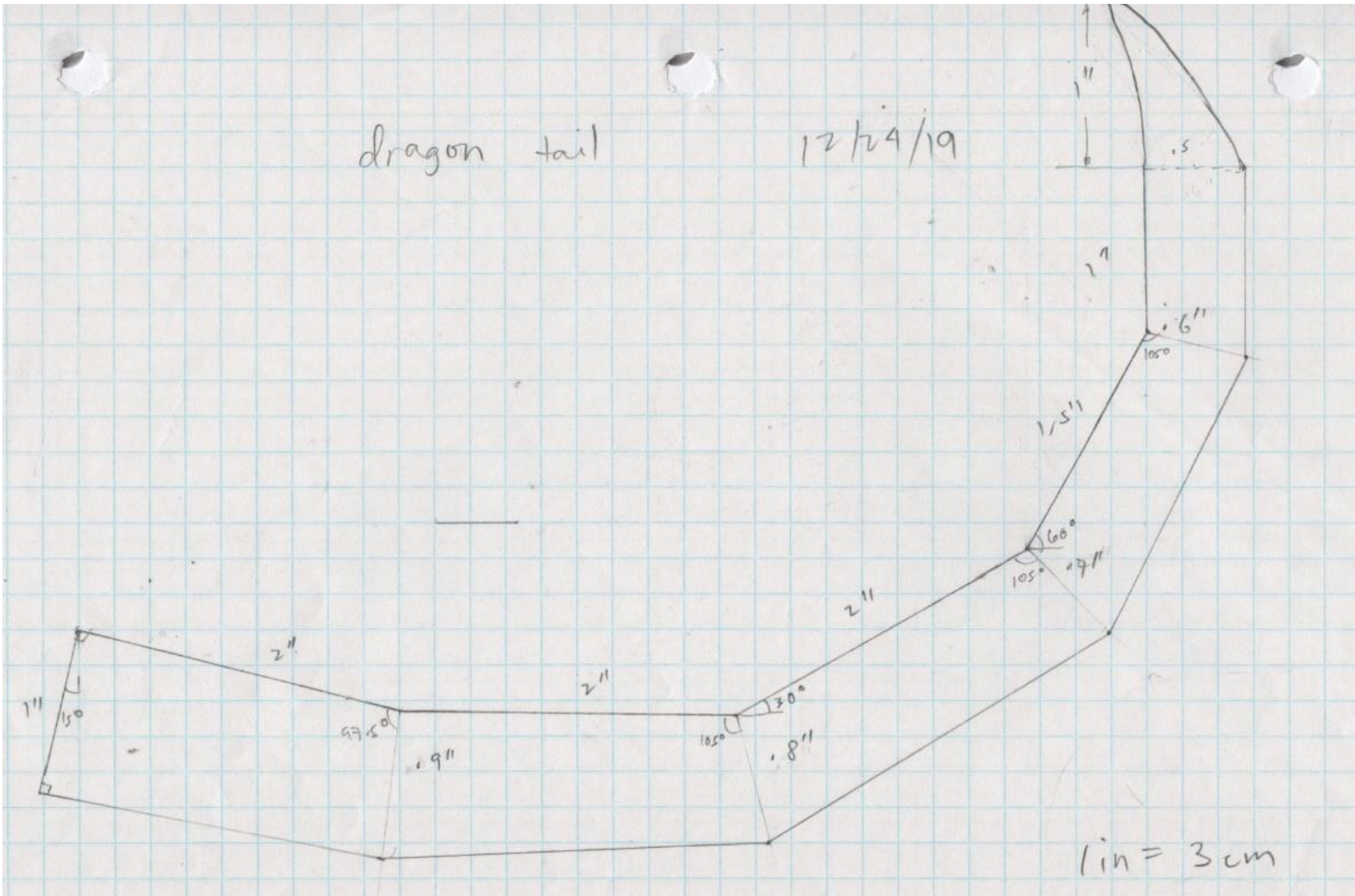

Figure 24: Dragon Tail

I used a crocodile tail [18] as a reference for sketching the dragon tail for Figure 24. The tail is longer than the spine to help the assembly to stand up. Extra details will also be added to the end of the tail.

16.6 Legs & Arms

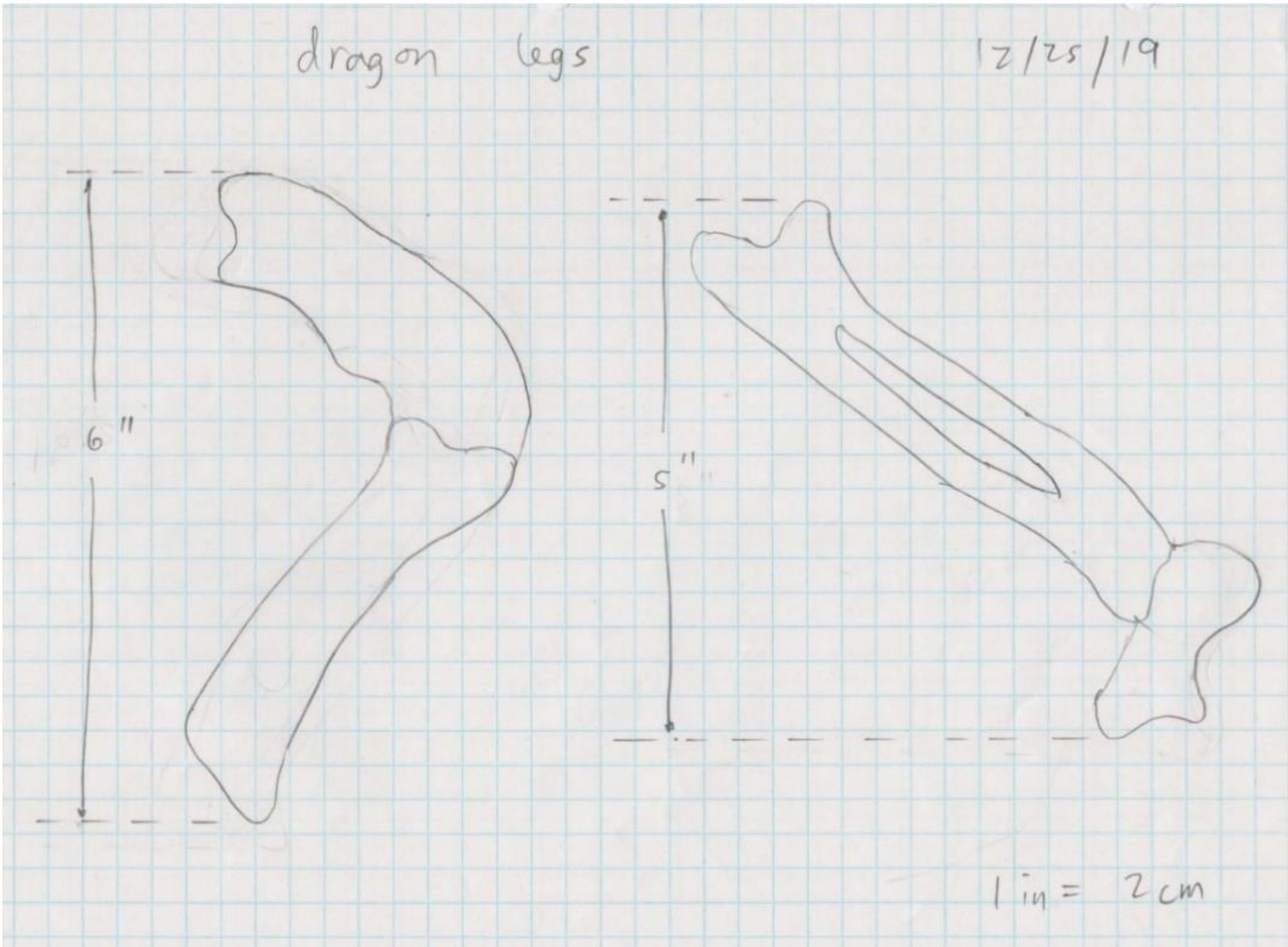

Figure 25: Dragon Legs

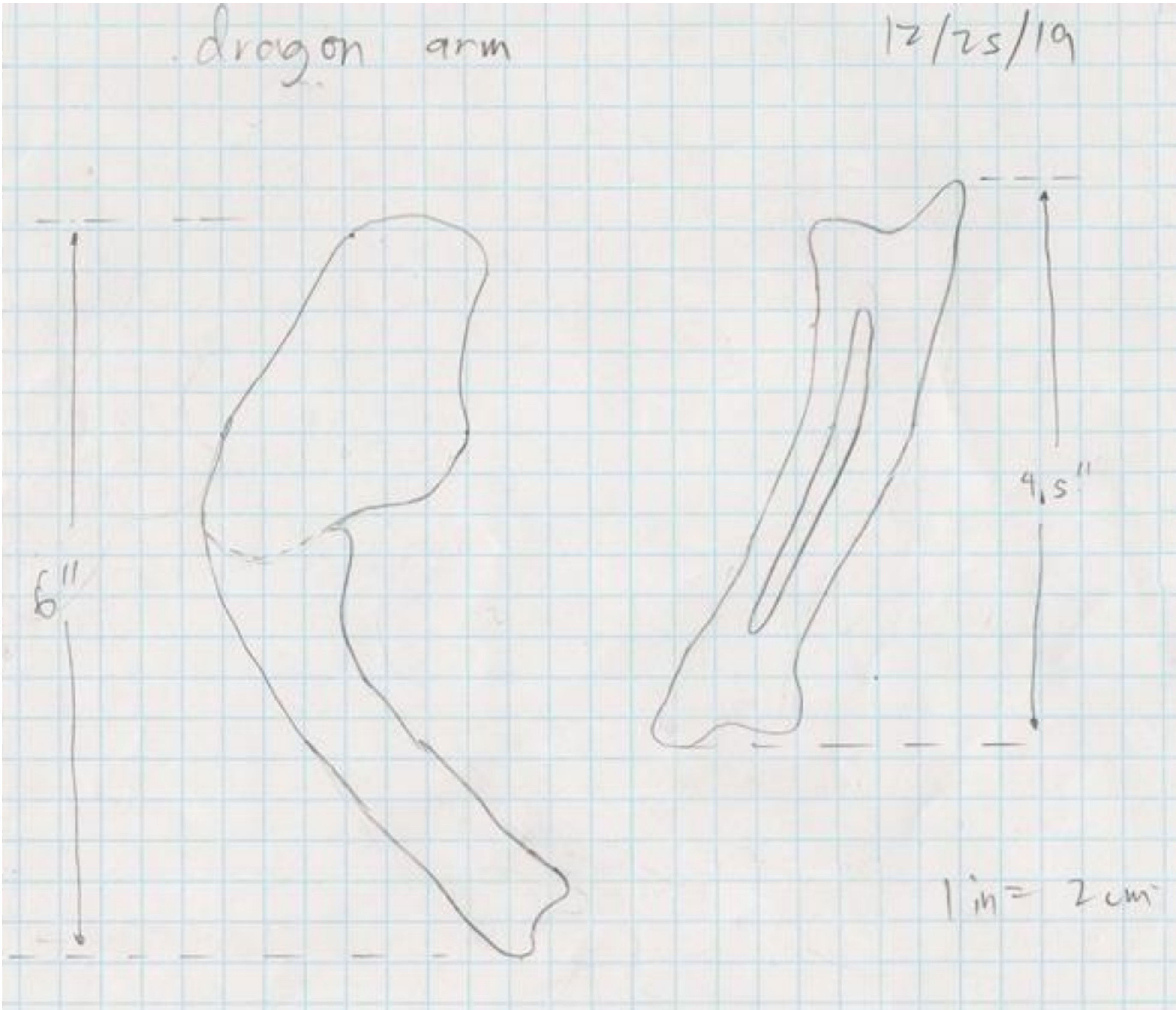

Figure 26: Dragon Arms

The reference for the sketching the dragon legs for Figure 25 and arms for Figure 26 are the legs of a lion [19]. The legs of lizards are too short and won't offer sufficient support for the body. I sketched the arms and legs together to further emphasize the scaling of each part. Each part is manufactured twice, both for the left and right side for symmetry.

16.7 Claw v1 & v2

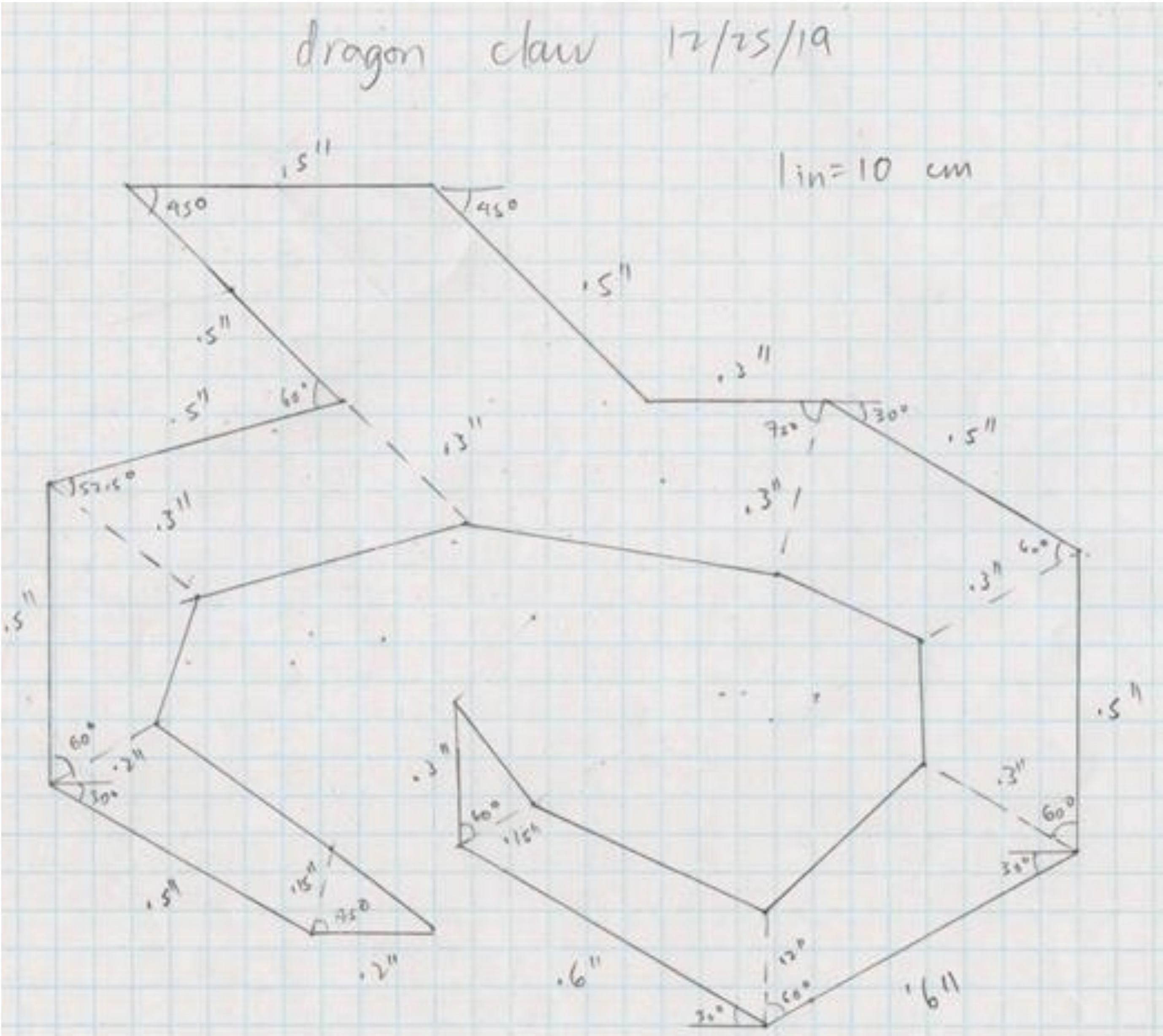

Figure 27: Dragon Claw – v1

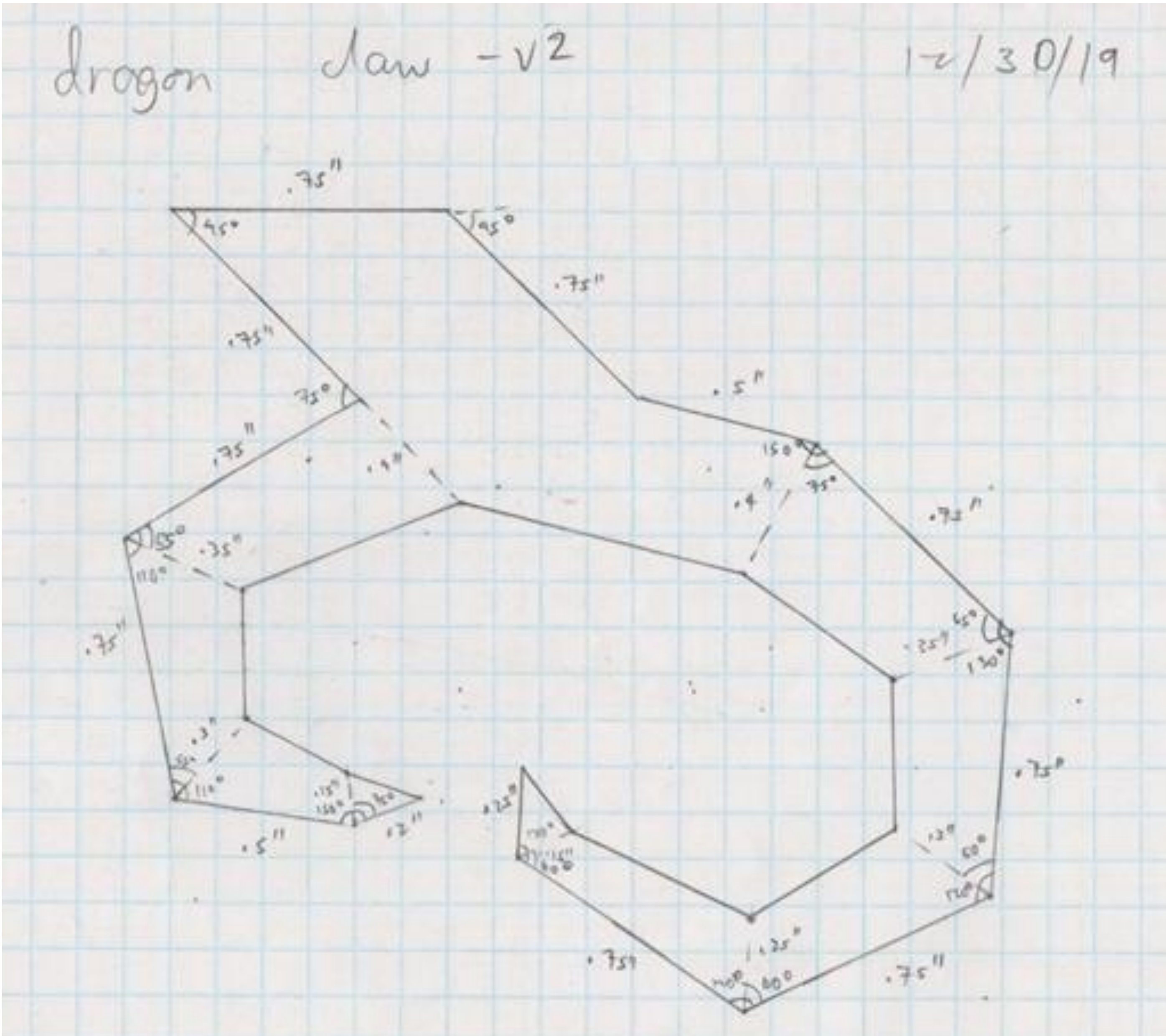

Figure 28: Dragon Claw – v2

Figure 27 is the first version for the dragon claw, it is based on the claw of the griffin. I remade the sketch since the claw is small and I wanted to make it larger as shown in Figure 28. Scaling the model in SolidWorks would also work, but I decided that it is better to remake the part. I also modeled the claw and arms together so a joint connector won't be needed. There are two claw parts that are derived from this sketch which will be connected to the claw. The main and the two derived parts are manufactured twice.

16.8 Feet

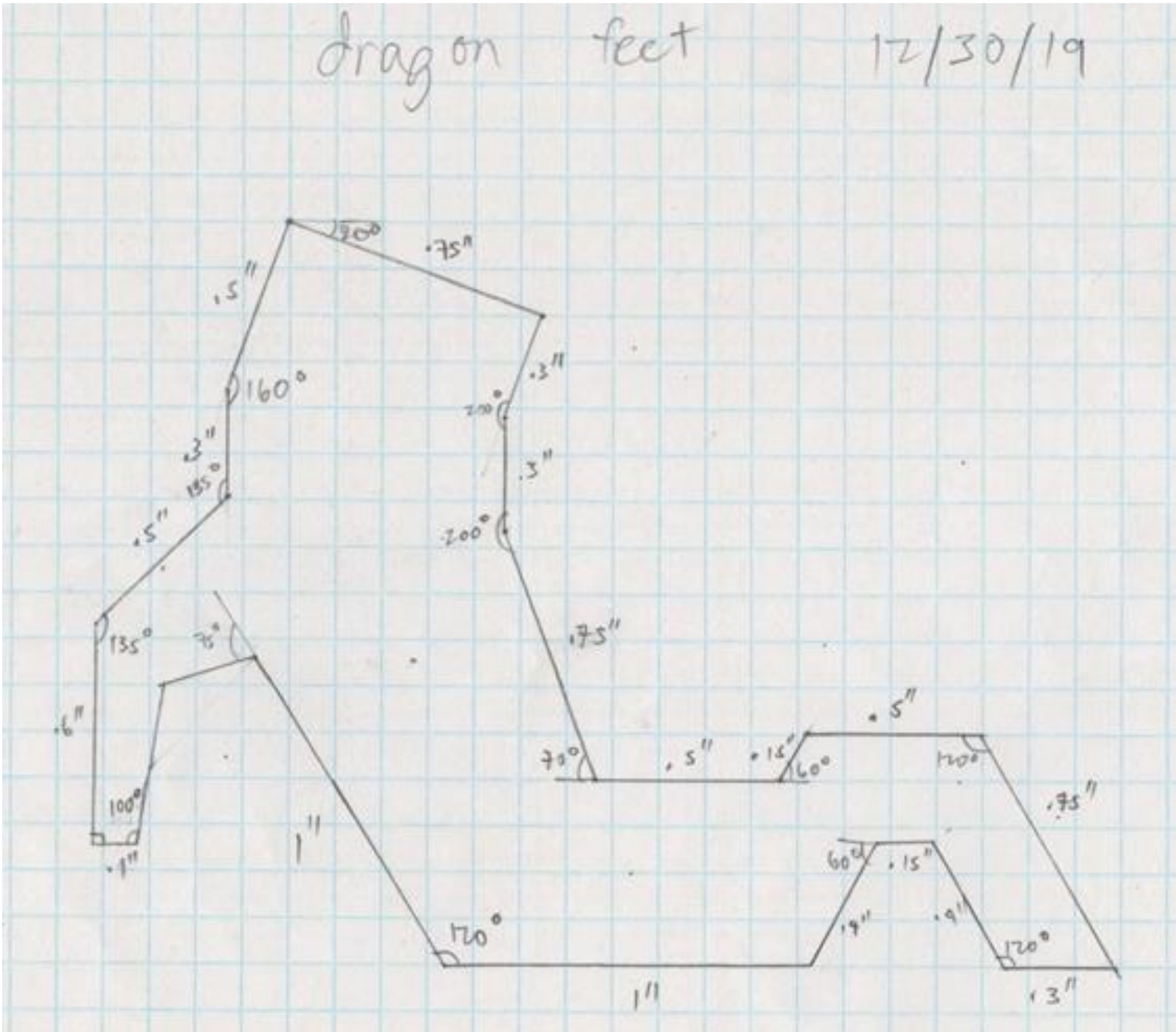

Figure 29: Dragon Feet

Figure 29 were supposed to be connected to one of the dragon legs with a joint connector, but I decided to model the feet and the legs as one part instead. Two derived parts are connected to the feet to balance the assembly. Just like the claws, the main and the two derived parts will be manufactured twice.

16.9 Connectors

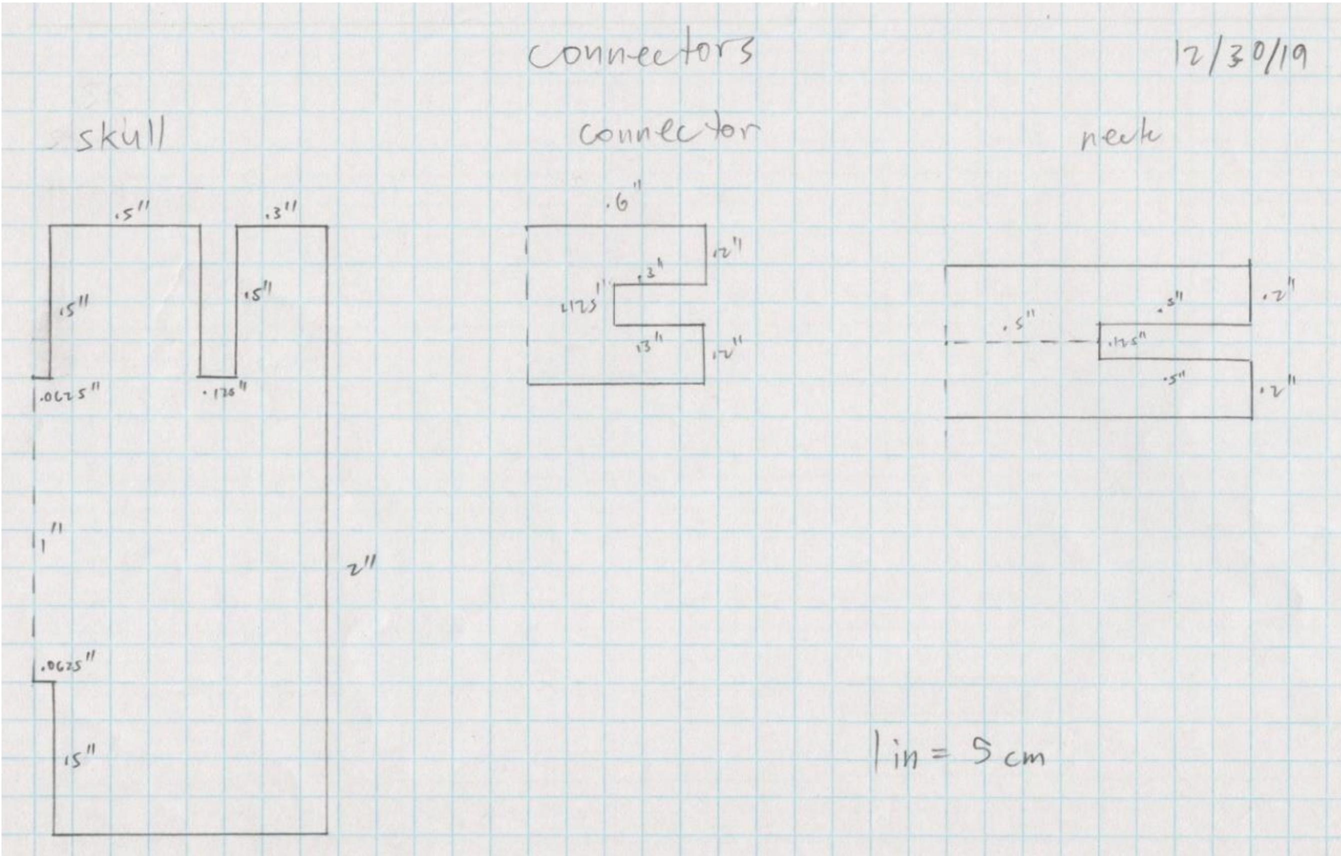

Figure 30: Connectors part 1

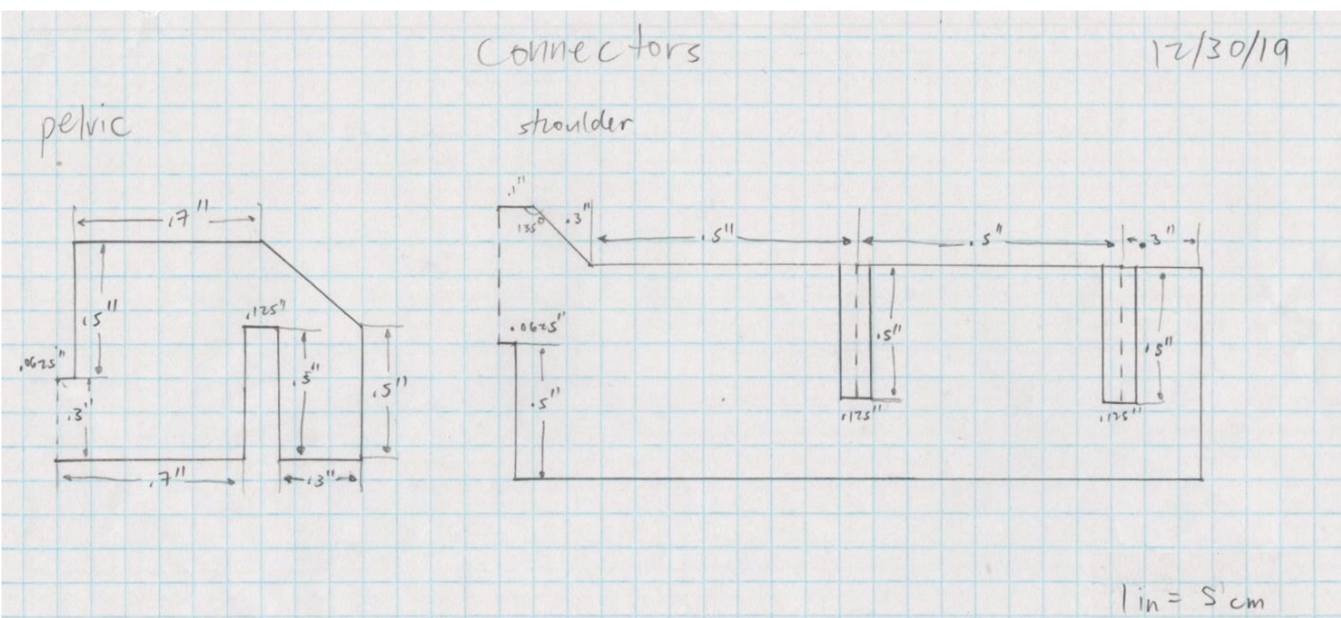

Figure 31: Connectors part 2

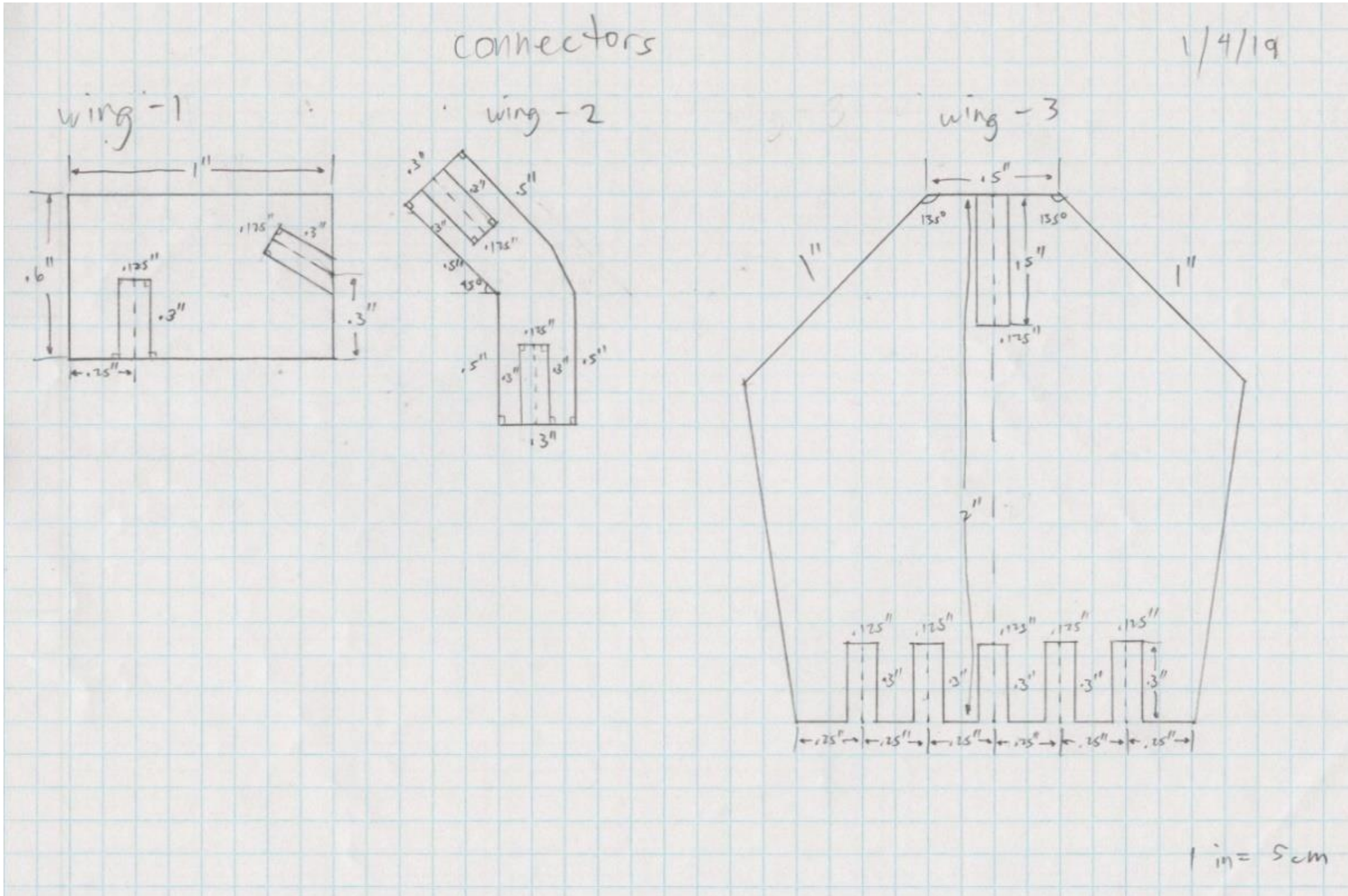

Figure 32: Connectors part 3

Figure 30 to 31 are connectors are used to join the parts together for assembly. Each connector is for specific parts to be joined except the “connector”, which is utilized 15 times throughout the assembly.

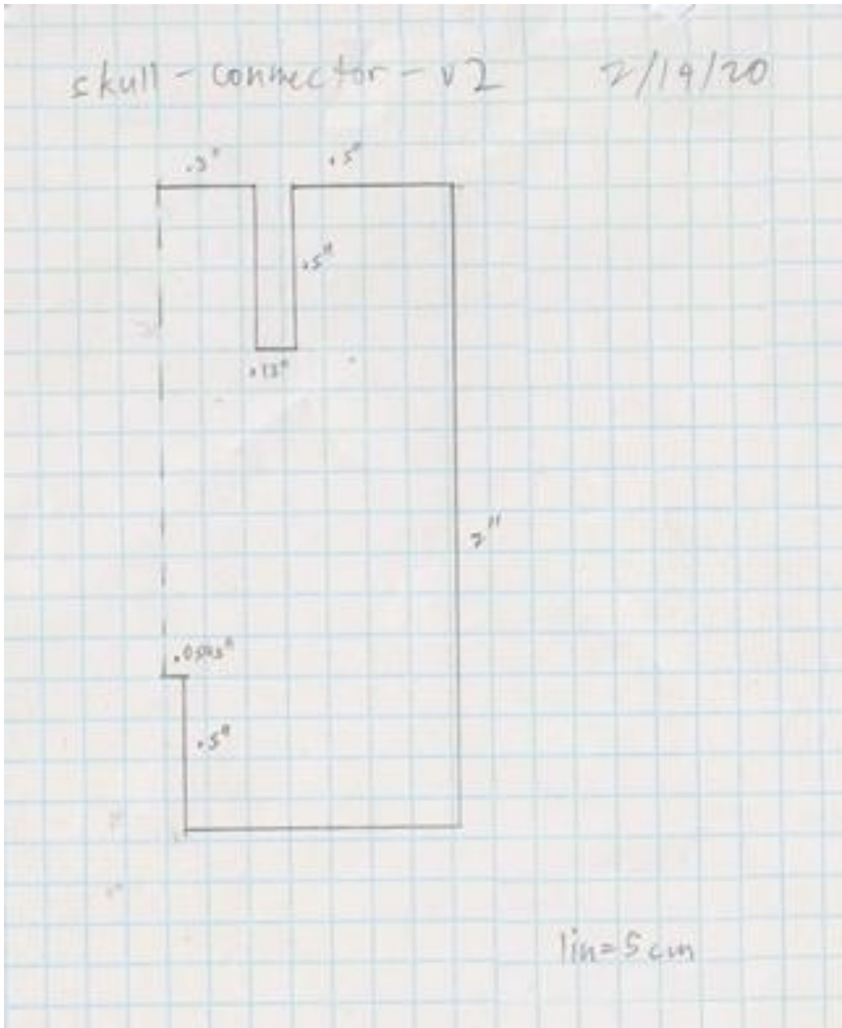

Figure 33: Skull – connector – v2

The manufacturing plan was changed and the dragon head will be casted instead. A new connector from the spine to head will be needed which generated this new sketch as shown in Figure 33.

16.10 Wing Extensions

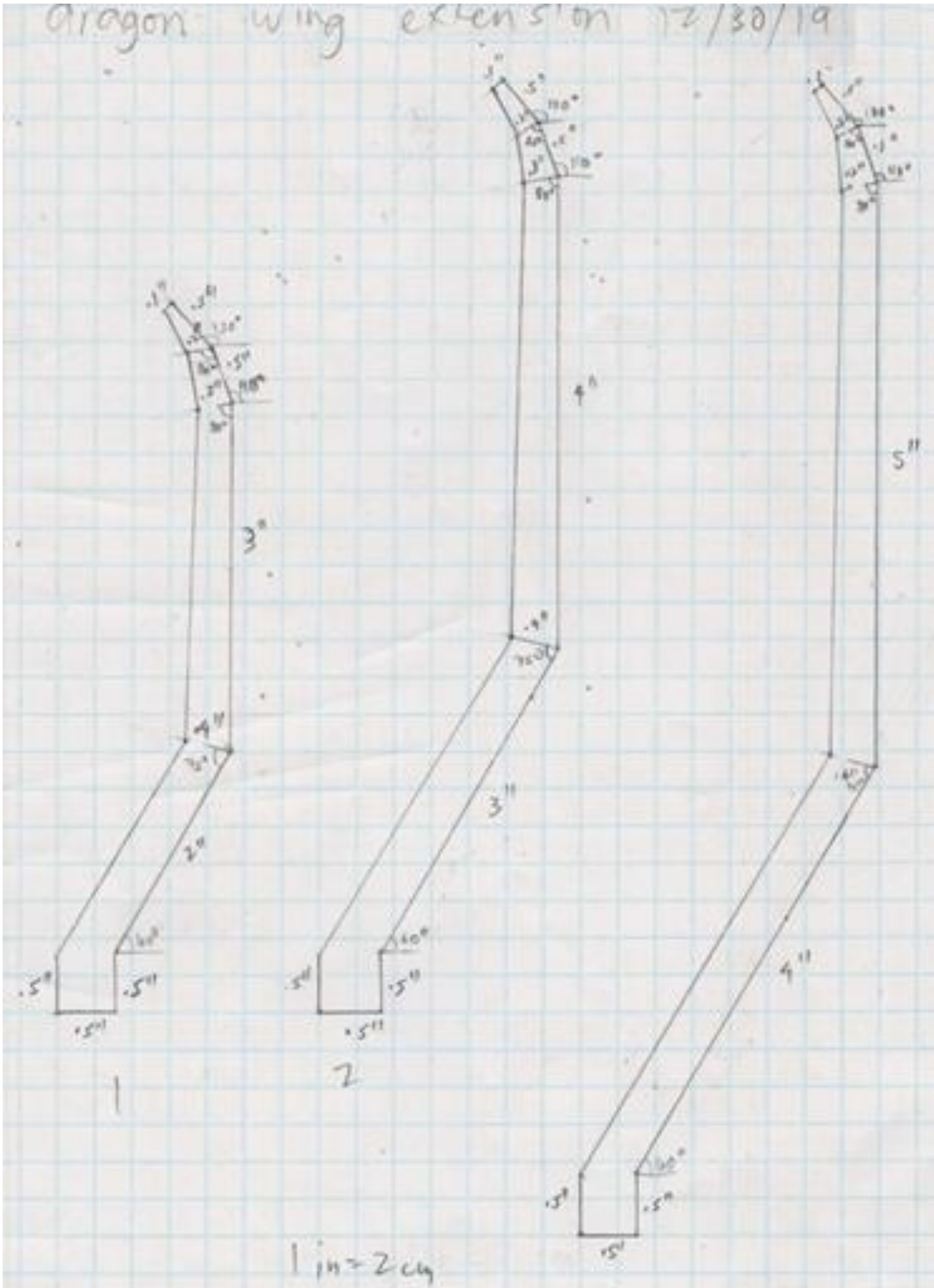

Figure 34: Dragon – wing – extension – part 1

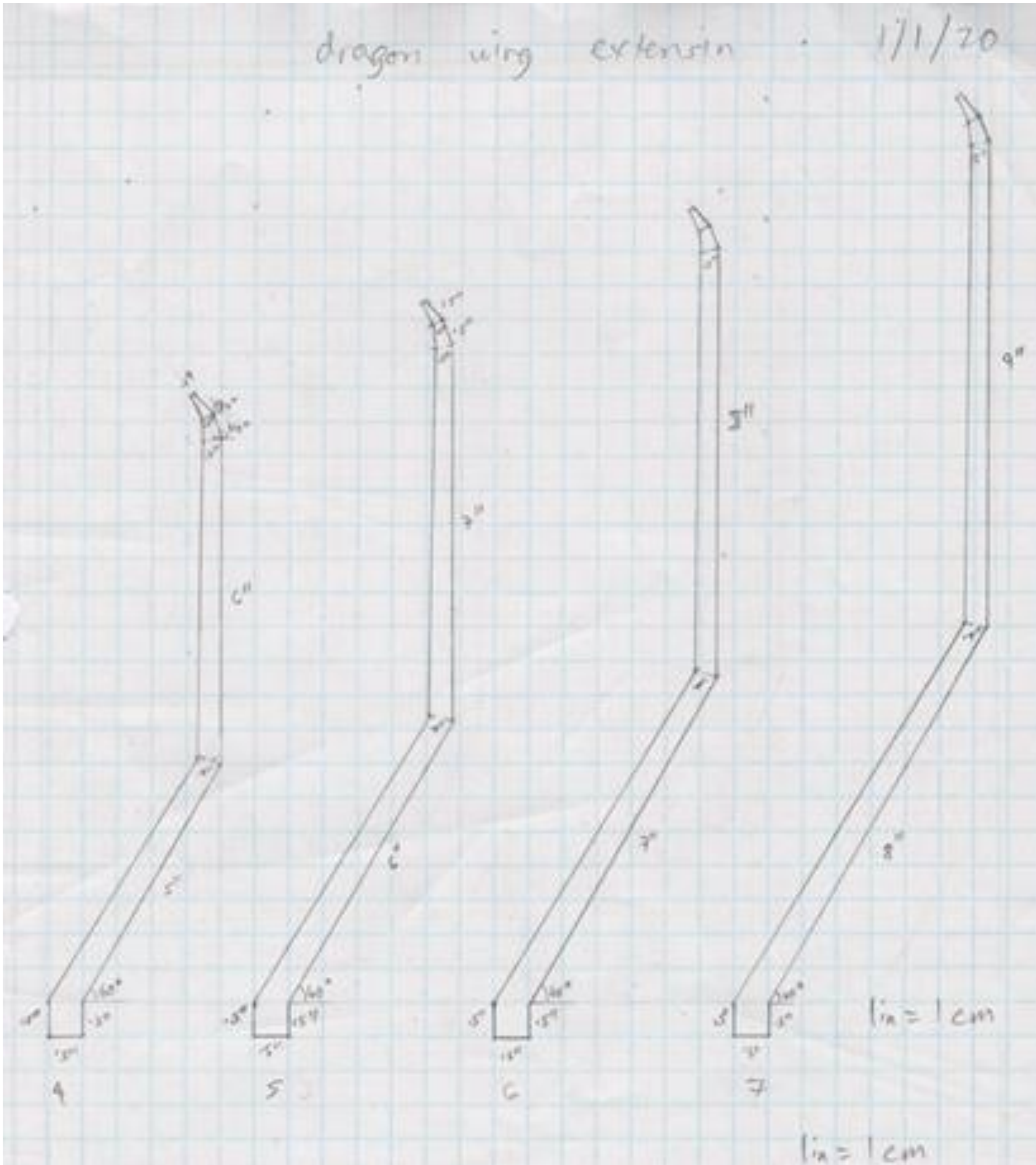

Figure 35: Dragon – wing – extension – part 2

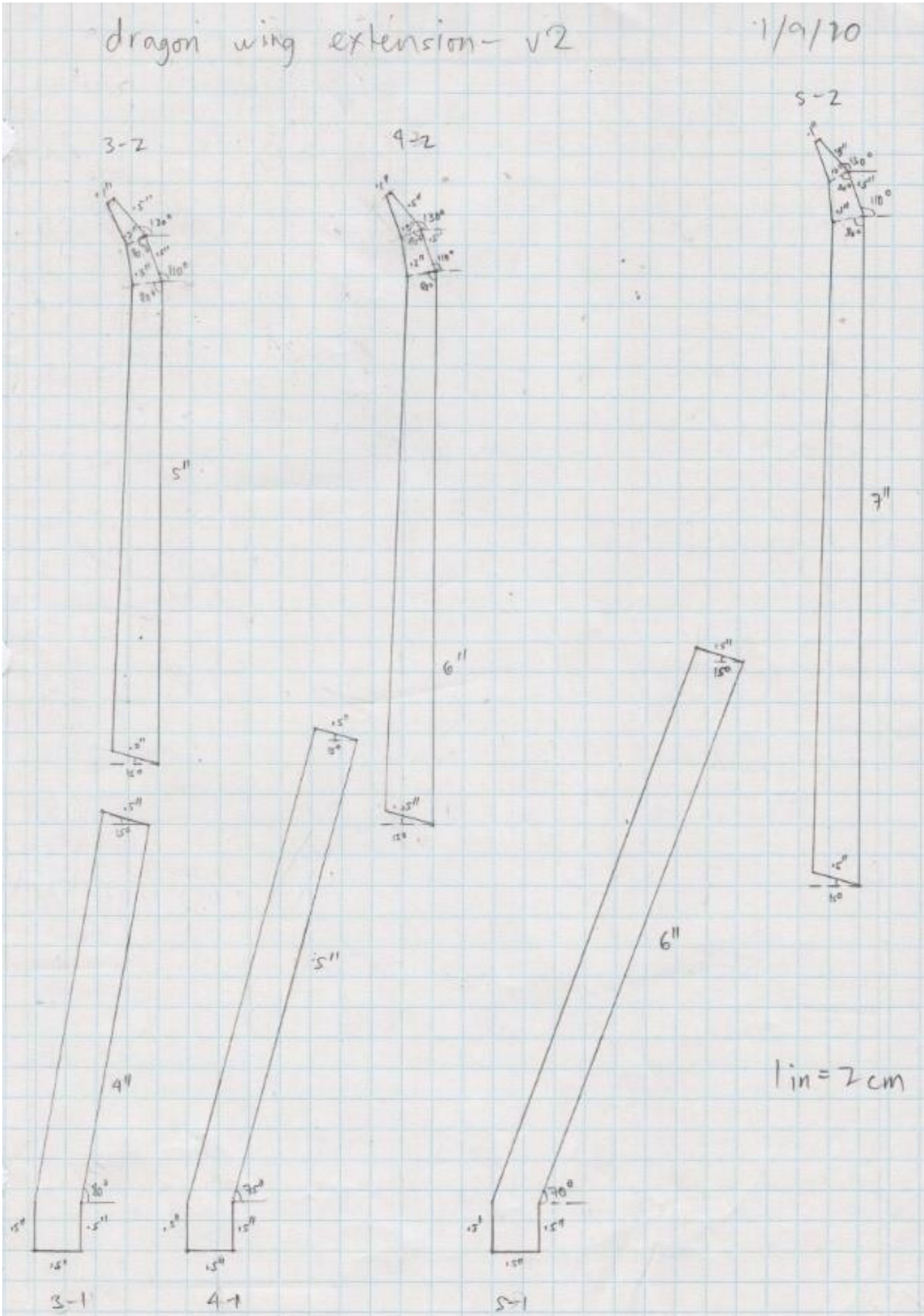

Figure 36: Dragon – wing – extension – part 1 – v2

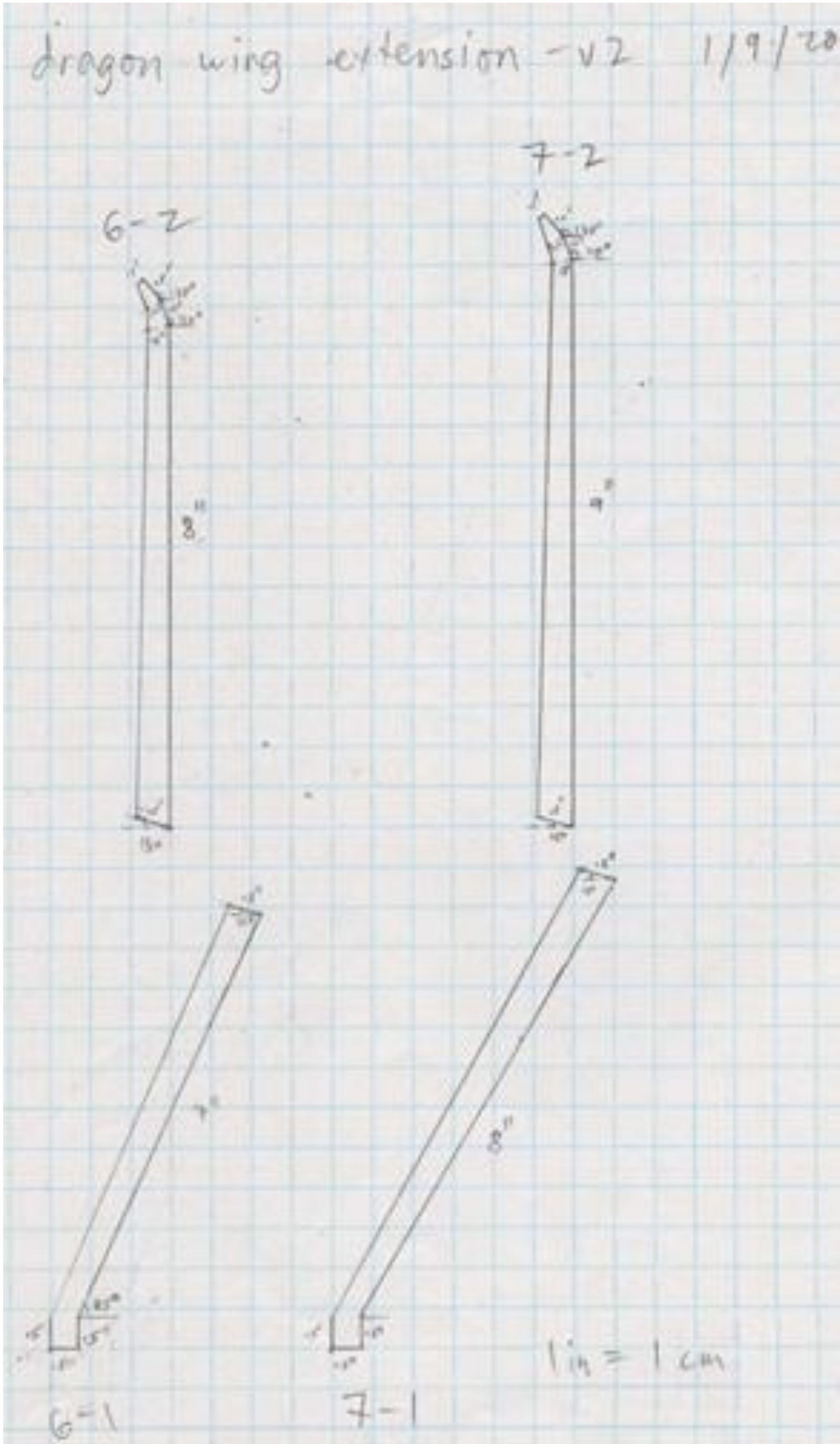

Figure 37: Dragon – wing – extension – part 2 – v2

Figures 34 to 37 are the wing extensions which are based on the fingers on the wing of a bat. I had resketched the extension since it was too long for the waterjet. The new sketch had to be divided into two parts and joined by a connector.

16.11 Circular Fillet

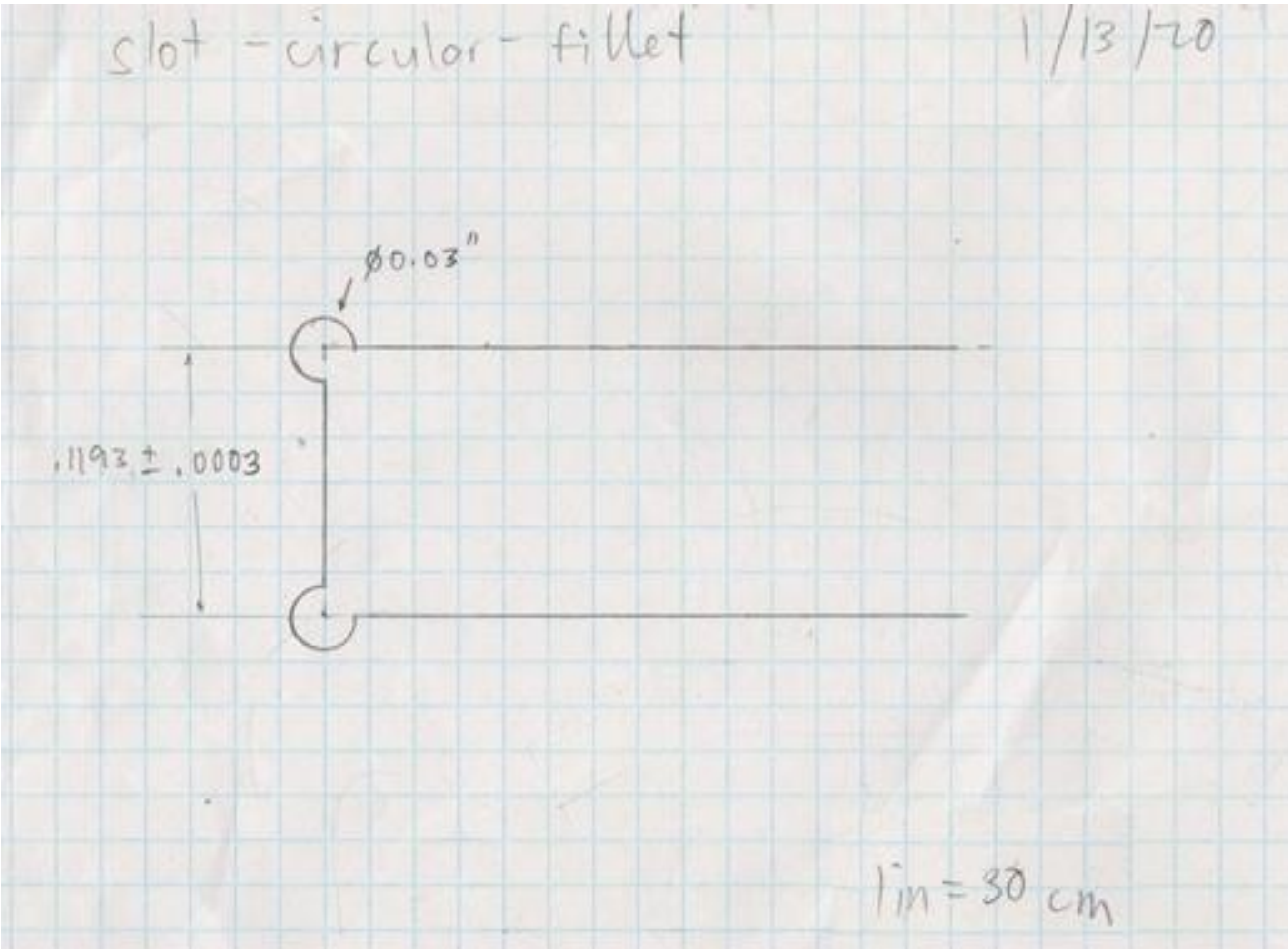

Figure 38: Circular Fillet

I added a .03 in. diameter circular fillet for the models since a 90° corner is a stress concentrator as shown in Figure 38. The depth of each joint varies from .3 in. to .5 in. depending on where the part is located.

16.12 Assembly Dimensions

There was an advice that only the assembly and the dragon head should be dimensioned.

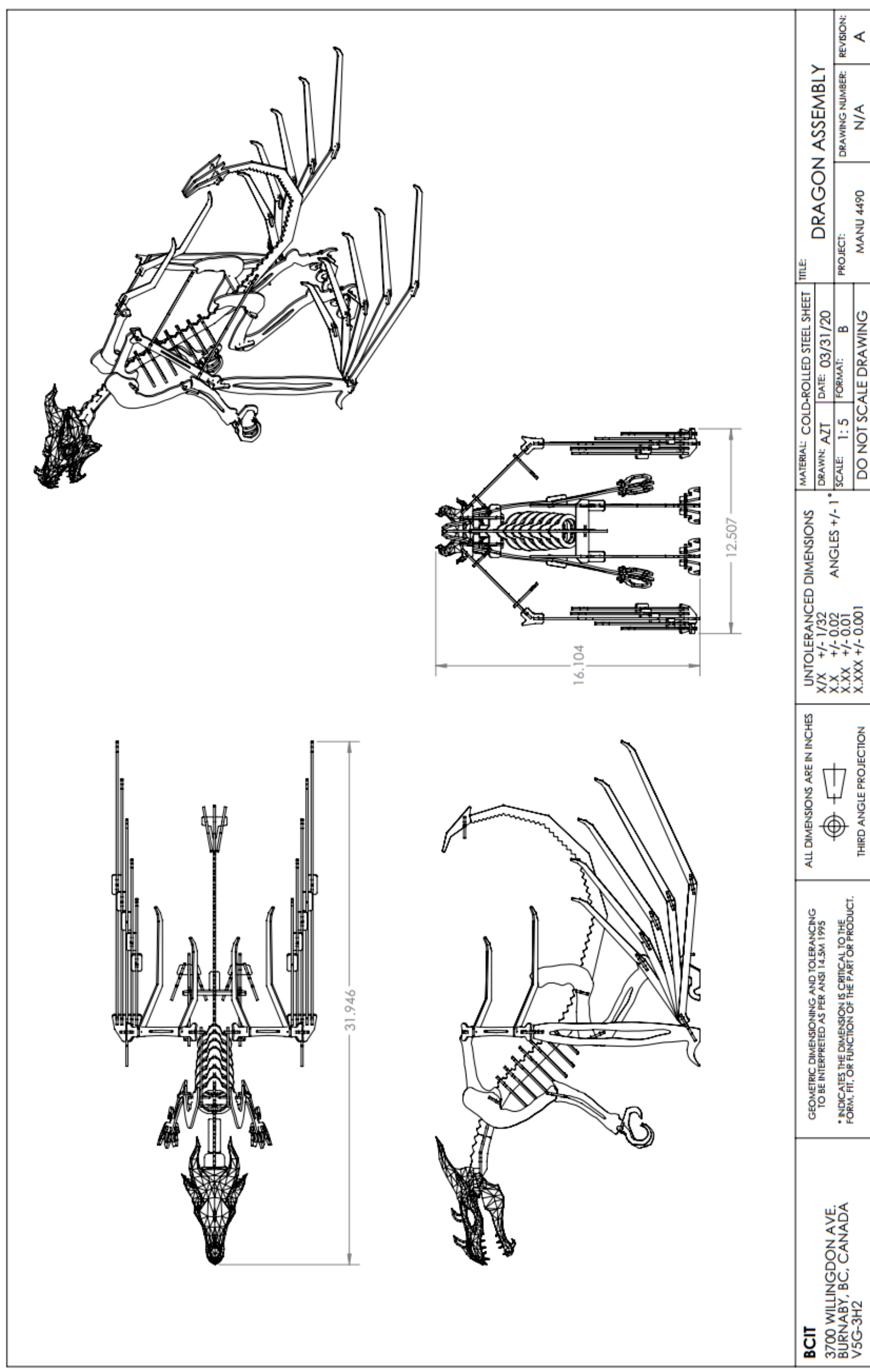

Figure 39: Final Manufacturing Project Overall Dimension

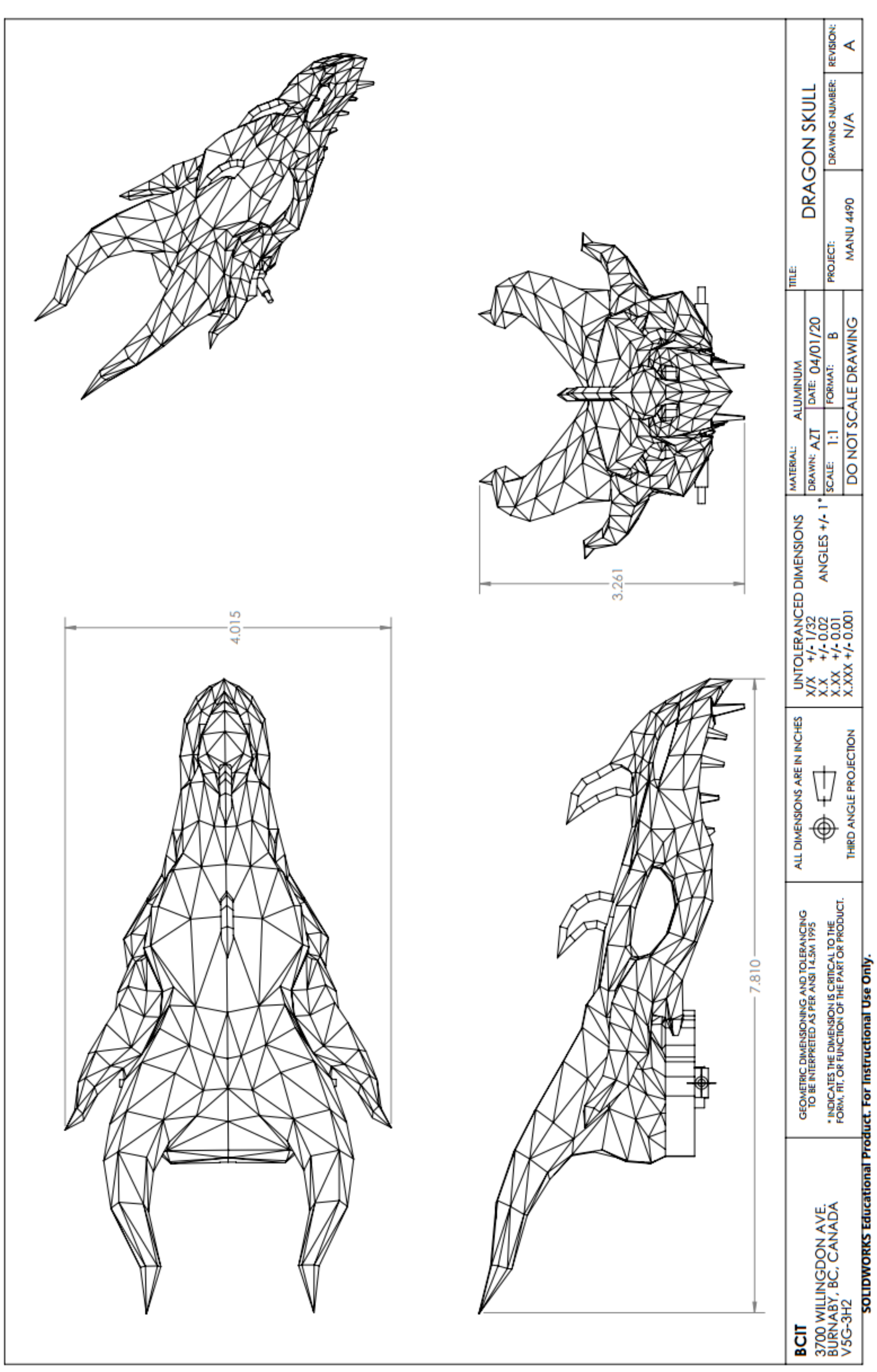

Figure 40: Dragon Skull Dimensions

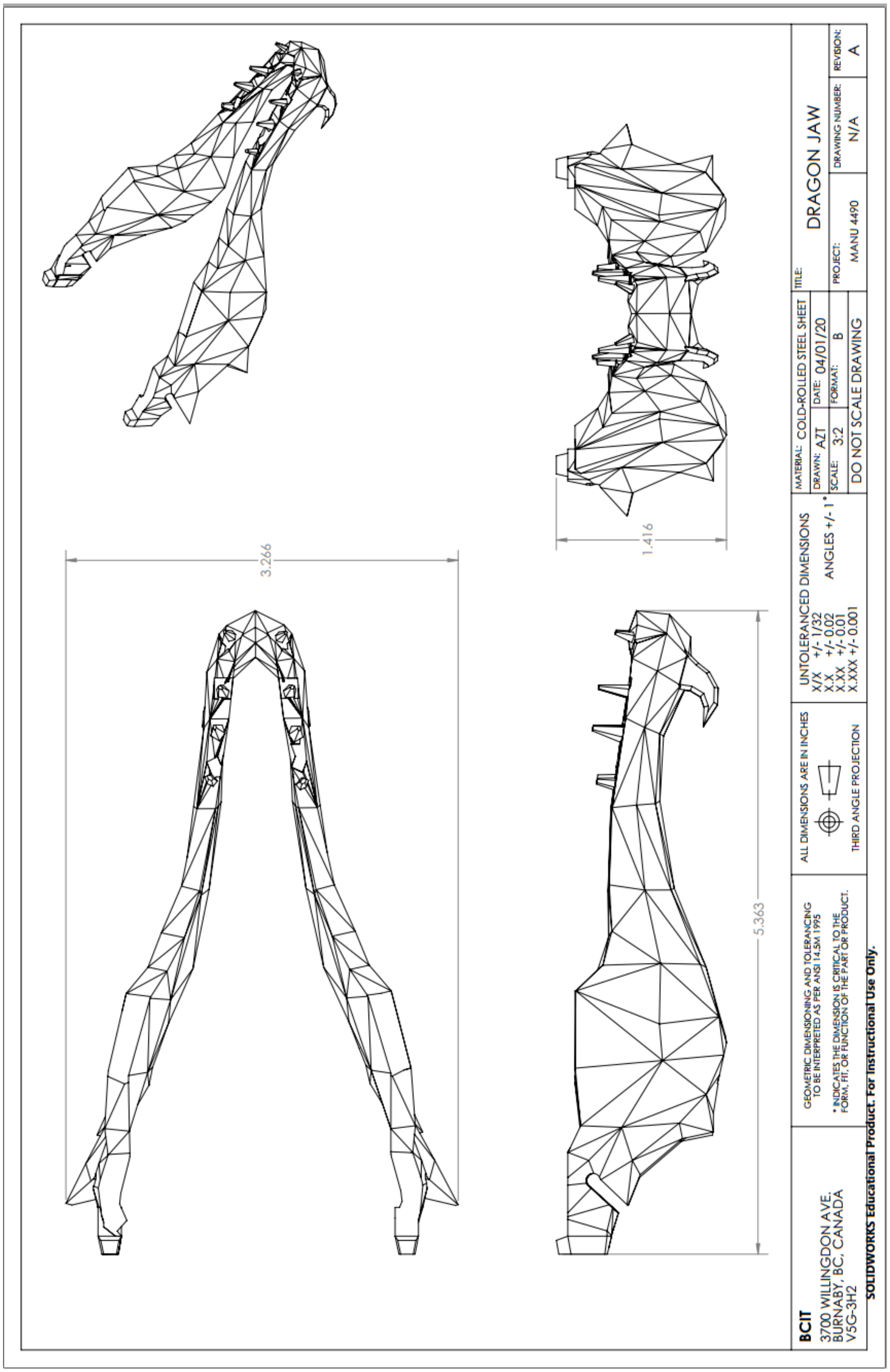

Figure 41: Dragon Jaw Dimensions