FINAL DESIGN REPORT:
ENGINE TURBINE BLADE REMOVAL PROCESS REDESIGN

PROJECT TEAM NO. 19: AEROSOLUTIONS CONSULTING

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UNIVERSITY OF MANITOBA

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E2-262 Engineering & Information Technology Complex
University of Manitoba
Winnipeg, Manitoba
R3T 5V6

December 7, 2015

StandardAero

Winnipeg, Manitoba

Dear Mr. Bartel,

We are pleased to present our Final Design Report to you. The purpose of this report is to propose a preliminary design for the turbine disk rivet disassembly fixture as desired by StandardAero. This report defines the problem along with all the associated needs, constraints, and specifications. This report then describes our team's proposed solution, including all the design components, as well as our team's preliminary engineering analyses. If you have any questions, please feel free to contact us at

Sincerely,

Aero Solutions Consulting

Sarfraz Ahmed	Rae Castro	Tung Huynh	Machao Si
x	x	x	x

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____________x	____________x	____________x	____________x

EXECUTIVE SUMMARY

The purpose of this project is to design an improved rivet removal process for the client, StandardAero, which will ensure consistent alignment accuracy during drilling of the rivets. The client is StandardAero and the design team (Team 19) comprises four undergraduate students from the University of Manitoba's Faculty of Mechanical Engineering. The team have used their collective engineering skills and experience developed over the past 4-5 years of education and related internship experience to design an alignment guide and fixture design that will provide for consistent alignment accuracy between the rivets.

This design consists of two main components; a drill alignment guide and a redesigned disk mounting assembly. The alignment guide provides for initial alignment of the drill bit with the rivet bore on the turbine disk. The guide consists of a tubular shaft, with an outer diameter of 0.20" and length of 0.85". It has an inner bore running through its length at a diameter of 0.074". The guide also has a knurled handle with a diameter of 0.35", and is perpendicular to the tubular shaft. The material specified for this guide is high strength polypropylene thermoplastic. The bottom end of the guiding shaft matches the shape of the chamfer that surrounds the rivet bore, and is designed to sit on the chamfer so that the inner bore is aligned with the rivet bore.

The redesigned disk mounting assembly replaces the current bearing system with a motorized rotary stage, by ThorLabs Inc. Once the initial drill alignment is set, the rotary stage rotates the turbine disk to subsequent rivet bore positions by a specified distance, and ensures that movement is consistent throughout the drilling process. The rotary stage is run by a stepper motor which is controlled by a motor controller with pre-programmed software, allowing an operator to set the specified distance and control the rotary stage through a simple GUI menu on a PC workstation.

The estimated cost of the redesigned fixture assembly (excluding the alignment guide) was determined to be approximately $4000. However, if the implementation of this design results in a reduction of even a single turbine disk saved from drilling damage per year, the savings of one saved disk would offset the cost of the new design, making a payback period of one year possible and therefore making this design economically viable.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Since 1911, StandardAero has established itself as a world leader in providing maintenance, repair, and overhaul (MRO) services for aviation engines. As such, Standard Aero has a continual interest in the improvement of its MRO services in order to continue to meet customer satisfaction. StandardAero has requested AeroSolutions Consulting to develop such an improvement.

This report focuses on the presentation and analysis of an improved turbine blade rivet drilling and removal process. This report presents an overview of the background and objectives, and client's needs, as well as a presentation of the improved process, which will include the design of an improved rivet drilling fixture. An overview of the concept selection and development process, detailed analysis of the design, engineering drawings, and operation guide can be found in the appendices.

1.1. PROBLEM BACKGROUND

Aviation engines manufactured by companies such as GE Aviation, Rolls-Royce, and Pratt & Whitney Canada are routinely sent to StandardAero facilities around the world to undergo maintenance, repair, and overhaul (MRO) services [1]. Notably, StandardAero's Winnipeg facilities provide MRO services for Pratt & Whitney Canada's PT6A and PW100 turboprop engine models. During the MRO process, these engines are disassembled, their parts are closely inspected and repaired as needed, and then tested for performance before they are sent back to a customer.

The disk component of the engine's turbine section, as shown in Fig.1, requires the removal of all of its turbine blades as part of the disassembly process. These blades are secured to the turbine disk with rivets, which must be drilled out in order for the blades to be removed. This is done by securing the disk to a drilling fixture, which allows an operator to set the proper angle and alignment required to properly drill out the rivets. Each disk has between 40 to 80 rivets depending on the engine model, and the alignment and drilling procedure is repeated for each one. The drilling specifications (i.e. drill angle) for each disk model is given by the original equipment manufacturer (OEM), in this case Pratt & Whitney Canada, and must be strictly followed to ensure that the drill bit only makes contact with the rivet and not the turbine disk.

Figure 1: Compressor turbine disk of PT6A engine [2].

1.2. Problem Statement

The current drilling fixture, shown in Fig. 2, is operated manually, and therefore the accuracy required in setting the disk into the proper drilling angle and position is dependent on the operator's skill and experience. This variability in human skill is seen by StandardAero as a major cause of improper drill alignment, which leads to drilling damage to the turbine disk. This type of damage is usually significant enough to render the disks unserviceable, and each year several disks, which range from $30,000 to $40,000 each in value, are lost to drilling damage [3].

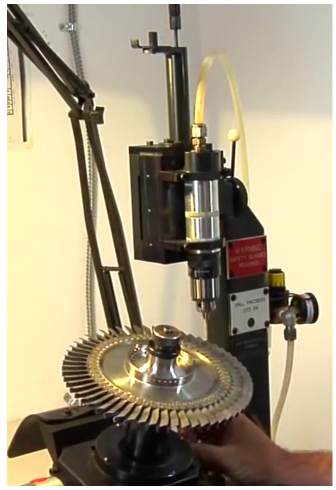


Figure 2: Current rivet drilling fixture [2].

1.3. Project Objectives and Scope

A number of design objectives, as well as a project scope, were established to properly define the final design goals, and to help guide the design process. These were determined through discussions with the client and the project advisor, as well as through internal team discussions.

1.3.1. Objectives

The primary goal of this project is to design an improved rivet removal process for the client, StandardAero, which will ensure consistently accurate alignment of the drill, significantly reducing the potential for damage to the turbine disk components caused by the current manual process [4]. Finally, the design should have a payback period of approximately one year, which will be achieved through the reduction of damaged disks per year.

Because the rivet removal process is done on all PT6A and PW100 disk models, the new design should be transferrable between different sized disk configurations. For the purposes of this project, however, the design process will be limited to developing a solution for a single, medium sized, 2nd stage power turbine (PT) disk (PT6A variant) in order to establish proof of concept. By focusing on a single test case, the redesigned process can be verified prior to full design adoption for all disk configurations.

Along with a new design, the project deliverables as requested by StandardAero include:

- CAD models of any new fixture designs.
- Operation guide (as required by the redesign).
- A list of any new equipment needed.
- Cost estimation and analysis of new design.

1.3.2. Scope

In order to avoid over extending our available resources, it is important to define limitations in terms of the project scope. Our four-student team is tasked to carry out this project with the given time of three months, and therefore only main areas directly related to the project are included. A narrow project scope allows for thorough and rigorous design of a smaller subsection of components. The areas of engineering design and analysis that our team focused were constrained to the following:

- Dynamic Analysis:
    - Consideration of engineering principles for the selected technology.
    - Interference, compatibility and synchronization checks between all the components that will form the overall fixture design.

- Detailed SolidWorks models and engineering drawings.
- Fixture operation guide.
- General ideas for the electrical and software solutions will be provided and discussed but not analyzed or designed:
    - Consideration of items that either fall outside of the mechanical engineering discipline or are not feasible due to the time constraint will be left out of the project scope. These items are as follows:
        - Design of an electrical or software
        - Procurement of materials and contracting services
        - Assembly services and completed design inspections
        - Machine design analysis on components that are available off-the-shelf (e.g. analysis of bearing design, gear design, shaft design, belt design and chain design).

1.4. PROJECT NEEDS, CONSTRAINTS AND SPECIFICATIONS

The project needs outlined in this section display the requirements of the design. These needs were defined through discussion between the team and the client. The needs were categorized into technical, financial and safety needs, and with the use of a scoring matrix the needs were given a weight to describe their level of importance. Table I displays the desired needs and their relative percentage weight. Each need is assigned an identification number (ID No.) to aid in clarity and organization.

TABLE I

CLIENT NEEDS AND RELATIVE WEIGHT

ID No.	Client Needs	Relative Weight (%)
	Technical Needs	
N1	Must accommodate different sizes of PT6A and PW100 engine rotor disks	8.66
N2	Controls rotation of the disks	6.06
N3	Ensures accuracy of alignment	6.06
N4	Allows for consistency in removing all the rivets	3.46
N5	Must control the drilling angle	8.66
N6	Allows ease in setting the angle before the drilling process	3.46
N7	Must control lateral position of the fixture	7.79
N8	Must restrict the fixture during angle setup and drilling operation	6.93
N9	Accommodates the existing spindle size(s)	2.60
N10	Must accommodate the existing drill bits size(s)	7.36
N11	Accommodates the existing punch size(s)	0.43
N12	Has a high design life	1.30
N13	Provides for appropriate drilling pressure	4.33
N14	Must have a reasonable size	2.16
	Financial Needs	
N15	Allows easy replacement/maintenance of the worn-out parts	1.73
N16	Can be maintained with the available tools	0.00
N17	Requires less manual dexterity than the current process demands	5.19
N18	Demands minimal experience from the operator	6.06
N19	Reduces the initial setup time	0.87
N20	Requires low maintenance cost	3.03
N21	Has a reasonable payback period	4.76
	Safety	
N22	Must operate safely	9.09

Needs that exhibited a high relative weight (other than safety) were needs that related to the disk alignment process (N5, N7, N8, N2, and N3), as well as the need to accommodate all PT6A and PW100 engine configurations. The high weights associated with these needs reflected the fact that these are considered essential by the client, and therefore any new concepts that will be generated must address these needs. Lower ranked needs (N20, N14, N15, and N20) are deemed as “nice to have.” These needs will not drive our design process, but will be kept in consideration in order to improve our client's overall satisfaction with our proposed solution.

The needs were then associated with quantifiable metrics and associated target specifications. These metrics were also analyzed by scoring the metrics in comparison to their associated needs, in order to measure their sensitivity to change when designing to meet the needs. Table II displays the metrics, the associated target specifications, and the resulting metric sensitivity. As with the needs, the metrics were assigned metric ID numbers to aid in clarity and organization.

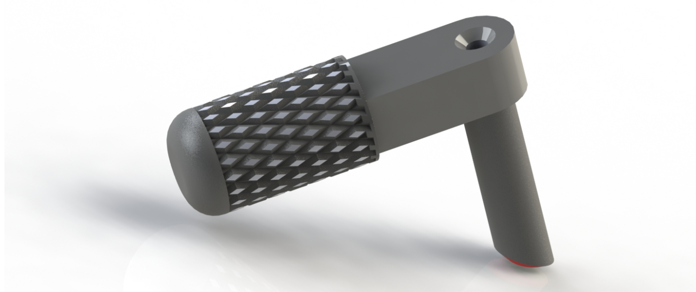
TABLE II

METRICS, TARGET SPECIFICATIONS, AND METRIC SENSITIVITY

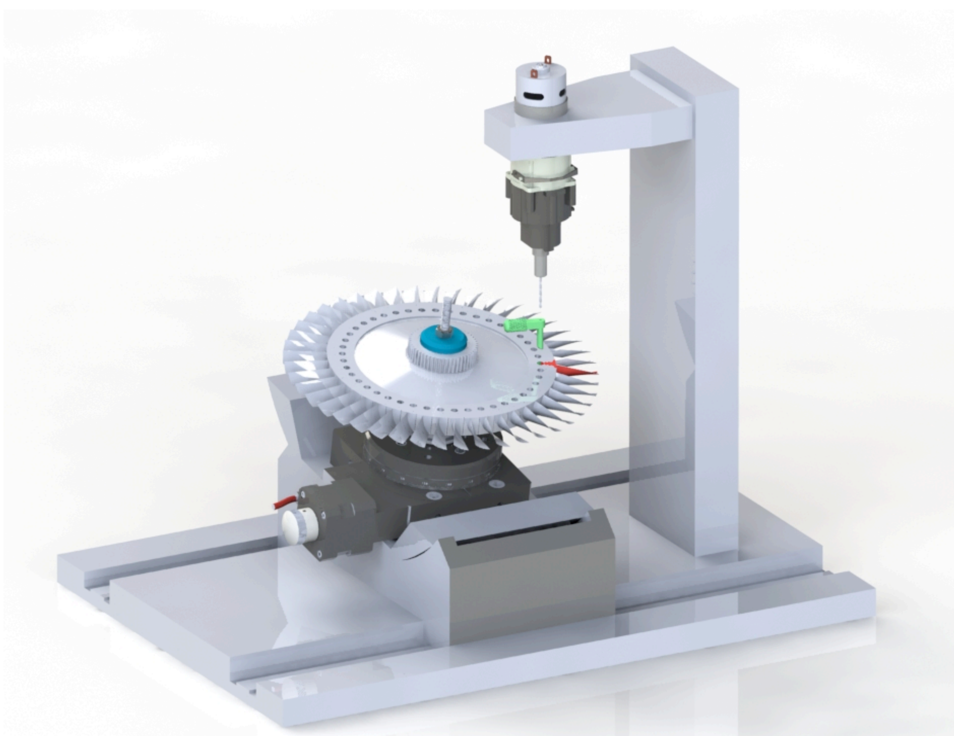
Metric ID	Need ID	Metric	Target Specification	Units	Metric Sensitivity Score
M1	N1, N14, N7	Disk Diameter	$8 < D < 16$	inches	3.9545
M2	N2, N3, N4	Rotational Angle	$\phi_r < 9$	degrees	3.9091
M3	N4	Angular Tolerance	$\phi_{tol.} < +/- 0.5$	degrees	3.318
M4	N5, N3, N8, N6	Tilt Angle	$-8 < \phi_t < 25$	degrees	3.273
M5	N7, N1	Lateral Distance	$Dl < 16$	inches	3.227
M6	N9, N1	Spindle Diameter	D_{sp}=constant	inches	3.182
M7	N10	Drill Bit Diameter	$D_{db} < 0.073$	inches	2.723
M8	N10	Shank Diameter	D_{sh}=constant	inches	2.4091
M9	N11	Punch Pin Diameter	$D_{pp} < 0.065$	inches	2.091
M10	N12, N18	Operational Hours	Minimize t_{oh}	hours	2.045
M11	N13	Drilling Pressure	$90 < P_d < 100$	psi	1.955
M12	N14	Fixture Size	$V_{cube} < 7000$	cubic inches	1.7727
M13	N17, N18	Human ability	Minimize	subj	1.4545
M14	N19, N6	Setup Time	$t_s < 10$	minutes	1.364
M15	N19, N20	Cost	Minimize	dollars	1.273
M16	N21	Payback Time	$t_p < 12$	months	1.182
M17	N22	Safety Measure	Pass/Fail	subj	0.5454

2. DESIGN DETAILS

The final design concept for the rivet removal process consists of an alignment guide for aligning the drill bit, as well as a redesign of the disk mount assembly found on the current drilling fixture. Both of these components are illustrated in Fig. 3.



(a)



(b)

Figure 3: Illustration of the alignment tool (a), and the disk mount assembly (b), mounted on the drill press fixture.

The final alignment guide and fixture design were achieved as a result of a process involving the exploration of various methods and concepts through internal and external research. This process is further outlined in Appendix A. The following sections provide an overview of the alignment guide and disk mount assembly, along with a discussion of the features found in the design. These sections will also include a description of the guide and assembly operation, as well as an estimation of cost for the overall design. Detailed analysis on the selection and design of these components is also provided in Appendix B. Engineering drawings for the components covered in this section can be found in Appendix C.

2.1. OVERVIEW OF THE DESIGN

In order to address the problems of drilling alignment accuracy and operator variability, the new design was divided into two main components. The first component is a drill bit alignment guide that was devised to accurately align the drill bit with the rivet bore where the rivet shank is located. This replaces the current method of manually aligning the drill bit with the rivet head, which may not always provide an accurate reference to the actual rivet bore position.

The alignment guide is used in conjunction with the second design component: a redesign of the disk mount assembly that is found on the current drilling fixture. The current bearing system used to rotate the turbine disk, is replaced by a motorized rotary stage. Once an initial alignment of the drill bit is achieved with the alignment tool, the motorized stage rotates the disk to each subsequent rivet bore position in an accurate and consistent manner. This consistency is key to eliminating the variability found in the current, highly manual process. With the new process, the operator is only required to align the drill bit once with the assistance of the alignment tool. Overall, this new design will result in a reduced process time, higher accuracy in drilling the rivets, less disks damaged during the process, and money saved from a reduction in disks lost to such damage.

2.2. FEATURES OF THE DESIGN

The alignment guide and the redesigned disk mount assembly consist of implemented features that comply with the client's needs. The following is an examination and discussion of the various features of the design components.

2.2.1. DRILL BIT ALIGNMENT GUIDE

The drill bit alignment guide, illustrated in Fig. 3 (a) and Fig. 4, is a tool that is used by the operator to determine the initial alignment of the drill bit with the rivet bore.

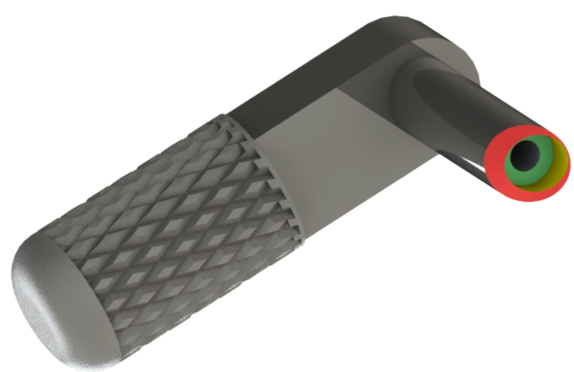


Figure 4: Drill bit alignment guide.

The guide consists of a shaft with an inner bore running through its length, and a knurled handle perpendicular to the guiding shaft. The knurled handle has outer diameter of 0.35", and length of the overall handle piece is 1.16". The guiding shaft has a diameter of 0.20” and a length of 0.85”, and the inner bore has a diameter of 0.086”, which is the same diameter of the rivet bore on the turbine disks. The material specified for this guide is a high strength polypropylene thermoplastic.

The alignment guide is designed to sit on the chamfer that is found surrounding the rivet bore, shown in Fig. 5. The end of the tool shaft, highlighted in red in Fig. 4, is machined to match the shape and angle of the chamfer. In order to fit around the rivet head, the bottom of the guide is recessed by 0.09”, highlighted in yellow. Once seated, the inner bore of the guide will be aligned with the rivet bore, allowing for the operator to position the disk and the drill bit accordingly. This alignment is done on the first rivet, which establishes the initial position for the rotary stage.

Figure 5: Location of the chamfer around the rivet head [property of StandardAero].

Using the geometry and location of the chamfer, rather than the rivet head, to find the location of the rivet bore means the alignment guide is relying on a consistent point of reference. This is because the rivet heads may differ in geometry based on how they are formed, and may not be perfectly aligned with the rivet bore. Using the actual geometry of the turbine disk provides a higher level of accuracy, which is crucial for the disk mount assembly to function properly.

2.2.2. Disk Mount Assembly

The disk mount assembly, on which the turbine disk sits and is rotated, was redesigned to be motorized to provide accurate movement between each rivet bore position, once initial alignment is achieved. The assembly consists of the base and cradle (taken from the current fixture design), the motorized rotary stage, and a redesigned spindle. These various components are outlined in Fig. 6.

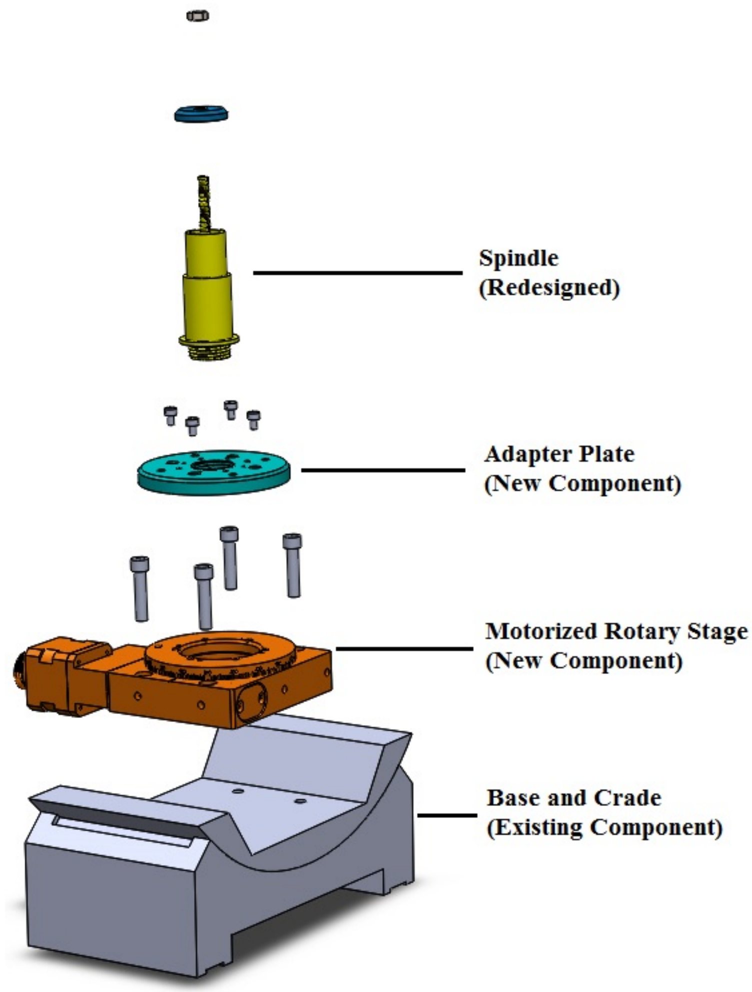


Figure 6: Exploded view of the disk mount assembly.

2.2.2.1. Base and Cradle

The base and cradle components have not changed in design from the current fixture. This is because the current method of attaining the appropriate drilling angle and lateral position provided the appropriate amount of accuracy. The mounting of the base and cradle onto the fixture and to each other are therefore unchanged, along with their function and operation. These, along with other components originating from the current fixture in use, are made of black oxide all-steel, as specified by the client.

2.2.2.2. MOTORIZED ROTARY STAGE

The rotational movement is achieved by replacing the current bearing mechanism with a motorized rotary stage that is run by a stepper motor. By switching to a motorized actuator, the rotational movement of the turbine disk between each rivet position becomes more consistent, allowing for the drill alignment to be maintained throughout the process. The rotary stage is a commercially available unit known as the NR360S NanoRotator, produced by ThorLabs Inc., and shown in Fig. 7. Constructed primarily of aluminum, it is 3.94” by 3.98” in size and weighs 1.4 kg.

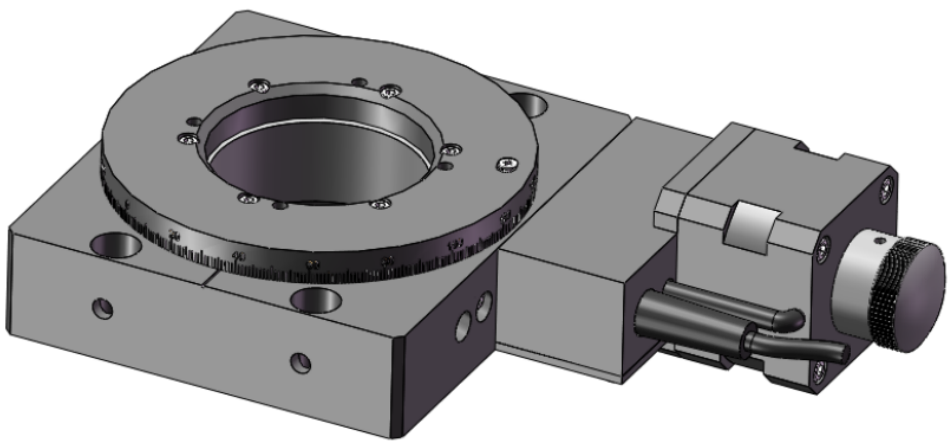


Figure 7: NR360S NanoRotator [5].

The NR360S is driven by a stepper motor, which moves the actuator in “steps” of a specified size (i.e. degrees or radians). Once the initial alignment of the drill bit is achieved using the alignment guide, the stage is prompted to move, or “step”, a specified amount to the next rivet position, so that the drill bit remains aligned with the next rivet bore. This is an improvement over the current procedure, wherein the operator turns the disk by hand and aligns the drill bit both visually and by feel for each rivet bore. The

NR360S also features a knob that allows for manual movement of the motor and stage during the initial alignment of the drill and disk.

The stepper motor is controlled by the BSC201 stepper motor controller, shown in Fig. 8, also from ThorLabs Inc. The controller comes preloaded with software drivers needed for controlling the rotary stage, and uses a USB connection to a PC workstation, increasing the ease of implementation of the system given its plug-and-play characteristics.

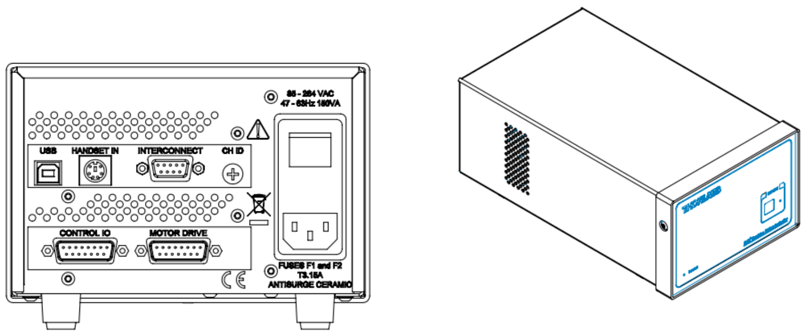


Figure 8: BSC201 Benchtop stepper motor controller [6].

Control of the rotary stage is presented on a graphical user interface (GUI) on the workstation, allowing the operator to move the rotary stage as needed, as well as change the required step size. Operation of the user interface software is given in Section 2.3.

2.2.2.3. Adapter Plate and Spindle

The implementation of a new rotary system called for a redesign of the spindle that is used to attach the turbine disk to the cradle. To facilitate such a design, an adapter plate, shown in Fig. 9, that is also available from ThorLabs Inc., is attached to the top of the rotary stage.

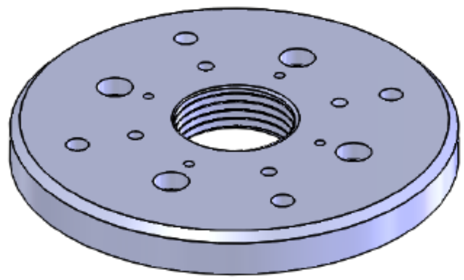


Figure 9: NR360SP8 adapter plate [7].

The center hole of the adapter plate has a center hole with a diameter of 1.035”, and, like the rotary stage, is made of aluminum. The center hole is threaded with a SM1 (1.035-40) series internal thread, and is where the spindle is attached.

The new spindle design incorporates a threaded connection point (SM1 1.035”-40) at the bottom of the spindle, which allows the spindle to be screwed into the center hole of the adapter plate, and thereby secured to the rotary stage. Fig. 10 illustrates the new spindle, as well as the disk pad and the hex nut used to secure the turbine disk to the spindle. As different turbine disk configurations have different sizes, the spindles required by different disks will also change in size. However, the overall concept is the same as the below figure, with a threaded bottom to connect to the rotary stage, a wide, hollow shaft to support the disk, and a threaded rod (1/4”-28 UNF-2B) to secure the disk to the spindle.

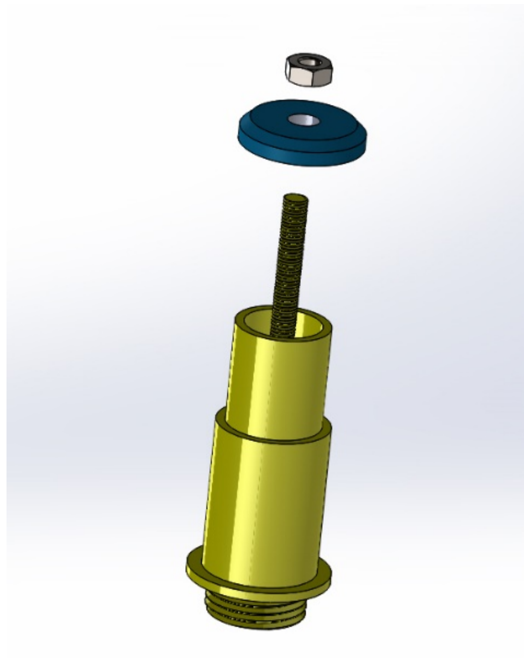


Figure 10: New spindle design.

The new spindles will be made of the same black oxide all-steel material as the current spindles. It must be noted that this model was designed to accommodate the turbine disk and fit into the adapter plate. No analysis pertaining to the stresses on the spindle was done due to the limited time. Therefore, in order to fully implement this design, further analysis needs to be carried out.

2.3. DESIGN OPERATION

As with the current process, the operator can refer to an operation manual which outlines the steps required to perform the rivet drilling from start to finish. An operation guide for the new design has also been developed for the same purpose and is provided in Appendix D.

In the redesigned removal process, the angular position is set in the same manner as in the current procedure, with the operator using the protractor to set the tilt angle as per

OEM specifications for the respective disk model. An appropriate sized spindle is then screwed onto the rotary stage, and the turbine disk is secured to the top of the spindle with a pad and nut.

Primary control of the rotary stage is done on a PC workstation, where the control software displays control buttons displayed on a GUI menu, as seen in Fig. 11. Notably, the “Jog” buttons rotate the rotary stage by a specified step size, and the “Enable” button toggles the motor power on and off.

Figure 11 : Main GUI menu [6].

Using the GUI interface, the motor power is disabled to allow use of the manual motor knob. The alignment guide is placed on the rivet bore chamfer, and using the manual knob and the cradle slider, the turbine disk is positioned until the drill bit is aligned with the alignment guide bore, as illustrated in Fig. 12. The correct alignment is achieved when the drill bit, the alignment guide and the rivet shank is on the same line of action (all are concentric).

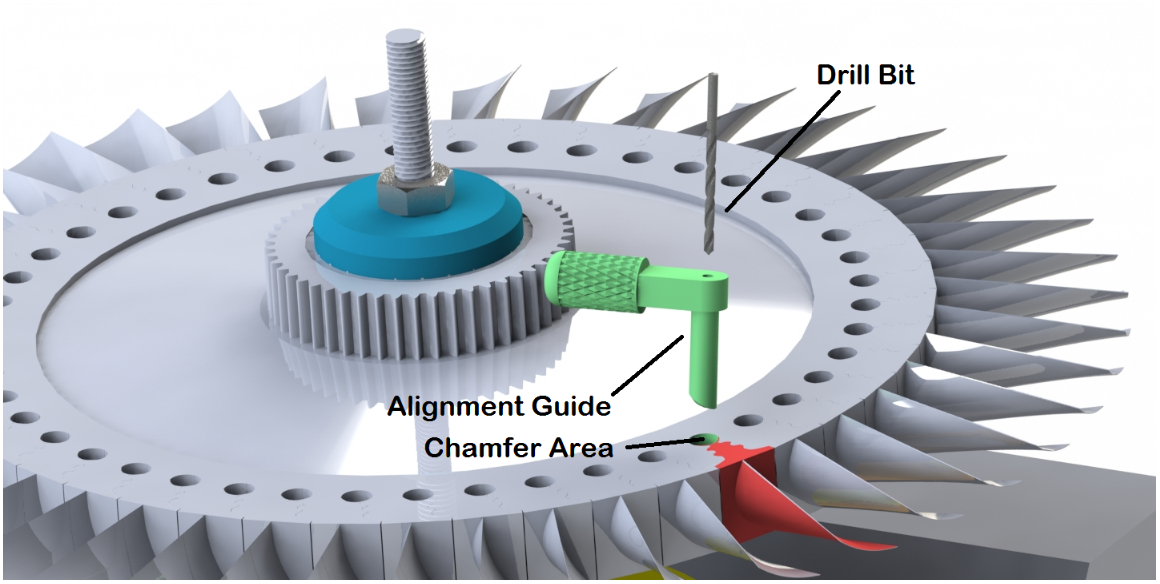


Figure 12: The drill bit is aligned into the guide bore.

Once this position is determined, the motor power is re-enabled to lock the disk position in place. The operator then sets the step size/distance of the rotary stage in the Motor Driver Settings, shown in Fig. 13.

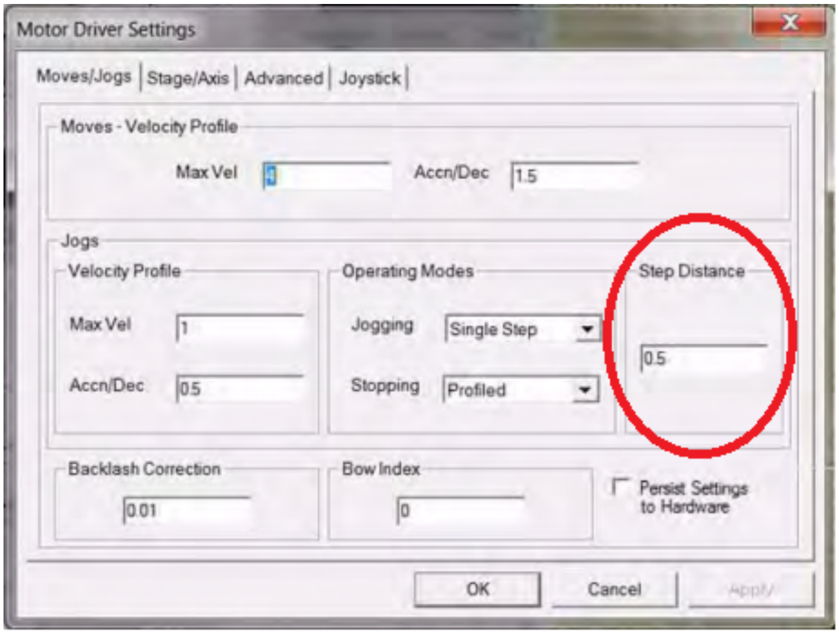


Figure 13: Motor parameter settings [6].

The step size is determined by the number of rivets a given disk has, summarized in the equation:

$$Step\ Size\ [degrees] = {}^{360°}/_{\#\ of\ rivets}$$

This information is to be provided to the operator in tabular form.

Now that the initial alignment and step size have been set, the operator drills the rivets using the drill press in the same manner as the current procedure. When the disk needs to be moved to the next rivet position by clicking the “Jog” arrows on the main GUI menu.

2.4. DESIGN FEATURES VERSUS CLIENT NEEDS

Table III outlines the features that meet the project objectives and high level client needs.

TABLE III

SUMMARY OF THE REDESIGNED FIXTURE DESIGN FEATURES VERSUS CLIENT NEEDS

Client Needs	Design Features
Must accommodate different sizes of PT6A and PW100 engine rotor disks	▪ Although the alignment guide was designed to accommodate only the PT 2nd stage medium disk, it can be modified to provide for the initial alignment for the other PT6A models as well as the PW100 disks. ▪ Multiple sizes of spindles will be available to accommodate the mounting of different disk models.
Controls rotation of the disks	▪ The new disk mount assembly utilizes a motorized rotary stage to rotate the disk during the drilling process.
Ensures accuracy of alignment	▪ The bottom end of the alignment guide is designed such that its internal diameter is always aligned with the rivet more center, thus allowing for high alignment accuracy. ▪ The motorized rotary stage ensures that the drill bit is accurately aligned at each rivet location once an initial position has been established.
Allows for consistency in removing all the rivets	▪ Because the disk rotation is motorized and software controlled, the rotary stage will rotate the disk in a constant and consistent manner, given that the initial alignment position has been correctly established.
Allows ease in setting the angle before the drilling process	▪ The method of setting the drilling angle has not been changed, as it was seen to be sufficient.
Must control lateral position of the fixture	▪ The method of moving the disk mount assembly laterally has not been changed, as it was seen to be sufficient.
Must restrict the fixture during angle setup and drilling operation	▪ The method of locking the angular position and the lateral position has not been changed, as it was seen to be sufficient. ▪ The rotary stage locks position after each rotation, ensuring the disk remains unmoved during drilling.

Client Needs	Design Features
Accommodates the existing spindle size(s)	▪ The spindles will need to be redesigned to allow for connection to the rotary stage.
Must accommodate the existing drill bits size(s)	▪ The internal diameter of the alignment guide is designed such that it is slightly bigger than the drill bit thus allowing for easy movement of the drill bit through it.
Must have a reasonable size	▪ The alignment guide has a length of 0.85” which makes it compact and user-friendly ▪ The rotary stage is 3.94” x 3.84” in size, small enough to fit in the existing cradle. This results in a new disk mount assembly that is comparable in size to the existing fixture.
Allows easy replacement/maintenance of the worn-out parts	▪ Replacement parts for commercially obtained components are available through ThorLabs, along with technical support and warranty coverage.
Requires less manual dexterity than the current process demands	▪ Use of an alignment guide for the initial alignment and using the rotary stage for step rotation of the disk through a GUI interface allows for low manual effort in carrying out the entire rivet removal process.
Demands minimal experience from the operator	▪ Owing to its simplicity, the alignment guide can be used by an operator with minimal to no experience.
Reduces the initial setup time	▪ The new process improves setup time by requiring alignment of only one rivet position in order to establish an initial position, and the changing of the step size parameter in the software control.
Has a reasonable payback period	▪ At an approximate cost of $4000, the new process design can reduce the number of disks lost to damage per year, where the savings from even a single disk saved will offset the design costs.
Must operate safely	▪ The sturdy design of the redesigned fixture allows for safe operation. ▪ The reduction of manual operation through the motorized rotary stage helps to increase the operational safety of the new design.

2.5. COST ESTIMATION

The total cost of the redesigned fixture is approximately $4000, covering the components of the disk mount assembly while excluding the alignment guide or any labor fee associated with the implementation of the design. This cost mostly comes from the purchase of components required to build the disk mount assembly, along with some to-be-determined (TBD) costs of components that require further analysis and prototyping before being manufactured and implemented, such as the redesigned spindle and the alignment guide. These analyses have been excluded as they are beyond the scope of this project and can be carried out by a subsequent capstone design team. The cost breakdown that features all the components is explained in Appendix B, along with the bill of materials that outlines the main components, part numbers, suppliers, prices and all the accessories needed to build the complete redesigned drilling fixture.

3. Conclusion

AeroSolutions Consulting (Team 19) was tasked by StandardAero to develop an improved turbine disk rivet removal process. The goal of the new design was to decrease the chance of drilling damage to the turbine disk during rivet removal by reducing the variability of a human operator, and thereby ensuring accurate and consistent alignment between the drill bit and the turbine disk. The design process was limited to developing a solution for a single, medium sized, 2nd stage power turbine (PT) disk (PT6A variant) in order to establish proof of concept. This allowed the redesigned process to be verified prior to full design adoption for all disk configurations.

The new design consists of two main components. The first is a drill alignment guide, which is used to establish an initial alignment between the drill bit and the rivet bore on the turbine. The guide consists of a shaft, with an outer diameter of 0.20” and length of 0.85”, which has an inner bore running through its length at a diameter of 0.074”. The guide also has a knurled handle with a diameter of 0.35”, and is perpendicular to the shaft. The guide is made of high strength polypropylene thermoplastic. The bottom end of the guiding shaft matches the shape of the chamfer that surrounds the rivet bore, and is designed to sit on the chamfer so that the inner bore lines up with the rivet bore.

The second component is a redesigned disk mounting assembly, which replaces the bearing system with a motorized rotary stage, produced by ThorLabs Inc. Once the initial drill alignment is set, the rotary stage rotates, or “steps” the turbine disk to the next rivet bore positions by a specified distance, and ensures that movement is consistent throughout the drilling process. The stepper motor in the rotary stage is controlled by a motor controller with preprogrammed software, allowing an operator to set the step distance and control the rotary stage through a simple GUI menu on a PC workstation.

The estimated cost of these new design components was determined to be approximately $4000 (excluding the alignment guide). However, if the implementation of this design results in a reduction of even a single turbine disk saved from drilling damage per year, the savings of one saved disk would offset the cost of the new design, making a payback period of one year possible and therefore making this design economically viable.

4. RECOMMENDATIONS

This section of the report provides a list of recommendations that our team finds necessary to be considered by the client, StandardAero, in order to fully implement the new disk mount assembly design.

- Since the team relied on some really basic measurement tools, such as Vernier calipers, to obtain the measurements of the chamfer area, a better measurement technique or equipment should be used to measure this area around the rivet prior to manufacturing the alignment guide.
- Although a material was specified for the alignment guide (i.e. polypropylene thermoplastic), a thorough research in materials and prototype testing using different materials needs to be carried out in order to guarantee complete successful implementation of this guide.
- In order to verify the design of the new spindle, a proper stress analysis should be performed. The procurement of this analysis can be assigned and carried to a subsequent capstone design team.
- All the components of the new disk mount assembly design should be prototyped and tested to verify proof of concept.

5. REFERENCES

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APPENDICES

Team 19 - AeroSolutions Consulting was given the task of providing the client, StandardAero, with an improved rivet removal process which ensures consistent accuracy in alignment of the drill, thus eliminating the potential for damage to the turbine disk components. The improved fixture design ensures that the variability in alignment accuracy is reduced owing to its level of automation. This design is transferrable to all sizes and configurations of turbine disks of the PT6A and PW100 family of turboprop engines. The cost of implementing this fixture design was estimated to be $4000, excluding the alignment guide and other components that require further analysis.

Appendices A through C are provided to give details of the final design generated for this project. Appendix A displays the concept generation and screening process conducted for this project. This includes all of the design concepts that were generated from the brainstorming sessions described with a picture and written explanation, as well as pros and cons of the design. Also included is an explanation of the screening process, depicting the process of how the final design was determined from the various concepts, with tables and results.

Appendix B shows the analysis completed in generating our final design. This includes research, analysis and design of the rotary stage and tubular guide. Lastly, the details of the project costs are displayed with references.

Appendix C displays the manufacturing and assembly drawings of the final design for the major components. This includes drawings of the complete disk mount assembly, the redesigned spindle, the cradle, the securing pad, the alignment guide, the adapter plate and the rotary stage.

Finally, Appendix D provides the operation guide that summarizes the steps need to be taken to carry out the rivet removal process using the redesigned fixture.

APPENDIX A

PRELIMINARY DESIGN CONCEPTS

TABLE OF CONTENTS

List of Figures

LIST OF TABLES

A.1. INTRODUCTION

This section introduces the results from the concept development stage, which involved brainstorming and TRIZ to generate all the concepts for the design. Using system engineering approach, the team has broken down the design problem into stages associated with the procedure, and further investigated the uncertainty and factors that may cause trouble. Each component contributed to the current design has been fully studied and understood in order to yield a local solution, and then all the local solutions were combined to determine the final solution. Depending on the source and severity of the component problem, a total redesign of the system is considered. All the preliminary concepts are the combinations of ideas and solutions to three main principles: translational positioning, rotational positioning and drilling alignment. Each concept is assessed and evaluated for their pros and cons, and then concept screening and concept scoring stages are performed to determine the most feasible concepts that can be continued, considered, or discarded. The results are the top three concepts to be presented to the client and to be developed upon. All other concepts will also be revised to filter their good features and utilize them. The final design concept is subjected to change and will be improvised to satisfy design requirements and client's needs.

A.2. PRELIMINARY DESIGN CONCEPTS

The design concepts that were generated from the determination of the customer needs and target specifications are given below. Each concept is described with the original drawing and a written explanation. Each concept's sketches, a list of the pros and cons for each design provide justification for the scores that were obtained in the screening and scoring matrix. The concepts are organized in the order that they were analyzed within the screening process of the Conceptual Design Report. The top concepts were given names (A, B, and C) in order to ease communication with the client.

TABLE I

DETAILS OF CONCEPT #1

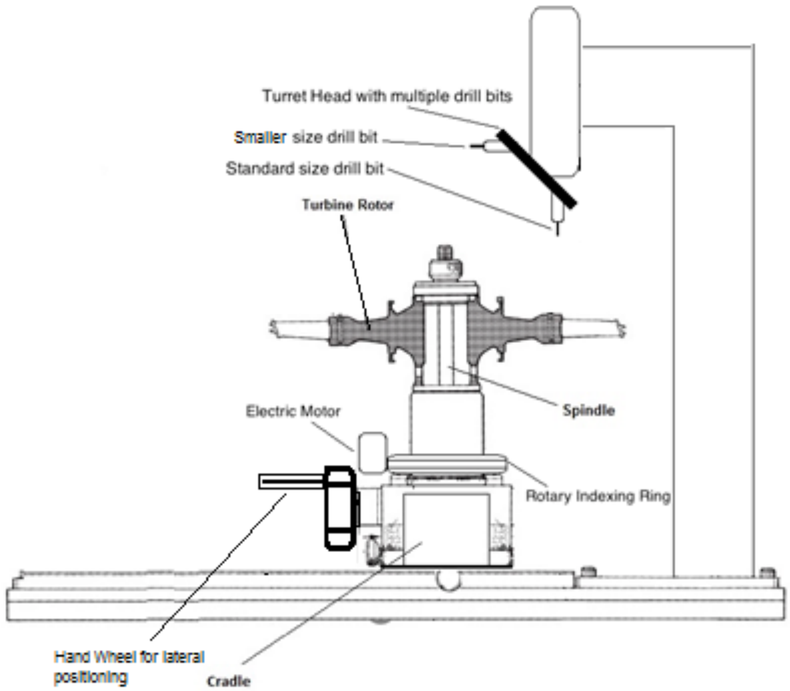

Figure 1: Illustration of concept #1

Concept #1 - Description
• Fix the turbine rotor on to spindle firstly. • Then use a manual hand wheel that controls the lateral movement of the cradle to a desired position along the lateral axis of the fixture. • A rotary indexing ring used for precision drilling alignment after the cradle is locked. • A turret head drilling machine used that switches between different sizes of drill bits to remove rivets out. • A smaller diameter drill bit size will be used to make a guide way for the OEM recommended drill bit.

Pros	Cons
- Good alignment accuracy - Good drilling precision - The rotary ring is customizable and can be programmed to meet plurality of conditions - Low implementation cost	- Manual process (dependent on the operator's experience and skill level) - Translational component wear - Slow Process - Complicated turret head drilling machine implementation

TABLE II

DETAILS OF CONCEPT #2

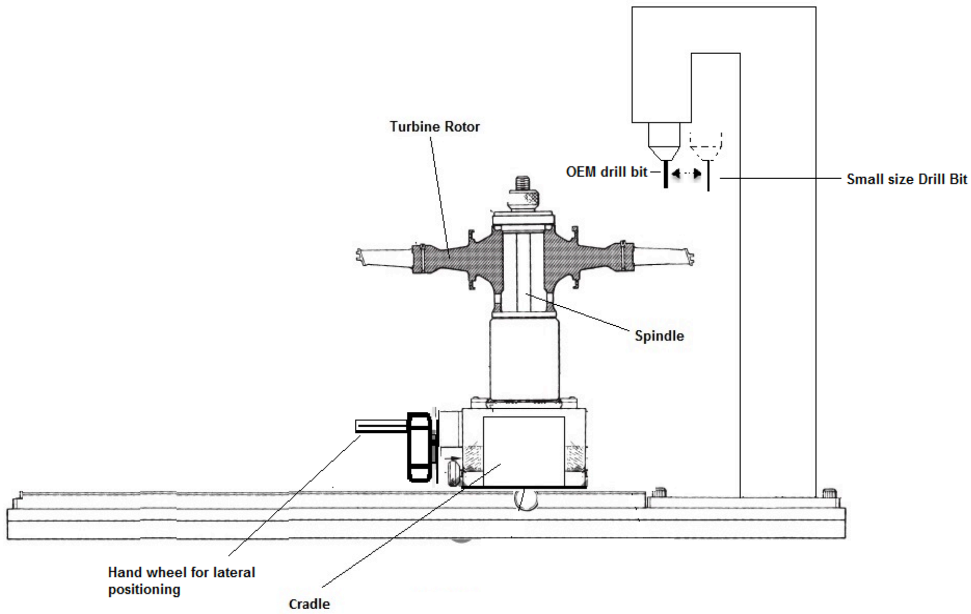

Figure 2: Illustration of concept #2

Concept #2 - Description
• Fix the turbine rotor onto the spindle manually. • Use a manual hand wheel that controls the lateral movement of the cradle where moves to a desired position. • The translation motion of the cradle is locked. • The spindle is manually rotated to align the drill bit with the centerline of rivet. • A smaller drill bit is then used to manually drill into any contorted rivets in order to make a guide way for a bigger drill bit. • Then the OEM recommended drill bit is used to drill the rivet to an appropriate depth.

Pros	Cons
- Low cost - Satisfactory alignment accuracy - Good drilling precision - Decreases manual dexterity compared to the current process - Simple	- Entirely manual process (dependent on the operator experience and skill level) - Translational component wear - Slow Process

TABLE III

DETAILS OF CONCEPT #3

<table>
<tr><td colspan="2">

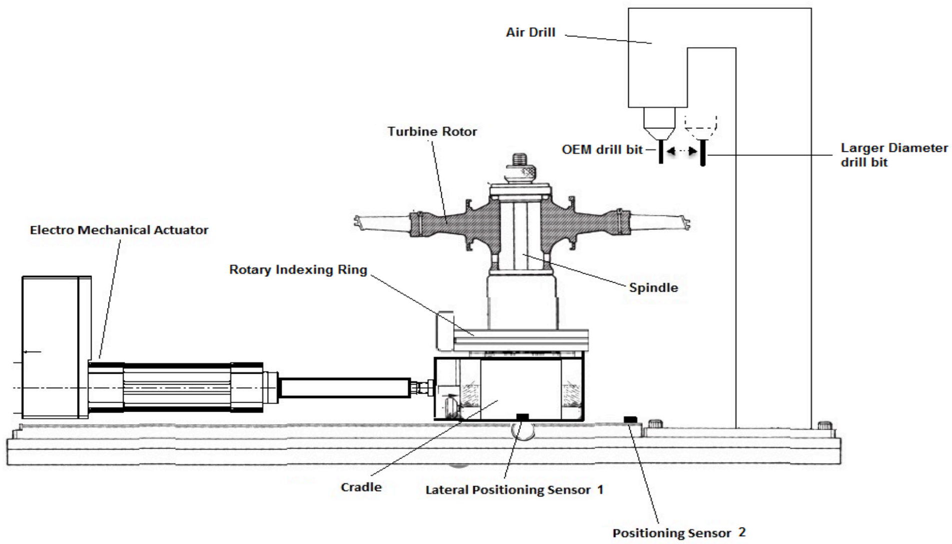

Figure 3: Illustration of concept #3</td></tr>
<tr><th colspan="2">Concept #3 - Description</th></tr>
<tr><td colspan="2">

- An electromechanical actuator used to provide for ease in lateral movement and control the cradle to move the desired position.
- A combination of optical sensors (one located on the cradle and another one is on the base of the fixture) will monitor the lateral position of turbine disk as well as the rivet positions with relation to the drill bit.
- To adjust the disk to the desired angle manually.
- Then use a rotary indexing ring attached to the spindle which be used to rotate the disk and align the drill bit with the rivet.
- A rivet predrilling process would be used a larger drill bit to pre-drill any contorted rivet head into a uniform shape in order to employ for drilling alignment accuracy and consistency.
</td></tr>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>- Robust design
- Negates the need to adjust the position of the disk for contorted rivets.
- High drilling precision
- Good rotational accuracy
- Actuator and Ring are customizable and can be programmed to meet plurality of conditions
- Demands less work space
- Decreases manual dexterity</td><td>- Costs more than the current fixture
- The optical sensor may be affected by interference from ambient light
- Rotational and translational component wear
- Demands sensitive programming of the moving components
- Complexity of synchronization of all the components
- Requirement of component interference checks by the operator</td></tr>
</table>

TABLE IV

DETAILS OF CONCEPT #4

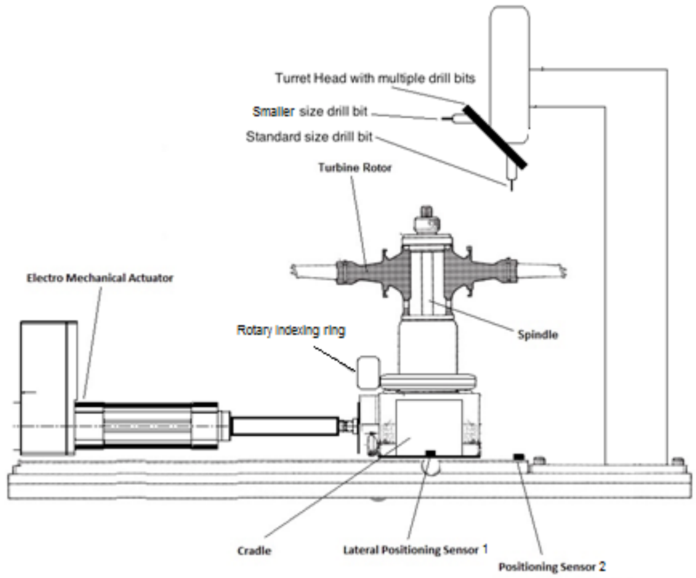

Figure 4: Illustration of concept #4

Concept #4 - Description

- An electro-mechanical actuator, used to provide for ease in lateral movement, will be used to move the cradle to the desired position.
- A combination of optical sensors (one located on the cradle and the other on the base of the fixture) will monitor the lateral position of turbine disk as well as the rivet positions with relation to the drill bit.
- The operator will manually tilt the disk to the desired angle as recommended by the OEM.
- Then a rotary indexing ring attached to the spindle will be used to rotate the disk and align the drill bit with the rivet.
- A turret head drilling machine is used that automatically switches between different sizes of drill bits.
- A smaller diameter drill bit size will be used to make a guide way for the OEM recommended drill bit.

Pros	Cons
- Robust Design - Good alignment accuracy - High drilling precision - Decreases manual dexterity	- The optical sensors may be affected by interference from ambient light - Rotational and translational component wear - Demands sensitive programming of the moving components - Complicated turret head drilling machine implementation - High implementation cost

TABLE V

DETAILS OF CONCEPT #5

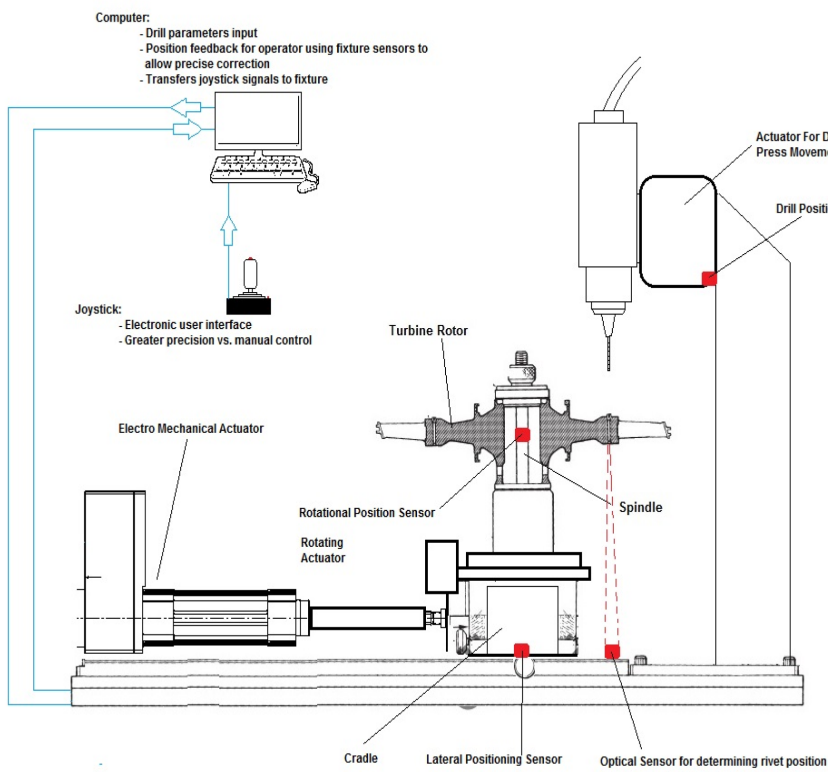

Figure 5: Illustration of concept #5

Concept #5 - Description

- The electro-mechanical actuators to control lateral movement of the disk, as well as the vertical movement of the drill.
- Then various optical sensors will be used to provide position information to a computer control system.
- The computer control system uses the information from these sensors as well as user-inputted drilling parameters (as found in OEM manuals) to provide the operator feedback on the position of the rivets with respect to the drill bit.
- The system will indicate to the operator if the drill bit is properly aligned.
- Electric pinion gear system used to control to the rotational of spindle
- Position control is done using an electronic user interface (e.g. a joystick) to control all fixture actuators.

Pros	Cons
- Robust Design - High alignment accuracy - Electronic data feedback - High drilling precision - Decreases manual dexterity	- The optical sensors may be affected by interference from ambient light - Rotational and translational component wear - Demands sensitive programming of the moving components - Feedback system requires sensitive programming - Added feedback system maintenance (compared to the Concept 3) - High complexity of synchronization of all the components - No ability to compensate for malformed rivets

TABLE VI

DETAILS OF CONCEPT #6

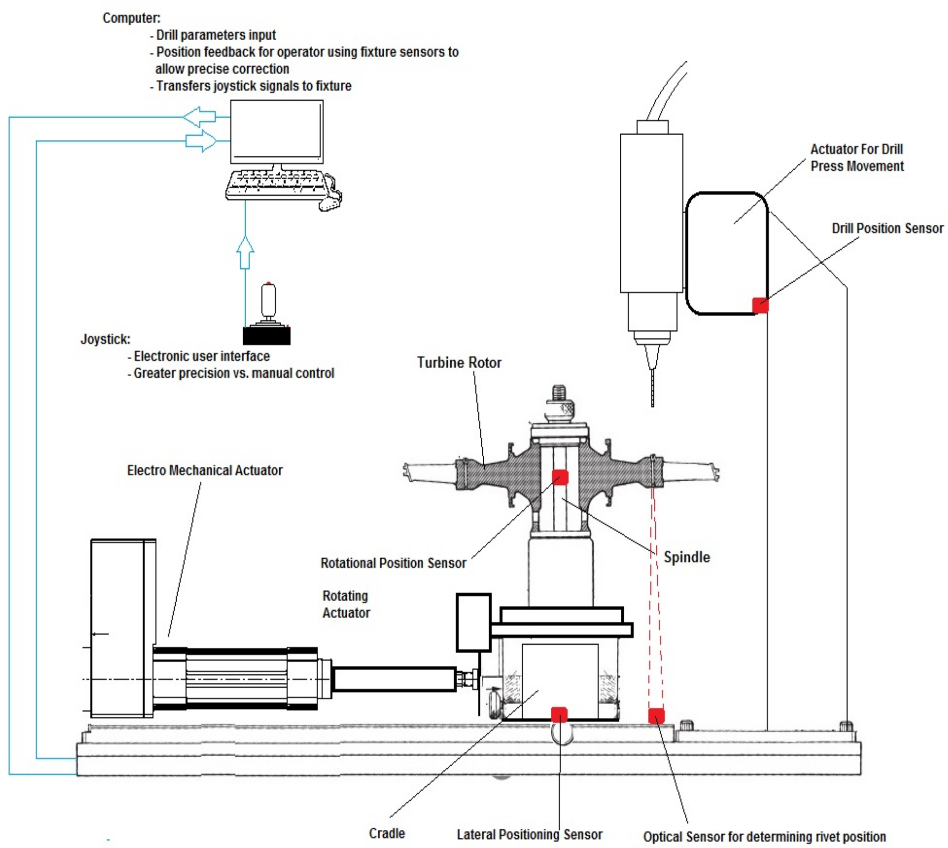

Figure 6: Illustration of concept #6

Concept #6- Description
• This concept is depending on the fully automated computer control system. • The electro-mechanical actuators to control lateral movement of the disk, as well as the vertical movement of the drill. • Electric pinion gear system used to control to the rotational of spindle and align the drill bit with rivets. • Then various optical sensors will be used to provide position information to computer control system, and the information from optical sensors mounted throughout the fixture. • Information from sensors would cross-referenced to the OEM drill specifications, which would be entered in by a user prior to the drilling process • The computer control system is then able to manipulate actuators on the fixture to move the disk into the proper alignment needed to drill the rivet head.

Pros	Cons
- Robust Design - Good alignment accuracy - High drilling precision - Manual dexterity fully eliminated	- The optical sensors may be affected by interference from ambient light - Rotational and translational component wear - Demands sensitive and complex programming of the moving components, feedback system, and computer control system - Complicated turret head drilling machine implementation - High implementation cost - High complexity of synchronization of all the components -No ability to compensate for malformed rivet heads

TABLE VII

DETAILS OF CONCEPT #7

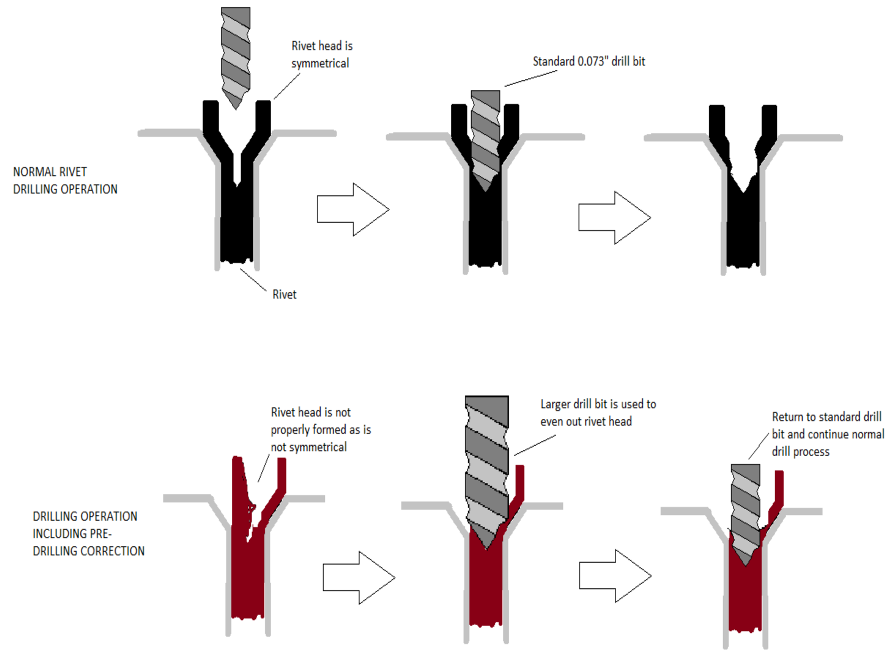

Figure 7: Illustration of concept #7

Concept #7 - Description	
From demonstrations during site visits, it was apparent that many rivets on the disks were formed in a way that the rivet head was not uniform. This leads to the drill bit not being centralized over the rivet holes, and can cause the drill bit to deviate and potentially make contact with the disk and cause damage. • Firstly, an operator should encounter an improperly formed rivet head, would switch the standard drill bit with a larger one. • This larger drill bit corrects the shape of the rivet head into a more uniform and centralized geometry. • Then the operator would switch back to the standard drill bit and continue the drilling process as normal.	
Pros	**Cons**
- Low cost implementation - Simple improvement - Addresses the concern of improperly formed rivet heads - Shorter training time for operators	- Still required significant manual dexterity - Increased risk of drill damage by switching to a larger sized bit - Not guaranteed to correct for all rivet heads

TABLE VIII

DETAILS OF CONCEPT #8

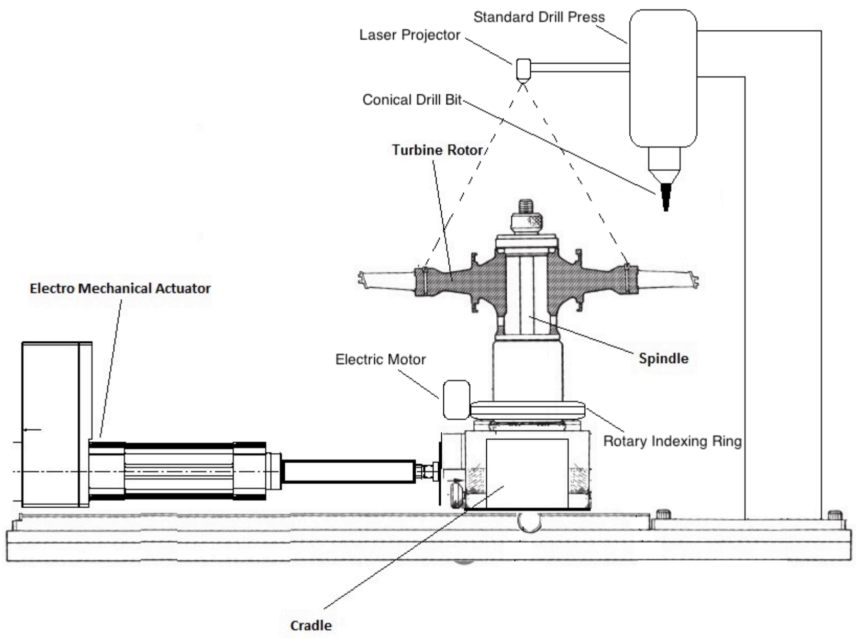

Figure 8: Illustration of concept #8

Concept #8: Description
• An electro-mechanical actuator used to move the cradle in the lateral position and the ring rotates the turbine disk. • The spindle and cradle are redesigned to be paired with the electric-driven rotary ring in order to provide with a more precise method of controlling rotation. • A laser projector shines the position image of rivets onto the disk to aid the operator with alignment and aiming the drill bit • The conical drill bit is used to drill out the rivets completely, with the small diameter at the tip acts as a guide into the rivet heads.

Pros	Cons
- Robust design - Visual aid - Actuator and Ring are customizable - Demands less work space - Decreases manual dexterity - Minimal training time	- The laser projector is not as accurate - Demands specification of each disk for movements - Requires experience from operator - Alignment is still partly manual

TABLE IX

DETAILS OF CONCEPT #9

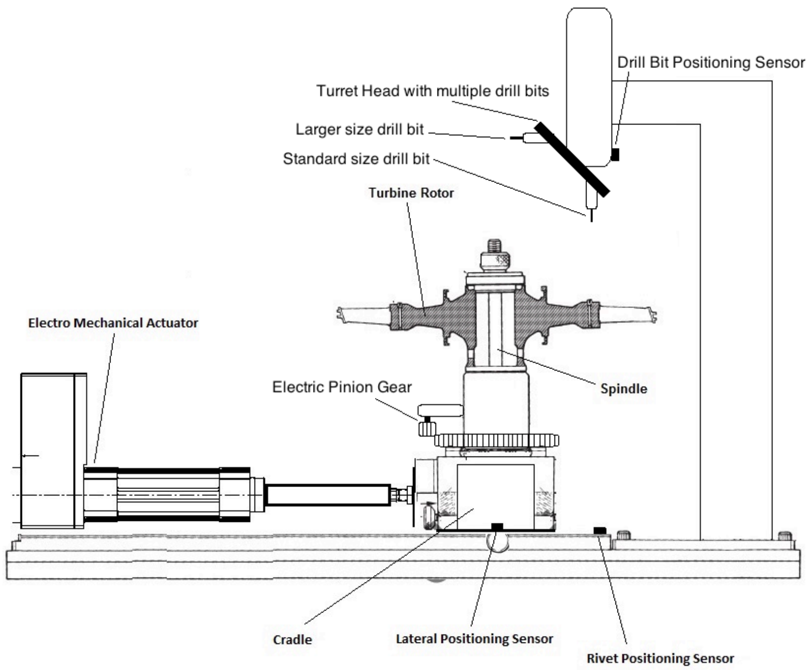

Figure 9: Illustration of concept #9

Concept #9 - Description
• An electro-mechanical actuator controlled the lateral the cradle in the lateral position to the desired position. • An electric pinion gear system used to control the rotation of disk spindle and align the drill bit with rivets. • The positioning sensors provide feedback on the relative position of the turbine disk and the rivet, and compare them with the original input data for higher alignment accuracy (compared to Concept #8). • The turret head machine which is used that automatically switches between different sizes of drill bits. • In any case if a crooked rivet is spotted, the operator can switch to larger size drill bit already mounted on the turret head to flush out the uneven rivet head.

Pros	Cons
- Accurate alignment - Fast tool changing - Can accommodate various drilling jobs with multi drilling chucks available	- High complexity of the turret head - High set up and maintenance costs - Requires lubrication of gears

TABLE X

DETAILS OF CONCEPT #10

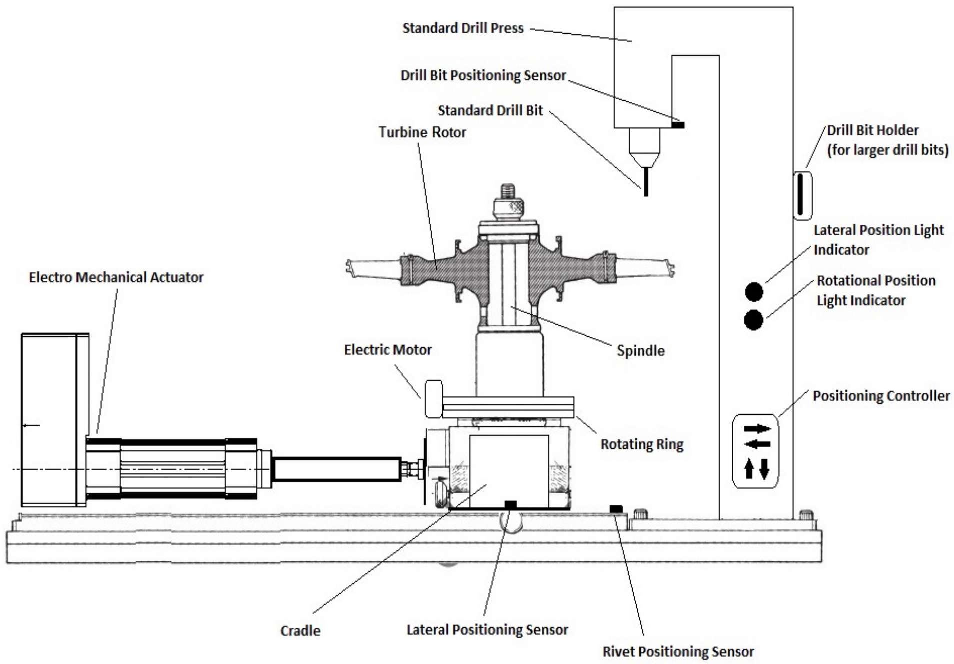

Figure 10: Illustration of concept #10

Concept #10 - Description

- An electro-mechanical actuator is used to move the cradle in the lateral position and the ring rotates the turbine disk to the desired position.
- An electric motor driven ring used to control the rotation of disk spindle.
- Three optical positioning sensors provide feedback on the relative position of the turbine disk and the rivet, so the operator can align the disk properly by using the controller (left/right and clockwise/counter-clockwise movements).
- As soon as the rivet is aligned perfectly, the light indicators will turn to green to notify the operator that the drilling process can begin.
- The existing air drill and the cradle are still used in fixture.
- In any case if a crooked rivet is spotted, the operator has to perform corrective action by using larger drill bit to flush out the uneven surface of the rivet before continuing the process.

Pros	Cons
- Robust Design - High alignment accuracy - Visual feedback - High drilling precision - Actuator and Ring are customizable and can be programmed to meet plurality of conditions - Demands less work space - Decreases manual dexterity	- The optical sensors may be affected by interference from ambient light - Rotational and translational component wear - Demands sensitive programming of the moving components - Feedback system requires sensitive programming - Added feedback system maintenance (compared to the Concept 3) - High complexity of synchronization of all the components - Requirement of component interference checks by the operator - Added cost (compared to the Concept 3)

TABLE XI

DETAILS OF CONCEPT #11

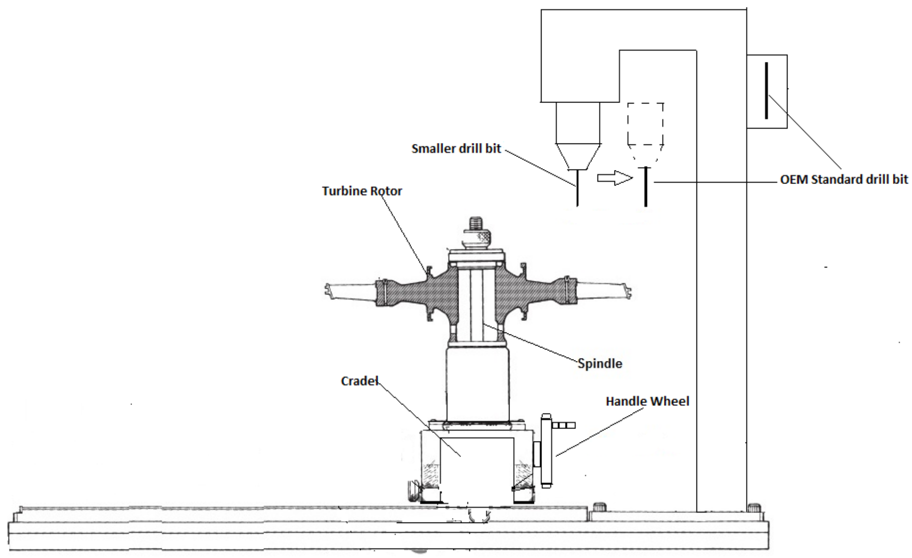

Figure 11: Illustration of concept #11

Concept #11 – Description

- The hand wheel system is used to control and adjust the lateral position through rotating the hand wheel, which ensures the accurate position of cradle.
- By rotating the hand wheel, small increments can be adjusted and thus the precision of the alignment is also improved.
- The small drill bit is used to make the pilot hole in the rivet head and then the OEM standard drill bit could be aligned to remove the rivet in the required depth.

Pros	Cons
- Easy to control. - Low cost. - Easy to implement - Minimum training time.	- Easy to wear out due to friction. - Requires manual dexterity. - Slow positioning process.

TABLE XII

DETAILS OF CONCEPT #12

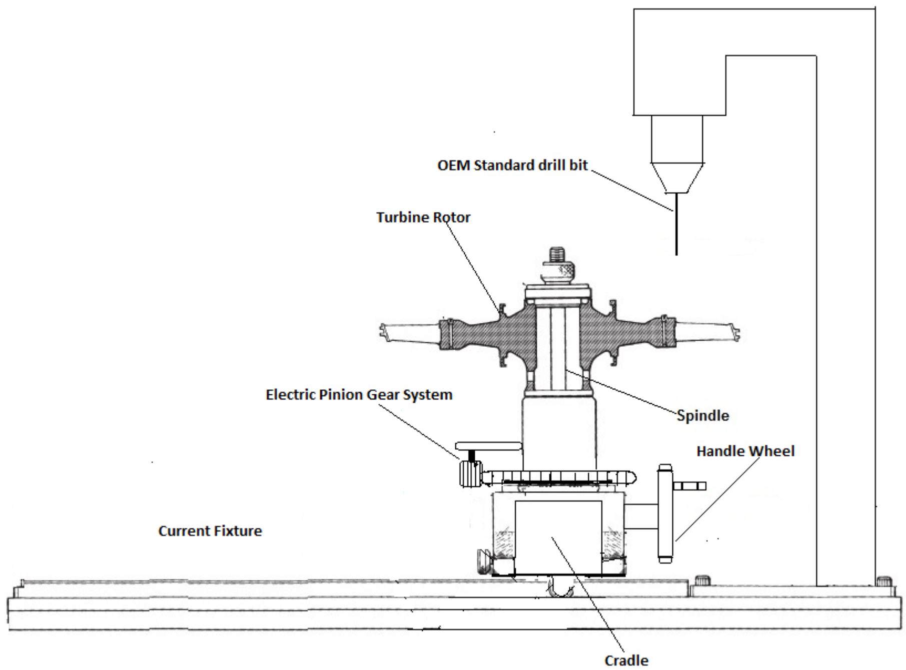

Figure 12: Illustration of concept #12

Concept #12 – Description

- The hand wheel system is used to control and adjust the lateral position through rotating the hand wheel, which ensures the accurate position of cradle.
- The electric pinion gear system rotates the turbine disk and align the drill bit with rivets.
- The standard drill press is utilized to simplify the fixture, and reduce training time.
- The alignment is still manual, but the lateral and rotational movement have been improved by these add-ons.

Pros	Cons
- Easy to control and implement. - Low cost. - Improve alignment accuracy.	- Easy to wear out due to friction. - Requires experience and dexterity from the operator.

TABLE XIII

DETAILS OF CONCEPT #13

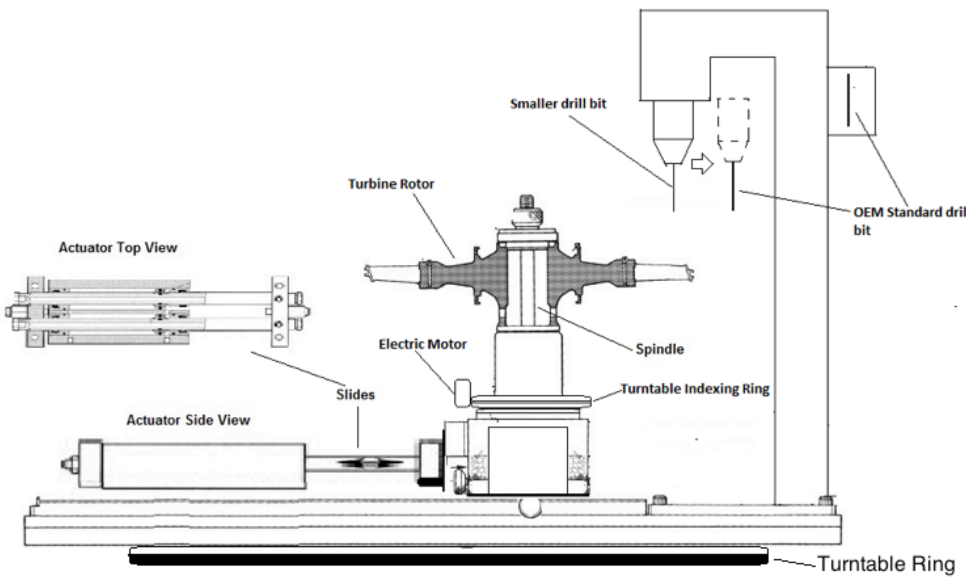

Figure 13: Illustration of concept #13

Concept #13 – Description
• The automated pneumatic system controls the fixture's lateral positon to ensure the accurate positioning. • The electric motor controls the rotation of the disk to ensure accurate alignment and avoid any backlash. • A turntable ring mounted under the fixture allows it to spin 180 degrees in order to let the operator select the best position to drill out the rivets from turbine disk. • The small drill bit would be used make the pilot hole in the head of rivet so that the standard drill bit could be guided into the rivet easily.

Pros	Cons
- Slow positioning process. - Relatively high rotational alignment. - Easy to observe the position of rivets for operator. - Reduces manual dexterity.	- Pneumatic actuator has relatively low precision level. - Turntable ring causes trouble with wires and cables connected to the fixture. - Still requires manual alignment.

TABLE XIV

DETAILS OF CONCEPT #14

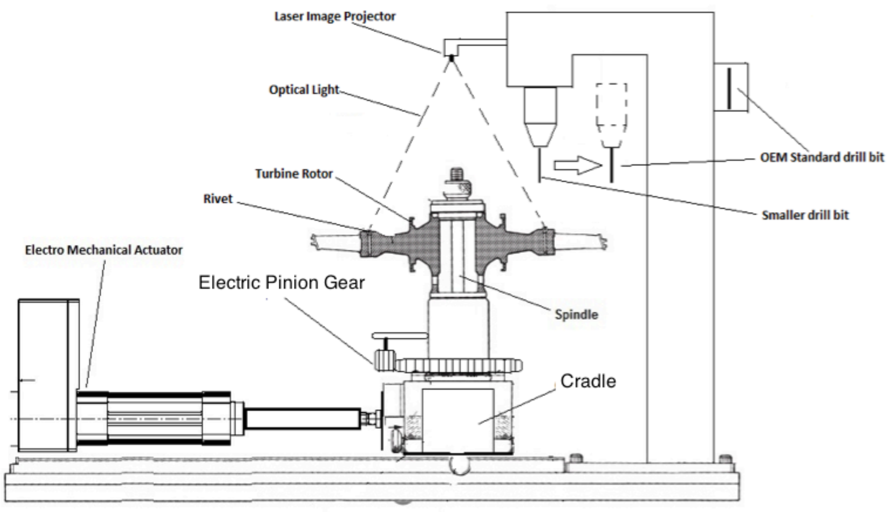

Figure 14: Illustration of concept #14

Concept #14 – Description
• The electro-mechanical actuator is used to control the movement the cradle in the lateral positon. • The electric pinion gear system controls the disk spindle, thus rotates the disk to the desired position for drilling. • The laser image projector uses optical light to aid the operator with aiming and aligning the drill bit by projecting the image of rivet onto the disk. • The small drill bit would be used make the pilot hole in the head of rivet so that the standard drill bit could be guided into the rivet easily.

Pros	Cons
- Robust design. - Higher alignment accuracy. - Higher drilling precision. - Requires less manual dexterity.	- The laser image projector may be interfered by ambient light. - Complex process for operator. - Not accountable for correcting the malformed rivets. - Wear due to friction of the gear in electrical motor system. - High cost.

A.3. CONCEPT SCREENING

After the evaluation of all the concept designs, concept-screening was performed to determine the concept our team would pursue and continue to develop. The screening process compared fourteen conceptual designs against a reference design. Each concept was rated, relative to the reference design, on its ability to meet our customer's needs. In the case of a '+', the concept more readily met a customer's need. A '-' meant the reference design more readily met a customer's need. If both the concept and the reference design equally met a customer's need, a '0' was given. The total score for each concept was calculated by subtracting the summation of all '+' signs from the number of '-' signs. Concept #3 was chosen as the reference concept due its relatively moderate design complexity. The concept screening matrix is shown in Table XV. The six concepts highlighted in green scored the highest and were carried through to the concept scoring phase.

TABLE XV
CONCEPT SCREENING MATRIX

Selection Criterion	Baseline Concept	1	2	3 (Baseline concept)	4	5	6	7	8	9	10	11	12	13	14
	Design Concepts														
Must operate safely	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Must accommodate different sizes of PT6A and PW100 engine rotor disks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Must control the drilling angle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Must control lateral position of the fixture	0	-	0	0	0	0	0	-	0	0	0	-	-	-	0
Must accomodate the existing drill bits size(s)	0	0	0	0	0	0	0	0	-	0	0	0	0	0	0
Must restrict the fixture during angle setup and drilling operation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Must control rotation of the disks	0	0	-	0	0	-	0	-	0	-	0	-	0	-	-
Demands minimal experience from the operator	0	-	-	0	0	-	-	-	0	0	+	0	0	-	-
Ensures accuracy of alignment	0	-	-	0	0	0	0	0	+	0	0	-	-	-	+
Requires less manual dexterity than the current process demands	0	-	-	0	+	-	0	0	0	0	0	-	-	-	0
Has a reasonable payback period	0	0	0	0	-	0	-	+	0	-	0	+	+	0	-
Provides for appropriate drilling pressure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Allows for consistency in removing all the rivets	0	0	-	0	0	+	0	-	0	-	0	-	0	-	-
Allows ease in setting the angle before the drilling process	0	0	0	0	0	0	+	0	0	0	0	0	0	0	0
Requires low maintenance cost	0	-	+	0	-	0	-	+	-	-	-	+	0	0	-
Accomodates the existing spindle sizes	0	0	0	0	0	0	-	0	0	0	0	0	0	0	0
Must have a reasonable size	0	-	+	0	-	0	-	+	0	-	0	+	0	0	0
Allows easy replacement/maintenance of the wornout parts	0	-	-	0	-	0	-	+	0	-	-	+	+	-	-
Has a high design life	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reduces the initial setup time	0	-	-	0	0	0	0	-	-	0	0	-	-	-	0
Accomodates the existing punch size(s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Can be maintained with the available tools	0	-	0	0	0	0	-	0	0	-	0	0	0	0	0
Scores	**Summary of the Results**														
Sum '+'s	0	0	2	0	1	1	1	4	1	0	1	4	2	0	1
Sum '0's	21	12	12	21	16	17	13	12	17	14	18	11	15	13	14
Sum '-'s	0	9	7	0	4	3	7	5	3	7	2	6	4	8	6
Net Score	0	-9	-5	0	-3	-2	-6	-1	-2	-7	-1	-2	-2	-8	-5
Relative Rank	1	9	5	1	4	3	6	2	3	7	2	3	3	8	5
Continue (Yes/No)?	Yes	No	Yes	Yes	No	Yes	No	Yes	No	No	Yes	Yes	No	No	No

As shown in Table XVI, the top six concepts that were chosen for further consideration include concepts #2, #3, #5, #7, and #11. Concepts #3, #5, #10 ad #11 were chosen to further develop as they ranked the highest. Even though concept #2 ranked low, the team decided to continue developing it owing to its simplicity and low cost of implementation.

TABLE XVI
METRICS, TARGET SPECIFICATIONS, AND METRIC SENSITIVITY

Metric ID	Need ID	Metric	Target Specification	Units	Metric Sensitivity Score
M1	N1, N14, N7	Disk Diameter	8< D<16	inches	3.9545
M2	N2, N3, N4	Rotational Angle	ϕ_r<9	degrees	3.9091
M3	N4	Angular Tolerance	ϕ_tol. < +/- 0.5	degrees	3.318
M4	N5, N3, N8, N6	Tilt Angle	-8 < ϕ_t < 25	degrees	3.273
M5	N7, N1	Lateral Distance	Dl<16	inches	3.227
M6	N9, N1	Spindle Diameter	D_sp=constant	inches	3.182
M7	N10	Drill Bit Diameter	D_db<0.073	inches	2.723
M8	N10	Shank Diameter	D_sh=constant	inches	2.4091
M9	N11	Punch Pin Diameter	D_pp<0.065	inches	2.091
M10	N12, N18	Operational Hours	minimize t_oh	hours	2.045
M11	N13	Drilling Pressure	90<P_d<100	psi	1.955
M12	N14	Fixture Size	V_cube<7000	cubic inches	1.7727
M13	N17, N18	Human ability	minimize	subj	1.4545
M14	N19, N6	Setup Time	t_s<10	minutes	1.364
M15	N19, N20	Cost	minimize	dollars	1.273
M16	N21	Payback Time	t_p<12	months	1.182
M17	N22	Safety Measure	Pass/Fail	subj	0.5454

A.4. CONCEPT SCORING

The concept screening matrix provided us with 6 concepts that had potential to be further developed. In order to justify the selection of our top three concepts, our team relied on the weighted customer needs. The weights associated with each need are representative of the relative importance of the need. For needs that are of greater importance, a high weight factor is seen. The weighting factors ensure that concepts which do not perform well with respect to a critical need are sharply penalized. The top 6 concepts were rated on a scale of one to five based on their ability to meet a specific need. The scale of one to five represents an increasing ability of a concept to meet a given need and the specific qualitative meaning of each rating is shown in Table XVII.

The total scores for each concept were augmented by the weights and tallied in Table XVIII. The top three concepts (concepts #3, #5, and #10) are selected through the scoring process along with their associated pros and cons, and relevant needs and metrics they comply with.

TABLE XVII
INTEPRETATION WITH SCALE ONE TO FIVE

Scale	Ability to meet the need	Associated level of Risk
1	Very Poor	High
2	Poor	Moderate
3	Satisfactory	Moderate
4	Good	Low
5	Excellent	No

TABLE XVIII
CONCEPT SCORING MATRIX

		Design Concepts											
		Baseline Concept (3)		7		10		5		11		2	
Selection Criterion	Weight (%)	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Must operate safely	8.33	4	33.32	4	33.32	4	33.32	4	33.32	4	33.32	4	33.32
Must accommodate different sizes of engine rotor disks	7.61	5	38.05	5	38.05	5	38.05	5	38.05	5	38.05	5	38.05
Must control the drilling angle	7.61	5	38.05	3	22.83	5	38.05	5	38.05	3	22.83	3	22.83
Must control lateral position of the fixture	7.61	5	38.05	2	15.22	5	38.05	5	38.05	4	30.44	4	30.44
Must accomodate the existing drill bits size(s)	6.88	5	34.4	5	34.4	5	34.4	5	34.4	5	34.4	5	34.4
Must restrict the fixture during angle setup and drilling operation	6.52	5	32.6	5	32.6	5	32.6	5	32.6	5	32.6	5	32.6
Must control rotation of the disks	6.16	5	30.8	2	12.32	5	30.8	2	12.32	3	18.48	3	18.48
Demands minimal experience from the operator	5.07	4	20.28	2	10.14	5	25.35	3	15.21	3	15.21	4	20.28
Ensures accuracy of alignment	4.71	4	18.84	3	14.13	4	18.84	4	18.84	3	14.13	3	14.13
Requires less manual dexterity than the current process demands	4.71	5	23.55	3	14.13	5	23.55	4	18.84	2	9.42	4	18.84
Has a reasonable payback period	4.35	3	13.05	5	21.75	2	8.7	3	13.05	5	21.75	5	21.75
Provides for appropriate drilling pressure	3.99	5	19.95	5	19.95	5	19.95	5	19.95	5	19.95	5	19.95
Allows for consistency in removing all the rivets	3.62	4	14.48	4	14.48	4	14.48	3	10.86	2	7.24	3	10.86
Allows ease in setting the angle before the drilling process	2.90	4	11.6	4	11.6	4	11.6	4	11.6	4	11.6	4	11.6
Requires low maintenance cost	2.54	4	10.16	5	12.7	3	7.62	4	10.16	5	12.7	5	12.7
Accomodates the existing spindle sizes	2.54	5	12.7	5	12.7	5	12.7	5	12.7	5	12.7	5	12.7
Must have a reasonable size	1.81	4	7.24	5	9.05	4	7.24	4	7.24	4	7.24	4	7.24
Allows easy replacement/maintenance of the wornout parts	1.45	4	5.8	5	7.25	3	4.35	4	5.8	4	5.8	4	5.8
Has a high design life	1.09	5	5.45	5	5.45	4	4.36	5	5.45	5	5.45	5	5.45
Reduces the initial setup time	1.09	5	5.45	2	2.18	5	5.45	4	4.36	3	3.27	3	3.27
Accomodates the existing punch size(s)	0.36	5	1.8	5	1.8	5	1.8	5	1.8	5	1.8	5	1.8
Can be maintained with the available tools	0.00	5	0	5	0	5	0	5	0	5	0	5	0
Summary		Baseline Concept (3)		7		10		5		11		2	
Total Score		415.62		346.05		411.26		382.65		358.38		376.49	
Relative Rank		1		6		2		3		5		4	
Develop (Yes/No)?		Yes		No		Yes		Yes		No		No	

A.5. RESULTS AND DISCUSSION

The top three concepts obtained through concept scoring yielded competing results and thus required a sensitivity analysis to distinguish the one that best fits the needs of the design project.

Concept A (Concept #3): This concept combines the actuator, rotary indexing ring, positioning sensors, pre-drilling process and the standard drill press. The design gives the operator total control on drilling step (control on the pull down lever used to drill into the rivet) and thus requires experience and concentration. The automatic system takes care of the movement of the turbine disk (both in lateral and rotational directions), and avoids any uncertainty (tolerance or backlash) due to misalignment compared to the current fixture. A pre-drilling process is used to pre-drill any contorted rivet heads into a uniform shape thus eliminating the slippage of the drill bit that may cause disk damage.

TABLE XIX

DETAILS OF CONCEPT #A

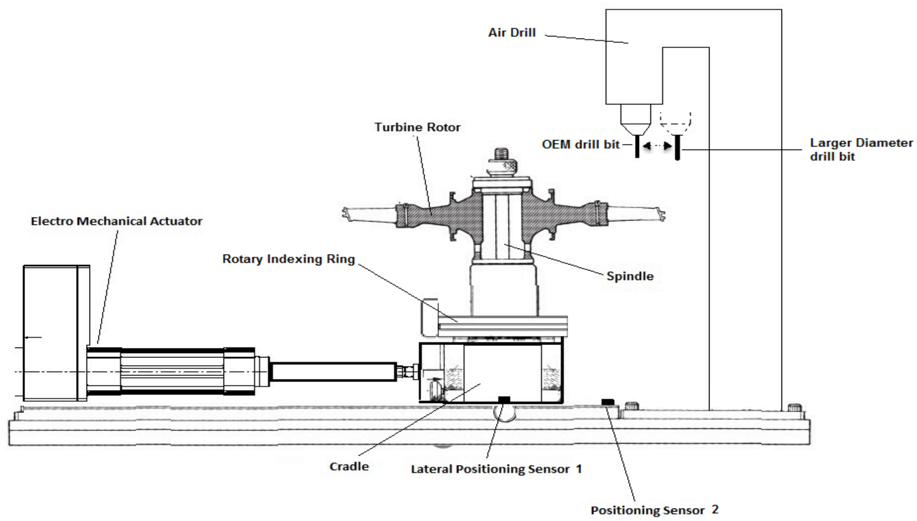

Figure 15: Illustration of concept A

Concept A (Concept #3) - Description
• An electromechanical actuator used to provide for ease in lateral movement and control the cradle to move the desired position. • A combination of optical sensors (one located on the cradle and another one is on the base of the fixture) will monitor the lateral position of turbine disk as well as the rivet positions with relation to the drill bit. • To adjust the disk to the desired angle manually. • Then use a rotary indexing ring attached to the spindle which be used to rotate the disk and align the drill bit with the rivet. • A rivet predrilling process would be used a larger drill bit to pre-drill any contorted rivet head into a uniform shape in order to employ for drilling alignment accuracy and consistency.

Pros	Cons
- Robust design - Negates the need to adjust the position of the disk for contorted rivets. - High drilling precision - Good rotational accuracy - Actuator and Ring are customizable and can be programmed to meet plurality of conditions - Demands less work space - Decreases manual dexterity	- Costs more than the current fixture - The optical sensor may be affected by interference from ambient light - Rotational and translational component wear - Demands sensitive programming of the moving components - Complexity of synchronization of all the components - Requirement of component interference checks by the operator

Concept B (Concept #10): This concept is similar to Concept A with addition of the controller, more sensors and a light indicator. The design gives the operator some control over the lateral and rotational movement of the turbine disk via the controller if the optimum alignment is not yet reached. At some point during the process, the operator has to take some corrective actions in order to deal with the contorted rivet heads. This correction can also be achieved with the use of the controller. Additionally, there are two light indicators which notify the operator as soon as the lateral and rotational alignments are achieved. This visual indication eases the process of manual alignment and reduces dependence on the operator's experience. Since the design is similar to the current fixture, the operator can get used to it with minimal training time.

TABLE XX

DETAILS OF CONCEPT #B

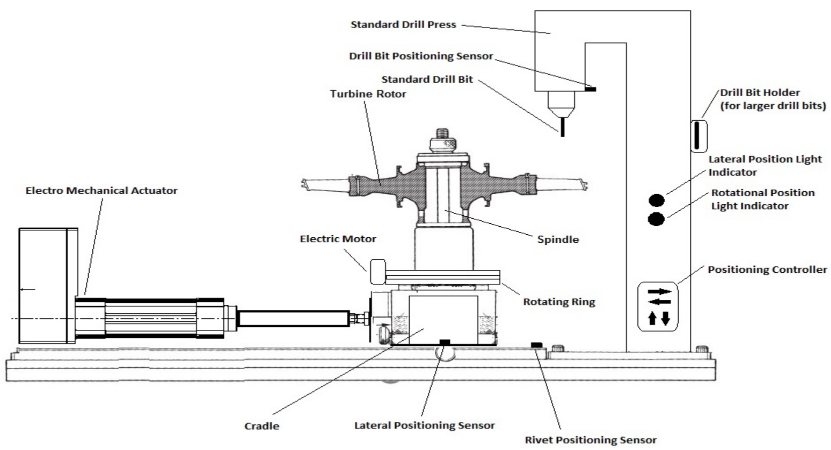

Figure 16: Illustration of concept B

Concept B (Concept #10) - Description	
• An electro-mechanical actuator is used to move the cradle in the lateral position and the ring rotates the turbine disk to the desired position. • An electric motor driven ring used to control the rotation of disk spindle. • Three optical positioning sensors provide feedback on the relative position of the turbine disk and the rivet, so the operator can align the disk properly by using the controller (left/right and clockwise/counter-clockwise movements). • As soon as the rivet is aligned perfectly, the light indicators will turn to green to notify the operator that the drilling process can begin. • The existing air drill and the cradle are still used in fixture. • In any case if a crooked rivet is spotted, the operator has to perform corrective action by using larger drill bit to flush out the uneven surface of the rivet before continuing the process.	
Pros	**Cons**
- Robust Design - High alignment accuracy - Visual feedback - High drilling precision - Actuator and Ring are customizable and can be programmed to meet plurality of conditions - Demands less work space - Decreases manual dexterity	- The optical sensors may be affected by interference from ambient light - Rotational and translational component wear - Demands sensitive programming of the moving components - Feedback system requires sensitive programming - Added feedback system maintenance (compared to the Concept 3) - High complexity of synchronization of all the components - Requirement of component interference checks by the operator - Added cost (compared to the Concept #3)

Concept C (Concept #5): This concept combines the pros of all design ideas and integrates them into a fully automated fixture. The human factor has been taken out since the computer is now in full control of the process. This requires complex analysis and computer-based programming steps to implement.

TABLE XXI

DETAILS OF CONCEPT #C

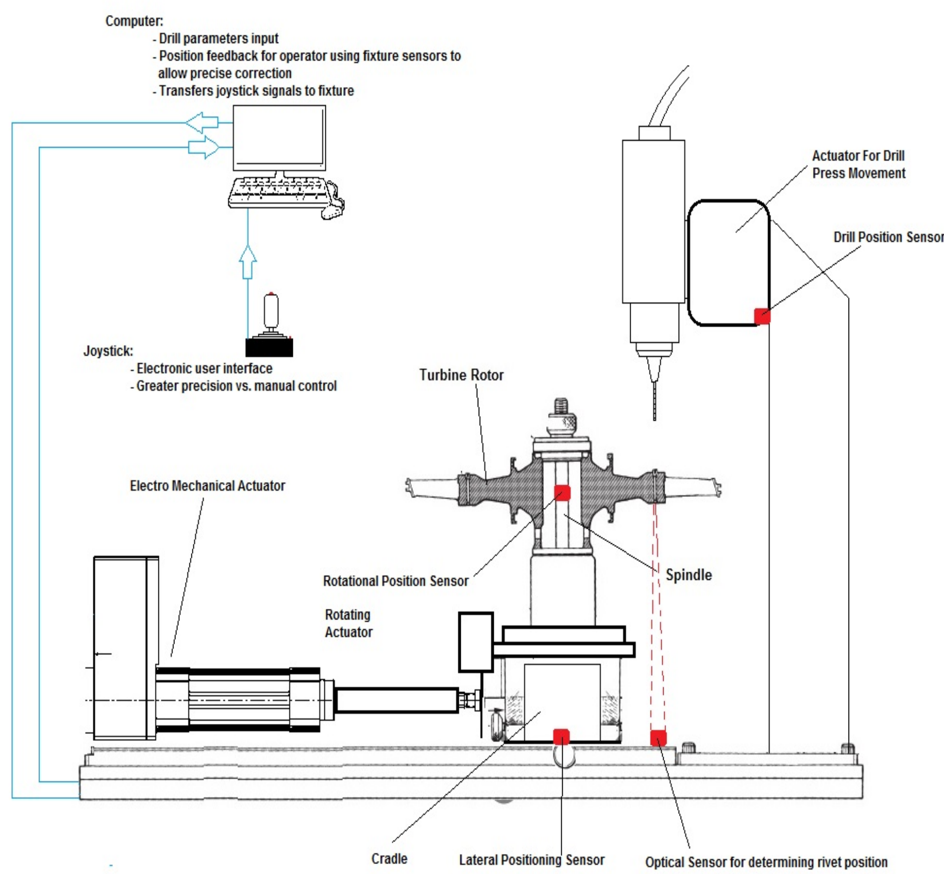

Figure 17: Illustration of concept C

Concept C (Concept #5) - Description
• The electro-mechanical actuators to control lateral movement of the disk, as well as the vertical movement of the drill. • Then various optical sensors will be used to provide position information to a computer control system. • The computer control system uses the information from these sensors as well as user-inputted drilling parameters (as found in OEM manuals) to provide the operator feedback on the position of the rivets with respect to the drill bit. • The system will indicate to the operator if the drill bit is properly aligned. • Electric pinion gear system used to control to the rotational of spindle • Position control is done using an electronic user interface (e.g. a joystick) to control all fixture actuators.

Pros	Cons
- Robust Design - High alignment accuracy - Electronic data feedback - High drilling precision - Decreases manual dexterity	- The optical sensors may be affected by interference from ambient light - Rotational and translational component wear - Demands sensitive programming of the moving components - Feedback system requires sensitive programming - Added feedback system maintenance (compared to the Concept 3) - High complexity of synchronization of all the components - No ability to compensate for malformed rivets

All of these concepts have their merits and demerits based on their level of automation, complexity, cost and implementation needs. Concept C eliminates the human factor from the drilling process which can cause error, thus minimizing damages. However, this concept was deemed unfeasible due to the fact that the team has limited time and the complexity of this design demands a higher level of analysis which is beyond the scope of this project. Concept A and B retain human involvement in the process to simplify the design, and to be accountable for any issue that occurs during the process. These semi-automatic concepts require the interaction of human, but keep it a minimum level. Both concepts show great potentials, but Concept A is the dominant one due to its simplicity and effectiveness.

After completing scoring process (Table XVIII), the team discussed the results with the client. The client expressed a number of concerns in this discussion. However, these concerns were due to lack of proper understanding of the new concept design and were later resolved after further clarifications. Based on the above stated reasons and the clarifications made regarding the concept A, the team has chosen this design as the recommended concept to use in the engineering design phase of the project.

APPENDIX B

DESIGN ANALYSIS

TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

B.1. INTRODUCTION

As concluded in section A.5, concept A was chosen to be the best concept based on the screening and scoring analysis. This concept uses an electromechanical linear actuator, a rotary indexing ring, positioning sensors for lateral alignment and a pre-drilling process for drilling alignment. However, as this design was further analyzed and discussed with the client, implementation of some of the components in this concept was found to be non-feasible. These components included, the positioning sensors (as they were considered to be "nice to have" feature rather than a "must have") and the electromechanical linear actuator (this component was not excluded from the report but no analysis was carried out to support it as it was deemed a low priority aspect of the fixture redesign by the client).

Through discussions with the client at various occasions after the Concept Design Phase (CDR) of the project, some of the design priorities were rearranged to fully meet our client's needs. This included putting a larger focus on the rotational and drill alignment aspects of the design. Therefore, most of the project time was invested in analyzing the rotary indexing component as it provides for a solution to the rotational aspect of the problem. An analysis of this component is provided in section B.3. A detailed analysis on the drilling alignment is also provided in section B.2.

B.2. Drilling Alignment Guide Research, Analysis and Design

In order to provide for accurate drilling alignment, a pre-drilling process was considered. This process uses a smaller drill bit to make a pilot hole to guide the OEM recommended drill bit. The underlying hypotheses for using a pre-drilling process was that 'the main reason for misalignment was the distortion of the rivet and if it can be corrected the alignment can be improved'. However, this hypothesis was later on found to be wrong.

Although the angle of the rivet head varied from rivet to rivet, the location of the rivet head hole was always centered on the shank of the rivet and since the internal diameter of the rivet head hole (as measured by a go/no-go gauge during rivet formation) was 0.083”-0.087” and the drill bit being used having a diameter of 0.073”, the drill bit will always end up within the hole and self-center at the bottom. Therefore, it was realized that using a smaller drill bit will self-center in the same location and will not improve the alignment when preceded by a larger bit.

B.2.1. Research

Although dropping the predrilling process was a major setback in terms of meeting the project deadline, the team kept looking for alternative ways of improving the drilling alignment. One of the options that was considered during our research on alternative ways of improving drilling alignment was to use a laser cross-hair guide. This device projects a laser cross-hair on the work piece thus providing for an accurate location for drilling as shown in Fig. 1.

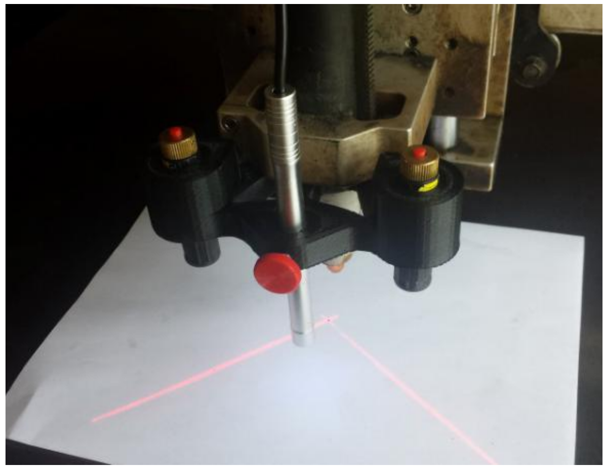

Figure 1: Cross-hair laser projecting device for drilling alignment [1].

However, this idea was dropped as it requires a routine calibration, a non-vibrating stand to be attached to, and lacks high level accuracy. Finally, the team developed the use of a tubular guide, shown in Fig. 2.

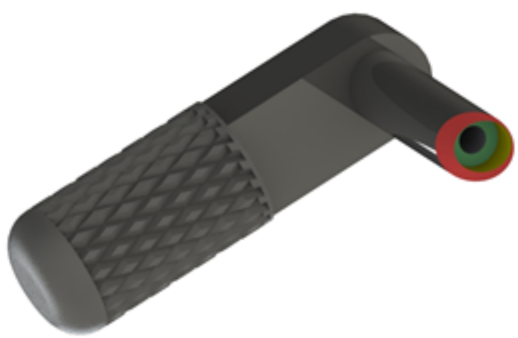

Figure 2: Drilling alignment guide developed using SolidWorks software.

The intention behind using a tubular guide is to align the rivet shank bore with the drill bit for the initial alignment. The rest of the process is carried out using a rotary indexing stage which is explained in the section B.3. The inner diameter as seen in Fig. 2 (in green) of the guide is slightly larger than the drill bit being used for the drilling operation and slightly smaller than the rivet shank so as to allow for appropriate flexibility tolerance level during the alignment. The outer diameter of the guide shown in Fig. 2 (in red) envelopes the rivet head (centralized or distorted) and rests on the chamfered area around the rivet head on the disk. The chamfered area where this guide sits is shown in Fig. 3.

[redacted]

Figure 3: Visual representation of the chamfered area of a PT 2nd stage medium model [property of StandardAero].

Although this guide was chosen to be our best option to increase the drilling alignment accuracy, it was noticed that the angle that the chamfer makes with the rivet bore centre was unique for each PT6A and PW100 model disks. Therefore, it was decided that the team would only design a guide for one model. Once this proof of concept has been tested, subsequent designs can be developed for the disks. This also helps us in constraining the project scope and investing more time in the analysis of this guide. Fig. 4 shows a rendering of this guide placed on the redesigned fixture.

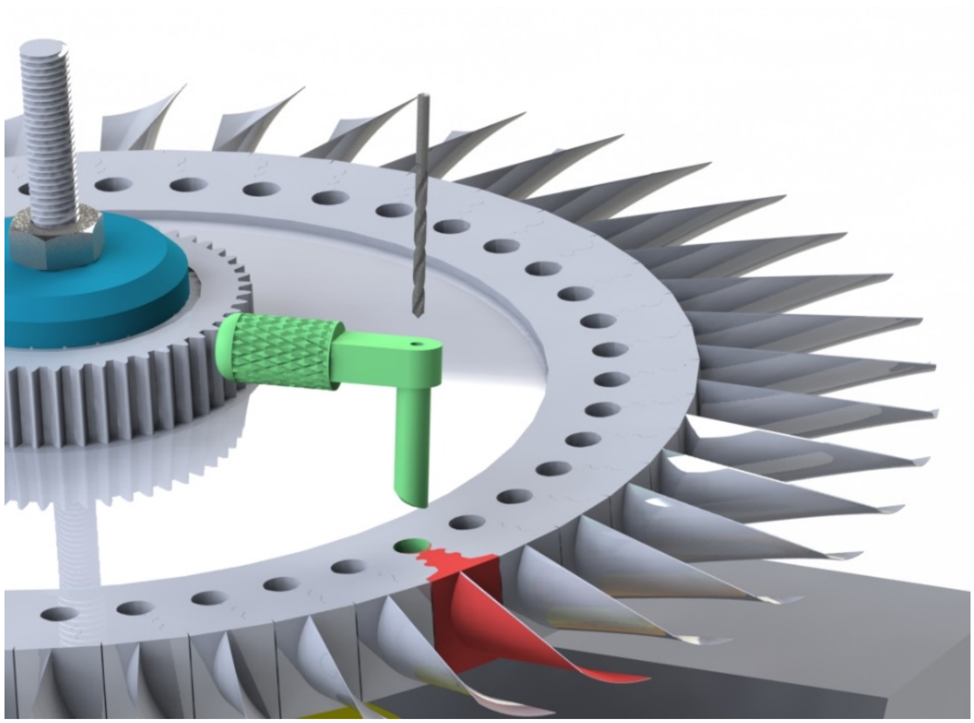

Figure 4: A visual representation of the placement of alignment guide on the turbine disk.

It must be noted that the CAD model of the turbine disk, designed on SolidWorks, only serves as a frame of reference and was developed using the high level measurement details of the disk obtained from StandardAero. These details however are not included in this report due to proprietary reasons. A thorough analysis of the alignment guide's design is provided below.

B.2.2. Alignment Guide Analysis

The first step in designing of this guide involved measuring the chamfered area on the turbine disk. This proved to be a difficult task as the surface area of the chamfer is extremely small (diameter of the chamfered area = 0.20in) and could not have been measured directly.

B.2.2.1. MEASUREMENT OF CHAMFER AREA

Two options were considered to measure the chamfer area. The first one included using a Coordinate Measuring Machine (CMM). This idea however was dropped as the chamfer area was later on deemed too small for this device to work. The second option (selected alternative) involved using a plastiform molding material in order to get an impression of the chamfer (with and without the rivet) for measurement. The Repliset-TI modeling set, as shown in Fig. 5, was used to obtain a replica of the chamfered area. This set provides an accuracy level of up to 0.1 microns.

Figure 5: Repliset-TI gun used for producing replicas of hard to reach surfaces [2].

Three molds (replicas) were collected for two configurations of the chamfered area. For the first configuration, the replica was created without the rivet and for the second one with the rivet in place. Fig. 6 shows the two configurations of molds that were used to measure the geometry of the chamfered area. These molds were measured using Vernier calipers.

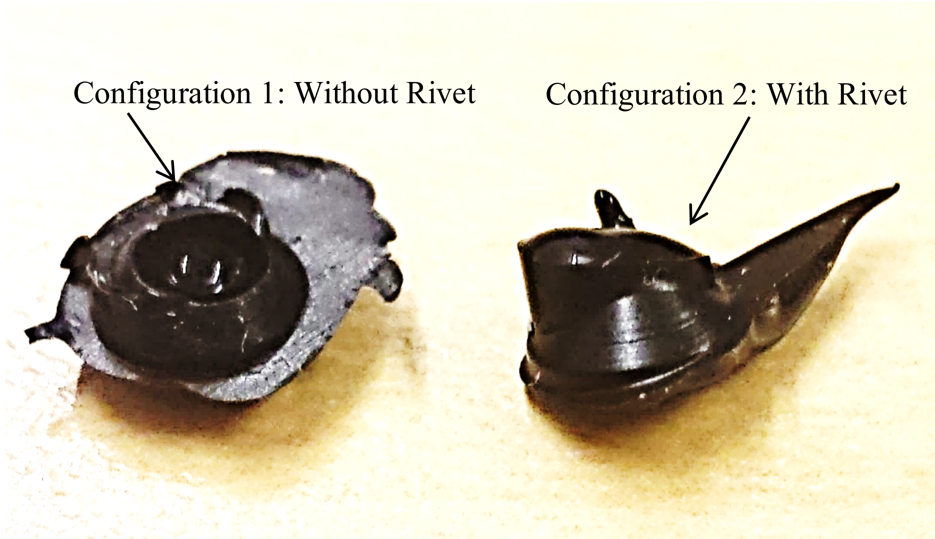

Figure 6: Two mold configurations created using the Repliset-TI gun at StandardAero.

An important thing worth mentioning is that the molds shown in Fig. 6 are extremely elastic in nature and therefore possess tendency of deforming under very low pressures. Due to this nature of the mold, it is expected that the measurements taken using Vernier Caliper may include uncertainty in them. Therefore, it is recommended that a more accurate way should be used to measure the chamfer geometry before manufacturing this alignment guide.

B.2.2.2. GEOMETRY ANALYSIS OF CHAMFER AREA

The parameters obtained from measuring the molds along with other important parameters that were used in defining the geometry of the alignment guide are provided in Table I.

TABLE I

PARAMETER OBTAINED TO DEFINE THE DRILLING AREA DETAILS AND THE GUIDE GEOMETRY

PT Medium Model 2nd Stage - Drilling Area Details			
Rivet and Disk bore Measurements			**Comments**
Drill bit diameter	0.073	in.	Provided by StandardAero
Rivet shank bore diameter - drb	0.08	in.	Provided by StandardAero
Rivet shank bore radius - rb	0.04	in.	rb = drb/2
Flared rivet head - internal diameter - dfr	0.083-0.087	in.	Confirmed with a go-no go gauge every time a disk is riveted
Flared rivet head - outer diameter - dofr	0.13	in.	Measured using Vernier Callipers
Bore in the disk - diameter	0.086	in.	Provided by StandardAero
Chamfered Area Measurements			**Comments**
Guide internal diameter	0.074	in.	Drill bit diameter + 0.001 in.
Guide outer diamter	0.199-0.2	in.	Measured with in the chamfer edge diameter
Chamfer Angle 'Φ'	28.93	deg.	With respect to the adjacent disk surface
Chamfer edge to edge diameter 'dc'	0.199-0.2	in.	Measured using Vernier Callipers
Distance b/w rivet bore diameter and chamfer edge 'dx'	0.0995	in.	dx = dc/2
Heigh of chamfer 'dy'	0.055	in.	Measured using Vernier Callipers

As shown in Table I, the parameters were divided into two sections. The first section consisted of details of the rivet and the disk bore, most of which were obtained from StandardAero, while the second section included measurements of the chamfered area as obtained by our team. The sketch in Fig. 7, was then drafted in order to define the geometry of the chamfered area on a horizontal plane.

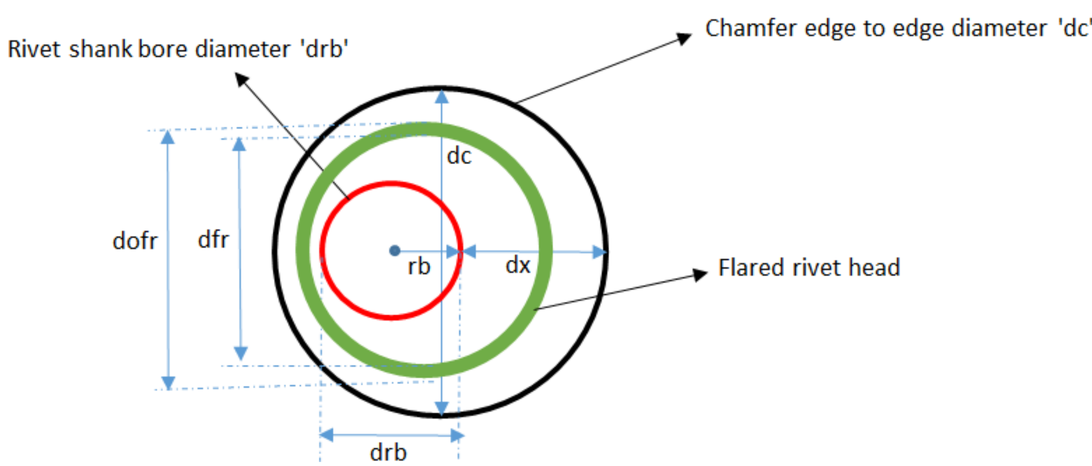

Figure 7: Visual representation of the chamfer geometry on the horizontal plane.

Another sketch used to define the geometry of the chamfered area on a vertical plane is shown in Fig. 8.

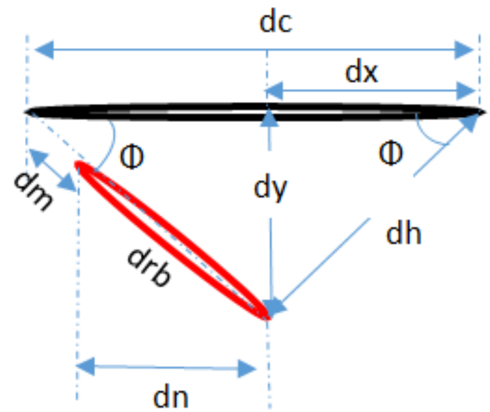

Figure 8: Visual representation of the chamfer geometry on the vertical plane.

Note that this sketch was overly exaggerated in order to provide ease of visualization, meaning that the value of d_y on the sketch is in reality small compared to d_x. Using the measurements shown in Table I along with these two sketches, a satisfactory approximation of the chamfer geometry was obtained. The equations used to evaluate the geometry of the chamfered area are as follow.

Using Fig. 8 and the parameters provided in Table I,

$$\emptyset = Tan^{-1}(\frac{d_y}{d_x})$$

Also,

$$d_h = \sqrt{(d_y^2 + d_y^2)}$$

And,

$$d_m = d_h - d_{rb}$$

Where $\emptyset$ is the chamfer angle, d_x is the distance between the outer edge of rivet bore diameter and chamfer outer diameter (shown in Fig. 7), d_y is the vertical height of the chamfer (shown in Fig. 8), d_h represents the hypotenuse with respect to d_x and d_y and d_m is the distance between the chamfer edge and the rivet shank bore diameter.

The value of d_c measured through calipers on average was recorded to be 0.199 inches. However, to account for the uncertainty associated with the technique of measurement, a value of 0.2 was chosen for the guide's outer diameter.

The outer diameter of the rivet was measured to be 0.13 inches using the mold with rivet heads impression and a safety allowance of 0.02 inches was used in order to accommodate any rivets that may be distorted or badly formed. The height of the guide area that envelopes the rivet head was measured to be 0.13 inches, however a safety allowance of 0.15 inches was used to account for the rivet heads that sit below the adjacent face of the disk and the ones that protrude above.

The parameters $\emptyset$, d_c, d_x, d_y, d_h, and d_m were evaluated for three mold samples. The reasons for this iteration are two fold; determining the variation of the chamfer angle at different locations and to get an average value that provides the most reasonable overall geometry. As shown in Table II, all the values measured were within 0.001 inches of each other and the vertical height of the chamfer was found to be constant. The results of this iteration are shown in Table II and Table III.

TABLE II

EVALUATION OF CHAMFER ANGLE USING THREE MOLDS

Iteration No.	Geometric Parameters	Results
Iteration 1 (Mold 1)	dc1	0.199
	dx1	0.0995
	dy1	0.055
	Φ1	28.9322
Iteration 2 (Mold 2)	dc2	0.2
	dx2	0.1
	dy2	0.055
	Φ2	28.8108
Iteration 3 (Mold 3)	dc3	0.198
	dx3	0.099
	dy3	0.055
	Φ3	29.0546

TABLE III

RESULTS OBTAINED FOR THE GEOMETRY OF THE CHAMFERED AREA

	Chamfer Angle Φ	dx	dy	dh	dm
Mold 1 - w/o Rivet:	28.9322	0.0995	0.055	0.11369	0.03369
Mold 2 - w/o Rivet:	28.8108	0.1	0.055	0.11413	0.03413
Mold 3 - w/o Rivet:	29.0546	0.099	0.055	0.11325	0.03325
Average:	**28.9325**	**0.0995**	**0.055**	**0.11369**	**0.03369**

The average results were then labelled on the sketch shown in Fig. 8 and can be seen in Fig. 9.

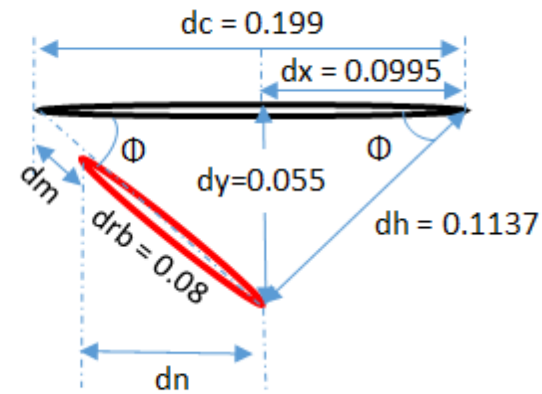

Figure 9: Visual representation of the fully defined chamfer geometry on the vertical plane.

Fig. 7 and Fig. 9 were then used as a reference to design a CAD model of the alignment guide geometry. The CAD file of this model will be provided to the client as part of the final report so that it can be manufactured. This part can be manufactured in a number of ways including injection molding, rapid prototyping and 3D printing. An elevation drawing of this model is also provided in the Appendix C (DWG 1-5) with high level measurements for reference purposes.

Currently the material decided to be used to produce the guide is a high strength polypropylene thermoplastic which can be injection molded to form the alignment guide. This material was chosen because of its resistance to corrosion, resilience against physical damage, including impact and freezing, its environmental benefits, ruggedness, and high fatigue resistance over a long period of time [3]. Also, the cost of the alignment guide was not specified because it is a function of the manufacturing technique and the geometry of the Cad model. Although this material provides for the required properties that this application requires, it must be noted that further research and prototype testing of different materials that suite this application needs to be conducted in order to fully guarantee the success of this guide.

B.3. ROTARY STAGE RESEARCH, ANALYSIS AND DESIGN

This section analyzes the rotary stage that will be used for positioning the turbine disk for accurate alignment and drilling operation.

B.3.1. ROTARY RING VERSUS ROTARY STAGE

The concept development stage introduced the idea of using an indexing ring to control the rotational movement of the turbine disk. Although this concept refers to an actual commercial product available on the market; literature and research have shown that this rotary ring is used for heavy load and large size items (industrial scale) and therefore, it cannot be implemented with the current drilling fixture or be combined with other components to form a good redesigned fixture.

Further research and brainstorming sessions have concluded that using the same principle with different approach is necessary. A smaller scale rotating mechanism is required so that it can fit into the design, while other characteristics such as power, accuracy and control must be preserved. In order to fulfill these requirements, the idea of using rotary stage (small scale) run by servo or stepper motors have been reached after literature research and discussion with our technical advisor. The rotary stage is a motorized stage powered by the servo or stepper motor so that it can reach certain rotational position with high accuracy and precision, while minimizing backlash and reducing weight added on to the design. For these reasons, the rotary stage has been decided as one of the main features of the redesign drilling fixture.

B.3.2. SERVO MOTOR VERSUS STEPPER MOTOR

Currently, there are two types of motorized rotary stages available, classified by their mechanical drives: servo motor or stepper motor. The basic difference between servo and stepper is the type of motor and how it is controlled. Steppers typically use 50 to 100 pole brushless motors while typical servo motors have only 4 to 12 poles [4]. Steppers don't require encoders as feedback since they can accurately move between their many poles whereas servos (using open loop), with few poles, require an encoder to keep track of their position (using closed loop) [4]. Table IV compares the pros & cons of servo and stepper motors for better understanding and motor type selection process.

TABLE IV

COMPARISON OF SERVO AND STEPPER MOTORS [5]

	Servo Motor	**Stepper Motor**
Pros	- Better efficiency - More reliable since control loop is required (closed loop) - Can compensate and make adjustments for any positioning mistake - High speed - High intermittent torque - Quiet - Works well for velocity control	- Less expensive - Easy to use, setup and control - Requires no feedback (open loop) - High torque at low speed - Excellent holding torque - Low maintenance - Very rugged at any environment - Excellent for positioning control - No tuning required - Better complete standstill stability
Cons	- More expensive - Requires feedback - Requires tuning - More maintenance - Offers less holding torque while idling	- Low torque at high speed - Consumes current regardless of load - Noisy - Can stall or lose positon while running without a control loop

After evaluating the pros and cons of both types or motors and relating to the constraints and scope of the project, stepper motor has been chosen since the nature of the design requires a steady, slow and accurate rotational movement with high holding torque, stability and easy to control via open loop system.

B.3.3. SELECTION OF STEPPER MOTOR ROTARY STAGE

In order to choose the right rotary stage, the needs of design must be identified. These needs include the number of rivets per disk and the maximum turbine disk's weight. For the all PT6A and PW100 turbine disks, the maximum weight has been measured to be 7.6 kg, and the number of rivets per disk varies from 41 to 71, depending on the model. So the rotary stage is required to carry the load of at least 20 lbs. (9.1kg) so it can accommodate the turbine disk and other disk mounting or securing components. Also, the rotary stage must be able to provide various precise rotational movement (angle between rivets on disk) as small as 5.1° to 8.8°, therefore the required resolution is set to be 0.005°, about 1% of the smallest incremental movement that the disk has to rotate (5.1°).

The selection of a suitable stepper motor rotary stage will be based upon those criteria such as: dimensions, load capacity, accuracy, weight, implementation and control. These requirements are explained in details in Table V.

TABLE V

REQUIREMENTS FOR STEPPER MOTOR ROTARY STAGE

Parameters	Requirements
Load capacity	At least 7.6kg (16.72lbs)
Speed	High speed is not preferred
Accuracy	Up to 0.005°
Weight	As light as possible
Dimensions	Must fit onto the base of the current fixture (5in. by 5in. square cradle with open ends on two sides)
Implementation	Must be easy to install with the least components
Control	Either via manual switch or computer-based interface

Research has been conducted in order to find the rotary stage available that can satisfy all the requirements of the design. Other factors encountered during selection process are: availability, compatibility, user-friendliness of the product, as well as the tech support and after-sale service of the manufacturer. These factors also contributed into selecting the desired rotary stage. Table VI shows the results of the research process, including the two stepper motor rotary stage available on the market that best fit into the design.

TABLE VI

COMPARISON OF STEPPER MOTOR ROTARY STAGES [6] [7]

Parameters/Manufacturers	Newmark Systems, Inc.	ThorLabs Inc.
Name	Motorized Rotary Stage	Nanorotator with SM2-Threaded Central Aperture
Part Number	RM-5-110H	NR360S
Resolution	0.36 arc-sec (0.001°)	<1 arc-sec (0.00278°)
Accuracy	60 arc-sec (0.167°)	5 arc-min (0.83°)
Maximum Load	100 lbs (45.4kg)	100 lbs (45.4kg)
Holding Torque	N/A	23.1 N.cm
Gear Ratio	72:1	66:1
Origin	Optical home switch	Indicating switch
Weight	8 lbs (3.6kg)	3.08 lbs (1.4kg)
Size (WxLxH)	5x5.38x2.716 in.	3.94x3.98x1.34 in.
Control	Controller and computer program	Controller/physical switch and computer program
Price	$2,050	$2,570
Manual Adjustment	No	Yes

Fig. 10 and Fig. 11 illustrate the rotary stage from Newmark Systems, Inc. and ThorLabs Inc.

Figure 10: Motorized rotary stage (RM-5-110H) from Newmark Systems, Inc. [6].

Figure 11: NanoRotator (NR360S) from ThorLabs Inc. [7].

Further evaluation from the specification sheets and manuals of each rotary stage and their associated software has concluded that the NanoRotator is the better option for the design. This rotary stage has been provided with the most accessible data, including price, spec sheets, drawings, related components to form a complete system, along with its size and geometry. The features of this NanoRotator are summarized as follow:

- Light weight and high load capacity: these features benefit the new fixture design, giving it enough room for implementation and expansion of other components.
- Unique geometry with built-in holes: this makes installing it onto the fixture base easier with minimal work and modifications to the current base.
- Holding torque: the rotary stage has enough torque to rotate the disk with high accuracy and precision, and also to hold the disk firmly for drilling operation.
- Origin: indicating switch is built in to notify the origin for every 360°. Also, the home position can be reached with a simple command.
- Manual alignment knob: this NanoRotator is equipped with the built-in knob that can be used for manual alignment with high precision. This feature works well

with the redesigned drilling procedure that aims at simplifying the process of aligning while not sacrificing accuracy and performance. The knob allows the operator to manually align the working object after securing it on the stage, and then move both together to avoid any relative movement between the stage and the object. The rotary stage from Newmark Systems doesn't provide this feature and the object has to be aligned first then secured onto the stage, which poses more potential misalignment issues. The lack of manual alignment feature will make the design assembly more complex if this Newmark rotary stage is selected (involving the use of closed loop and encoder). Also, the knob can be used for corrections and adjustments if misalignment occurs, as in the event of correcting the contoured rivet heads.

- Gear ratio: the resolution provided is the resolution of the stepper motor, with the gear ratio of 66:1 (1 revolution of the rotating platform equals to 66 revolution of the motor). Therefore the resolution of the platform is $4.35^{o}x10^{-5}$ (0.76 µrad)).
- Driving mechanism: the preloaded worm gear drive minimizes backlash and prevents the reversible rotation of the platform (one way transmission from the motor to the platform). This feature keeps the platform stationary during operation against external factors that can alter its position.
- Micro-stepping capability: the motor itself is equipped with 50 magnetic teeth and standard discrete step size of 1.8º. When pairing with the BSC201 controller, the standard step size can be reduced further to ensure smoother low-speed motion and low vibrational noise via microstepping. This feature provides 25,600 steps

per revolution of the motor, resulting in maximum platform rotation of 0.000213º (3.7 μrad) per microstep.

- Controlling software: user-friendly and functional interface makes it easy to set up and control the rotary stage with minimal training and experience. Furthermore, it can be expanded to accommodate a physical switch for improved ease of operation and control for the operator.

For all the reasons stated above, the NanoRotator is chosen. This rotary stage is compatible with the drilling alignment procedure developed in order to achieve high accuracy and precision. All of its features meet the requirements stated in Table V, although the price is higher than its competitor. This cost can be compensated by minimizing the amount of damaged disks per year. Since the objective of this project is to achieve high accuracy drilling alignment process while maintaining simple operation and implementation method, the cost trade-off is considered reasonable. Benefits of this selection is discussed in sections B.3.4 and B.3.5., which explain how the rotary stage is implemented and operated to achieve the design objectives.

B.3.4. IMPLEMENTATION OF SELECTED ROTARY STAGE

The use of the rotary stage requires additional components to form a complete control system – namely disk mount assembly. Table VII shows the components required for the assembly.

TABLE VII

COMPONENTS OF THE ROTARY STAGE DESIGN

Amount	Component	Part Number	Notes
1	NanoRotator	NR360S	Purchased [7]
1	Stepper Motor Controller	BSC201	Purchased [8]
1	Adapter Plate	NR360SP8	Purchased [9]
1	Software Interface	APT Software Package	Included with the controller [8]
1	Spindle	DWG 1-2	Redesigned
4	Securing screw, 1/4”-20	79047	Purchased [10]
4	Securing screw, #8-32	79013	Purchased [11]
1	Securing nut, 1/4”-28	77730	Purchased [12]
1	Securing pad	DWG 1-4	Redesigned
1	Cradle	DWG 1-3	Existing
1	Base	From OEM	Existing

The exploded view of the disk mount assembly is shown in Fig. 12. This serves to illustrate how the components are assembled together to form the disk mount assembly design.

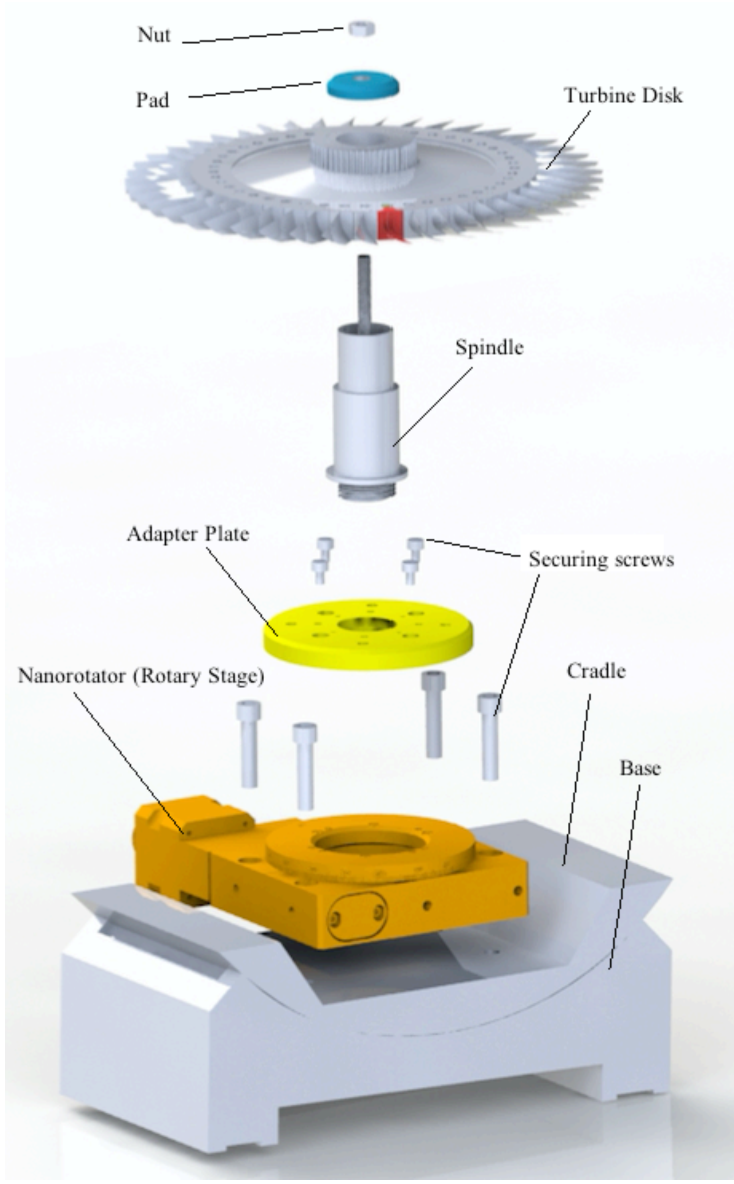

Figure 12: Assembly illustration of disk mount assembly.

In order to accommodate the rotary stage, the current drilling fixture has to be taken apart and redesigned. The redesigned fixture aims at utilizing the main components from the current fixture with some modifications to reduce cost, and also because these components have been determined to be reliable during drilling operation and thus, they don't need to be replaced.

From Fig. 12, it can be seen that the NanoRotator is mounted onto the cradle with securing bolts (securing screws) via its built-in holes, and the cradle sits on the base. On the cradle, four holes are required to be drilled and threaded to align with those on the NanoRotator, and four 1/4”-20 screws are used to secure the NanoRotator and the cradle together. The adapter plate is secured onto the NanoRotator also by 4 screws (#8-32 standard) via built-in holes that are already aligned between them. The redesigned spindle features the same top half of the current spindle, and is added with the external thread at the bottom half to fit into the internal thread of the adapter plate (SM1: 1.035-40 hole series). The shoulder plate separating the threaded and non-threaded parts of the spindle acts as the stopper when securing the spindle onto the adapter plate.

Once secured, the adapter plate and spindle act as one unit. The turbine disk is placed on the spindle and locked with pad and nut that fit 1/4”-28 UNF 2B threaded rod of the spindle. The movement of the turbine disk is now controlled by the rotation of the NanoRotator, as the adapter plate, spindle and turbine disk are interlocked and move as one unit. The NanoRotator is connected to the motor controller and then to the computer, where the interface program will allow the operator to set up a certain incremental angle that the disk has to rotate. This angle is dependent on the model of turbine disk and is determine by its number of rivet. Note that the tilting movement and translational movement of the disk are still controlled by the base and cradle, and they have to be adjusted by the operator prior to the operation of the disk mount assembly to rotate the turbine disk. The control of the rotary stage (NanoRotator) on the PC workstation via the software interface (APT Software Package) is explained in section B.3.5.

B.3.5. MOTOR CONTROLLER AND SOFTWARE

One of the major goals during the rotary stage selection was to find a system that required minimal programming, and therefore was easy to implement and use. Various rotary stage models, such as the RM-5-110H from Newmark Systems, are controlled by software which required additional programming in order to perform the functions needed for our new design. In contrast, the software that is loaded into the motor controller units from ThorLabs have been preprogrammed to include a graphical user interface (GUI), which clearly presents to the operator relevant motor controls and adjustable parameters.

The motor controller recommended by ThorLabs for use with the NR360S NanoRotator is the BSC201 controller model, shown in Fig. 13. It is USB compatible, allowing use with any USB capable PC.

Figure 13: BSC201 Benchtop Stepper Motor Controller [13].

The BSC201 comes preloaded with a software suite known as the "APT User Utility" [13], which displays the rotary stage motor controls as a graphical instrument panel, as illustrated in Fig. 14. While the user interface allows for interaction with a number of parameters and actions, only three were required for the implementation of our design: motor power toggle, jogging, and step size setting. These are highlighted in Fig. 14 and Fig. 15.

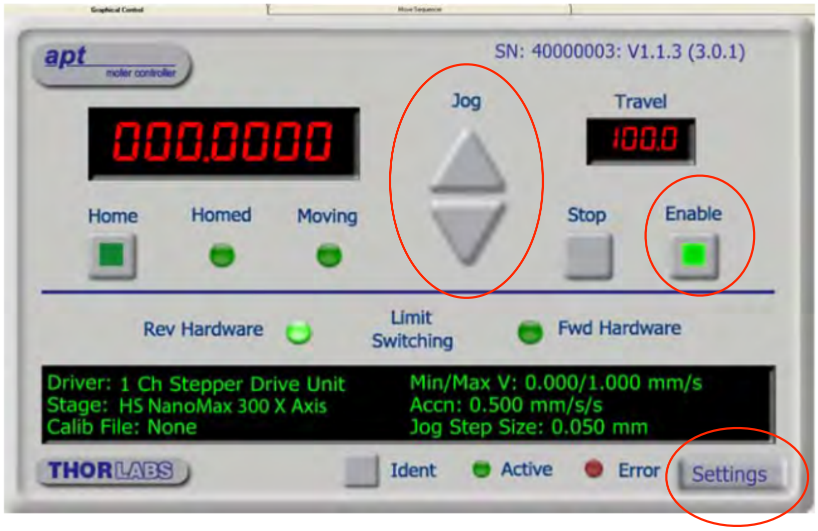

Figure 14: Motor controller software GUI [13].

As mentioned in section B.3.3, the NR360S rotary stage has a knob that allows for manual adjustment of the stepper motor. In order to use the knob, power to the motor must be shut off by toggling the “enable” button. This is again toggled to restore motor power and lock the motor in place until the motor controller commands a movement. Also in this menu panel are the “jog” arrow buttons. These are used by the operator to move rotary stage by a specified step distance with each press of the button. The step size parameter is adjusted before the drilling procedure begins for each turbine disk.

The “settings” button displays the motor driver settings, shown in Fig. 14, where various motor parameters can be adjusted. For the redesigned process, the operator will need to change the parameter known as the “step distance”, which is the distance the rotary stage rotates the disk between rivet bore positions.

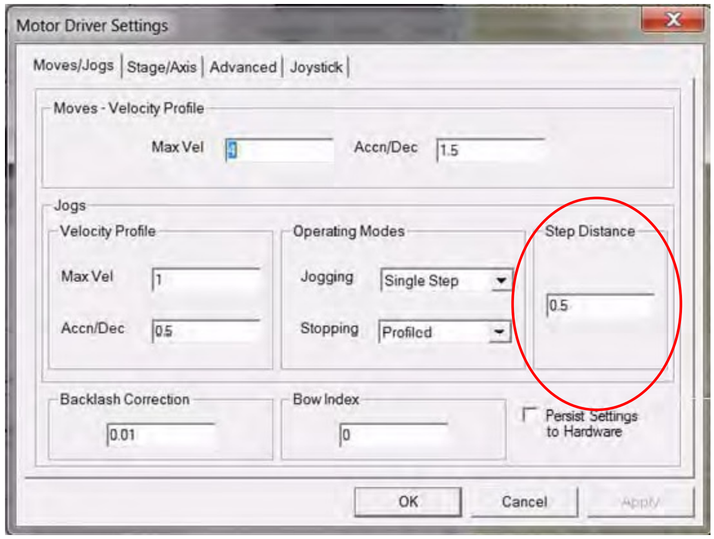

Figure 15: Motor setting panel [13].

The step distance is determined based on the number of rivets the turbine disk has, as given in the following equation:

$$Step\ Size\ [degrees] = {}^{360°}\!/_{\#\ of\ rivets}$$

It is important that the initial position found using the alignment guide is accurate to ensure that the rotary stage rotates the turbine disk to the next rivet bore positions correctly.

OPTIONAL COMPONENT – PHYSICAL SWITCH CONTROLLER

The rotation of the turbine disk can also be controlled by a physical switch that connects directly to the stepper motor of the NanoRotator. This switch must be set up by the same software package before operation to assign the incremental angle that the disk has to rotate for each drilling step. This switch is also produced by ThorLabs Inc., namely T-Cube Stepper Motor Controller and is mostly used to controlled small scaled stepper motor [14], as shown in Fig. 16.

Figure 16: TST101- T-Cube stepper motor controller [14].

This controller has similar features as the BSC201 that is currently implemented on the disk mount assembly design, with high resolution via micro-stepping and can be used to control the stepper motor that has the same specifications as the one on the NanoRotator. Implementing this unit to control the movement of the rotary stage has been considered due to its convenience and simplicity, as well as compact footprint and highly flexible parameterization. This unit is targeted at low power applications, but it can still accommodate wide range of stepper motors and associated stages and actuators [14]. The physical buttons on the TST101 allow the operator to control the functions of the rotary stage, initially set up by the software on the computer. Direct connection between the T-Cube and the NanoRotator makes the movement control of the turbine disk easy for the operator, as the controller can mounted close to the fixture for best accessibility.

Although these features seem more beneficial to the design than the BSC controller, this T-Cube unit is designed mostly for actuator applications. Adapting this to control the NanoRotator is still possible, but it is not recommended by the manufacturer as the NanoRotator will not operate at full capacity and performance. Since the TST101 is less powerful than the BSC201, the specifications of the rotary stage are reduced (velocity, load, accuracy…) and thus the correct alignment cannot be reached. Furthermore, the TST101 has to be connected to the computer to set up the step angle every time a different disk model (PT6A and PW100 models) needs to be drilled, as the angle between rivets varies from model to model.

Since the goal of the project is to achieve correct alignment of drilling operation, which requires the NanoRotator to function at its full capacity (accuracy and resolution). Reduced specifications are not allowed therefore this option has been dropped and not included to the final disk mount assembly design. Controlling the NanoRotator via the BSC201 controller and PC workstation is still the optimal solution that can achieve the correct alignment of the river removal process.

B.4. FMECA ANALYSIS

A Failure Modes, Effects and Criticality Analysis (FMECA) was implemented in order to identify the potential failure modes on the critical components of the redesigned fixture. Table X and Table XI provide the FMECA matrix of the critical components of this design. It must be noted that only the failures associated with the redesigned fixture and human interaction will be considered. Any external factors such as: failure due to the environment that may contribute to a failure are not included in this analysis. The critical component's features, interfaces, functionality, possible failure types, possible causes of failure, failure detection methods, effects of failure on the system, severity, failure rate, criticality, and preventive actions are outlined in the following analysis. For the fixture design, the critical components that were analyzed are as follows:

- Rotary Indexing Stage
- Alignment Guide
- Motion Controller and PC interface

B.4.1. FAILURE MODES

Failure modes can be defined in several ways depending on the level of analysis, the type of system, and the objectives of the FMECA. Listing the possible failure modes for the critical components provides documentation and awareness to the types of failure a component could experience. Some of the failure modes used for the purposes of this project include:

- Component fails to function
- Improper alignment

- Mechanical component wear
- Electrical short circuits
- System crashes
- Component becomes overheated

B.4.2. Failure Causes

The possible causes for each failure mode are identified and described in the FMECA matrix. Once the probable causes of each failure mode have been identified, we will be able to estimate the failure's probability of occurrence, uncover secondary effects of failure, and develop preventive actions for each failure.

B.4.3. Failure Effects

The failure effects of the analyzed components are stated in the FMECA matrix. Failure effects are consequences that could potentially occur in each of the identified failure modes. A failure effect may be the result of multiple failures. For consistency of analysis, the terminology used to identify the failure effects in the FMECA matrix is as follows:

- Fails to operate
- Capacity inadequate
- Fails to carry out a required operation
- Operates prematurely

B.4.4. Failure Severity

The severity of each failure mode is also assessed in the FMECA matrix. Table VIII tabulates the failure effect severity scale used in the analysis of the new fixture's design components. The failure severity was assessed on the basis of the effect of a failure on the equipment, system operation, and operator.

TABLE VIII

FAILURE EFFECT SEVERITY SCALE

Equipment	System operation	Operator	Severity level
None or negligible effect	None or negligible effect	No harm	**1**
Failure of a single component	-	-	2
Cascading failure resulting in damage to several components	Some loss of capability and no work around	Small risk of harm	3
Total destruction of system	Loss of capability that compromises operation availability	-	4
Total destruction of system and damage to other systems	Total loss of Function	Risk of serious injury	5

B.4.5. FAILURE RATE AND CRITICALITY

As part of the FMECA analysis, the rate and criticality for each failure mode was also evaluated. Table IX and Table X were used for the criticality assessment of the analyzed fixture components. Table IX shows the frequency of occurrence of all possible failure modes.

TABLE IX

FREQUENCY OF OCCURRENCE OF FAILURE MODES

Failure rate category	Frequency of occurrence of failure mode
1	Once in the life of the system
2	Once every ten years
3	Once every two years
4	Twice a year
5	Once a month

Table X provides an array of criticality bands consisting of letters A, B, C and D. These bands represent the correlation between the failure rate and severity level.

TABLE X

CRITICALITY BANDS

		Severity Level				
		1	2	3	4	5
Failure Rate Category	5	A	C	C	D	D
	4	A	B	C	C	D
	3	A	B	B	C	C
	2	A	A	B	B	C
	1	A	A	A	A	A

Table XI and Table XII provide FMECA analysis performed for the critical components of the redesigned fixture.

TABLE XI
FMECA MATRIX USED FOR THE REDESIGNED FIXTURE COMPONENTS (P–1)

Assembly Drawing No.	Dwg 1-1
Item Description	Rotary Indexing Stage
Interfaces	Protractor and rotary stage interface and Rotary stage and spindle interface
Features	Rotary stage, stepper motor, manual turning dial
Item Function	Provides incremental rotational indexing and positional correction
Failure Mode	Component fails to function, Mechanical component wear, Improper alignment, Component becomes overheated
Possible Causes	Loose spindle and rotary stage interface, loose attachment points, loose attachment points, component fatigue
Pre-failure Symptom	Decreasing alignment accuracy, vibration, noise, loss of sychronization at the interface
Effect on Overall System	Capacity inadequate, fails to operate
Compensating Provisions against Failure	Manual knob alignment, inspect and secure the attachment points
Severity - Equipment	2
Severity - System Operation	3
Severity - Operator	1
Failure Rate	3
Criticality	B
Preventive Actions	Routine inspections, frequent maintenance
***Comments**	Failure rate is based on item warranty
	Routine setup, calibration, and maintenance required
	Compliance with the recommended operation manual required
	Criticality level chosen based on the failure rate and the worst severity

TABLE XII

FMECA MATRIX USED FOR THE REDESIGNED FIXTURE COMPONENTS (P–2)

Dwg 1-5	N/A
Alignment Guide	Motion Controller and PC interface
Guide chamfer and disk chamfer interface and drill bit and guide bore	USB Connector
Guide head, shank, inner guide bore, chamfer rest	GUI interface, motion controller, PC workstation
Provides initial drilling alignment	Provides accurate motion control for the disk
Improper alignment, Mechanical component wear	Component fails to function, Electrical short circuits, System crashes
Improper handling technique, material fatigue	Loss of power supply, component fatigue, improper wiring and communication, wrong input parameters
Inaccurate alignment, material wear	Slow/no response to an input, wrong output, change of default GUI settings
Fails to carry a required operation	Operates prematurely, capacity inadequate
Replace with a new guide	Reset the controller, check the inputs and settings, restart the PC, check wire connection
2	3
4	5
1	1
4	3
C	C
Maintenance and material inspection before use	Routine calibration
Failure rate is based on research	Failure rate is based on item warranty
Training and practice required	Calibration, operation, and training required
Compliance with the recommended operation manual required	Compliance with the recommended operation manual required
Criticality level chosen based on the failure rate and the worst severity	May cause overshooting of the rotational motion (capacity inadequate)
	Criticality level chosen based on the failure rate and the worst severity

B.5. BILL OF MATERIALS

The bill or materials provides the quantity of each part need to be purchased, the suppliers part number, a description of the part, unit cost and total cost for each part. It is split into sections based on each component offering a sub-total cost of the component. At the end of the bill of materials the total cost of materials is given. The estimated cost of the project is based entirely on the total cost of materials which is roughly \$4000. This cost does not include the shipping fees and other taxes.

The total cost does not cover the price of the redesigned spindle, the pad and the alignment guide as they need further analysis in terms of stress, material and dimensions before being manufactured. These analyses are not included in this report and can be carried out by an outsourcer or a design team. It should be noted that the final cost of \$4000 is the cost of materials only, i.e. the components needed to build the complete design and not including labor fee. These costs have been assessed as ready-to-purchase and provided with part number from the suppliers, and how they are sold – either as a single unit or wholesale. The components that required manufacturing are provided with the detailed drawings in Appendix C.

Client: StandardAero

Date: 07/12/2015

Project: Engine Turbine Blade Removal Process Redesign

Invoice: Q-001

Motorized Rotary Stage					
Qty	**Supplier**	**Part No.**	**Description**	**Sales Price**	**Total Price**
1	ThorLabs	NR360S	NanoRotator	$2,570	$2,570
1	ThorLabs	BSC201	Stepper Motor Controller	$1,330	$1,330
1	ThorLabs	NR360SP8	Adapter Plate	$49.40	$49.40
4	Fastenal	79047	Socket cap screw, 1/4”-20, 1-1/2” long	$1.59	$6.36
4	Fastenal	79013	Socket cap screw, #8-32, 5/8” long	$0.6534	$2.62
1	Manufactured	DWG 1-2	Redesigned spindle	TBD	TBD
1	Manufactured	DWG 1-4	Pad	TBD	TBD
1	Fastenal	77730	Hex Nut, 1/4”-28	$0.3742	$0.3742
			Total		**$3958.75**

Drilling Alignment Guide					
Qty	**Supplier**	**Part No.**	**Description**	**Sales Price**	**Total Price**
1	Manufactured	DWG 1-5	Alignment Guide	TBD	TBD
			Total		**TBD**

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APPENDIX C

ENGINEERING DRAWINGS

LIST OF DRAWINGS

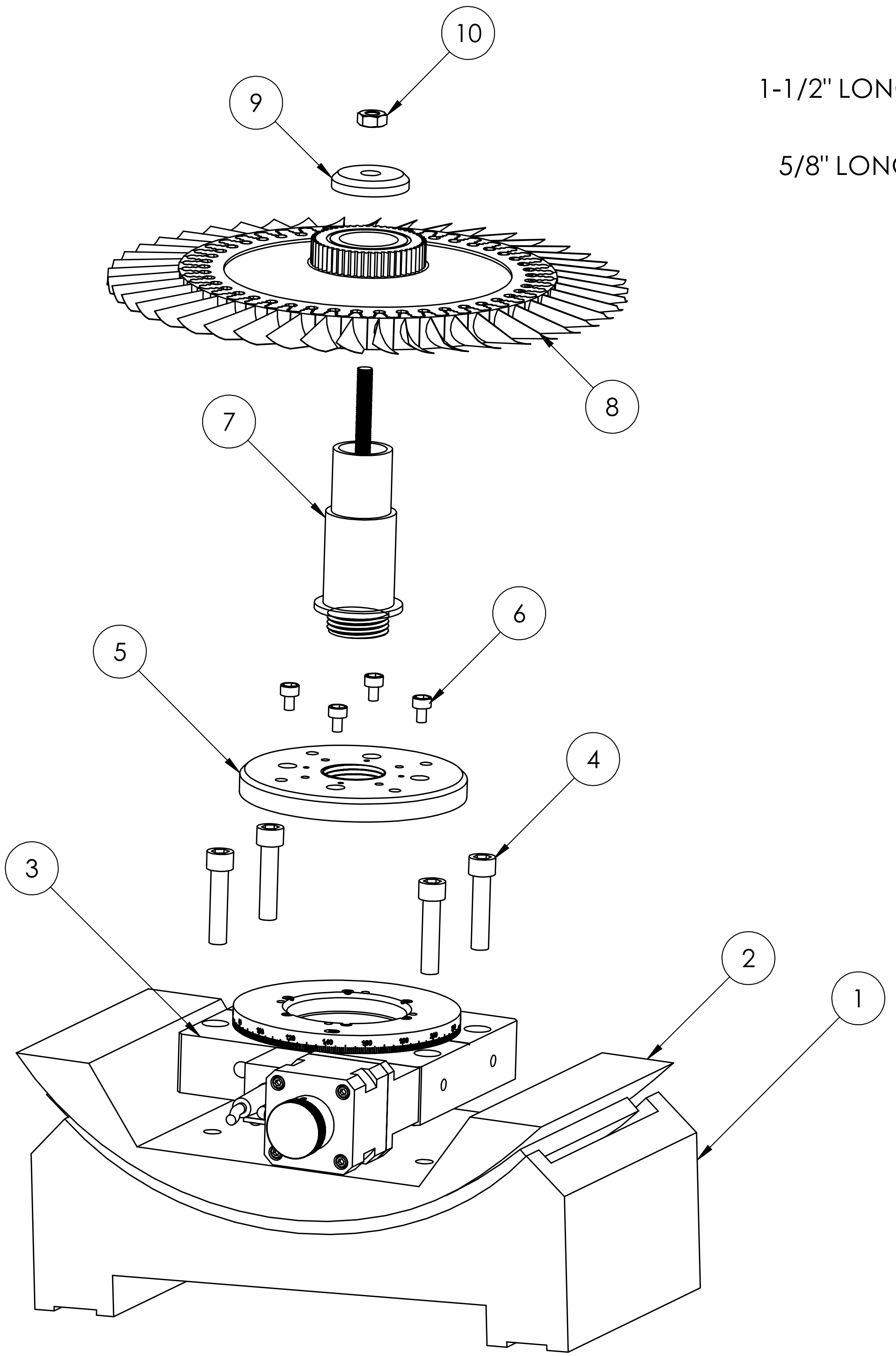
NAME OF DRAWINGS	DRAWING NO. / ITEM NO.
DISK MOUNT ASSEMBLY	DWG 1-1
SPINDLE	DWG 1-2
CRADLE	DWG 1-3
SECURING PAD	DWG 1-4
ALIGNMENT GUIDE	DWG 1-5
NANOROTATOR	NR360S
ADAPTER PLATE	NR360SP8

NOTES

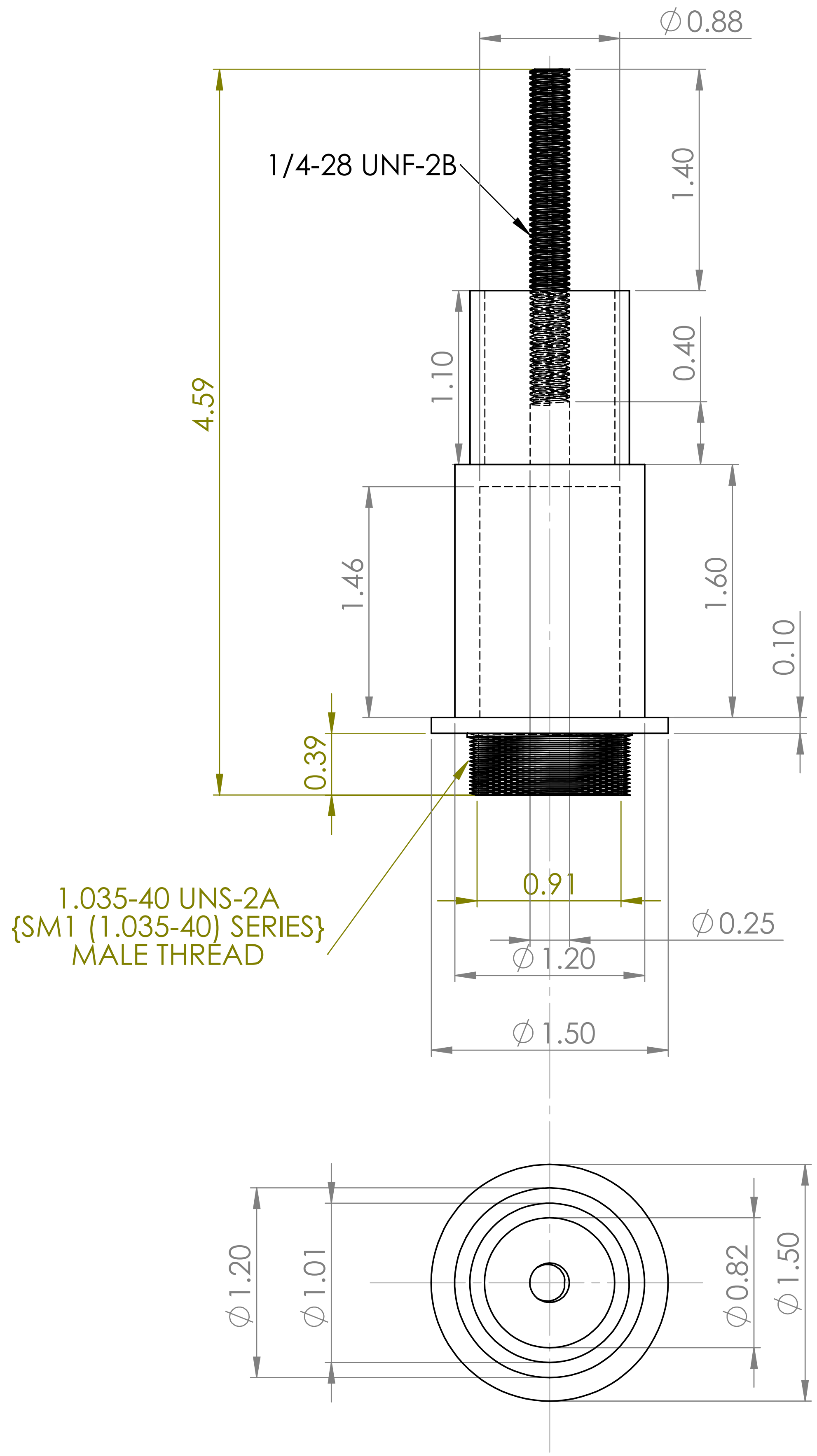
All drawings included in this Appendix are either sketched by the team or used with permission from the manufacturer (ThorLabs Inc.).

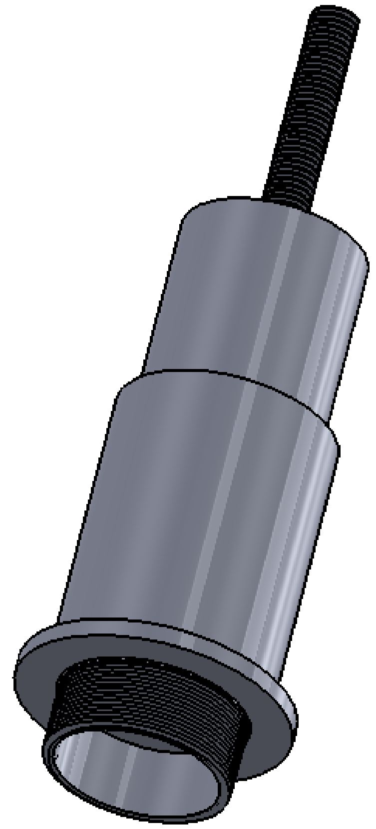
- Drawings 1-1 to 1-5 are sketched by the team with relative dimensions provided by the client.
- Drawings NR360S and NR360SP8 are used with permission from ThorLabs Inc.

	ITEM NO.	DESCRIPTION	QTY.
	1	BASE	1
	2	CRADLE	1
	3	ROTARY STAGE [NANOROTATOR]	1
1-1/2" LONG	4	1/4"-20 STAINLESS STEEL CAP SCREW, ~~2" LONG~~	4
	5	ADAPTER PLATE [CAGE SYSTEM ADAPTER]	1
5/8" LONG	6	8-32 STAINLESS STEEL CAP SCREW, ~~1/2" LONG~~	4
	7	SPINDLE	1
	8	TURBINE DISK	1
	9	SECURING PAD	1
	10	1/4" - 28 STAINLESS STEEL HEX NUT	1



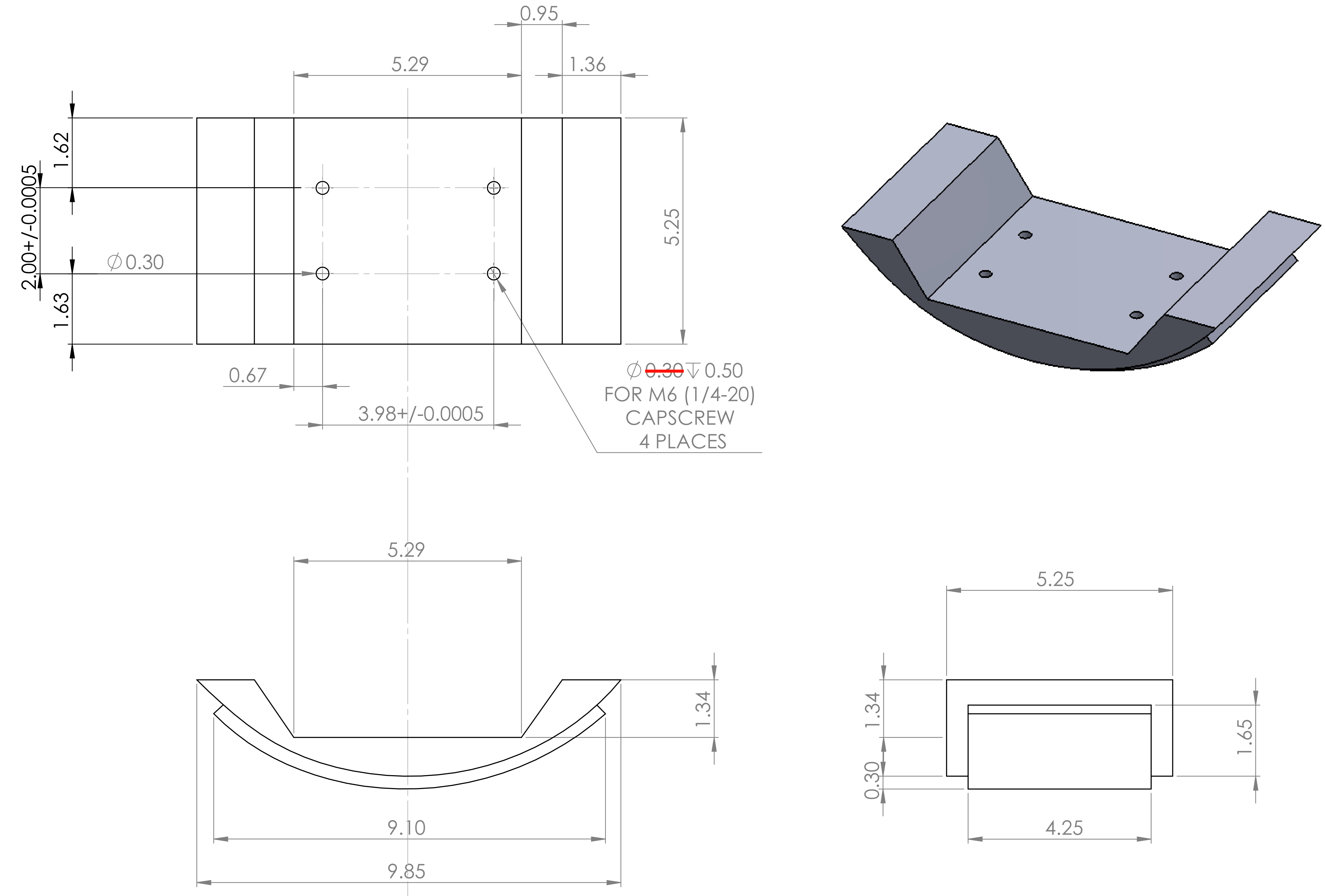
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	UNIVERSITY OF MANITOBA		REVISION	0
	ITEM NUMBER: 1			
	NAME	DATE	TITLE:	
DRAWN	TEAM 19	30-NOV-2015	DISK MOUNT ASSEMBLY	
CHK'D	TEAM 19	30-NOV-2015		
APPV'D	TEAM 19	30-NOV-2015		
MATERIAL: VARIOUS	DWG NO. 1-1		A3	
WEIGHT: N/A			SCALE: 1:2.3	SHEET 1 OF 5





Note: This drawing only serves to provide for the general dimensions of the redesigned spindle and highlight the main features.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: +/-0.005			UNIVERSITY OF MANITOBA	REVISION 0
			ITEM NUMBER: 2	
	NAME	DATE	TITLE:	
DRAWN	TEAM 19	30-NOV-2015	SPINDLE	
CHK'D	TEAM 19	30-NOV-2015		
APPV'D	TEAM 19	30-NOV-2015		
MATERIAL: BLACK OXIDE ALL STEEL			DWG NO. 1 - 2	A3
WEIGHT: N/A			SCALE: 1:1	SHEET 2 OF 5



NOTE: THIS DRAWING ONLY SERVES TO SHOW THE LOCATION OF THE HOLES THAT ACCOMODATE THE ROTARY STAGE. FOR MEASUREMENT DETAILS OF THE CRADLE, REFER TO PWC38292.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: +/- 0.0005

UNIVERSITY OF MANITOBA

REVISION 0

ITEM NUMBER: 3

	NAME	DATE
DRAWN	TEAM 19	30-NOV-2015
CHK'D	TEAM 19	30-NOV-2015
APPV'D	TEAM 19	30-NOV-2015

TITLE:

CRADLE

MATERIAL: BLACK OXIDE ALL STEEL

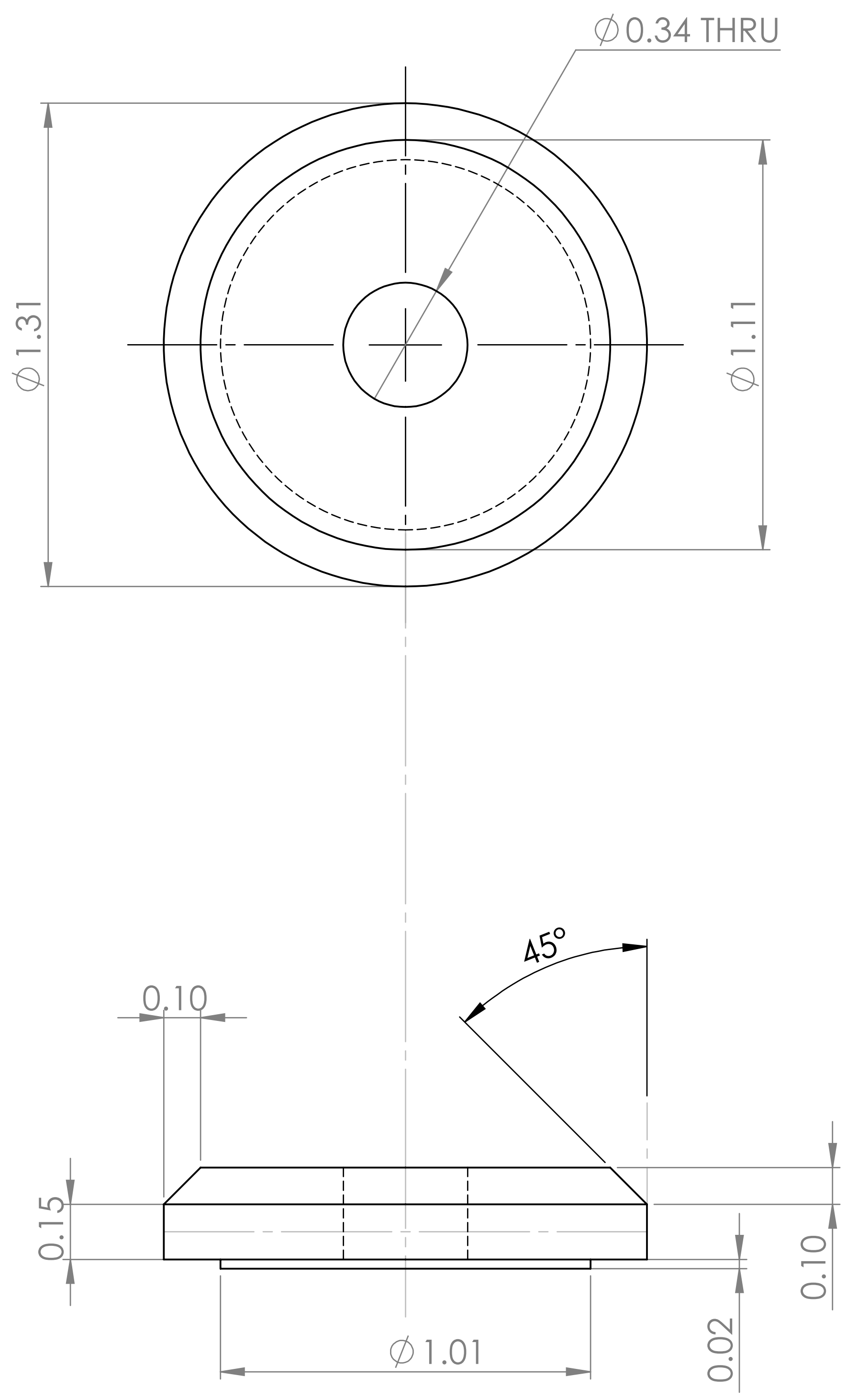
DWG NO. 1 - 3

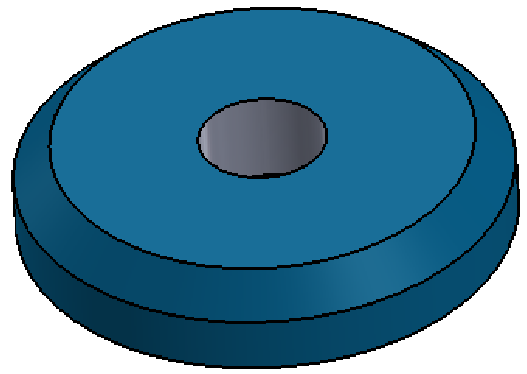
A3

WEIGHT: N/A

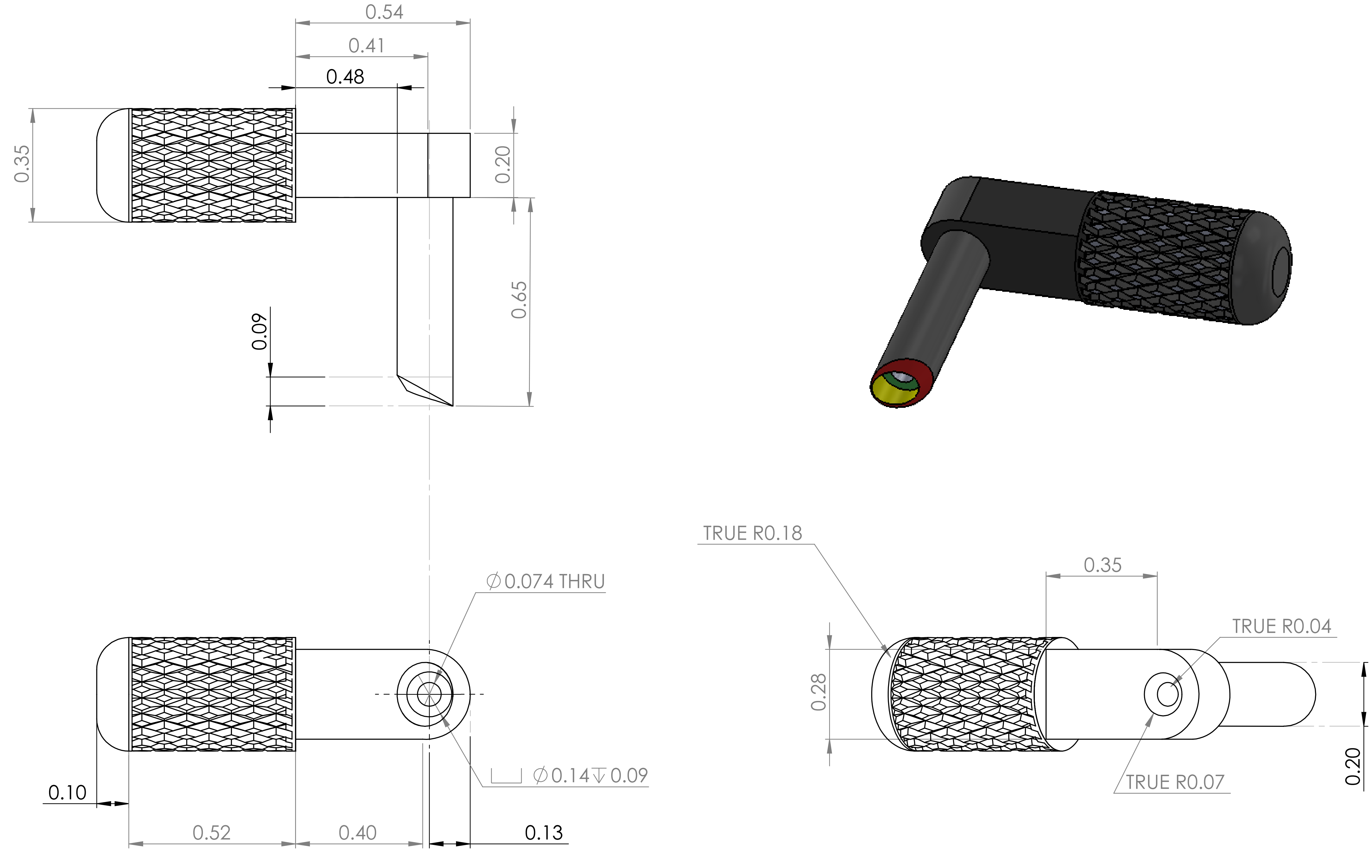
SCALE: 1:2.5

SHEET 3 OF 5



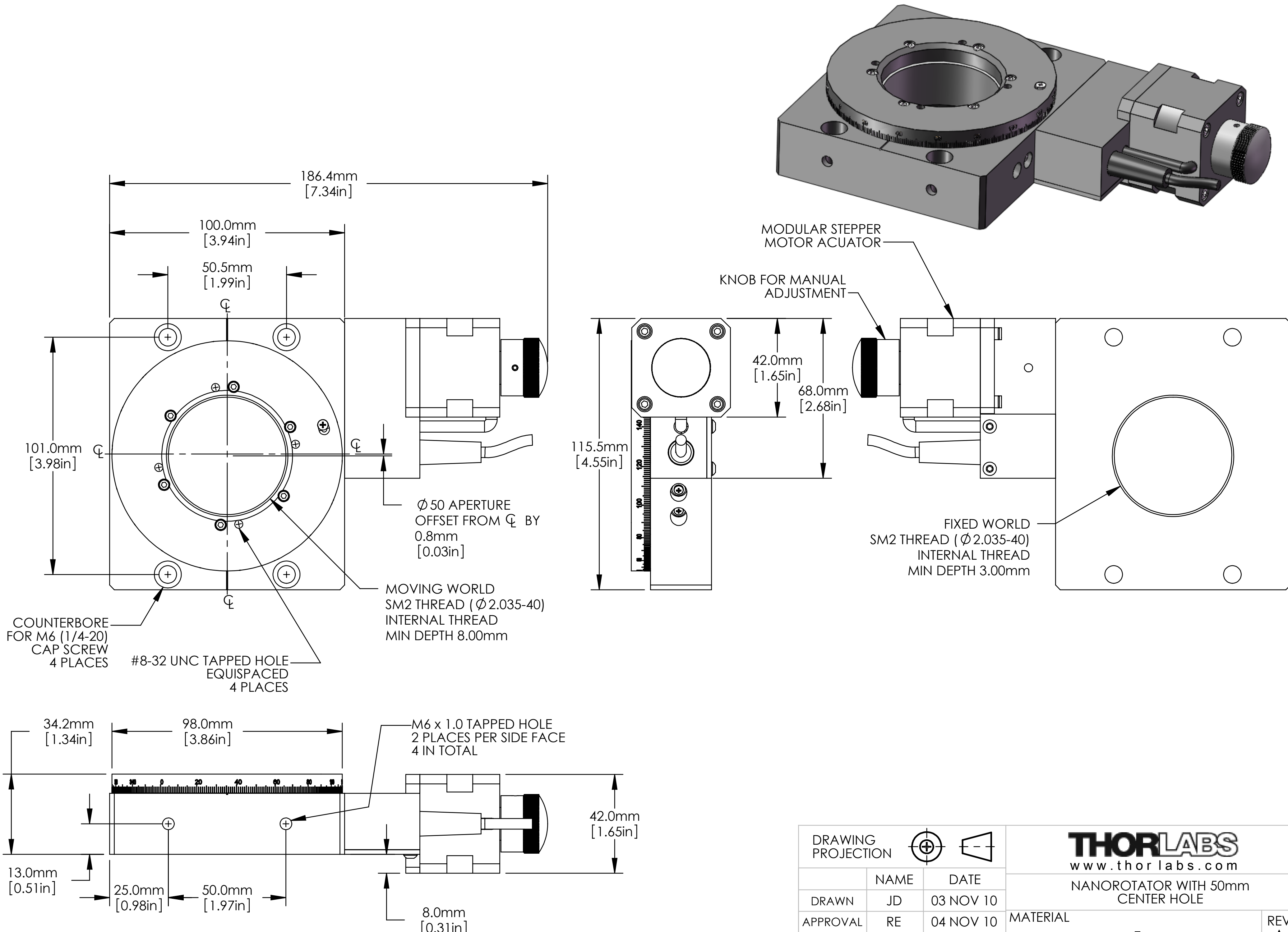


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: +/- 0.005			UNIVERSITY OF MANITOBA	REVISION 0
			ITEM NUMBER: 4	
	NAME	DATE	TITLE:	
DRAWN	TEAM 19	30-NOV-2015	SECURING PAD	
CHK'D	TEAM 19	30-NOV-2015		
APPV'D	TEAM 19	30-NOV-2015		
MATERIAL: BLACK OXIDIZE ALL STEEL			DWG NO. 1 - 4	A3
WEIGHT: N/A			SCALE: 2:1	SHEET 4 OF 5



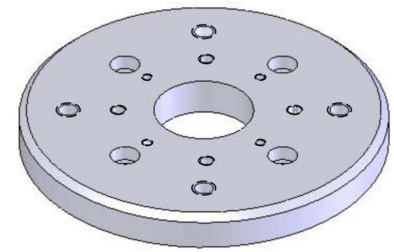
NOTE: THIS DRAWING ONLY SERVES TO SHOW THE HIGH LEVEL DIMENSIONS OF THE ALIGNMENT GUIDE. DETAILS OF THE GEOMERTY ON THE BOTTOM CAN BE OBTAINED USING THE GEOMETRIC ANALYSIS PROVIDED IN THE ATTACHED REPORT AND THE CAD MODEL, AND MAY BE MANUFACTURED USING A 3D PRINTER OR A RAPID PROTOTYPING EQUIPMENT.

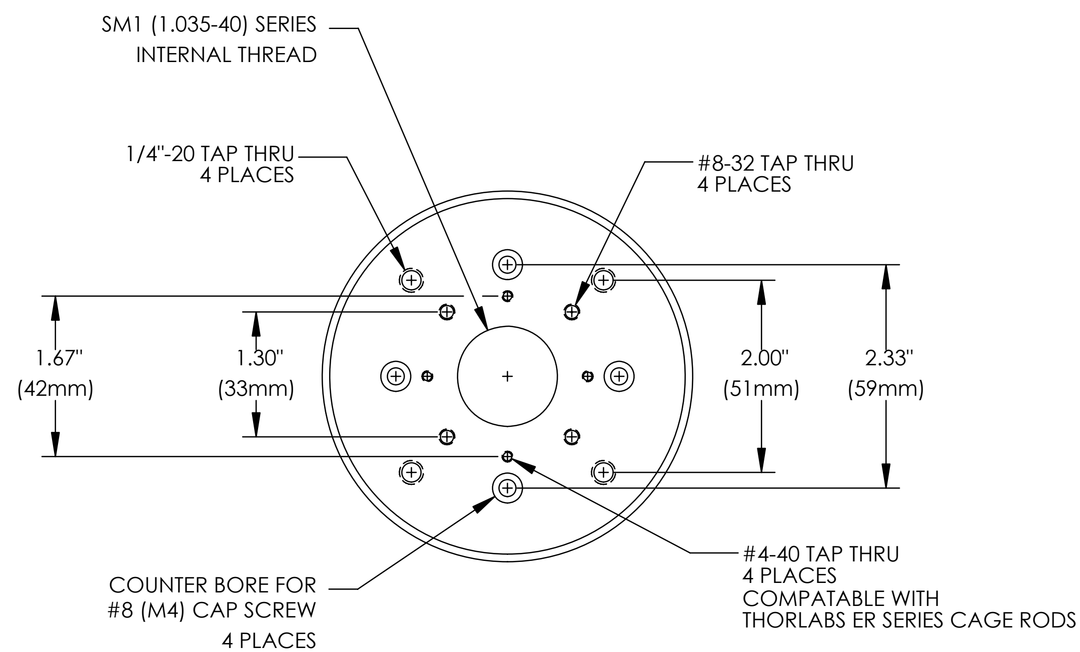
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES			UNIVERSITY OF MANITOBA; REVISION 0; ITEM NUMBER: 5
	NAME	DATE	TITLE: Alignment Guide
DRAWN	TEAM 19	30-NOV-2015	
CHK'D	TEAM 19	30-NOV-2015	
APPV'D	TEAM 19	30-NOV-2015	
MATERIAL: POLYPROPYLENE THERMOPLASTIC			DWG NO. 1 - 5; A3
WEIGHT: N/A			SCALE: 3:1; SHEET 5 OF 5

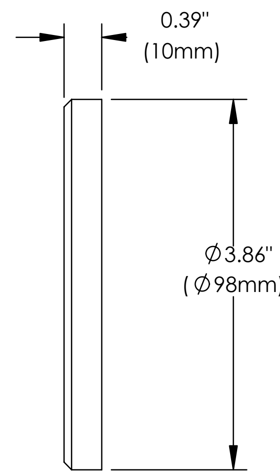


FOR INFORMATION ONLY
NOT FOR MANUFACTURING PURPOSES

DRAWING PROJECTION			THORLABS www.thorlabs.com	
	NAME	DATE	NANOROTATOR WITH 50mm CENTER HOLE	
DRAWN	JD	03 NOV 10	MATERIAL -	REV A
APPROVAL	RE	04 NOV 10		
COPYRIGHT © 2010 BY THORLABS			ITEM # NR360S	APPROX WEIGHT 1.4 kg
VALUES IN PARENTHESIS ARE CALCULATED AND MAY CONTAIN ROUNDOFF ERRORS				







	NAME	DATE
DRAWN	JMM	09/01/05
ENG APPR.	JMM	09/01/05
MFG APPR.	BG	11/01/05

THORLABS INC. PO BOX 366 NEWTON NJ

TITLE: SM1 AND 1" CAGE SYSTEM ADAPTER FOR NR360 STAGE

MATERIAL: BLACK ANODIZED ALUMINUM

SIZE: A

REV.: A

SCALE: 1:2

SHEET 1 OF 1

DWG. NO. 13067-E01

PART NO. NR360SP8

5 4 3 2 1

APPENDIX D

OPERATION GUIDE

OPERATION GUIDELINE

General Description:

This guide is an addition to the manual part no. 3021243 (Compressor Turbine Disassembly – Pratt & Whitney Canada). Any or all the information provided herein should be strictly followed in order to achieve correct alignment of the rivet for drilling operation and to avoid damaging the turbine disk.

References:

The manuals and guides listed below are used in the following procedure.

- Manual Part No. 3021243
- User Guide of NR360S-Motorized 306 Rotation Stage (ThorLabs Inc.)
- User Guide of BSC201-Benchtop Stepper Motor Controller (ThorLabs Inc.)

Applicable Tools:

The special tools listed below are used in the following procedure.

Tool No.	Name	Application
PWC38293	Drill	Obsolete – replaced by a standard 0.073 inch drill bit
PWC38288	Base	-
PWC32251	Disk Support	Obsolete – replaced by a redesigned spindle
DWG 1-2	Spindle	Redesigned from PWC32251
DWG 1-3	Cradle	-
DWG 1-5	Alignment Guide	-
NR360S	Rotary Stage	-
NR360SP8	Adapter Plate	-

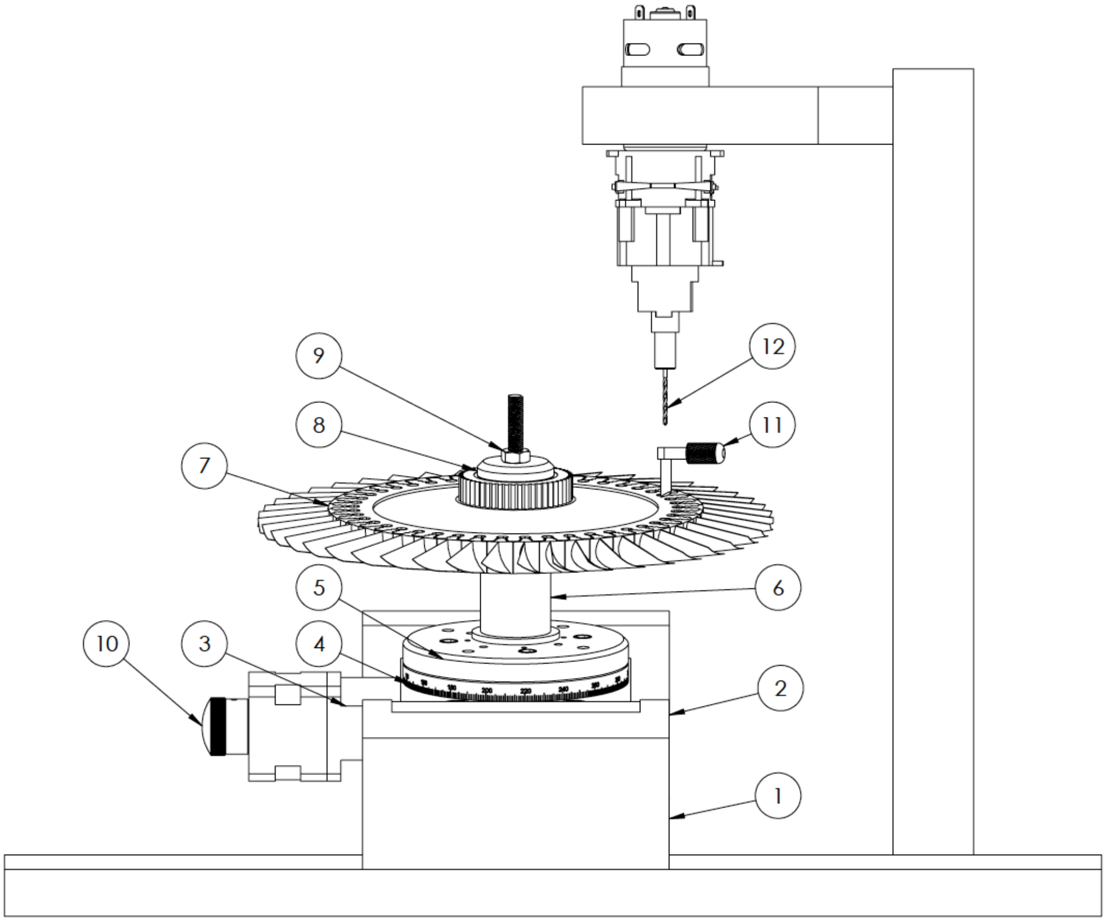


Figure 1: Redesigned Rivet Drilling Fixture.

Key to Figure 1

1. Base
2. Cradle
3. Rotary Stage
4. Rotation Platform
5. Adapter Plate
6. Spindle
7. Turbine Disk
8. Pad
9. Nut
10. Manual Knob
11. Alignment Guide
12. Drill Bit

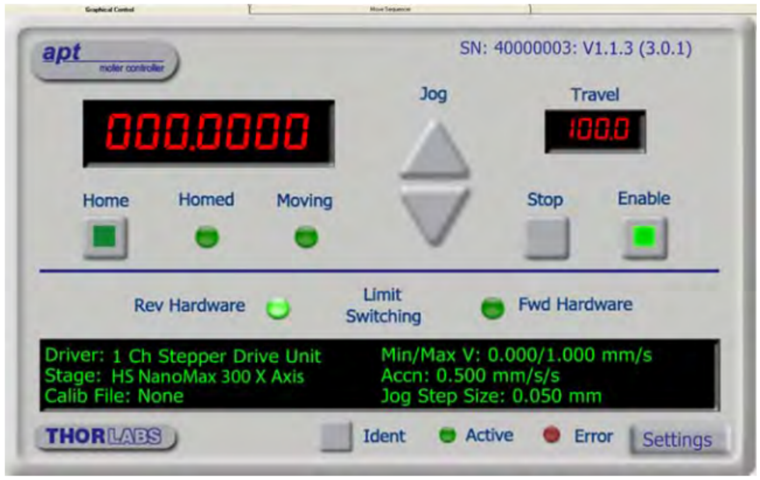


Figure 2: APT Software Interface.

Key to Figure 2

Enable: turns on/off power supply to the stepper motor

Jog: moves the motor (and thus the rotation platform) by a step

Settings: opens the setting panel

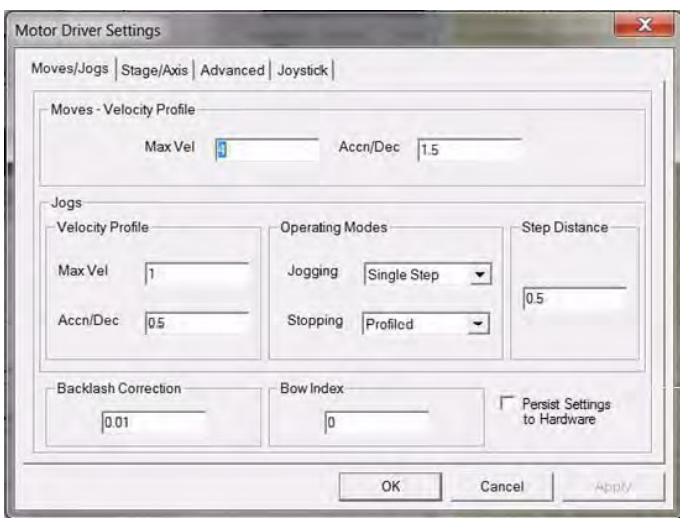


Figure 3: Motor Setting Panel.

Key to Figure 3

Step Distance: set up the “step” corresponding to the angle between rivets

Procedure:

This section provides step-by-step instructions on the initial alignment and the drilling operation for the disassembly of a turbine disk. These steps are to be followed strictly to ensure correct drilling alignment and accuracy during the operation. Refer to manual no. 3021243 for the installation and verification of the standard procedure.

(a) Sliding the base (1) to the left (away from the air drill) for clearance.

(b) Adjust the cradle (2) to the neutral position (zero on the Vernier protractor).

(c) Ensure the adapter plate (5) is secured to the rotation platform (4), tighten screws if necessary.

(d) Secure the spindle (6) onto the adapter plate (5).

(e) Install the turbine disk (7) on the spindle (6), and secure with pad (8) and nut (9).

(f) Select a drill bit (12) of 0.073 inch in diameter and install it onto the air drill (as per manual no. 3021243).

(g) Toggle off the power supply to the stepper motor clicking the "Enable" button on the APT software interface (Figure 2) – the green light goes off.

(h) Position the disk (7) by sliding the base (1) and adjusting the tilt angle on the cradle (2) (as per manual no. 3021243).

(i) Using manual knob (10) and alignment guide (11), position the rivet bore directly below the drill bit (12). Hold the alignment guide (11) so it sits on the chamfer of the rivet head (of the disk), lower down the drill bit (12) and adjust manual knob (10) until the drill bit (12) is aligned with the inner hole of the alignment guide (11).

(j) Once the initial alignment is achieved, using the APT Software Interface (Figure 2) set the initial position by clicking the "Enable" button. Set the angle by clicking "Settings" and go to "Step Distance" on the Motor Setting Panel (Figure 3). Refer to the BSC201 User Guide for details to set up angular distance (either in degrees or radians). Enter values for step size corresponding to the number of rivets on disk (7), as shown in the Table I.

Table I: Step size conversion table

Engine Models	Disk Types	Number of Rivets	Step Size (°)
PT6A	CT Disk	58 / 59 / 43	6.2 / 6.1 / 8.4
	PT1 Disk	41 / 47	8.8 / 7.7
	PT2 Disk	43	8.4
PW100	LPT Disk	53 / 47	6.8 / 7.7
	PT1 Disk	66	5.5
	PT2 Disk	71	5.1

(k) Click "OK" to establish the initial position and the step size. Double check the alignment by repeating step (i). Alignment correction can be made by repeating step (i) to (k).

(l) Once the initial alignment is obtained, remove the alignment guide (11). The operation can proceed by turning on the air drill via pedal and lowering down the drill bit (12) (as per manual no. 3021243).

(m) Move to the next rivet position by clicking the "Jog" button on the APT software interface. Complete the drilling process by repeating step (m) and the steps mentioned in manual no. 3021243.

(n) When all the rivets are drilled, turn off the stepper motor by repeating step (g). Slide the base (1) to the left for clearance. Loosen nut (9), remove pad (8) and turbine disk (7) and spindle (6) from adapter plate (5) and install assembly on base (PWC38288). Refer to manual no. 3021243 for details on shearing rivets and removing turbine blades.