Blisk Inspection System

A Major Qualifying Project
Submitted to the Faculty of
Worcester Polytechnic Institute
In partial fulfillment of the requirements for the
In cooperation with
GE Aviation in Hooksett, New Hampshire
Submitted January 22nd, 2018

Submitted By:
Michael Hopkins

Project Advisors:
Craig Putnam
Kenneth Stafford

CONTENTS

LIST OF FIGURES

Automated Blisk Inspection System

Michael Hopkins
Advised By: Craig Putnam, Kenneth Stafford

***Abstract*—The Automated Blisk Inspection System uses an ABB robotic arm with custom end of arm tooling, a custom turntable, and a computer vision algorithm to preform a QA check on bladed disk (blisk) root fillets. This process is currently preformed by hand at the Hooksett New Hampshire GE Aviation plant. The current inspection process requires extensive labor costs and consumables. This system is being developed to reduce overall cost of production while increasing factory output. Bi-directional compliance combined with precision pathing ensure proper inspection of root fillets and a tool changer enables seamless switching between blisk stages.**

I. INTRODUCTION

THIS project is a capstone MQP with the goal of automating the inspection of GE Aviation bladed disks. GE Aviation has a plant located in Hookset New Hampshire that manufactures bladed disks. These bladed disks, also known as blisks, rotate inside GE jet engines and act to compress the air passing through the engine. GE manufactures a wide variety of blisks, however, the Hooksett facility is transitioning from their current output to an output of 60%-80% LEAP series blisks by 2021.

The LEAP series consists of 3 different blisks. This project will focus specifically on the two stage blisk in the series pictured in Figure 1. This blisk has two rows of blades that are separated in the middle. Each blisk, after being manufactured, is inspected closely to insure they are within specification. One thing that is inspected during QA is the radius of the fillet where the blade meets the hub. These fillets are referred to as “root fillets.” The radii of each root fillets has a defined maximum and minimum value and having fillets within specification is critical to insure the blisks work as designed.

The goal of this project is to automate the inspection of the root fillets with a robotic system. Currently fillets are inspected by operators. The goal of automating this process is to help reduce labor costs on inspectors and increase the output potential of the factory. Although this project will focus on the two stage blisk, the solution will be designed to function on all of the LEAP series blisks.

II. BACKGROUND

A. Current Inspection Methods

There are currently two methods approved by GE Aviation to inspect the blisk root fillets. For the primary method an operator sprays a thin powder, called developer, on the fillet. The operator then runs a precision ground ball gauge along the fillet. The operator has to complete this process twice. Once with a gauge ball the size of the minimum fillet, and a second time with a ball the maximum size of the fillet. After running the ball along the fillet the operator can tell if the fillet has passed or failed based on the number of contact points between the ball and the blisk surface. Each contact point is shown as a track of developer that has been scraped off of the fillet surface. If there is one contact point the fillet is larger than the gauge ball and if there are two contact points the fillet is smaller than the gauge ball. This inspection method takes between 15 minutes and a half hour for each stage of a blisk.

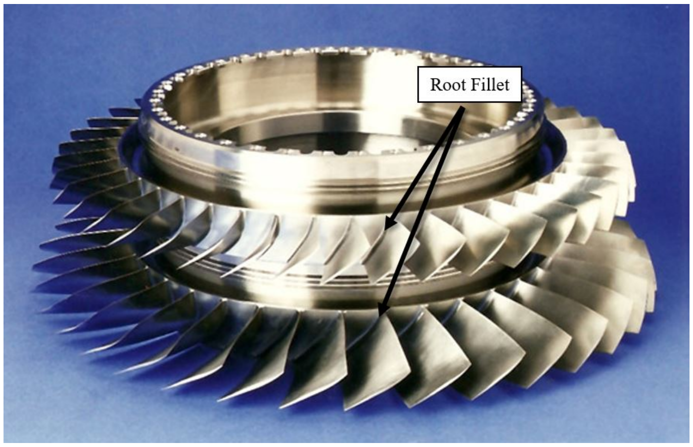


Fig. 1. Two stage blisk with labeled root fillets

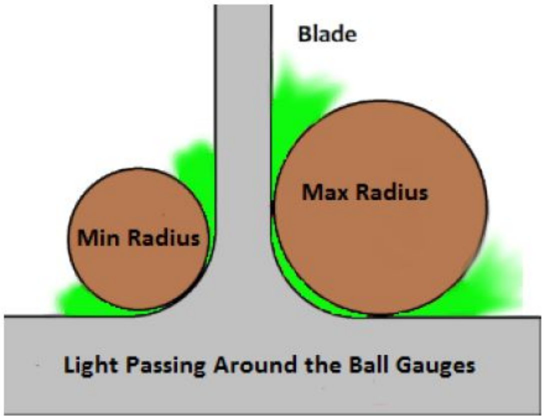


Fig. 2. Light pattern example created by 2017 project group

The secondary inspection method approved by GE Aviation utilizes the same gauge balls, but instead of using developer the operator shines a light from behind the ball. The operator then looks at the light pattern produced. Figure 2 shows an example of a passing test for both the minimum radius check and the maximum radius check. This method is utilized when the primary method fails to provide definitive results. The downside is that this method is slower for operators, but it is considered equally reliable.

In order for an automated system to be considered viable it must keep the inspection time for one stage to under an hour. This will insure that the full inspection process for a stage stays under the three hour time limit that GE Aviation currently maintains.

B. Previous Project Results

This project has been run twice before, however both attempts have left room for improvement. The current system was developed by the 2016-2017 project team and is made up of an ABB 1600 industrial robot, a Raspberry Pi single board computer, a stepper motor driven turntable, and a custom built End Of Arm Tooling (EOAT).

1) Controller and System Layout: Currently the system is controlled by a Raspberry Pi. This hobby grade single board computer controls the computer vision processing, displays the user interface, instructs the ABB robot to start and stop inspecting, and controls the stepper motor driver. The robot used is an IRB 1600 manufactured by ABB. This robot is run by an IRC5 ABB controller.

2) Turntable: The current turntable is pictured in Figure 3. This turntable uses a GE Aviation mounting fixture to hold each LEAP series blisk. The main turntable is two laser cut acrylic sprockets sandwiched between two larger aluminum disks. This platform is then connected to the base with a lazy-Suzanne style bearing. The platform is rotated by a rubber belt that is tensioned with a custom built belt tensioner. This belt is driven by a Polulu stepper motor. With the current stepper driver, the motor is set to have 3,200 steps per revolution. This was calculated to have a rotational accuracy of ±0.00060 inches at the blisk hub by the previous team. The stepper motor driver is a Pololu A4988 Black and is controlled by the Raspberry Pi.

Fig. 3. Existing turntable

3) End of Arm Tooling (EOAT): The current EOAT contains three main sections and is pictured in Figure 4. The first is the compliance section of the tooling. The tool is compliant in two axes and rigid in one. Compliance in the z-axis is accomplished with two pins passing through a machined block. This block is then tensioned with two springs forcing the tooling outward towards the tip. X-axis compliance is accomplished with a piece of spring steel. This spring steal is a thin wide strip. As a result, it will bend in one direction but is rigid in the other. This was used to help guide the tooling into the fillet. The compliance was placed close to the ABB robot. The intention was that the LED, gauge ball, and camera would all deflect together keeping them in the same position relative to each other. This section also includes a cantilevered load cell that provides feedback of the force being experienced by the end of arm tooling.

The next section allows switching between the maximum and minimum gauge balls. This is done using a micro servo that rotates two gauge balls mounted at a right angle to each other. Originally this switching was designed to have positive retention of the balls using electromagnets. However, due to issues with the current draw of the electromagnets, and overheating, they were eliminated from the design. As a result the current EOAT has no positive retention of the gauge balls. Each ball gauge was permanently mounted to a machine block that held them perpendicular to each other. When switching between stages of a blisk the operator would have to remove and install a new right angle block with new gauge balls.

The final section is the ball gauges, camera and LED. Due to a series of ordering errors and time constraints the current design does not have the correct gauge balls. Instead of this, the end of arm tooling has two 3D printed shafts with ball bearings affixed to the end. These act as stand-ins for the proper precision ball gauges, but would not be acceptable for use in GE Aviations factory. The camera used was a small USB web cam with a 45 degree mirror. This allowed the camera to be mounted perpendicular to the direction the camera was inspecting. The LED was a surface mounted green LED powered by the Raspberry PI. The camera and LED were both mounted such that they did not rotate with the ball gauges. This allowed a single camera and LED to be used as opposed to one for each ball. In addition, at the tip of one of the ball gauges there is an exposed copper wire. This is used to sense when there is contact between the EOAT and the blisk. This information is used to initialize the location of the first blade when an inspection is started on a blisk.

III. METHODOLOGY

A. Procedure

This project was done through A and B terms in the 2017-2018 academic year. The first steps taken were to identify the accomplishments and shortcomings of the previous two attempts at this project. From this, key shortcomings in the EOAT and overall system design were identified. The control system and subsystem communication was the first thing to be redesigned. Afterwards a new end of arm tooling was prototyped and improved through several rounds of testing. Once the EOAT design was able to be slid smoothly along the fillet by hand while producing a reliable light pattern a final version was manufactured. Next, the ABB robot was programed to path along a single fillet on the two stage blisk.

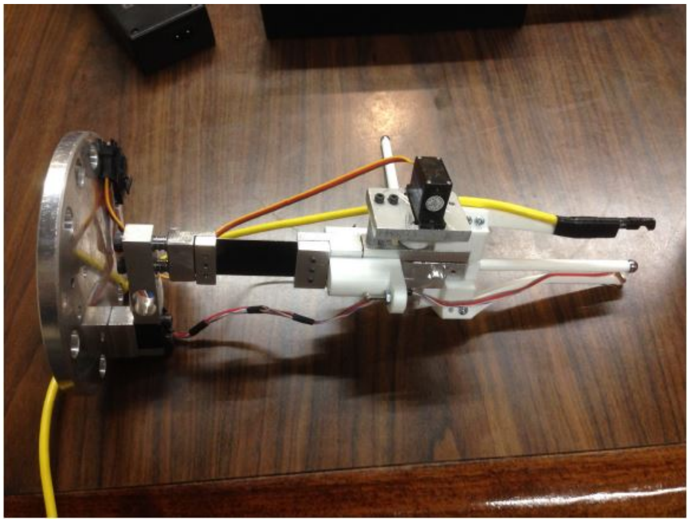


Fig. 4. Existing end of arm tooling

After the robot was able to recreate the results from our early tests done by hand the ABB robot was programed to inspect all four root fillets on the two stage blisk. Once the four paths were created a PLC was configured to rotate the turntable from one blade to the next when it received a signal from the IRC5 controller.

B. Physical Components

After doing research on industrial systems it was determined that the use of the Raspberry Pi would not be sufficient to control a system in any industrial setting. As a result it was decided to utilize a PLC to control the system. This would be very robust and is the type of controller utilized in just about every industrial system. An Automation Direct Do-more T1HE programmable logic controller, along with a large compliment of modules was already available and as a result it was selected as the PLC to run the system. The ABB IRB1600 six degree of freedom robot manipulator, shown in Figure 5, was determined to be the best option as it was available to the team and ABB's compliment of software is extremely well put together. This would allow the team to create and simulate routines without physically testing them on the robot. The robot was controlled by the same IRC5 controller used by the previous teams. The final major component is the turntable. It was confirmed that rotating the blisk from blade to blade would be ideal as opposed to having the blisk stationary. This reduced the number of paths that needed to be created for the robot. The final component is the computer vision. This component will be created by another team working concurrently with this MQP but is outside the scope of this project.

Fig. 5. ABB IRB1600

C. Control System

As stated above, control of the system as a whole was handled by an Automation Direct Do-more T1HE programmable logic controller. This is the device that each component will be attached to and the hub that information passes through when different systems interact. Utilizing a PLC will make the final system far more professional and much closer to a state where it could be used in a factory environment. The PLC functions on ladder logic which is a series of conditional statements that run in sequence continuously. This is ideal because we will be able to take digital status inputs from each component and systematically follow through the inspections process. This implementation of a PLC also allows individual systems to be changed and substituted very easily. Further, no drivers needed to be developed to allow communication between components. As long as the replacement component can provide the same status updates, the PLC is none the wiser if a component is replaced.

1) PLC Configuration: As stated above, the PLC used for this application was a T1HE; this PLC is pictured in Figure 6. This was combined with a T1H-EBC100. The EBC100 acts as a remote base and enables the T1HE to control modules remotely over Ethernet. This was utilized so that a remote pod of modules could be placed closer to the turntable and inspection area. The T1HE and EBC100 were both connected via CAT5 through a network switch. This created a private network that both devices could communicate over. While setting up the network there was extensive difficulty connecting to the EBC100. This stemmed from the EBC100 being configured on a different subnet than the T1HE. In order to resolve this the network was set up without a DHCP server so that every device would have a static IP. The EBC100 was then reconfigured with a new IP within the correct subnet. This resolved the communication troubles between the T1HE and EBC100. In addition, the IRC5 was configured to share a subnet with the T1HE and the EBC100. This created a network where both the PLC and the ABB controller could communicate.

The EBC100 was set up with a CTRIO module as well and a 16 channel digital input and a 16 channel digital output module. These would be all of the modules needed to operate the system as a whole. Although the PLC and IRC5 were capable of communicating over the network it was determined that due to the extremely limited and simple information that needed to be passed back and forth using digital inputs and outputs would be sufficient.

Fig. 6. Do-More PLC

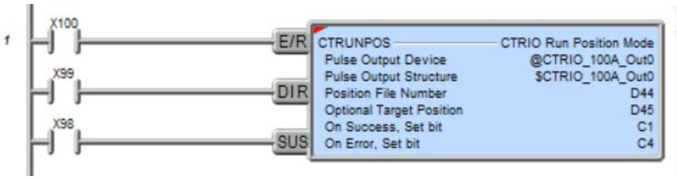
2) *Ladder Logic:*

The PLC was the backbone of the system and was programed to react to simulated inputs from computer vision. This was done so that the system could be tested without the vision system being completed.

The first challenge was to get the PLC to rotate each blisk from one blade to the next. As stated above, this will be done using the CTRIO module. The module was configured to operate one of its two channels as a stepper driver. The second channel was unused. In addition, it was configured to be a step and direction control. The alternative control method was clockwise and counterclockwise where one pin is used to step clockwise and another pin is used to step counter clockwise. There was no significant advantage of one control method over the other. Step and direction was selected because it was the default setting for the stepper driver. Next the pulse curves were programed as will be discussed in the stepper driver section. A separate pulse curve was defined for each stage due to the spacing between blades being different.

Originally the motor was to be driven by the CTAXDYNP block. In order to utilize this the motor needed to be configured in a CTAXFG block. The configuration block allows the maximum and minimum steps per second to be set. This equates to setting the maximum and minimum rotational speed of the blisk. In addition, the configuration allows you to set maximum acceleration and deceleration values. Once the configuration is set the CTAXDYNP block can be used to update the set position of the blisk. From here the stepper motor will be driven within the specified constraints to the desired position. This had the advantage of no control curves needing to be defined. The lack of pulse curves simplifies adding new blisk stages making it easier to expand the system. However, after further reading into the Do-More documentation these blocks are only available with the CTRIO2 module. The module that the group had access to was only the CTRIO.

Due to this compatibility issue a secondary approach had to be used. This came in the form of using the CTRUNPOS block. This did not provide the dynamic speed changing functionality of the previous approach. With this approach the configuration happens within the move block. The configuration of frequency curves must be predefined as discussed in the stepper driver control section. These curves can be switched between using an internal variable defined within the block. Predefining curves still allows you to specify the acceleration values, however, they must be defined using run up time and run down time. This means that if you have a goal acceleration you must calculate the slope of the run up and run down sections. This makes adding additional blisks slightly more involved but it is the only way to drive the stepper with the CTRIO module.



CTRUNPOS —— CTRIO Run Position Mode
Pulse Output Device @CTRIO_100A_Out0
Pulse Output Structure $CTRIO_100A_Out0
Position File Number D44
Optional Target Position D45
On Success, Set bit C1
On Error, Set bit C4

Fig. 7. CTRUNPOS Implementation

The CTRUNPOS block has 3 inputs that control its function. E/R that starts the rotation, DIR that selects the direction of rotation, and SUS that acts to pause the rotation. The implementation of this block is shown in Figure 7 Once the rotation is complete it changes a bit in the internal memory. In addition, inside the block you can select a position file. This file is what holds the rotation profile. The way the block was implemented was with E/R tied to a digital input from the ABB robot. This pin was brought high in the RAPID code once the robot arm was clear of the blisk and ready for it to be rotated. Direction was tied to an unallocated input. This was not used in the current implementation but was left available in case the computer vision group wanted to be able to recheck a past fillet. SUS was also tied to an unallocated pin. This would be implemented with an emergency stop in the software. Once tied to an emergency stop this would ensure that if an emergency stop is hit the blisk will stop rotating. Once the emergency stop is reset the blisk will continue to rotate to the proper position.

MATH —— Calculate Expression
stepsToRotate
Result D0
Expression 1000

MATH —— Calculate Expression
numBlades
Result D3
Expression 40

MATH —— Calculate Expression
stepsToRotate
Result D0
Expression 2000

MATH —— Calculate Expression
numBlades
Result D3
Expression 40

Fig. 8. Setting of the stage number variable

The position file number was controlled by a variable within the PLC. This variable was set based on input from the computer vision software, as shown in Figure 8. The input was configured to be a 2 bit selector that choose from one of the four possible stages. Once the blisk is successfully rotated a digital output is raised to the ABB robot signaling the blisk is stationary and it is safe to resume inspection. In addition, when a rotation is complete the PLC increments a counter. This allows it to compare the number of inspected blades to the number of blades on each stage. It is likely that the counting responsibility will be given to the vision system but at this time the PLC was used.

D. Turntable

The current turntable was able to successfully rotate the blisk from one blade to the next. The next step that was taken was measuring error in each root fillet location when the blisk was rotated from one blade to the next. This was done by mounting a dial gauge on the turntable base and measuring the location of the root fillet in the z and x-axes while rotating the blisk through several rotations. By taking the difference between the maximum and minimum measured values the tolerance for the root fillet was calculated to be ±3mm in all 3 axes. This was within the specifications needed by the system so a redesign of the turntable was deemed unnecessary. However, after further discussion about the overall system and looking at the necessary paths to inspect each root fillet, it was determined that the best way to simplify pathing would be to mount the blisk vertically. The advantages of this will be discussed further in the pathing section. The current design of the turntable utilized a ”Lazy Susan” bearing. These bearings are not designed to operate under any radial load. This was an issue because when the fixture was rotated the blisk acted as a purely radial load. This meant that despite the turntable having adequate precision the bearing assembly would have to be redesigned in order to function properly. This redesign was determined to be outside of the scope of this project. After consulting with the other team it was decided that the same stepper motor would be used with the redesigned bearings.

Fig. 9. GE Aviation blisk holder

The blisk is mounted to the turntable with a GE Aviation provided holder. This holder, shown in Figure 9, is made of a plastic material and is capable of holding all of the blisks in the LEAP series. The blisks are mounted by screwing in the blue top piece. This clamps on the center hub of the blisk. This holder is mounted on an aluminum plate that is rotated by a stepper motor driven rubber belt.

The only change made to the turntable was how the stepper motor was driven. The existing Pololu driver was perfectly matched for the stepper and did an excellent job controlling the stepper. However, much like the raspberry pi it was not an industrial solution and would likely need to be redesigned in order to function in a factory environment. There were two possible solutions to make the turntable more industrial.

The first was to re-engineer the existing hardware into a more industrial package. Industrial digital IO traditional functions at 24V as opposed to the pololu driver which was 5 volt logic. In order to resolve this we could have kept the same pololu driver and placed it in a more robust enclosure located on the turntable base plate. From here it the turntable would have had to be converted into a completely independent fixture. This would have included adding level shifters to convert the incoming 24v signals to 5v and the outgoing 5v status signals to 24v. As well as adding a transformer to take 120V AC and convert it to DC in order to power the stepper and driver.

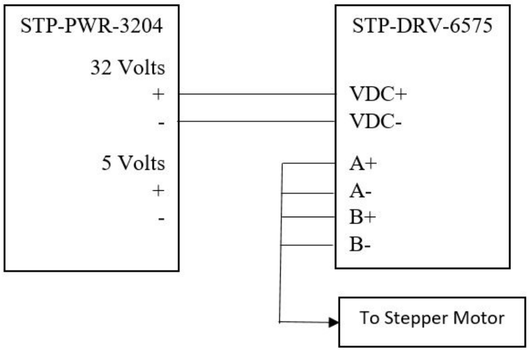


Fig. 10. Stepper Driver Power Circuit

The second solution, and the one that was used, was to replace the driver with an industrial stepper driver and power supply. This was determine to be the ideal solution because it would create a more professional and robust system. At the same time changing to an industrial solution was not a significant cost increase over the hardware currently being used. The driver that was ultimately selected was an Automation Direct STP-DRV-6575 Stepper Driver, shown in Figure 11. This was paired with an Automation Direct STP-PWR-3204 Power Supply. Both of these units are industrial grade and extremely robust. The power wiring digram for the driver is shown in Figure 10.

1) Stepper Driver: The driver was selected due to its direct compatibility with the Do-More PLC as well as its compatibility with the existing motor. The driver accepted control input voltages from 5-24 VDC. This meant there was no need for level shifters and integration into the system would be smooth. Further, the driver included optically isolated inputs and outputs making it extremely resistant to IO noise commonly found in industrial environments. At the same time optical isolation completely separates the motor driving circuit from the input circuits. The drive is capable of an output of between 1.0 and 7.5 A/phase. This output is configurable through a series of DIP switches on the driver. These select which Automation Direct motor is being driven. In addition, you can select the percentage of max current that you want to cap the driver at. Despite the drive not having a setting for the existing Pololu motor, the motor was satisfactory for the systems needs. As a result it was determined that buying an Automation Direct motor was unnecessary. In order to properly drive the motor a combination of motor options and max Amp settings needed to be determined that most closely matched the Pololu motor. The existing motor was rated at 2.8 A/phase which was exactly the same as one of the options on the Automation Direct drive. When micro-stepping a motor, it is recommended to run the motor at 120% of the rated A/phase. This was again a setting built into the drive. From here the drive was configured to provide approximately 3.3 A/phase to the motor. In addition, the driver is capable of micro stepping at up to 20,000 steps per revolution compared to the polulu's 3,200 steps per revolution maximum. In order to make the turntable as precise as possible the drive was set to the maximum micro-stepping setting. The maximum linear error was calculated for both the top stage, 39 blades, and the bottom stage, 49 blades, as shown in Equation 1. The delta theta of the blisk for each motor tick was found by multiplying the delta theta per tick of the motor by the gear ratio of the turntable's belt. These calculation show a maximum linear error of 0.000057 inches. This is roughly 10 times more accurate than the previous turntable motor driver.

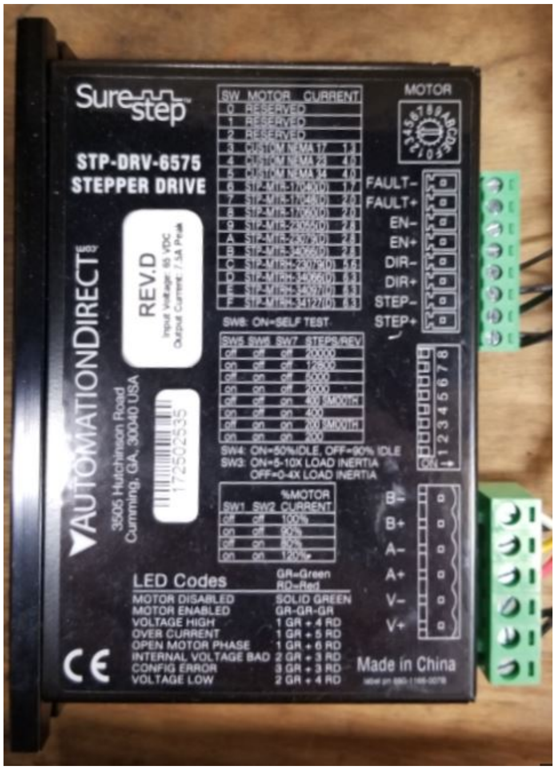


Fig. 11. Stepper Driver

$$
\begin{aligned}
\Theta_{step} &= \frac{360}{20,000} * \frac{1.5}{15} = 0.0018 \\
\Theta_{BladeTop} &= \frac{360}{39} = 9.23 \\
\Theta_{BladeBottom} &= \frac{360}{49} = 7.35 \\
Error_{AngularTop} &= MOD(\theta_{blade}, \theta_{step}) = 0.000369 \\
Error_{AngularBottom} &= 0.00138 \\
Error_{LinearBottom} &= \frac{0.00138}{360} \times 15.1 = .000057\text{''}
\end{aligned}
\tag{1}
$$

The power supply selected was an Automation Direct STP-PWR-3204. This was selected as it was the recommended power supply for the drive that was used. It provided both a 32 Volt output and a 5 Volt output and could be powered with either 120 or 240 volts AC. The power supply was configured to operate on 120 volts AC for this application.

2) Stepper Driver Control: The driver was controlled by a T1H-CTRIO module on the Do-More PLC. This module is a high-speed pulse combo module. The PLC as a whole is not designed for extremely fast and precisely timed output pulses. The driver is controlled by two input signals. One of the signals indicates to step the motor and the second input designates the direction for the motor to step. Due to this, two output pulses would have to be sent at precisely the same time and be cycled on and off at a very high rate. A normal digital output module of the PLC is not capable of this high cycle rate functionality. The CTRIO is designed to fill this purpose. The CTRIO acts as an independent processor and is programed with frequency curves. The CTRIO then executes the action based on a single bit change in the main PLC. The CTRIO module is configured within the Do-More software. It has a setting specifically to configure the CTRIO to drive steppers. This setting enables the use of a block in the software that would step the motor a specified number of steps as discussed above. The wiring diagram for the the system is shown in Figure 12.

The number of steps needed to rotate between blades for both the bottom and top stage of the two stage blisk was calculated as shown in Equation 2. From here a frequency curve was defined for both the top and bottom blades. This insured that the drive did not try to take the blisk from stationary to rotating at full speed instantaneously. These curves are shown in Figure 13.

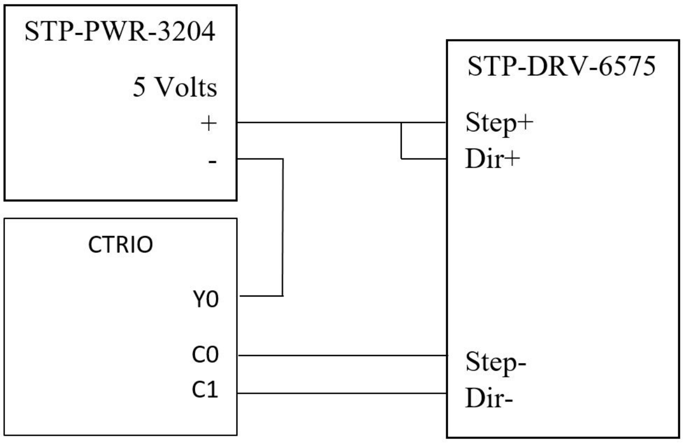
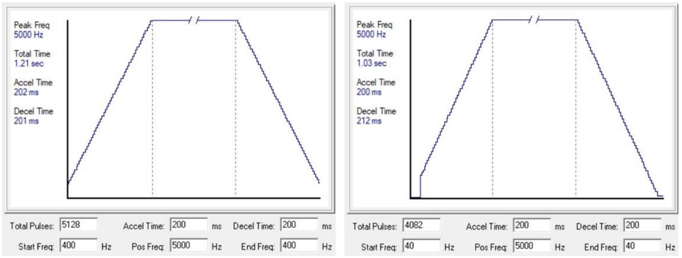


Fig. 12. Control Circuit Diagram



Total Pulses: 5128 Accel Time: 200 ms Decel Time: 200 ms
Start Freq: 400 Hz Pos Freq: 5000 Hz End Freq: 400 Hz

Total Pulses: 4082 Accel Time: 200 ms Decel Time: 200 ms
Start Freq: 40 Hz Pos Freq: 5000 Hz End Freq: 40 Hz

Fig. 13. Stepper Pulse Curves

$$\begin{aligned} \frac{20,000}{\text{num blades}} * 10 &= \text{Number of Steps Per Blade} \\ \frac{20,000}{39} * 10 &\approx 5,128\text{Steps} \\ \frac{20,000}{49} * 10 &\approx 4,082\text{Steps} \end{aligned} \tag{2}$$

E. End of Arm Tooling (EOAT)

The existing EOAT was analyzed closely and it was clear that it would not be adequate for inspection. The overall quality of manufacturing was below the standards necessary for repeatable tip locations. Some testing with the EOAT showed that there was quite a bit of slop in the system and that the compliance implemented was not stiff enough to support the weight of the tooling. This lead to both sagging and the tip of the EOAT moving independently of the base. These two errors compounded on each other leading to unacceptable repeatability for EOAT tip position. In addition, the EOAT was very bulky making it difficult to fit it between the blades on certain blisks. The final issue was that the EOAT was designed to path perpendicular to the fillet. This attack angle led to the EOAT skipping along the fillet as opposed to sliding smoothly. The skipping caused pictures to be captured by the camera where there were zero points of contact between the ball and the fillet—a condition that should never be the case.

To resolve this it was determined that a complete redesign of the EOAT would be ideal. The specifications that were determined to be critical were: positive retention of the ball gauge, compliance perpendicular to the root fillet of at least 3mm, adequate lighting the ball, EOAT tip error of less than 0.1mm, ability to slide along the fillet without skipping, and changing between maximum and minimum balls in less than a minute.

Fig. 14. Redesigned end of arm tooling

1) Gauge Ball Switching: The first challenge tackled was the ability to switch between maximum and minimum balls. The existing mechanism utilized a micro-servo. This was a large source of error because the servo could not reliably hold the ball gauge in place. It was determined that positive retention of the ball gauge was a critical to reliable tip location. This would ensure that the ball is fully actuated and in the proper position for inspecting the root fillet. The first solution considered was to add positive retention to the existing mechanism. With the failure of the electromagnet setup last year two other solutions were considered. The first was adding a second actuator to lock the ball into place.

However, this was not seen as ideal due to the added bulk and additional point of potential failure for the system. The next solution considered was a single pneumatic actuator. This would have the ability to hold the ball in place under constant pressure without any wear on an electric motor. This was considered a strong option. The downfalls that were noted included that it would require addition bulk to mount the pneumatic piston. In addition, it would lead to the the ball assembly being difficult to change out for a different stage's ball set. Instead the balls would have to be pulled out of the assembly and replaced independently. This greatly increases the chances that balls could be mixed up and by changing balls individually you introduce an additional cause of error.

2) Tool Changer: From this it was determined that a different approach would likely be a more successful solution than modifying the existing mechanism. The method of switching ball gauges that was used in the final iteration was an ATI QC-11 industrial robotic tool changer, shown in Figure 15. The tool changer was seen as the ideal solution because it would allow any number of ball gauges to be substituted in and out in the same amount of time. This meant that any blisk stage could be inspected without any additional set up time to switch between ball sets. This was particularly advantageous on the two stage blisk as both stages could be inspected one after the other without any intervention from the operator. To achieve this the system has to automatically switch between four different ball gauges. For the entire LEAP series there are 4 stages. This means that in total 8 tool side plates would be required to inspect all of the blisks. In addition, using a commercially available tool changer provided virtually perfect repeatability. The QC-11 tool changer that was used in the final product has 0.0102mm repeatability in the X Y and Z directions. This accuracy would greatly aid in programing the paths for the robot as the EOAT tip would be closer to where it was theoretically located. The tool changer was also purchased with an 8 bit electrical pass through. This would allow power to be passed through to the LEDs mounted on each ball gauge despite the EOT being changed out. The QC-11 is the smallest tool changer in the ATI lineup and was more than capable of the loads experienced in our application. The suggested payload limit is 35 lbs and the locking force is 240 lbs. This was significantly more than what was necessary in this application.

Before purchasing the tool changer the concept of engineering a tool changer from scratch was discussed. This had the advantage of saving the large expense associated with purchasing a commercial tool changer. However, it was unlikely that a tool changer built from scratch would come close to the repeatability of the ATI solution. Due to the need for as high precision as possible a commercial tool changer was seen as the ideal choice.

Actuation of the tool changer was accomplished with a pneumatic solenoid. This solenoid would switch the 80 PSI shop air between two pneumatic lines. The solenoid was mounted on the elbow of the ABB robot and was actuated by a digital output from the IRC5. These lines were connected to the lock and unlock ports on the tool changer using quick disconnect M5 pneumatic fittings.

Fig. 15. QC-11 tool changer

In order to interface with the tool plate of the QC-11 a piece was designed such that it had the same bolt pattern with 4 holes for M5 bolts to pass through. In addition, on the mating side of the custom tool a reference pin was machined, this is shown in Figure 16. This was machined on a lathe and test fit into the tool changer in between passes. This insured that the pin fit as perfectly as possible into the tool changer. This pin was absolutely vital to the function of the EOAT as it ensured that the center of the gauge ball was perfectly in line with the center of the tool changer.

One challenge created by this pin was that the radius on the cutting tool used to machine the pin left a fillet between the pin and flat mounting surface. This prevented the EOAT from sitting perfectly flush onto the tool changer. In order to remedy this the pin was machined narrower for the few thou leading up to where the pin met the mounting surface. This insured that the two mounting surfaces were referencing on each other. Once the tooling was mounted to the tool changer the entire assembly was rotated by hand in the lathe. While rotating, a dial indicator was used to measure the run out of the full system. This measurement would be the true indicator of how accurate the EOAT would be. After rotating through several turns the total run out was found to be less than 0.025mm. This was well within the specified ±0.1mm.

The lead time on the tool changer was 3-4 weeks so in order to get a jump start on pathing, a temporary tool changer was machined. This allowed the EOAT to be mounted to the end of the ABB robot before the tool changer had arrived. This temporary mounting solution utilized an existing interface plate that was made for undergraduate courses. The temporary plate was machined on a lathe to bring the surface finish back to perfectly true. A center hole was then bored. This hole was intentionally machined slightly larger than the tool changer specification. This meant that the pin on the EOAT could be machined a little bigger and once the tool changer arrived the pin could be slowly machined down to a perfect fit into the tool changer.

3) Compliance: The next key challenges were compliance and sliding smoothly along the fillet. Compliance was another aspect of the previous design that lead to large repeatability issues. In order to combat these two issues, the attack angle of ball gauge was changed. Rather than a perpendicular approach angle, an angle of 20 degrees was used. In addition, the

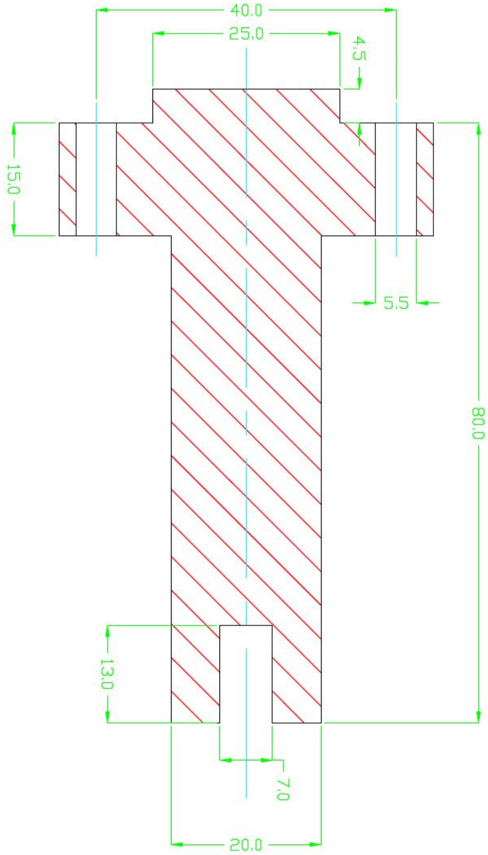


Fig. 16. Cross section of EOAT

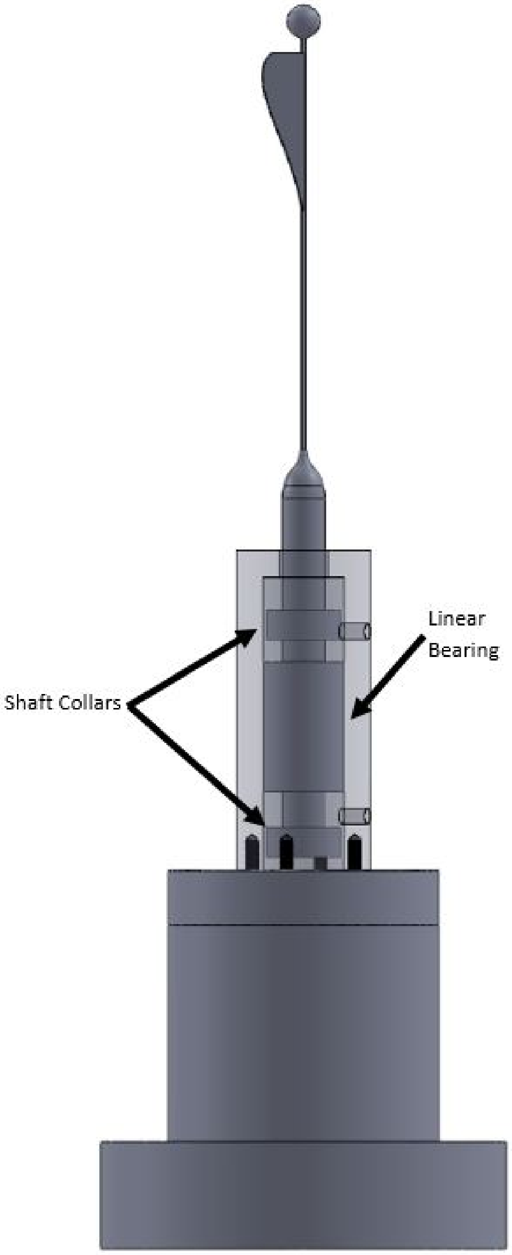


Fig. 17. Z-compliance mechanism first revision EOAT

compliance was moved much closer to the ball. The first iteration included x and y compliance as well as z-axis compliance.

Z-axis compliance was accomplished by the mechanism pictured in Figure 17. The mechanism was designed to enable easy changes in both the stiffness of the compliance and the amount of compliance. This was accomplished using two shaft collars on a precision ground shaft. The shaft passed through an LM8UU linear bearing. Utilizing a precision ground shaft and matching linear bearing would eliminate the sagging and shaking that resulted from the previous EOAT's Z-axis compliance design. The linear bearings are designed to fit the 8mm shaft perfectly. Utilizing movable shaft collars meant that the distance between the fully extended position and the fully compressed position could be changed. In addition, the mechanism could easily be opened and the spring replaced with a spring of different stiffness. The ease of changing compliance was an important consideration as real world testing was thought to be the best way to establish ideal compliance. This easily changed compliance allowed for testing different compliance setups without re-manufacturing an entire EOAT. The compliance was designed so that the ball would be at its maximum length when no forces were acting on it. This prevented the ball from getting caught on the fillet as it was sliding along the fillet and extending further than its rest state. After preliminary testing dragging gauge balls along the root fillets it was found that z-axis compliance would not be necessary with the new, shallow, angle of attack. The removal of this compliance also simplified the EOAT removing another possible source of error.

The X and Y axis compliance is accomplished using the elastic deflection of the gauge ball stem. The compliance in the XY plane, as stated earlier, needed to be roughly 3 mm in both the x and y directions. In order to accomplish this with the given setup the elastic deflection of the cylindrical cantilever beam was calculated, as shown in Equation 3. From this it was decided the the ideal length for the beam would be roughly 6 inches. This calculation assumed a load of 0.5 pounds of force perpendicular to the shaft, the ideal operating load for the EOAT. This would allow for the proper deflection under the working load. In addition, this ensured we were well within the elastic deflection of the stem and permanent bending of the shaft would be unlikely. This compliance was not localized to one axis as in previous designs. Due to the bending properties of the cylindrical shafts any force acting perpendicular to the shaft would have equal resistance regardless of the side. This was a distinct advantage because it allowed the rotation of the EOAT relative to the root fillet to not impact the compliance. This helped the gauge ball slide more reliably into the fillet. Also, the location of the EOAT tip relative to the root fillet was less important because the ball could make contact with the blade or the hub and still locate into the fillet. This simplified path generation for the ABB robot. The ball gauges were press fit into a precision reamed hole. The press fit was machined tight enough such that no addition retention was needed prevent rotation or translation of the ball gauge. When press fitting the ball gauge into the holder it is critical that the LEDs be orientated with one over each of the center pneumatic passthroughs. This orientation ensure that the LEDs locate properly in the fillets when pathing. This was preferred because using a mounting technique such as a set screw would have made it much more difficult to ensure the ball gauge was mounted perfectly centeredf.

$$
\begin{gathered}
\sigma_B = \frac{F_a * L^3}{3 * E * I} \\
\\
\sigma_B = \text{Maximum Deflection} \\
F_a = \text{Force at EOAT Tip} = 2.22 \text{ N} \\
L = \text{Length of Beam} = 0.1524 \text{ m} \\
I = \text{Moment of Inertia} = \frac{\pi * r^4}{4} = 3.976{\times}10^{-12} \text{ m}^4 \\
E = \text{Young's Modulus} = 200{\times}10^9 \text{ Pa} \\
\\
\sigma_B = \frac{2.22 * 0.1524^3}{3 * 200{\times}10^9 * 3.976{\times}10^{-12}} = 3.29\text{mm}
\end{gathered}
\tag{3}
$$

4) Illumination Of The Ball: The next choice was how to light the ball. With the change in attack angle the location of the LED relative to the ball needed to change as well. The first step was to test the gauge balls with different LED locations and orientations. In order to complete these tests a gauge ball was mounted to the end of a 3D printed shaft. This assembly was dragged along the fillet, by hand, with the LED in various orientations and mounted with different means. The light pattern formed by the ball was recorded with a fixed web-cam. Results from this test found, as shown in Figure 18, that the best location for the LED was mounted directly on the stem parallel to the stem. Further, the best mounting approach was to affix the LED to the shaft by encircling both the shaft and the led with opaque tape. The tape acted to focus the light on just the gauge ball. This reduced the amount of light reflecting off nearby surfaces and created a much clearer image for the camera. The changed LED orientation and location led to a much lower profile design than when the LED was mounted on a separate stalk. Although a fixed web-cam was used to ensure good image quality camera location is outside the scope of this project. However, due to camera positioning having a large impact on the LED mounting collaboration with the second blisk inspection team was critical.

Fig. 18. Preliminary Computer Vision Results

Due to preliminary designs from the computer vision group, it was determined that the EOAT should be able to inspect both the fore and aft root fillet of each blade, without rotating the EOAT about its z-axis. This was due to a possible camera mount that would crash into the blisk hub if the EOAT was rotated 180 degrees to inspect the aft fillet. As a result it was determined that two LEDs would be needed. The LEDs would be mounted opposite of each other. One would be mounted on top and the other on the bottom of the gauge ball stem. When the EOAT was being used to inspect a fillet only the LED between the fillet and the stem would be illuminated. An additional advantage of this approach is that the shaft would be bent in alternating directions. This should further ensure that the shaft is not permanently bent in one direction or the other.

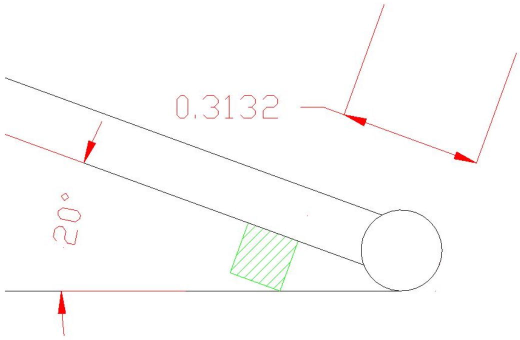


Fig. 19. LED location CAD drawing

One set back that mounting the LED in-line with the ball shaft lead to was that the LED needed to be completely occluded by the stem. This is critical because it insures that the camera sees only the light passing between the ball and the fillet. In order to accomplish this and cut down on light bleeding around the ball a 3 mm LED with a 30 degree light spread was selected. In addition, a through hole LED was determined to be the best option for this application. The through hole design provided a format where the electrical connections were already directed in the exact opposite direction of the illumination. This meant that there would be no additional bulk from soldering a surface mount led to a board and running the leads down the shaft. The gauge ball shaft was selected to be 3 mm. This matched the size of the selected led and provided the compliance required as noted above. Another key design consideration was that the LED could not contact the fillet during inspection. Figure 19 shows how the the distance from the tip of the end effector to the LED was determined. In the diagram the LED is shown with the green hatch and the stem is shown at a 20 degree angle to the fillet. At this distance the LED would not make contact with the fillet when inspecting at the 20 degree angle of attack. In order to insure there was no contact the actual mounting location was moved further from the tip. In addition, at this distance the light pattern would spread between the fillet and the ball.

5) Ball Gauges: The sizes of the ball gauges are determined by GE Aviation's standards for each blisk series. For this project the four ball gauges needed to inspect both stages of the two stage blisk were purchased. The balls that were purchased came on stems with a diameter and length that were specified to be 3mm and 6in respectively. These dimensions were determined by the compliance requirements for the EOAT. Both the balls and the stems were made from hardened stainless steel. The diameter of the balls had a tolerance of +.0001in and the roundness was out by at most 25 millionths of an inch. Due to a significant lead time the correct ball gauges were not available in time for testing. However, last years group had purchased ball gauges from the same supplier. These were used as stand ins for the correct balls.

F. Tool Holder

With the addition of the tool changer to the system came the need for a tool holder. This holder needed to be able to hold each EOAT accurately within the maximum coupling offsets for the QC-11. These were specified as ± 0.039 inches in the X and Y directions, a cocking offset of ± 0.8 degrees about X and Y axes, and a twisting offset of ± 2 degrees. The definition of each of these specifications is shown in Figure 20. This meant that the tool holder would have to have positive rotational retention of the tooling as well as retention in the X and Y directions.

The first key choice was what orientation to mount the tools in. It was decided to mount the tools vertically as this allows the weight of the tooling to help pull the tool out of the tool changer. The next design challenge was how to retain the tool accurately. The final EOAT design had 4 exposed end cap bolts on a flat surface. It was determined that utilizing the bolt heads along with the shaft of the EOAT would be the ideal way to retain the tools. When placed on the shelf the tool's center of gravity is directly over furthest extent of the shelf. This meant that theoretically the tool would balance perfectly. Despite this the localizing holes helped ensure that the tool is not able to slide off of the shelf. A prototype holder was manufactured out of plywood and is shown in Figure 21. These pieces were manufactured using a laser cutter. Each piece was manufactured to slide in to one another to eliminate the need for any mounting hardware. The first revision of the holder was very successful in retaining the tools within specification while allowing the robot to easily mount and dismount tools. However, there was interference with the ball gauge and the stabilizing feet of the fixture. The interference did not prevent the tool from being held in the fixture but it did lead to slight deflection of the ball gauge. This was resolved by lowering the height of the front feet and moving the tools holders so that the ball gauges would hang in between the feet as opposed to directly over top of them. The final tool holder would be laser cut out of acrylic and the size of each tool would be engraved above each holder. This would ensure that when an operator was loading tools into the holder that each tool was in the correct location.

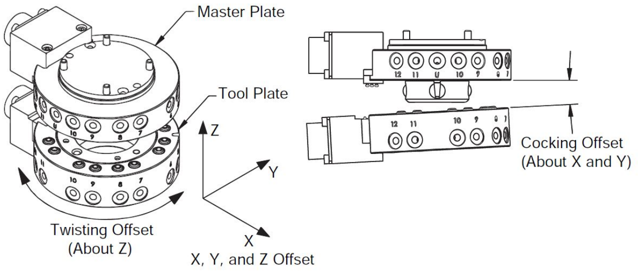


Fig. 20. Tool changer coupling specification definitions from QC-11 documentation provided by ATI

Using a fully machined aluminum fixture was considered, as was interlocking extruded aluminum. The commercial solutions provided by ATI are made of extruded aluminum. However, these were determined to be extremely over engineered for the weight of the EOAT. Aluminum had no significant advantages over the acrylic. Further, aluminum would have been more expensive to procure and would have been much more involved to machine. Acrylic was extremely quick and easy to laser cut while at the same time maintaining excellent tolerances. After testing the acrylic fixture it was found to be plenty rigid to hold the relatively light tooling and was heavy enough to maintain its position in the workspace.

G. Robot Pathing

Once the EOAT was designed and the ideal approach angle determined the ABB robot was programed to path along each fillet. This was originally started with the blisk in the horizontal position used by both past groups. When this was done with the new approach angles it became clear that the ABB robot would not be able to reach the necessary poses to inspect the bottom stage of the two stage blisk. In order to inspect the lower stage the tooling would have to come in from below the blisk. This was because if the tooling came in from the top it would crash into the upper stage. This left only

Fig. 21. Prototype tool holder with EOAT stored

an approach from below the blisk which was problematic as the poses were out of the robot's work space. This was caused by axis 5 not being able to actuate far enough.

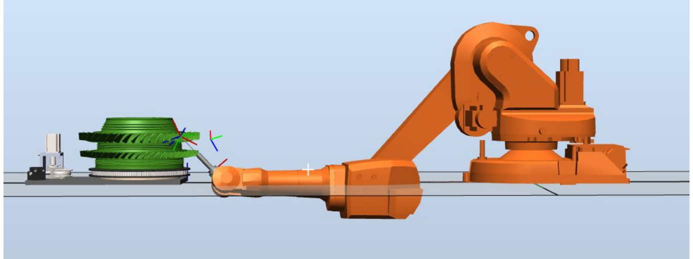


Fig. 22. Robot configuration with turntable at base level

The first attempt to remedy this was to lift the entire fixture vertically up off of the table, as shown in Figure 23. However, even once there was physically room for the tooling to be in position the ABB was only able to reach the poses in an elbow down configuration. In this configuration the elbow joint would have to be below base of the robot. An example of this configuration is shown in Figure 22. This is something the robot is capable of but the mounting configuration had a table at the base of the robot preventing any part of the robot from physically being able to move below the base frame. The only way to resolve this was to continue moving the fixture up vertically until the elbow was no longer below the base frame. This required lifting the fixture a little over a foot and a half above the base frame. The key downside to this solution was that any inaccuracy in the table would be extenuated with every inch that we raised the fixture. With one of the project's main goals being to reduce every possible source of error, mounting a fixture approximately a foot and a half in the air seemed like a poor solution.

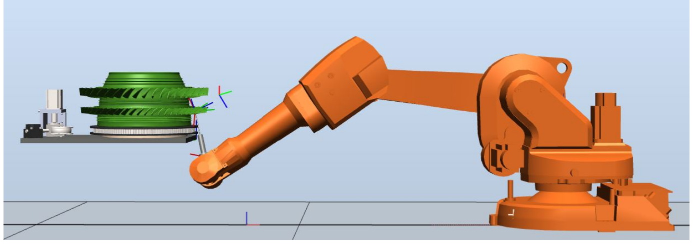


Fig. 23. Robot configuration with turntable raised

Another solution considered was flipping the blisk over after inspecting the top stage. This would mean there would be no interference for the tooling. This was a poor solution because it would eliminate the system's ability to inspect an entire two stage blisk without needing any operator intervention. In addition, the two stage blisk had two center-holes of differing diameters. In order to mount the blisk upside-down the larger center-hole would have to be above the smaller center-hole. This would have required virtually a complete redesign of the mounting mechanism and would complicate the mounting process for operators.

The final solution was to find another orientation for the blisk that allowed the robot to more easily inspect both stages of the two stage blisk. The challenge of the two stage blisk was that there was interference from the top stage when inspecting the lower stage. Therefore, if there were a way to eliminate that interference both stages could be inspected easily. The orientation that was tested first was mounting the blisk perpendicular to the ground and perpendicular to the robot. This allowed the robot to reach both stages without interference from the other. Figure 24 shows the robot configuration while inspecting the lower stage of the two stage blisk. This clearly shows that rotating the fixture creates an easier configuration for the robot and by being closer to the base frame it increases the poses that the robot is capable of reaching.

In order to create the paths along the each root fillet a blisk CAD model, provided by GE, was imported into ABB's RobotStudio software. A work object was then created based on the turn table. This ensured that if the turntable was moved relative to the robot all of the paths would still be accurate. Each path was created by RobotStudio's auto path feature. From here the targets were rotated individually to get the correct approach angle relative to the fillet. In addition, the

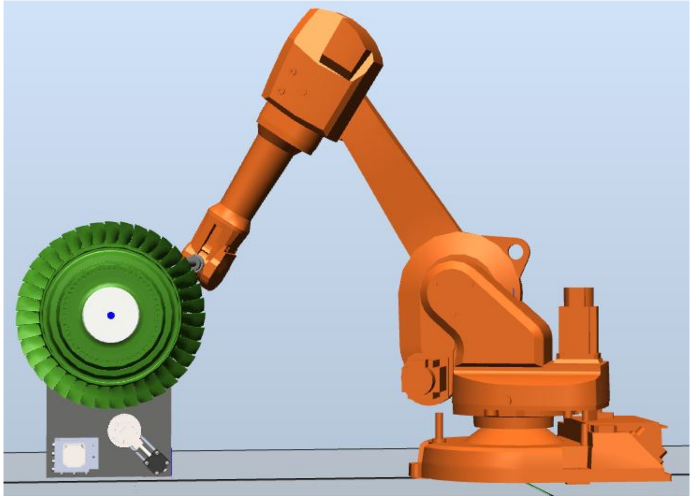


Fig. 24. Robot configuration with turntable rotated

orientation was carefully selected so that the tooling would not come in contact with any other blades. Great care was taken while machining the EOAT so that it could be reliably represented in robot studio.

To get the exact z-offset from the tool head to the tip of the EOAT it was measured on the robot by jogging the EOAT perfectly vertically and moving the tip down until it just touched the base. By using the robot itself to measure the EOAT offset it ensured that the measurement was virtually perfect.

The pathing for the tool changing operation was also created in robot studio. Each tool holder was created as its own work object. This meant that additional tool holders could be added by duplicating the path and associating it with a new work object. When creating the approach path the zone was set to “fine.” This prevented the robot from trying to round corners while approaching the holder. Rounding corners would have lead to the tooling crashing into the fixture as opposed to sliding into the correct holes. In addition, setting the zone to ”fine“ stops the robot from looking ahead. This means that the IRC5 controller would make sure that the robot had completed the current instruction before reading the next instruction. This was important as it prevents the robot from dropping the tool before it is over the holder. When releasing and grabbing the tools consideration was taken to make sure that a collision would not occur between the camera and the fixture.

Once the paths were created digital input and output statements were added to the main program. These were used for the PLC to communicate with the robot.

IV. RESULTS

A. Turntable

The redesign of the turntable for vertical use was outside the scope of the project. This meant that the EOAT needed to be tested without having the blisk properly mounted. A temporary solution was found to prop up the existing turntable in a vertical orientation. This was not a great solution. It was very difficult to get the turntable to be perfectly perpendicular to the table the robot was mounted on and the entire fixture was unstable often shifting and swaying. Another key drawback was that the bearing used by the existing turntable was not designed for such large radial loads. This meant that the stepper was not able to rotate the blisk when it was propped up in a vertical orientation. To work around this the stepper was tested with the turntable horizontal to test the accuracy of the new driver and control system. The rotation was found to be well within the 3 millimeter radial specification. The redesign of the turntable will make likely change these values. However, it does show that the new driver is able to achieve the performance required for inspection.

B. End of Arm Tooling

The end of arm tooling was found to have no measurable inaccuracy in the z axis repeatability and the X and Y axes were only slightly out of spec with a plus or minus position error of 0.25mm after pathing along the same fillet several times. This was suspected to be the due to the stand-in gauge ball shafts. While testing pathing if the ball was deflecting even slightly further than it was supposed to the stem would permanently bend as opposed to returning to straight. This should be eliminated by the specified 3 mm shafts. The new shafts should also reduce this error to within the goal specification of 0.1mm. The tool changer worked exactly as expected and was exceeding successful. The manufactured EOAT mounted precisely into the tool side of the changer. There was no measurable play in the tool changer or the custom EOAT mounted to the tool plate.

The new approach angle on the end of arm tooling was also very successful. It was difficult to get repeatable pathing results due to the lack of a proper vertical turntable. To simulate the vertical turntable, the existing turntable was propped up temporarily. Once upright a work object was defined for the turn table. A single fillet was pathed repeatedly. This helped eliminate the variation caused by the inadequate turn table. In these focused tests the new angle of attack provided smooth sliding of the ball along the fillet. In addition, consistent loading on the ball gauge was seen. It was difficult to insure the ball gauge did not over deflect due to the thinner stems. However, it was clear that with a properly mounted turntable the tooling would be able to path smoothly along the fillets.

C. Tool Holder

The tool holder was very successful. It was manufactured out of plywood pieces that were cut out with the laser cutter. A couple iterations needed to be tested as the laser does have some kerf when cutting. This kerf means that the internal dimensions of the localizing holes were not the diameter that was specified on the drawing. However, after a few test pieces were cut the correct size was found for a perfect fit. The robot was easily able to place tools in the holder and retrieve them. In addition, the robot was able to place the tools without having to contact the holder. This was ideal because it prevents unnecessary wear on the holder and greatly reduces the chance of a small error causing the robot to crash and possibly break the holder. This was accomplished by moving the bolts into their locating holes but not having the tools bottom surface make contact with the holder. After testing placing and picking the tool many times the operation did not fail a single time.

D. Control System

The control system was a very successful part of this project. The Do-More T1HE was configured to communicate with the modules connected to the remote slave over Ethernet. This functioned well and allowed the CTRIO to be placed close to the stepper motor. This simplified wiring and made the overall system more compact. The Do-More was also successfully able to read digital inputs from the ABB controller. This was done by having the ABB controller tell its DIO module to change the status of a pin. That pin was then wired to a digital input module on the PLC. Using this, the robot was able to communicate when it was clear of the blisk and ready for the blisk to be rotated. In addition, the ABB controller was able to receive inputs from the Do-More. This was accomplished by wiring a digital output modules pin on the Do-More to the digital input on the ABB DIO module. This will allow the PLC to signal the ABB when it should start inspecting a fillet and when it is done with a stage.

In addition, the PLC was able to rotate the blisk accurately from one blade to the next while keeping count of the total number of blades that had been inspected. This functioned well and the number of blades per stage was able to be changed based on simulated inputs from the vision software. This was implemented as the user will select the blisk being inspected within the computer vision software. When changing the number of blades per stage another variable was updated that changed the number of steps that the motor should be driven when advancing from one stage to the next. This allowed all of the settings for the system to be controlled by the computer vision software leaving the mounting and removal of blisks as the only non-software interaction.

V. CONCLUSION

The project was successful in completing its main objective which was to design a complete and functional EOAT tooling. In addition, the system infrastructure was improved to be run by robust industrial equipment over hobby grade hardware. This being said, due to the change in turntable orientation a fully functional demonstration of the system was not possible.

A. Future Work

1) End of Arm Tooling: The end of arm tooling was very successful. The only notable areas for improvement would be the mounting of the LEDs and use of the proper gauge balls. Not having the the proper stem thickness made mounting the LEDs more difficult and hindered the repeatability of the EOAT in the X and Y directions. The correct balls are currently on order and will be installed by the other team before continuing work on computer vision. Another way the mounting of the LEDs could be improved is with the use of adhesive shrink wrap tubing. This was the product originally specified in the design but was unavailable at the time of manufacturing.

2) Turntable: The table will need to be redesigned to function properly in the new orientation. This will involve redesigning the bearing system to support the radial load created by the new orientation.

3) Overall System: The key next steps will be the creating the camera mount and implementing the computer vision system. In addition, the creation of a user interface for operators to start and run the inspection will be necessary.

VI. ACKNOWLEDGMENT

I would like to thank Professors Craig Putnam and Ken Stafford for their devotion and invaluable guidance to the project. In addition, I would like to thank the primary contact at GE aviation John Graham.

APPENDIX
TOOL HOLDER CAD DRAWING