Fixture for Carbon Fiber Spar of Human Powered Helicopter

A Senior Project submitted

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ABSTRACT

Fixture for Carbon Fiber Spar of Human Powered Helicopter

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The following report describes our contribution to Cal Poly Human Powered Helicopter for the 2012 competition for the Sikorsky Prize offered by the American Helicopter Society. In order to win this prize the team needs to build and fly a human powered helicopter for more than 60 seconds reaching and altitude of 3 meters while staying in a 10 meter square box. Our team was created to support the integration of Carbon Fiber parts, specifically the carbon fiber spars with rotor and landing gears. Precise cutting and accurate drilling was needed and our team was tasked with creating a fixture and to assist with both operations.

After the requirements were taken into consideration, we successfully created fixtures that meet those requirements in the prototype stage. It was found the some of the requirements were over calculated, such as using cooling fluid, and others overlooked, like choosing the proper cutting tooling. Unfortunately the prize was granted over the summer of 2013 and the HPH project was shut down, but the fixture was still completed and selection of cutting tools was recommended.

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I. Introduction

The Igor I. Sikorsky Human Powered Helicopter competition was created by the American Helicopter Society in 1980, named after one of the founders of this society. The requirements of the $250,000 prize consisted of building and flying a human powered helicopter for more than 60 seconds reaching and altitude of 3 meters while staying in a 10 meter square box. Cal Poly's Da Vinci III design was the first to achieve any flight in 1989.

To reduce the weight of the aircraft the HPH team will be using carbon fiber spars along the wings and parts of the body. The Human Powered Helicopter Project needs to integrate the spars and the rotors as one assembly but many processes such as sanding, drilling and cutting need it to be done beforehand, since those processes were very unique for this project, special tooling and fixtures were required. On top of that, since the HPH could be an extended project it is necessary to keep record on the process used and tooling for future members and to continue progress after members graduated.

More than solve a problem the role as manufacturing engineers is to help and facilitate the spars integration by providing fixture(s) and or Drill Jigs. We worked together with the HPH club to provide parts for the HPH and assist when tooling was need it. The subject of this report is the development of a fixture to aid in the production of carbon fiber spars that will be used in Cal Poly's Human Powered Helicopter.

To develop this fixture we will review past practices with fixtures as well as go through the process of design, fabrication, and testing/experimentation of the fixture. The fixture was evaluated against various fixture criteria and most importantly its ability to create a part to specification. This report will cover the literature review, design theory, methodology, results, and conclusion of the fixture development problem stated as: "Lightweight carbon fiber spars will be used on the wings of Cal Poly's Human Powered Helicopter. The spars must be accurately machined to specification, but currently there is no tool to do so. The project team asked for a fixture to aid in their production and machining of their carbon fiber spars.

II. Background

Much progress has been made in the fixture world, but with each new part, a new fixture is usually needed. Especially with the new materials, such as carbon fiber, that modern technology can provide, there is an increase need to reevaluate fixture design theories and processes to match with the new materials. Although, the basic design of the spars has been used in the past, the carbon fiber material, length of part, and variance in specifications create the need for a more complex fixture. To better understand the principles of fixture design, the needs of the part, and what practices or theories have worked best, we conducted a thorough literature review focusing on fixture design theories, carbon fiber machining factors/theories, and material selection, among others.

Literature Review

Once the partnership was established with the Human Powered Helicopter Team, and the project of developing the fixture was set, we began conducting an extensive literature review. This literature review was aimed at gaining insight on what others have done on the past with similar situations. The focus was to better understand fixture design theories, carbon fiber machining theories, as well as material selection criteria. To research these areas of interest, databases such as "Web of Knowledge", "Engineering Village", and "Google Scholar" were utilized with search terms relating to our focus. Some of the more general search terms we began with were "fixture design", "carbon fiber", "machining", etc and more constraints were added to refine the searches. The following articles added valuable knowledge related to the problem of designing a fixture for machining on carbon fiber spars.

The majority of articles chosen were focused on fixture design. A main source that was started from was John Nee's, *Fundamentals of Tool Design* as it covers a shallow yet broad base of fixture design knowledge. According to Nee, there are seven functional requirements all fixtures must adhere to: locate, hold, support, material must not fail, must not interfere with tool path, must allow part removal and cleaning, and must not damage or distort the part surface (186). The text expands on these requirements and introduces practices such as the 3-2-1 planar location method, concentric locating, and more. Various clamping mechanisms were discussed such as the wedge and lever mechanisms and the positives and negatives with the use of each.

Also, when designing a fixture, criteria based on cost, productivity, health and safety, and quality must be considered (Nee 175. Some basic considerations for health and safety are to implement poka-yokes that help to reduce the error possible during an operation. One should also minimize pinch points and sharp corners to increase safety of the workers. The text also covers more detailed aspects of fixtures that can be reviewed.

A Clamping Design Approach for Automated Fixture Design, by J. Cecil, describes a new clamping approach in the context of computer-aided fixture design activities. This article discusses the overall approach to clamp design and also specification son how to use their methodology. "The purpose of clamping is to hold the parts against locators and supports." (Cecil 784). The strategy behind clamp design is broken down into 6 steps summarized as:

1. Consider the Set-up
2. Identify the direction and clamp type

3. Determine highest machining force
4. Calculate clamp dimensions based on forces
5. Determine clamping face
6. Position of clamp on face

To identify and determine some of these steps one must use various inputs:

> "The inputs include the winged-edge model of the given product design, the tolerance information, the extracted features, the process sequence and the machining directions for reach of the associated features in the given part design" (Cecil 785).

Once all inputs are understood and organized one can follow the six step process as discussion in detail throughout the article to be applied and personalized for individual part designs.

A functional approach for the formalization of the fixture design process discusses an opportunity to "facilitate the automation of the fixture design process based on a functional approach" (Hunter 683). This article attempts to "provide a suitable framework and methodology for the definition of a sequence of activities" (Hunter 683). Functional Requirements "represents what the product has to or must do independently of any possible solution", while a Constraint is a "restriction that in general affects some kind of requirement, and it limits the range of possible solutions while satisfying the requirements" (Hunter 683).

To create a fully supported fixture, knowledge-based engineering must be adapted so as to capture, formalize, and document solutions and processes. However, the methodology proposed here goes beyond this to include phases (numbered 1-5): Functional requirements development, definition of Fixture design Functions, Functional Design fixture solution, Detailed Design fixture solution, and Fixture final design solution Validation. Each of these five phases is discussed in detail beginning on page 688 of the article.

Also, the article discusses the IDEFO methodology, where the first step is to create a context diagram. This context diagram also works as a highest-level diagram of the fixture design process. With this methodology the final outputs are the "fixture detailed design, and the fixture assembly plan." (Hunter 691).   From this methodologies diagram one can visualize the activities that deal with the analysis and definition of the three information units: part geometrical information, manufacturing process plan and fixture design plan. There are over thirty activities to consider and document with this methodology (Hunter 694). The article, *A functional approach for the formalization of the fixture design process*, concluded the following on page 696:

- "The starting step is the definition of the fixture functional requirements"
- "There is a need to capture and formalize machining fixture knowledge"
- "There is a need to define and represent the machining fixture design process"
- "There is a need to define software fixture functions, whose objective is to create solutions that fulfill the fixture functional requirements. And the definition has to be independent of any implementation system"

A review and analysis of current computer-aided fixture design approaches attempts to organize ideas and practices generated towards increasing manufacturing flexibility through the use of fixtures. This article outlines approaches from setup planning, to fixture requirements, to constraining requirements, and even collision detection requirements verification.

"Typically the design process by which such fixtures are created has four phases: setup planning, fixture planning, unit design, and verification." (Boyle 2). According to Boyle, the generic requirements for fixtures cover the areas: physical, tolerance, constraining, affordability, collision prevention, and usability (3). To accomplish this, practices such as 3-2-1 locating principle are discussed to restrict all 6 degrees of freedom that a part can have. The four phases are discussed in detail starting on page five of the article.

Setup planning identifies the individual setups that allow features to be machined without reorienting the work piece. "The key task within setup planning is the grouping or clustering of features that can be machined within a single setup." (Boyle 4). Fixture planning is done by defining the requirement areas given for generic fixtures. A fixture layout plan, a document that shows where the clamping and locating points on the work piece would be, as well as specifies the position. This Fixture Planning forms part of a feedback loop, trying to optimize the layout plan when compared against the requirements. "Unit design involves both the conceptual and detailed definition of the locating and clamping units of a fixture, together with the base plate attached" (Boyle 7). The conceptual definition of unit design involves organizing the types and number of elements that are involved in a single unit. A Detailed Unit Design has three dominant techniques that are either: rule, geometry, or behavior based. It is in the detailed unit design that the material selections, dimensions, tolerances and more are determined. Geometry most affects the height limiting of the fixture or part as compared to each other. Lastly, Verification ensures that all fixture requirements are met and that the fixture holds up against process forces.

In *Computer aided fixture design: Recent research and trends*, they discuss the results of a literature review focused computer aided fixture design and automation over the past decade. Much of the article is redundant to what has already been found in previous articles relating to fixture design, but there is also a discussion on prospective research trends that provided new methods. Wang discusses the emerging field of intelligent computer programs that can design a fixture based on given criteria, form simply the working part and process forces (1092). The article discusses how "a more systematic way of integrating various techniques, such as FEM methods for workpiece-fixture system stiffness analysis, advanced mathematical analysis on tolerance design, 3D planning, and collision detection analysis on cutting tool path." (Wang 1093). Although much of the information was repeated in previous articles, the prospective methods of using intelligent programming for fixture design were very intriguing to understand where the field may be in the future.

In every article they discussed the importance of locating the part within the fixture and in *Locating completeness evaluation and revision in fixture plan* they discuss the process of evaluating the correctness of the location and also the process to go about revising the fixture if location is incorrect. Three terms are used throughout the article to ease understanding: Well-constrained (deterministic), Under-constrained, and Over-constrained. Well-constrained means "the workpiece is mated at a unique position when six locators are made to contact the work piece surface." (Song 368). Under-constrained is when "the six degrees of freedom of work piece or not fully constrained" (Song 368). Lastly, Over-constrained is when "the six degrees of freedom of work piece are constrained by more than six locators" (Song 368).

The Song article goes into a discussion of "Locating completeness evaluation" using a matrix system to understand the degrees of freedom relative to the number of locators. The matrix allows the user to determine whether the location is deterministic, over or under-constrained. This matrix goes further to be part of an algorithm that allows the user to understand which directions or degrees of freedom are unconstrained.

A novel approach to fixture design based on locating correctness, discussed formulating the constrained degrees of freedom as a function of the machining requirement and locating correctness. The locating scheme discussed in this paper seemed less effective than methods discussed in other articles. The article used a venn diagram and generic algorithms to explain its function, but still seemed inadequate. The only interesting point was the articles emphasize on the relative position of the work piece to the machining tool as a parameter for locating correctness, minimize loads and supports.

Genetic algorithms have been "developed to optimize fixture layout through integration of finite element code running in batch mode to compute the objective function values for each generation." (Kaya 112). This seems to mean that the genetic algorithm works differently than other programs in that it conducts a finite element analysis using criteria born from past applications and through integration of forces for various points. Genetic algorithms have been used to optimize and evaluate the support, clamps, and locators of fixtures. Because the genetic algorithm keeps track of previous designs, the evaluation functions decrease by nearly 93% after each application (Kaya 112). The algorithm even has built in mutations that create small variances within the calculation to better mimic the forces a process will actually incur. The article also discusses case studies to help better understand the implications of using genetic algorithms to optimize positioning features. This self-learning genetic algorithm approach seems to be a great tool to evaluate and understand fixture designs while they're in their design stages.

Finite element analysis is a method of understanding a components structural integrity, rigidity, performance quality and more. *Development of a Finite Element Analysis Tool for Fixture Design Integrity Verification and Optimization*, an article written by Nicholas Amaral, attempt to "develop a method for modeling workpiece boundary conditions and applied loads during a machining process" (Amaral 409). This article was using in understanding software capabilities to reduce "trial and error" methods of testing fixtures. Where most studies choose to use rigid fixture constraints in their analysis, "this study acknowledges that work piece boundary conditions are deformable" and therefore are modeled by springs in parallel at the boundary condition (Amaral 409). This new method eliminates the need for an external software for optimization and allows for conditions, loads, constraints, clamps, locators, and more to be accurately determined for a fixture design.

The article, *Drilling carbon fiber-reinforced composite material at high speed,* describes a test on drilling operations for carob fiber reinforced materials at three levels of high speeds:9550, 24100 and 38650 rev/min and at three feed rates of .03, .05, .07 mm/rev. The drill lengths were 13.5, 59.4 and 94.5 mm. A carbide CUMET 7 mm twist drill with 25 helix angle and 120 point angle was used. Also, a CUMET 7mm tungsten carbide micro-grain multi facet drill with 30 degree axial rake angle, 15 degree lip relief angle, 30 degree radial rake angle , and 30 degree helix angle was used (Lin 157).

It was found that thrust forces are smaller using multi-facet drills, which may reduce the appearance of delamination at much smaller speeds then where this test was conducted. The thrust force was also shown to be "drastically increased as the cutting speed increased" (Lin 157). This result was found to be true for both multi-facet and twist drills.

Other results showed that the average torque slightly increases as cutting speed increases for a multi-facet drill, while it decreases for twist drill. Also, "the average torque increased linearly for a multifaceted drill, and the increase in torque for twist drill as federate increased was less consistent" (Lin 158).

One of the major reasons for the changes in force is the tool wear that occurs during the process runs. Tool wear is mainly affected by cutting speed and drilled length within the range examined. Tool wear increases significantly as cutting speed increases. This will be a major constraint for using carbide tool to cut carbon fiber reinforced composite materials at such high speeds. Tools wear out quickly and the thrust force increases drastically as cutting speed increases.

Tool selection for the drilling operation in our fixture design is important since the carbon fiber spars are thin is necessary to find a way of drilling holes causing the least amount effects in carbon fiber properties. The article suggests the multi-facet drill is not superior in performance to twist drill in the range examined.

Much of the information considered in the article, *On machinability of fiber reinforced polymeric composites,* had been considered previously in the literature review. Through experimentation they considered cutting parameters for optimal machining results. These results were expanded upon more to highlight the areas that need further study, such as angle point design and consideration and thrust force.

According to *Influence of material properties on the drilling thrust to hardness ratio*, "The drilling thrust depends on the geometry of the drill (diameter, point angle, lip length, evolution of the cutting angles along the edges, etc)" (Mauvoisin 825). The article finds that the drilling thrust should only depend on material hardness given constant cutting conditions and type of drill. The article discusses how ductility, hardness, plasticity, cut depth and more play into the thrust force during drilling, and although this test is conducted on mild steel, the thrust calculations should be considered for drilling on carbon fiber. The lower thrust force the cleaner entry and exit quality of the hole.

To understand the de-lamination affects on carbon fiber reinforced plastic composites during high speed drilling, the article: *Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites*, was very helpful. As a drill enters the work piece there is usually damage, or delamination that occurs. This delamination is evaluated through speeds, feeds, and point angle. For this article, "the drilling experiments using cemented carbide (k20) twist drills were performed based on full factorial design of experiments with three levels defined for each of the process parameters" (Gaitonde 431). Through the experiment it was found that high-speed cutting significantly reduces the delamination effects. The study also found that to reduce the delamination affect further the process should employ low feed rates and a point angle between 0/90 degrees. The validity of the results were verified using linear correlation plots, ANOVA testing, and generating 3D contour plots (Gaitonde 437)

III. Design

From the given drawings and input from the Human Powered Helicopter team the following specifications requirements and constraints were given:

- A single fixture that holds and support 2 – 3 inches diameter carbon fiber spars.
- Since the length of the spars can range from 8 to 12 foot long, the HPH wants be flexible on where are setting their cutting operations inside shop or outside.
- Be able to use hand drill or bench drill.
- Cutting tooling: the HPH would like drill the holes in small increments to prevent stress the fibers
- The fixture should resist coolant if need it.
- Fixture testing on May 1st 2013

The following specifications were taken directly from the HPH design drawings as seen in appendix:

- Drill a thru hole 0.625 ± .01 in, diameter 3 ± .005 inches depth a given distance away from one end of the spar within +/- .1 inch.
- Drill a thru hole 0.625 ± .01 in, diameter 2.50 ± .005 inches depth a given distance away from one end of the spar within +/- .25 inch
- Drill a hole thru 0.750 ± .01 in, diameter 3 ± .005 inches depth a given distance away from one end of the spar within +/- .1 inch.

Voice of the customer into design requirements:

- Adjustable Jaws 1- 4 inches.
- No specific mounting brackets, flat bottom easy access to generic C-clamps.
- Light compact and easy to carry.
- Chose a proper drill bit(s) the meets this and other requirements (kind, material, special coating)
- Avoid easily corroding materials.
- Complete prototype by April 30 2013.

IV. Methodology

The way we are going to approach this problem is:

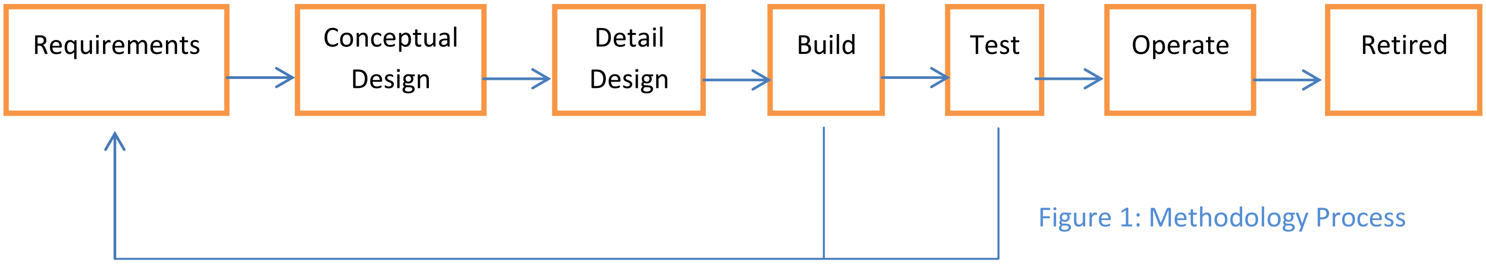


Figure 1: Methodology Process

1. **Requirements**: we collected all the data need it from drawings and HPH members (page 16).

2. **Conceptual Design**:

Tool design objectives: According to the book, Fundamentals of Tool Design, a tool is designed to increase production while maintaining quality and lowering costs. The designer must:

- Reduce the cost of manufacture by producing good parts at the lowest cost.
- Increase the production rate by designing tools to produce a quickest cycle possible.
- Maintain quality accuracy and repeatability of tool.
- Reduce the cost of special tooling by using standard and available material.
- Design tool that are safe to operate.

There are seven functional requirements for a fixture design:

1. Locate

   Part must be positioned with respect to tool to with respect to tool to within a specified amount of its intended position.
2. Hold

   Part must not deform or move more than a specified amount during process.
3. Support

   Fixture/part must not vibrate excessively during process.
4. Material must not fail under process
5. It must not interfere with tool path
6. It must allow for part removal and cleaning
7. It must not damage or distort part surface.

To take into consideration the tool design guidelines one of them being no tool should cost more than the savings in production it was decided to work with the available materials and avoid costly machining.

- To locate the center axis of a pipe a V block was provided.
- The support plate was a previously used plate for other project.
- The clamp part had already two holes
- **Tool should no cost more than what it saves in production**

3. **Detail design**, using CREO the fixture prototype was modeled as seen in figure 2. As we model we considered the stock material available and made adjustments to first model to avoid custom made parts or expensive machining (spacers, bolts, nuts washers, V-blocks etc.).
4. **Build**, materials were cut, purchased, borrowed and assembled and new details were found:
    a. The need to adjust for spar variance within on fixture
    b. How to accurately measure from center hole to end of spar within specs.
    c. Drilling tool was not available in the labs.
5. **Test**, the first prototype was assembled from scrap pieces and tested on April 30.
6. **Operate** More tests were done on carbon fiber pipe segments
7. **Retire** The last fixture should work to a wider range of pipe diameters. Unfortunately the HPH project was retired, but the tool would be reused in other Cal Poly Projects

V. Experimentation

The first prototype (figure 3) was tested on May 3rd, 2013. The fixture was set up in a bench drill press, a set of clamps were used to hold the fixture on the bench. A scrap piece of a spar was place in the V-block the nuts and butterfly nut were adjusted to hold the spar. The bench height and drill end was adjusted for the proper travel distance. For the lack of a stepping drill, multiple size twist drills were used until the correct size was achieved, some lose fiber were noted in the inside of the spar (at low speed) and speed was change to 1500 rpm. No difference was found drilling with or without coolant; no excessive heat or tool wear was noted.

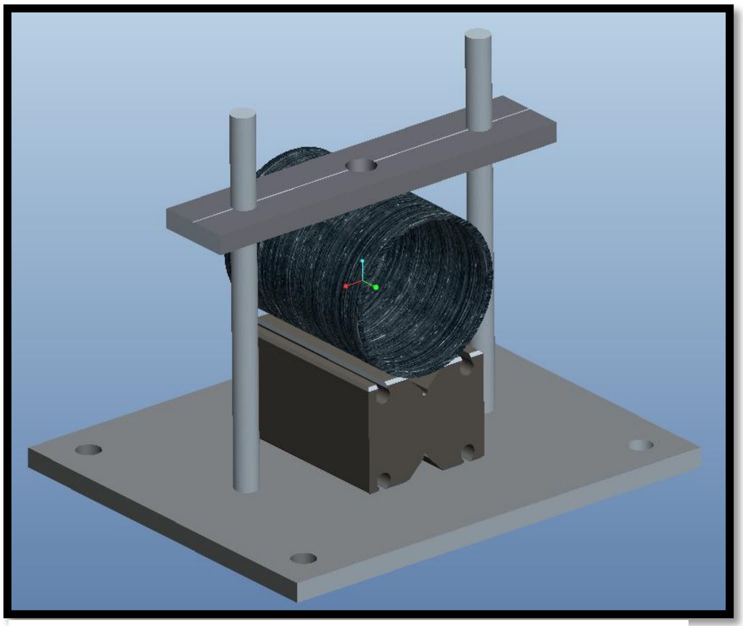


Figure 2 CAD Model of prototype

The first working prototype encountered several issues and add new requirements

- The spar would be cut a drill press not with a hand drill.
    - This means that the bottom plate of the fixture should be adapted to the work on a drill press slots or table.
    - There is a need for a clearance hole in the V block for the drill bit to clear.
    - Sharp corners were present on the fixture plate.
    - No coolant would be necessary

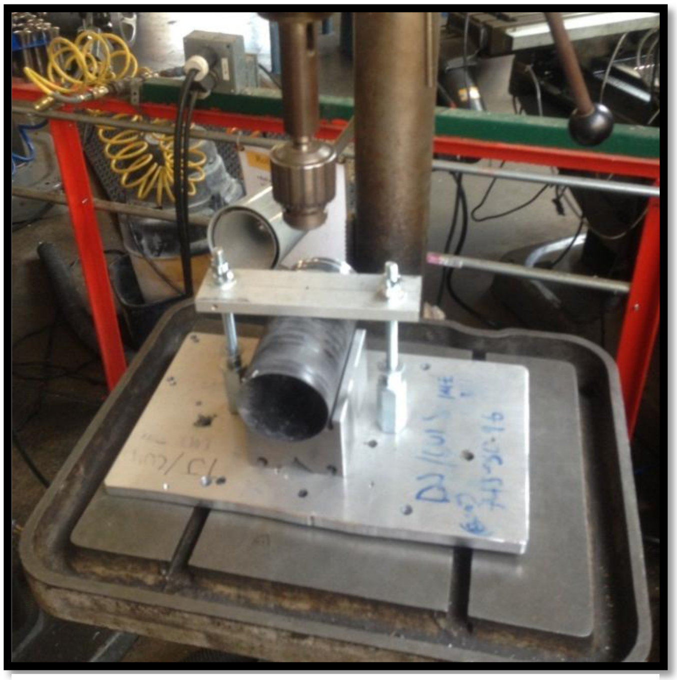


Figure 3: Testing prototype

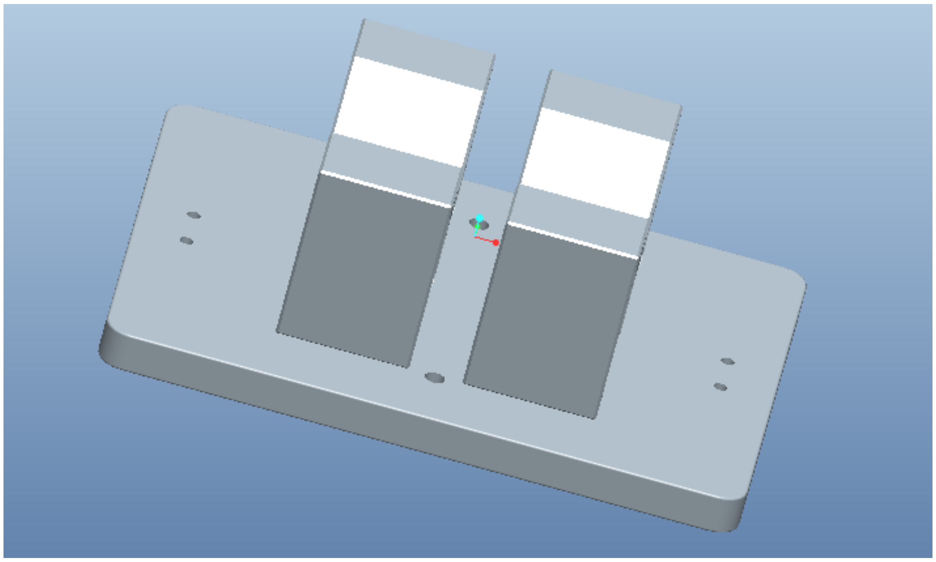
since the drilling procedure would be dry.

- Recommend a proper drill bit for carbon fiber without coolant.

For the final fixture few changes were made here some of the changes:

A bigger size “V” block would use to easily accommodate up to a 4 inch pipe. Also this new design of V blocks would be lighter than the solid previous one. Using two V blocks rather than one would allow easy drill clearance while drilling the pipe.

Figure 4: CAD final design



A new stepper drill was introduced into the process to decrease cycle time. A characteristics of this a stepper drill bit would make drilling a ¾ inch hole into carbon fiber and easy task yet cost effective. In the previous test we had to stop and change tool going from small size to ¾ making this very time consuming and giving more room to introduce operator error like accidently moving the position of the fixture while changing tools.

A drill extension would be used to be able to drill to a 3 inch pipe with a short drill bit.

Also shown in the picture below, tie down straps would replace the aluminum clamp to hold the pipe down. This change allows

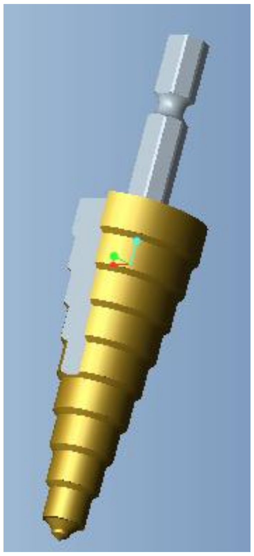


Figure 5: Stepped Drill

quicker adjustments and better support since the force is spread over a larger surface area. The final fixture design is shown below, with the stop gauge, tie straps, 2 V blocks, and base.

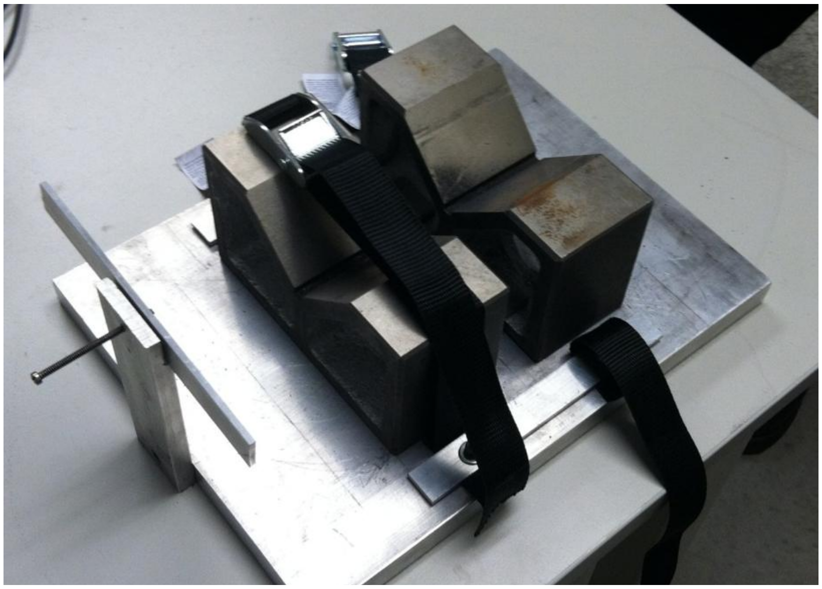


Figure 6: Final Design

VI. Results

With the final design met all our customer needs and requirements. The adjustable straps and large V-blocks allows for various diameter spars to be machined with the fixture. The straps spread the load of the clamping force, reducing the deflection that spar undertakes during processes. The adjustable stop gauge, that utilizes a screw stop, can be adjusted to meet all distances in the process. The new tool, the stepped drill, combined with the fixture, drastically reduced the cycle time to complete the parts. Tests were done to determine new cycle times, cost estimates, and quality control. The cost breakdown of the final design is shown below over a 14 part life cycle (the amount of parts needed).

Fixture Cost			
Name	**Hours**	**Rate/Hour**	**Costs**
V Block set	N/A	N/A	$15.00
.75 x 9 x12 6061 Al plate	N/A	N/A	$17.46
Straps #85243	N/A	N/A	$8.61
Misc. screws and washers	N/A	N/A	$2.00
Machine time	1	40	$40.00
Assembly	0.5	15	$7.50
		Total Parts	**$90.57**

Table 1: Cost Estimates

Operator Savings				
	Time (min)	**Parts**	**Rate/Hour**	**Costs**
without fixture	12	14	40	$112.00
with fixture	2	14	40	$18.67
			Total Savings	**$93.33**

Table 2: Cost Savings

VII. Conclusion

This Senior Project allowed us to utilize many aspects of engineering that we've developed throughout our coursework at Cal Poly. Working with a client, we faced the challenges of communication and expectations from both parties. On time deliverables and solutions to a real problem were implemented for their project team. By working with a process that was still being developed we were able to react fast and provide quick solutions to problems in order to not slow down the final product. Our project developed a cost effective fixture that kept the quality high and consistent, no matter who the operators are. The overall project saves money, even within just the initial run of 14 parts, and any other use is more savings. Unfortunately, the Sikorsky Prize was awarded to the University of Toronto before our project could be fully completed, but there are already new projects in the works at Cal Poly that can utilize the fixture and or its' components.

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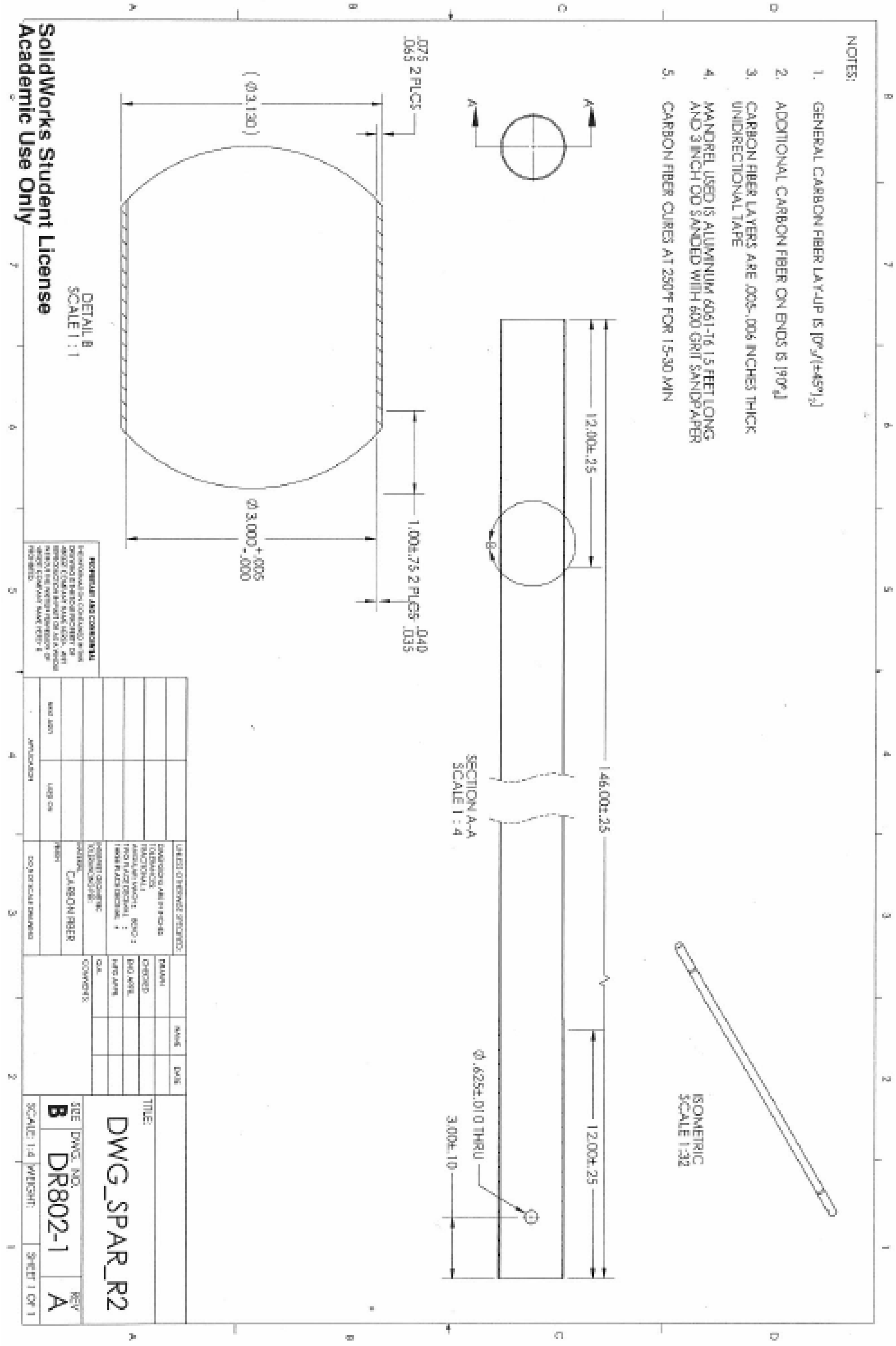
Appendices

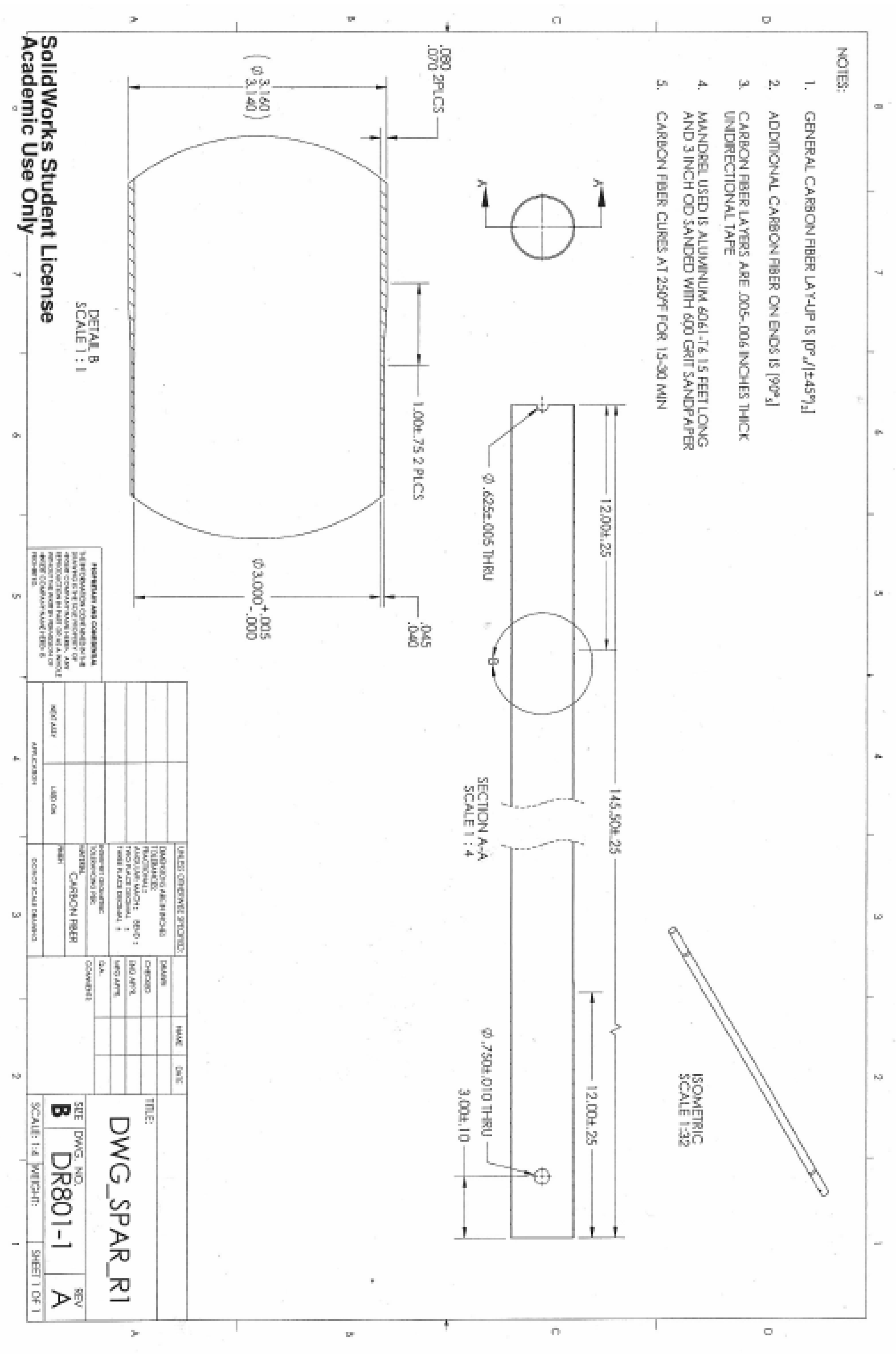
SPAR – two sided



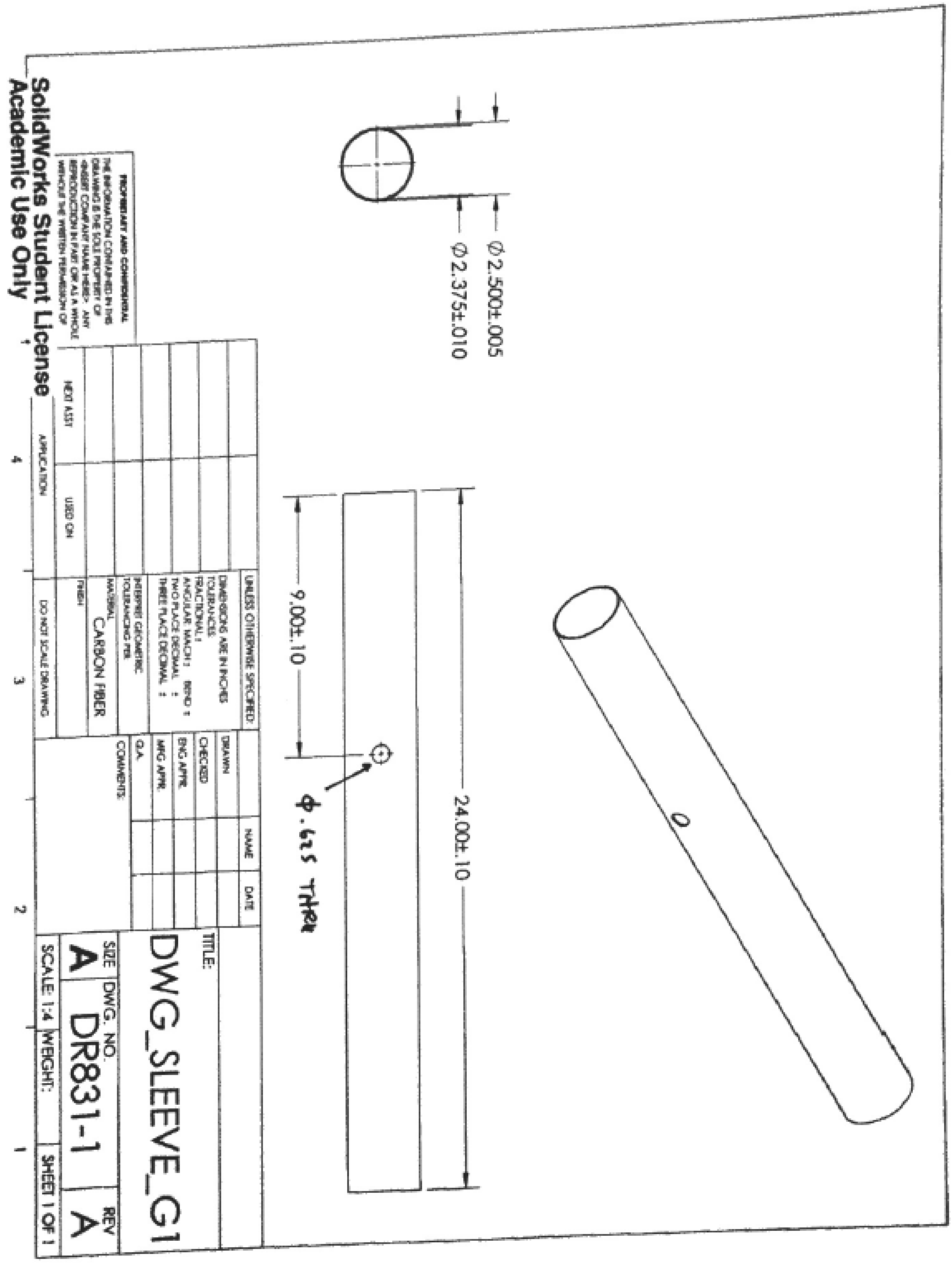
NOTES:

1. GENERAL CARBON FIBER LAY-UP IS $[0°_3/(\pm45°)_2]$
2. ADDITIONAL CARBON FIBER ON ENDS IS $[90°_8]$
3. CARBON FIBER LAYERS ARE .005-.006 INCHES THICK UNIDIRECTIONAL TAPE
4. MANDREL USED IS ALUMINUM 6061-T6 15 FEET LONG AND 3 INCH OD SANDED WITH 600 GRIT SANDPAPER
5. CARBON FIBER CURES AT 250°F FOR 15-30 MIN

Bottle Neck Sleeve



SPAR – R1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MATERIAL
CARBON FIBER
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
DWG_SLEEVE_G1
SIZE
A
DWG. NO.
DR831-1
REV
A
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
4
3
2
1