Automated Runout Measurement Tool

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1. Executive Summary

This report details the design and implementation of a partially automated measurement tool and process for commutator total indicated run-out and bar-to-bar measurements.

The interfaces between the brushes and commutator in a DC Starter Generator need to be closely controlled. A poorly manufactured interface will result in an unacceptably high rate of brush wear and poor commutation. The commutator needs to have an exceptionally low runout and bar-to-bar around its entire circumference to avoid these problems.

Prior to installation in machinery, all commutators are inspected to assure they meet the design requirements for total indicated run-out and bar-to-bar. The method for measurement varies across the several company locations that the armatures may be inspected at.

The existing methods for measuring total indicated run-out and bar-to-bar on armatures are purely manual and involve the attention of highly skilled labor to operate correctly. The various non-standard methods for measurement are difficult to reproduce between sites. These existing measurement processes are slow, costly, and frequently produce incorrect measurements.

New measurement methods and tools were developed to measure the commutators metrics more effectively. The new method developed provides standardized measurement across all company sites. Additionally, the improved process will result in readings that are more reliable, shorter measurement times, and require less involvement of highly skilled labor. The new measurement method is centered around a partially automated tool that employs an eddy current sensor and linear stages to take precise and repeatable measurements.

This report details the design process involved in creating the new tool and method of measurement. Every step has been reflected in the report from determining the problems of the existing method through manufacture and implementation of the final tool.

2. Introduction

Safran is an international high-technology group, operating in the aircraft propulsion, equipment, space, and defense markets. Within Safran the group there is a subdivision referred to as *Safran Electrical and Power* which focuses on power generation, distribution and use.

A Starter Generator is common aerospace component produced by SAFRAN Electrical and Power. Starter generators are a dual-purpose device found in many aircraft. The device initially behaves as an electric motor used to start an aircraft or APU. After the motor or engine is running under its own power, the starter generator reverses its function and acts as a generator to provide electrical power to the aircraft.

A range of brushed DC starter generators currently in production by Safran Electrical and Power were first produced as early as 1959 and remain popular due to their low cost, light weight, and simple operation. These machines operate at 100 to 550 amperes at 23-30 volts over a wide range of speeds.

The Generators are designed to be as small and light as possible to accommodate the size and weight needs of their aerospace application. This results in the units running at high temperatures, stresses, and speeds compared to their land bound automotive counterparts.

The interface between the commutator and the brushes is critical and must be highly controlled to assure the brushes do not wear at an accelerated rate or form a poor electrical connection. The properties of an ideal commutator are low runout and low bar-to-bar height. A poorly manufactured interface will result in an unacceptable rate of brush wear and poor commutation.

The high importance of the commutators geometry prior to installation results in the need for each individual unit to be inspected before installation. Unfortunately, the existing methods for measuring runout and bar-to-bar height on armatures is purely manual and involves the attention of highly skilled labor to operate correctly. The various non-standard methods for measurement are difficult to reproduce between sites. These existing measurement processes are slow, costly, and frequently produce incorrect results.

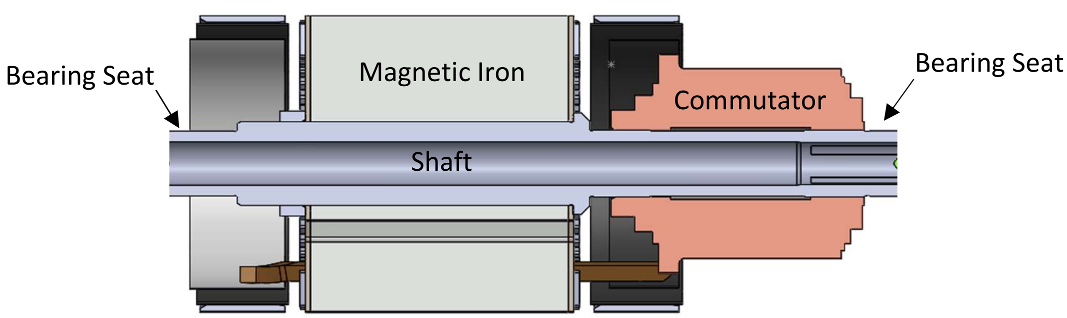


Figure 1. A lateral cross sectioned view of an armature.

There was substantial economic pressure to develop an improved method for measurement. The new method would need to be more consistent, operate quickly, and produce measurements that are more reliable.

The first section of this report is titled “Existing Methods” and covers the methods used by operators prior to the completion of this project. This section will be followed by a section titled “Design Brief” that will outline the specific objectives of the tool. The main body of this report will cover the conceptual, embodiment, and detail design. These sections are titled “Conceptual Design”, “Embodiment Design”, and “Detail Design” respectively. The final major sections of this report are “Discussion” and “Conclusion” which review the lessons learned and assure that the project satisfied the customers original needs.

3. Existing Methods

The existing method used to measure commutators TIR and bar to bar height varies between sites within the company. The exact equipment used at each site was determined independently by each location based on the equipment they had readily available.

A general process is as follows:

1. An armature is placed on a set of V-blocks, knife-edges, or precision rollers.
2. A dial indicator is placed over the commutator above one bar.
3. A dial reading is recorded.
4. The armature is manually turned until the next commutator bar is beneath the dial indicator.
5. Steps three and four are repeated until a measurement has been taken for each commutator bar.
6. A different but unspecified location along the commutator is sometimes selected and steps two through five are repeated.
7. Step six is often repeated multiple times.
8. The collected readings are then processed to determine bar-to-bar and runout.

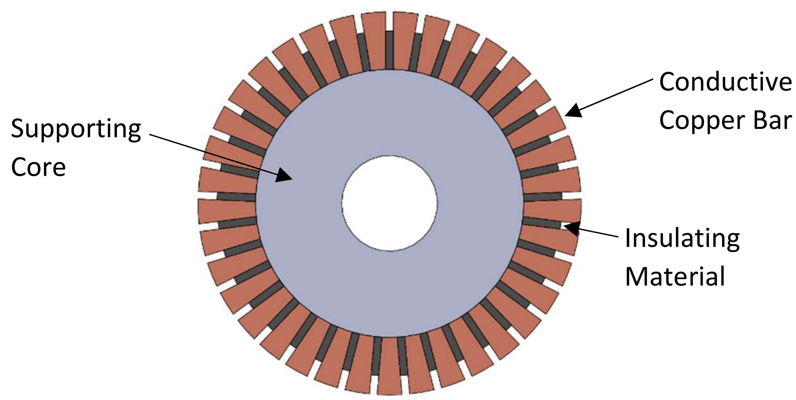


Figure 2. A labeled end-on view of a typical commutator

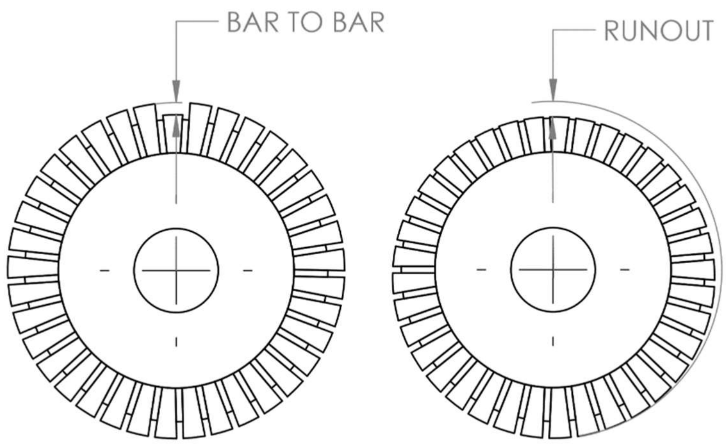


Figure 3. Visualized bar to bar and runout measurements.

DC armatures designed by Safran electrical and power have between 24 and 65 commutator bars. This typically results in more than 100 measurements per armature. Taking such a large quantity of high precision measurements by hand presents two major drawbacks.

- Time consumption.
- poor reliability of measurements.

Firstly, the time needed to make one measurement is multiplied by the total number of measurements that need to be taken. Even a talented operator capable of taking one measurement every three seconds can still spend nearly ten minutes measuring a larger commutator. Production runs of approximately 20 units can completely consume the resources of a talented operator for more than three hours.

Secondly, with such a high volume of human driven measurements the chances of an error resulting in an incorrect rejection or incorrect acceptance are problematically high. The existing methods also introduce error through the setup used. Anything from a loose indicator stand to dial hysteresis can produce incorrect measurement results.

It has also been discovered that some sites use inadequate or imprecise equipment to take measurements. Instances of unacceptably long mounting arms, dial tips, and low precision indicators have created incorrect results and consequently a high volume of unnecessary rejections.

When a measurement is disputed, it is sent to a different site, often in another country, to be verified. Repeated shipping and re-measuring consumes an immense amount of financial resources. The time it takes to ship parts to so many locations can increase lead times by several months.

4. Design Brief

After consulting with the company, a list of deliverables was created outlining the tools functions. The remainder of this section covers the deliverables and scope of this project generated by those discussions.

The new method should be standard across all sites. As a result, the method will need to be reproducible regardless of other equipment or materials that may or may not be available at every location. As levels of skilled labor and product knowledge also vary between locations, it is desirable that the new method will be reproducible without specially trained operators.

Time consumption is a significant target for improvement. The new method should reduce the time needed to examine an armature to less than half of its original time.

Human error should be mitigated in the new measurement system. This will increase repeatability of the measurement and reliability of the produced data.

Any new tools manufactured should avoid exotic machining processes when possible. The low production volume of tooling will make abnormal features exceedingly costly to manufacture and increase lead times.

Any new tools manufactured should avoid exotic materials. The low production volume of tooling will make specialty materials exceedingly costly to obtain.

All tools developed should be easily repairable to assure they continue to function as they age. Wear surfaces should be easily reworked, and fragile components shall be adequately protected. Standard hardware should be used whenever possible to assure replacements will be readily available in the future should any parts need replacing.

Adjustability can allow one tool to accommodate all existing product as well as future product within the design margins of the tool. A table has been compiled containing critical dimensions of features on all armatures in production. This table indicates that commutators diameters vary by approximately 1.1 inches, shoulder to shoulder distance varies by 2.3 inches, overall diameter varies by 2 inches, and shaft diameters varies by 0.25 inches.

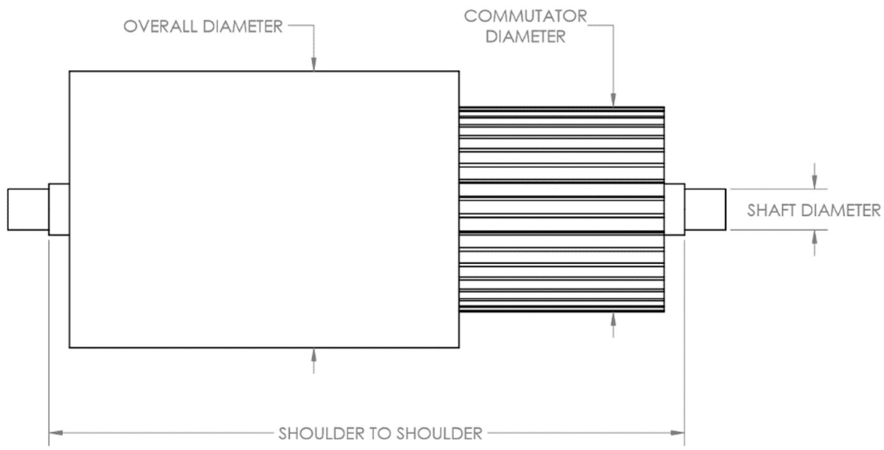


Figure 4. An outline drawing of an armature with labeled critical dimensions.

Precision is tightly controlled on commutators. The drawings specify that total indicated run-out shall be within 0.0005 inches and bar-to-bar should be at most 0.0001 inches. The stricter measurement of one ten thousandths of an inch will set the necessary level of precision for measurement. It is common practice in metrology to be able to measure at least one order of magnitude higher precision than the measurement that is being taken requires. This sets the necessary precision of the measuring method to 0.00001 inches or ten millionths of an inch.

5. Conceptual Design

Primary design goals are reproducibility, ease of use, resistance to operator error, low production cost, low upkeep cost, and measurement precision. These desired properties have placed in a tree diagram and assigned values based on research, brainstorming and consulting with my engineering peers.

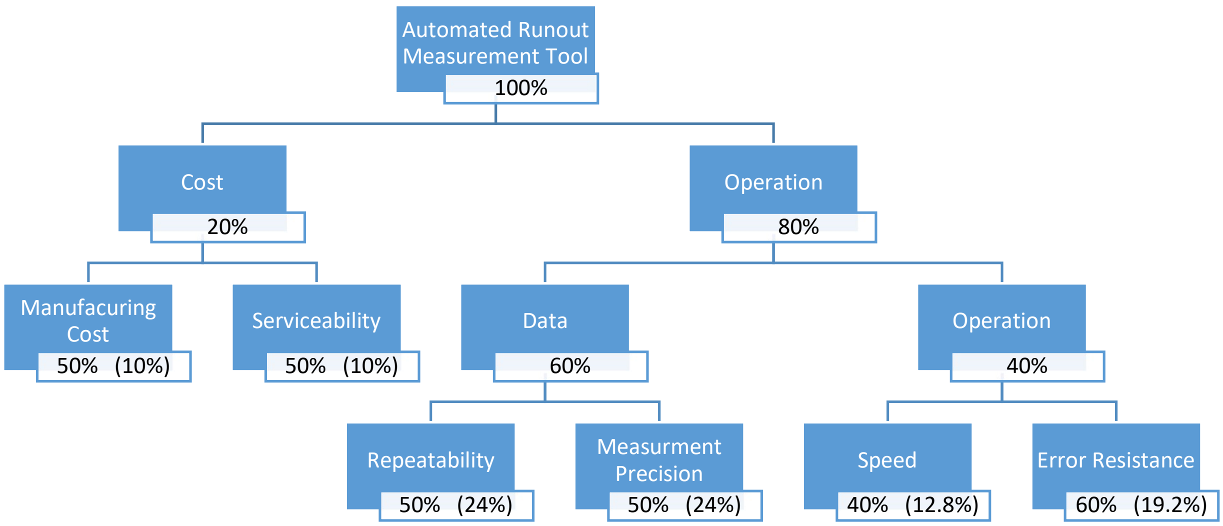


Figure 5. The tree diagram used to weight the objective properties of the tool.

The design problem has been divided into several subassemblies based on function. These functions are armature positioning, measuring device positioning, armature rotating, and the measurement device to be used. Through research, brainstorming and consulting with my peers, a variety of possible solutions were selected for evaluation.

Armature Positioning

- Centers

It is possible to position an assembled armature between a pair of machining centers by taking advantage of the existing centers used to machine the inner shaft.

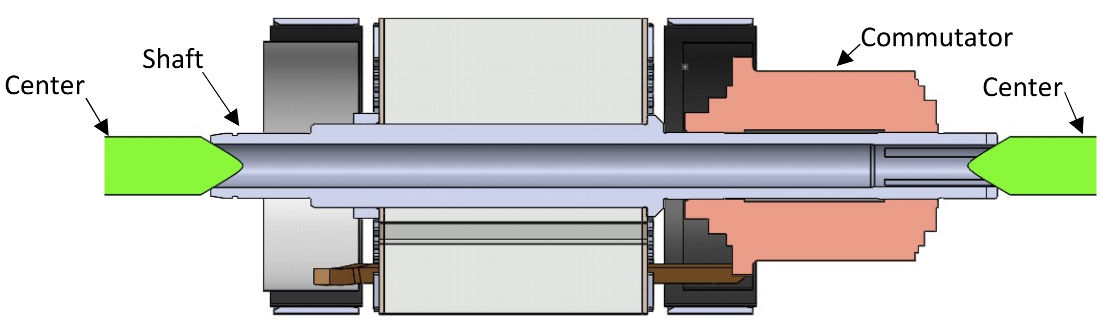


Figure 6. A cross section vie wof an armature in lathe centers.

Positioning each armature between a pair of centers has significant advantages and disadvantages. Centers such as those used in a lathe are readily available, easily replaceable, and highly standardized. These properties lend lathe centers to be long term cost effective. Unfortunately, Due to the methods used to manufacture the armatures, the centers of the shaft may be eccentric to the centers of the bearing journals by several times more than the allowable tolerance of the measurement. It can also be a time consuming and awkward process to load armatures repeatedly on to centers in a manufacturing environment.

- Cams

Armatures can be placed bearing seats of the rotor shaft with cam followers.

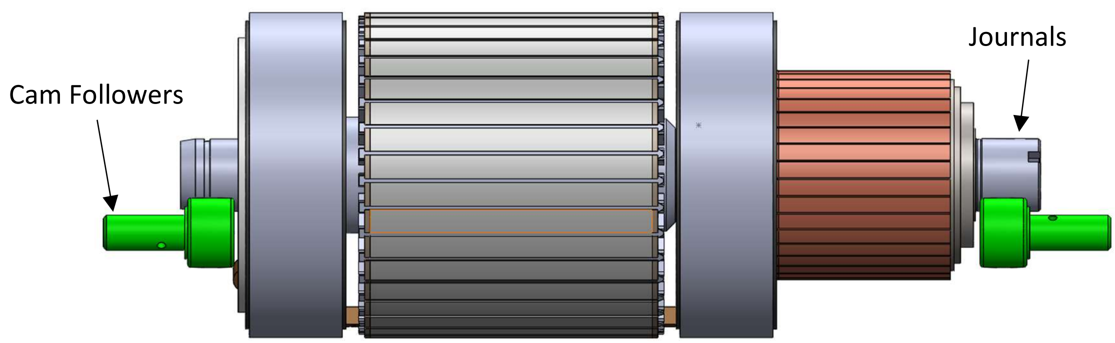


Figure 7. A view of an armature supported by cam followers.

Sitting an armature on cam followers has several advantages. No locking features are necessary allowing the armature to simply be inserted or removed by the operator without additional setup. Additionally, cam followers can run directly on the bearing seats accurately representing the machines behavior in use. Cams are also cheap, easily replaced, and made with precision beyond what is necessary for accurate measurement. The main detractor to cam followers is their maintenance and fragility. They require routine lubrication and can be damaged by significant impacts.

- V-blocks

Armatures can be placed between a pair of V blocks similar to the methods currently being used by some facilities for manual measurement. The armature would sit on the bearing seats of the rotors shaft.

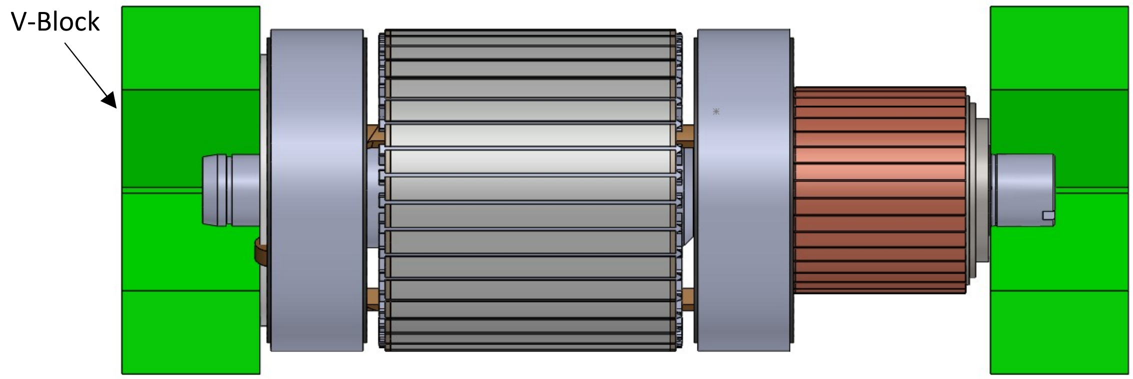


Figure 8. A model of an armature resting in a set of V-blocks

The primary advantages to V-blocks are cost and simplicity. They are moderately difficult to service and require skilled labor to set up and use properly. They offer a high turning resistance, which can introduce errors as stresses are applied to the equipment. To prevent these errors the device would have to either run slower or introduce a lubricant that may contaminate the product.

Armature Rotation

- Manual Rotation

  Rotating the armature by hand requires no special equipment or set up. This makes this method extremely cheap. However, rotating by hand introduces significant room for operator error and variability.

- Journal Drive

  A drive wheel powered by an electric motor could be set on the bearing journal and provide consistent motorized rotation.

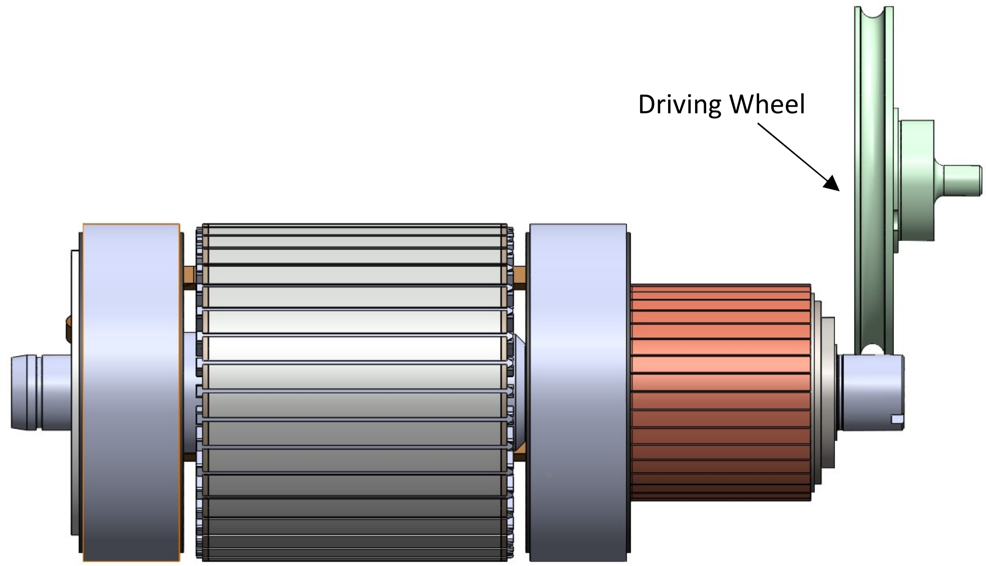


Figure 9. A simplified modelsl of an armature with its journals being contacted by a whelel.

Applying a torque to the bearing journal has several advantages. Firstly, the bearing journal on every armature in a product line is virtually identical, precision ground, and nearly perfectly round. The bearing journals also have consistent positions across all machines. This allows for a drive system that does not need to adjust for the length of the machine. The largest detractors are economic and caused by the manufacture and repair of electric motors, custom parts, and bearings.

- Drive Belt

  A drive belt could be fit over either the bearing seats of the armatures or over the body of the armature.

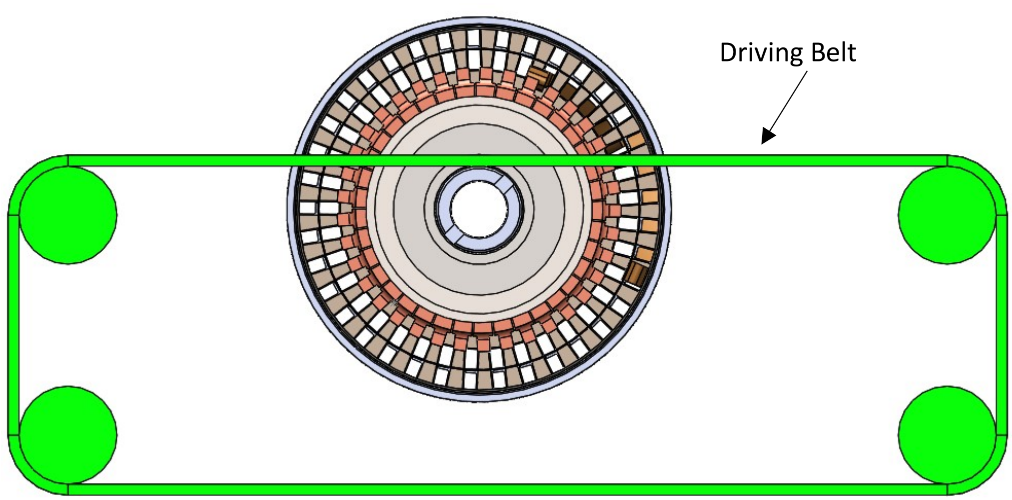


Figure 10. An end-on view of an armature with its bearing journal inc cantact with a moving belt.

A drive belt offers significant adjustability and can accommodate any diameter of rotating machinery. Unfortunately, manufacturing a drive belt system requires a large number of moving parts that can rapidly increase cost when manufacturing and servicing the machine. Exchanging armatures would also require the belt to be pulled out of the way.

Sensor Positioning

- Manual Positioning

  Positioning the sensor by hand requires no special equipment. Unfortunately, the repeatability, and precision of the measurements are entirely dependent on the operators' skill and method. This method is very prone to human error and can be time consuming to obtain a reliable setup.

- Sensor Array

  Several sensors could be permanently installed in a fixed line along the length of the commutator.

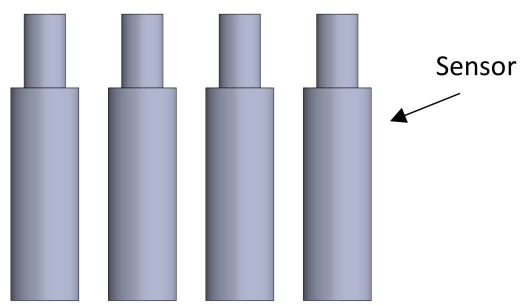


Figure 11. An array of sensors.

  The use of multiple fixed sensors guarantees repeatable, precise, and reliable measurement. This method can be costly due to the use of multiple high precision sensors. It presents a major difficulty to adjustment because the commutators vary in both length and diameter.

- Linear Stages

  Linear stages like those used to position microscope slides could also be used to move a single sensor along the length of a commutator.

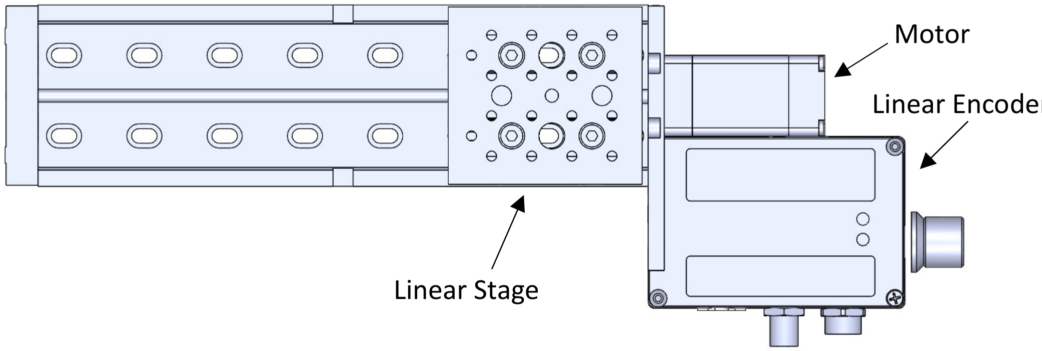


Figure 12. A computer model of a linear stage.

Attachment to linear stages provides repeatable and precise positioning of the sensor. The stages also allow the sensor to compensate for the variety of commutator lengths, diameters, and positions. Linear stages are expensive and require a control system, which further increases their cost.

Sensor Type

- Eddy Current Sensor

  Eddy current sensors can be extremely lightweight and can be calibrated for high precision measurement. These sensors do not contact the surface being measured and can operate at high frequencies taking thousands of samples every second. These sensors are costly to purchase and calibrate but offer excellent precision and measurement speed. The overall range of the sensor is very limited and requires calibration using the target material.

- Proximity Sensor

  Proximity sensors use an ultrasonic soundwave that reflects off a targeted surface. They offer a significant overall range up to several feet with a modest precision closer to one thousandths of an inch. Hey also offer a lower sample rate typically in the kilohertz range. Being an acoustic measuring tool, it is prone to interference from other sound sources as well as temperature changes in the acoustic transfer media (usually air).

- Dial Indicator

  Dial indicators are cheap, readily available, and easily replaceable. The indicator contacts the surface and is prone to hysteresis as the dial moves across the commutator. A dial indicator must also be read manually which significantly limits the rate at which measurements can be taken.

The morphological table below evaluates the concepts discussed above 1 to 5 based on their ability to meet the design needs.

Table 1. A morphological chart used to rank the multiple design options by their ability to meet the criteria layed out in the design tree.

Concept	**Manufacturing Cost (0.100)**	**Serviceability (0.100)**	**Repeatability (0.240)**	**Measurement Precision (0.240)**	**Speed (0.128)**	**Error Resistance (0.192)**
Armature positioning						
Centers	3	4	4	3	3	2
Cams	4	4	4	4	5	4
V-blocks	4	3	3	3	3	3
Armature rotating						
Manual Rotation	5	5	1	2	1	1
Journal Drive	3	3	3	4	4	4
Drive Belt	2	2	3	4	4	4
Measuring device positioning						
Manual Positioning	5	5	1	1	2	2
Sensor Array	1	3	5	5	4	4
Linear Stages	3	3	5	5	4	3
Measurement device						
Eddy Current Sensor	2	3	3	5	4	3
Proximity Sensor	2	3	3	4	4	3
Dial Indicator	4	3	2	2	2	1

The results of the morphological chart have been tabulated below

Table 2

Concept	**Score**	**Concept**	**Score**
Armature positioning		Sensor Positioning	
Centers	3.148	Manual Positioning	2.120
Cams	4.128	Sensor Array	4.080
V-blocks	3.100	Linear Stages	4.088
Armature rotating		Measurement device	
Manual Rotation	2.040	Eddy Current Sensor	3.508
Journal Drive	3.560	Proximity Sensor	3.268
Drive Belt	3.360	Dial Indicator	2.108

The tree diagram and morphological chart suggests the use of an eddy current sensor largely due to its sample rate and precision as well is its resistance to interference and operator error. Eddy current sensors calibrated for copper have the highest practical precision of any sensor available for the application. Linear stages appear to be the ideal choice for sensor positioning owing largely to their repeatable and precise positioning regardless of the dimensions of the armature being inspected. The charts also suggest the use of cam rollers owing largely to their high precision and the speed at which an operator can insert or remove armatures. A journal drive mechanism will provide consistent and repeatable rotation without requiring adjustability based on the armatures lengths.

Cam Positioning

With cam roller selected as the armature positioning method, a system needs to be designed to accommodate multiple journal-to-journal lengths of the armatures it will inspect. The considered conceptual designs are documented below.

Prefabricated Rail and Locking Carriage

A piece of extruded rail in combination with a linear bearing could be used to align the cams.

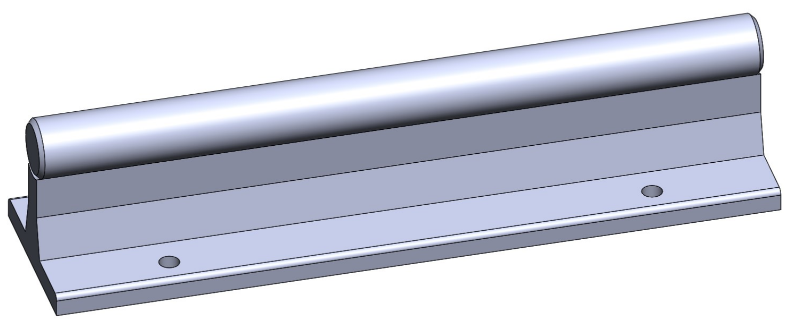


Figure 13. A computer model of extruded rail.

Mounting the cams to rails provides an extremely low friction mounting solution. Extruded rail is cheap and readily available. The extruded rails are aluminum and may wear faster than preferred. Additionally, the straightness of the rails is not ideal, over the full range of motion they may deviate unacceptably. A locking carriage can be installed over the bearings to easily fasten the cam mounts in to their desired locations.

Shoulders and T-slot

Shoulders can be machined directly into a base plate to align the cams.

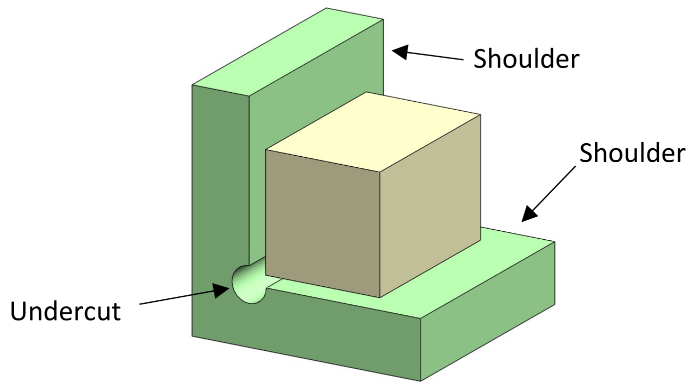


Figure 14. A computer model of a block resting agauinst two sets of shoulders.

A combination of undercut shoulder and flat surfaces on the cam mounts offers maximum precision through minimized stack up error. Machining and maintaining such a feature is exceeding expensive, as any damage requires the entire surface to be reworked. The mounts can be drawn tightly against the shoulders using an angled bolt installed through an angled T-slot machined in to the base plate. Upon contacting suppliers, it was found that the angled T-slot would be exceedingly difficult to manufacture.

Ways and T-slot

Ways like those found on a lathe and a T-slot for locking could be used for aligning the cams.

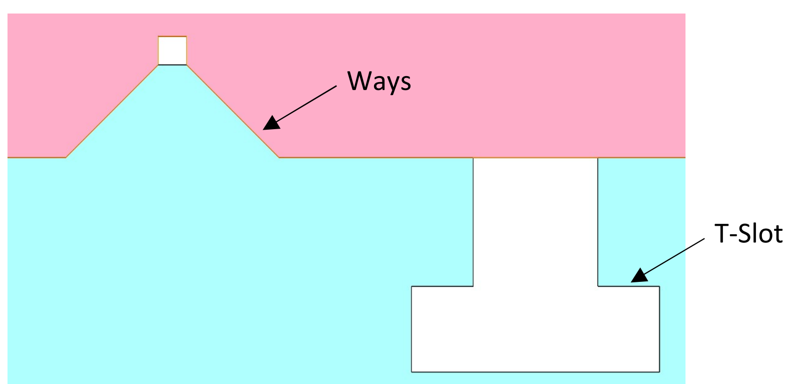


Figure 15. A cross section view of a T-slot and way slide.

Ways are relatively easy to machine and maintain. They offer excellent precision and maintainability. A T-slot can be added in parallel to allow the operator to fix the system in any position needed.

The ideas have been collected and analyzed using another morphological chart

Table 3. A morphological chart used to rank the multiple design options by their ability to meet the criteria layed out in the design tree.

Concept	**Manufacturing Cost (0.100)**	**Serviceability (0.100)**	**Repeatability (0.240)**	**Measurement Precision (0.240)**	**Speed (0.128)**	**Error Resistance (0.192)**
Cam Positioning						
Rail	5	3	4	2	5	4
Shoulders	1	1	5	5	4	5
Ways	4	4	4	5	4	4

The results of the morphological chart are below

Table 4. A table sumarizing the results of the above table.

Concept	**Score**
Rail	3.648
Shoulders	4.072
Ways	4.240

The tree diagram and morphological chart suggests the use of ways like those found on lathes in combination with a T-slot to position the cam rollers. This is due to a combination of their low manufacturing and maintenance costs and their high precision.

6. Embodiment Design

The tool will need to be adequately adjustable to accommodate any armature that requires inspection.

Dimensions such as bearing shoulder distance and commutator diameter vary between production units. A table was constructed containing the critical dimensions of every DC rotor in production. Decimal precision and part numbers have been obscured to protect the proprietary information of Safran Electrical and Power.

Table 5. A table of the part numbers that will be run on this tool and their critical dimensions.

Part Number	Commutator diameter	Shoulder Distance	Overall Diameter	Shaft Diameter
Armature 01	2.1[redacted]	4.4[redacted]	3.5[redacted]	0.6[redacted]
Armature 02	2.1[redacted]	5.5[redacted]	3.5[redacted]	0.6[redacted]
Armature 03	2.2[redacted]	6.5[redacted]	3.5[redacted]	0.7[redacted]
Armature 04	2.2[redacted]	7.9[redacted]	3.5[redacted]	0.7[redacted]
Armature 05	2.2[redacted]	7.4[redacted]	3.5[redacted]	0.7[redacted]
Armature 06	2.5[redacted]	6.3[redacted]	4.0[redacted]	0.6[redacted]
Armature 07	2.5[redacted]	6.3[redacted]	4.0[redacted]	0.7[redacted]
Armature 08	2.5[redacted]	6.3[redacted]	4.0[redacted]	0.6[redacted]
Armature 09	2.6[redacted]	6.1[redacted]	4.5[redacted]	0.7[redacted]
Armature 10	2.6[redacted]	6.1[redacted]	4.5[redacted]	0.7[redacted]
Armature 11	2.6[redacted]	7.4[redacted]	4.5[redacted]	0.7[redacted]
Armature 12	2.6[redacted]	7.8[redacted]	4.5[redacted]	0.7[redacted]
Armature 13	2.6[redacted]	6.9[redacted]	4.5[redacted]	0.7[redacted]
Armature 14	2.6[redacted]	8.7[redacted]	4.5[redacted]	0.7[redacted]

Journal Drive Assembly

- Configuration

The journal drive assembly will consist of several subassemblies.

It will require a stable base that can be securely mounted to the base plate of the tool.

A drive wheel will be manufactures by stretching an elastic O-ring into a groove cut in to a custom-machined wheel. The groove and wheel were designed by referencing the Parker O-ring Handbook.

The drive wheel will be driven by an AC gear motor through a shaft coupling to reduce the risk of damaging the motor as a result of misalignment.

The motor will be joined to the base with a bracket. This bracket will also house a supporting bearing to prevent damage to the motor by bearing a majority of the load. The bracket will be split in to three flat rectangular parts to reduce machining costs and to allow for shaft alignment during assembly.

The motion of the subassembly will be assisted by a gas spring connecting the base and the mounting bracket. It will make the mechanism self-securing in either the upright or downright positions.

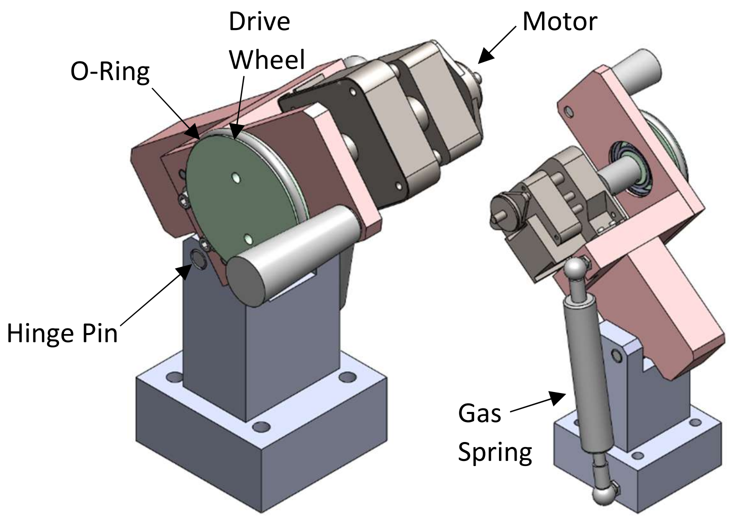


Figure 16 A computer rendering of the armature rotating assembly.

- Constraints

The drive mechanism will need to accommodate a range of bearing journals from 0.66[redacted]" to 0.78[redacted]" diameter. All bearing journals are at least 0.62[redacted]" long. The mechanism must also be easily moved out of the way of the operator while armatures are being exchanged.

The assembly shall not violate the footprint established by the base plate of the tool.

The tool shall be easily engaged without excessive physical exertion or operator skill.

- Durability

The primary wear component will be the elastic O-ring used to drive the armature. It should be easily replaceable without the use of special tools. The O-ring will be installed under its own tension. Replacing the O-ring is achieved by manually stretching it in to position. Although the O-ring in this application will not have indefinite life, replacement O-rings are very inexpensive and easy to obtain.

The secondary wear component of the drive assembly is the hinge. A pin has been selected so that it may be replaced with an oversized variant if the hinge should wear prematurely.

To prevent handling damage and allow for some re-machining, the components have been made thicker than otherwise necessary.

- Adjustability

To accommodate the differences in bearing journal diameters the drive wheel has an adjustable height. By placing the pivot point of the hinge level with the height of the journals, small changes in journal dimeter will cause the drive wheel to displace horizontally by a negligible amount.

The variance in length of the journals will be negated by designing the drive wheel to the shortest length extant in the entire product range.

The variation in journal-to-journal distance may also be negated by fixing the position of the one journal support of the armature positioning assembly.

- Calculations

It was decided to use an off the shelf motor when developing the tool. The motor was selected by matching the minimum torque and speed range of the motor to the inertia of the largest armature. A goal was set to have a spin up time of no more than 60 Seconds. The target speed of the armature is 60 rpm.

$$\ddot{\theta} = Rotational\ Acceleration, \qquad \omega = Rotational\ Velocity, \qquad T = Time$$

$$\ddot{\theta} = \frac{\omega}{T}$$

$$\ddot{\theta} = \frac{2 * \pi \frac{rad}{second}}{60\ seconds} = 0.105\left(\frac{rad}{s^2}\right)$$

The heaviest armature with the largest diameter is weighs approximately 10 pounds and has a dimeter of approximately 5.5 inches. By conservatively assuming all mass is at the maximum radius of the tool. The moment of inertia about the center axis can be calculated as follows.

$$I = Moment\ of\ inertia, \qquad M = Mass, \qquad r = radius$$

$$I = \frac{1}{2}M * r^2$$

$$I = \frac{1}{2}10lb * \left(\frac{5.5in}{2}\right)^2 = 75.63(lb \cdot in^2)$$

Knowing moment of inertia and desired acceleration, minimum torque can be computed as shown.

$$I = Moment\ of\ inertia, \qquad \ddot{\theta} = desired\ acceleration, \qquad \tau = Torque$$

$$\ddot{\theta} * I = \tau$$

$$\tau = 0.105\left(\frac{rad}{s^2}\right) * 75.63(lb \cdot in^2) = 7.94(lb \cdot in)$$

A nominal bearing diameter of 0.7” was assumed for all following calculations. The contact shear force between the drive wheel and the bearing journal was found with the following method.

$$F = Force, \qquad \tau = Torque, \qquad r = radius$$

$$F = \frac{\tau}{r}$$

$$F = \frac{7.94(lb \cdot in)}{(\frac{0.7in}{2})} = 22.69(lb)$$

A table was created with several practical motor and wheel combinations.

Table 6. A table usesed to select practical combinations of motor and wheel diameter.

Wheel Radius (in)	Min Motor Torque (lb.*in)	Min Motor Speed (rpm)
0.1	2.27	210
0.2	4.54	105
0.3	6.81	70
0.4	9.08	52.5
0.5	11.35	42
0.6	13.61	35
0.7	15.88	30
0.8	18.15	26.25
0.9	20.42	23.33
1	22.69	21
1.1	24.96	19.09
1.2	27.23	17.5
1.3	29.5	16.15
1.4	31.77	15
1.5	34.04	14
1.6	36.3	13.13
1.7	38.57	12.35
1.8	40.84	11.67
1.9	43.11	11.05
2	45.38	10.5
2.1	47.65	10
2.2	49.92	9.55
2.3	52.19	9.13
2.4	54.46	8.75
2.5	56.73	8.4
	$F * r_{wheel}$	$60 * \frac{D_{Bearing}}{D_{Wheel}}$

Based on available motor hardware, a 2" radius wheel and 10rpm motor combination was selected and implemented in the design.

A pulling gas spring was selected to increase the contact force between the wheel and the armature shaft bearing seats. The springs strength was selected by determining both the provided contact force and the added force applied to the operator.

The additional force the operator will need to apply to raise the drive wheel assembly

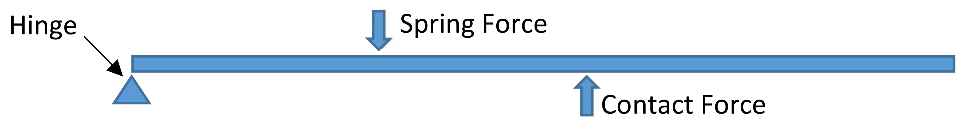


Figure 17. A kinematic diagram showing the contact force applied by the spring.

$$F = \frac{Length\ to\ spring * Spring\ Force}{Length\ to\ handle}$$

$$F = \frac{4.3in * 20lb}{12.6in} = 6.8lb$$

The contributed contact force between the drive wheel and the armature shaft bearing seats

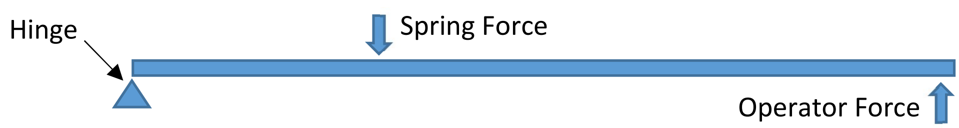


Figure 18. A kinematic diagram showing the force applied to the operator by the spring.

$$F = \frac{Length\ to\ spring * Spring\ Force}{Length\ to\ wheel}$$

$$F = \frac{4.3 * 20lb}{5.7in} = 15lb$$

- Material selections

  All structural components will be made from mild steel for its low cost and ease of machining. All these parts will be coated with a corrosion inhibiter to increase their use life.

  The O-ring will be made from Buna-N due to its wear resistance, chemical resistance, and commercial availability.

Sensor Positioning Assembly

- Configuration

  The sensor positioning assembly consists of two linear stages in an X-Z configuration. The sensor sits at the end of an extended bar that in turn sits in a fixture on the slides.

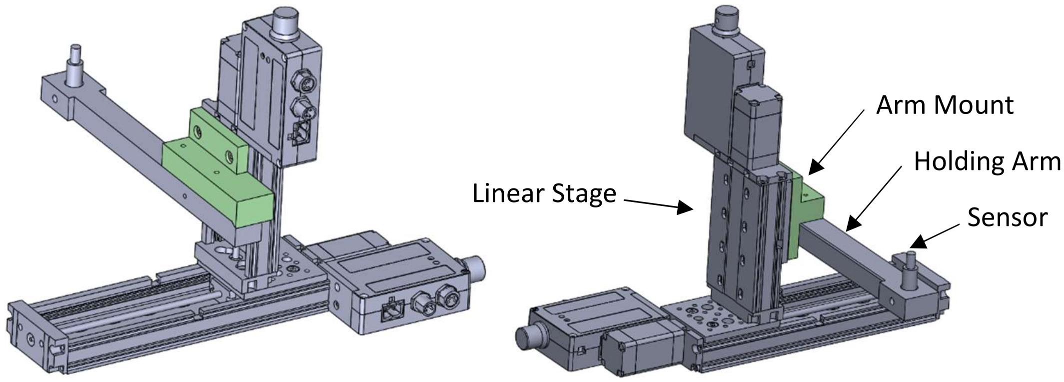


Figure 19. A computer rendering of the sensor positioning assembly.

- Constraints

  The slides and anything mounted to them shall not collide with any part other part of the tool or with any armature being measured.

- Durability

  To prevent damage to the slides caused by accidental collisions of the sensor arm with an armature, a detach mechanism was designed. The mechanism has pairs of magnets that draw the sensor arm into place but will release it under lower loads than could damage the slides.

- Adjustability

  The sensor positioning assembly needs to be able to position the sensor over the entire profile of any commutator. The largest commutator diameter is 3.3" and the smallest is 2.1". The vertical stage will need a travel range of at least half of that 1.2" difference. The longest commutator is 3.1". The horizontal stage will need a travel range of at least that same distance.

- Calculations

  The automatic detach feature was designed by determining the max allowable load that could be safely applied from the stage manufacturers specifications and creating a mechanism that will disengage prior to this limit.

$$Max\ allowable\ load\ =\ 17\ lbf$$

$$Magnetic\ contacting\ pull\ strength =\ 5\ lbf$$

$$\frac{17}{5} =\ 3.4\ pairs\ of\ contacting\ magnets$$

  Three pairs of magnets will be used with the remaining 2 pounds acting as a design margin.

- Material selections

The sensor arm and its mount are made from 6061-T6 aluminum to reduce weight and strain on the stages. These aluminums high temper value increases stability over time. The setscrew that holds the sensor is made of plastic to prevent it from damaging either the sensor or its holding arm.

Armature Positioning Assembly

- Configuration

The armature positioning assembly will consist of two sturdy cam-holding podiums. The podiums will be mounted to the base plate by a T slot and aligned by way slides like those found on a lathe bed way.

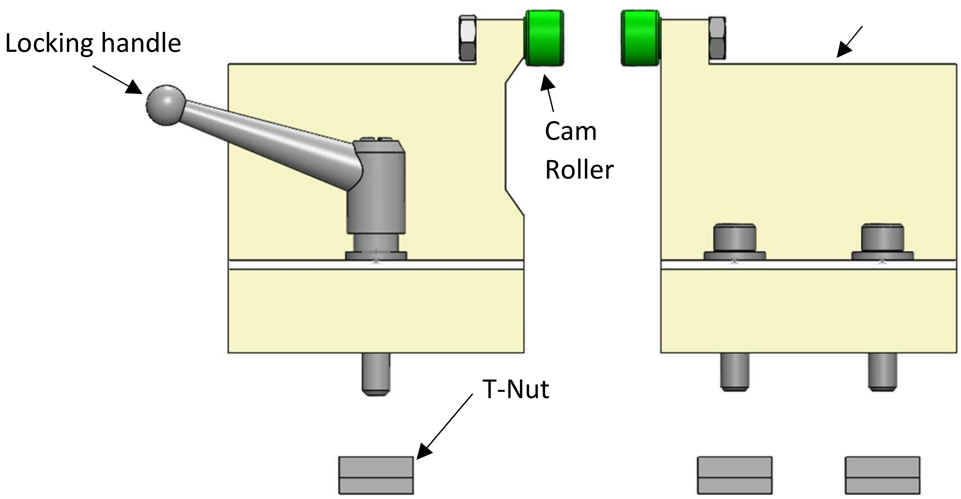


Figure 20. A computer rendering of the final armature holding assembly.

- Constraints

The armature holding assembly must not interfere with any other assembly or be interfered with by any other assembly. The operator should be able to easily fit their hands under the armatures to install or remove them from the machine. The armatures have a maximum overall diameter of 5.5" so the center height of the armature should be at least 2.75" with additional room for the operator's hands.

- Durability

The podiums will have a large contact area with the base plate to prevent wear from repeated use

The cam followers were selected to be easily replicable if need be. They may be easily reinstalled by turning a standard hex nut. They may be lubricated with an oil port on the front end and otherwise require very little maintenance through their use life.

- Adjustability

The shoulder-to-shoulder length of the armatures varies from 4.44” to 8.75” the tool will adapt by having one of the supporting podiums adjust by sliding along the length of the T slot. Alignment perpendicular to the T-slot will be ensured by the way slide

- Calculations

The alignment of the cam followers is crucial to the dependable operation of the tool. A special stack up was created to determine the misalignment that was possible. For the tool to operate correctly the misalignment may not exceed 0.005 inches.

A stack up was conducted to assure that the cams could not exceed tolerable limits of misalignment.

Table 7. A tolerance stack-up used to assure the alignment of the sets of cam followers.

Cam Alignment Y		**Cam Alignment Z**	
Flatness of Seat	0.001	Width of Negative V	0.0005
True position Cam	0.001	Width of Positive V	0.0005
Flatness Cam Holder Seat	0.001	True position Cam	0.001
Sum of Tolerances			
Sum of Positional Tolerances Y	0.003	Sum of Positional Tolerances Z	0.002
Max total cam misalignment (Euclidian distance)			
0.0036			

- Material selections

The podiums are to be made from an A2 tool steel. This material was selected to provide wear resistance and dimensional stability. The harder material will also be ideal for grinding allowing for a superior surface finish. The podiums will be hardened to 58-62 RC to amplify these desired properties. Both parts will be coated with a corrosion inhibiter to increase their use life.

Eddy Current Sensor

Cam Podium

- Configuration

The sensor will be fastened to the end of the sensor positioning assembly by placing it in the preexisting hole and fastening it with a setscrew.

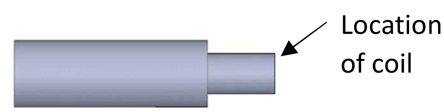


Figure 21. A computer rendering of the eddy current sensor.

- Constraints

The sensor may not run in to any of the other parts of the tool or into any of the armatures under inspection.

- Operation

  An eddy current sensor uses the electromagnetic phenomenon of eddy currents (also known as Foucault's currents) to detect proximity. As the magnetic field changes over a conductor current flows in closed loops perpendicular to the direction of the magnetic field in accordance with faradays laws. These loops or "eddies" create a magnetic field that acts in opposition to the change in field that induce it.

  In high frequency motor and generator applications this is a significant source of inefficiency. However, in sensing applications it allows for exceptional accuracy. As a result of induction, a higher frequency will not penetrate as deep as a lower frequency into the base material. By increasing the frequency into the megahertz range the sensor will only detect the surface of the material without interference from subsurface properties.

  They operate as follows. First, a closely controlled high frequency AC signal is driven through a small coil near the end of the probe. This induces an eddy current in the targeted conductor. The strength of the eddy current in the conductor is strongly related to the voltage, frequency, and proximity of the driving coil. The eddy currents generate an opposing magnetic field that in turn induces a voltage in the sensor. This voltage is then converted into a reading of proximity based on prior calibration.

Base Plate

- Configuration

  The base plate will be one large piece of metal that will serve as a common mounting platform for all the subassemblies.

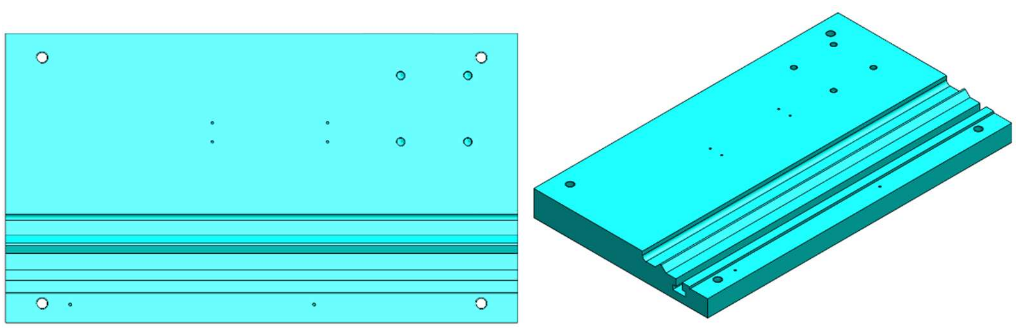


Figure 22. A computer rendering of the machines base plate.

- Constraints

  The base plate must not interfere with any other assembly or be interfered with by any other assembly.

- Durability

  The material selection and hardening assure that the tool shall resist wear and accidental damage. The ways shall be easily reground should they be accidently damaged.

- Adjustability

  A T-slot was cut along the length of the base plate to allow the Armature positioning assembly to accommodate different lengths of armature. A raised way slide will be cut in to the base plate to hold alignment while adjusting the roller positions.

- Material selections

  The base plate will be a monolithic piece of flame-hardened steel. This was selected for its wear resistance, ability to be ground, and dimensional stability. It will not be through-hardened as that carries too great a risk of fracturing in the thin sections near the T-slot due to internal stresses created in the heat treat process. This part will be coated with a corrosion inhibiter to increase its use life. This part will not be made from A2 tool steel despite its superior wear resistance, as a piece of the necessary size would be too costly.

7. Detail Design

A significant factor in many of the following decisions was the engineering overhead cost that would be involved. Although often neglected in school environments, the actual cost of my engineering hours needed to be considered in this project. With an approximate overhead rate exceeding 110$/hr and a low production volume (three units) any time spent optimizing or analyzing the tool had to be taken into consideration. With the given overhead rate and production volume, time spent on optimization or analysis would cost 37$ to the total cost of each tool. The best example of this is the hinge pin used in the armature rotating assembly. A table of pins I considered is shown below.

Table 8. an example of the cost conscious decisioon making process.

Diameter	Cost (each)
.125”	0.32$
.250"	0.42$
.500”	1.66$

Although the .25” or even the .125” pin may have been enough, the time taken to run an analysis on shear and fatigue loading would have exceeded the cost difference between any of the pins. For the analysis to be worthwhile, I would have needed to conduct it in under two minutes. As a result, this pin, and several other features, are conservatively overbuilt.

The ultimate design of the tool is captured in a series of 18 technical drawings. By recording the tool design in this way, we accurately define what the tool is and aid assembly. The remainder of this section will display these drawings and discuss the technical decisions involved. Some drawings will have selectively obscured features and dimensions to avoid violating export laws and protect the proprietary information of Safran Electrical and Power.

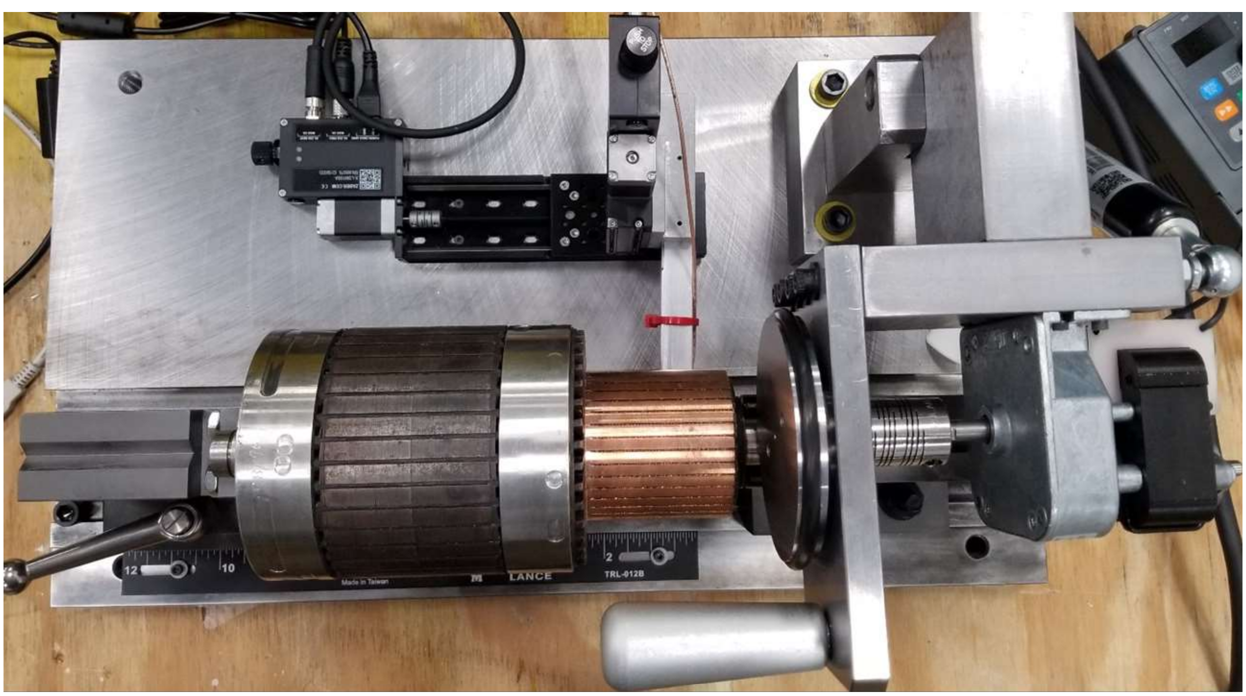
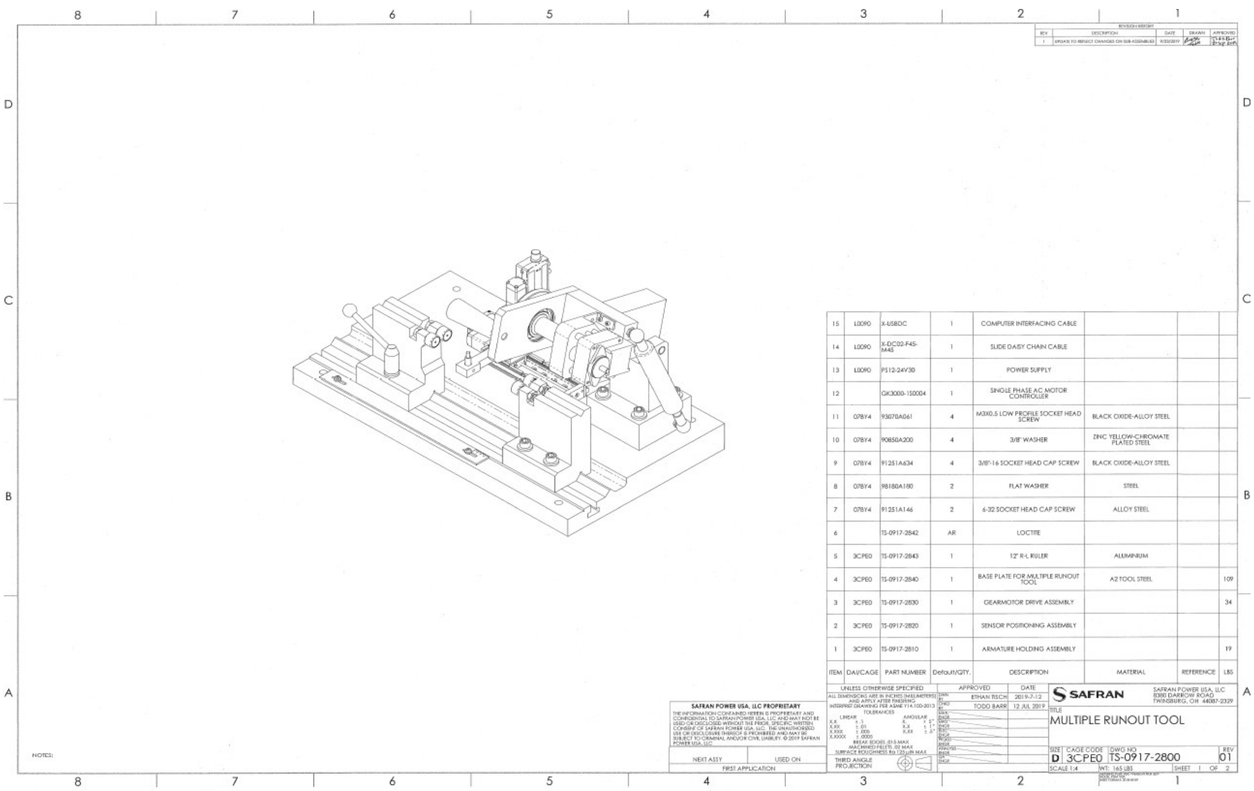


Figure 23. A photograph of the tool taken during testing.

TS-0917-2800 Multiple Runout Tool

This is the top-level drawing that specifies the general layout of the tool. This assembly drawing like the others contains a bill of materials (BOM) that provides the assembler a complete list of necessary parts to make the tool.



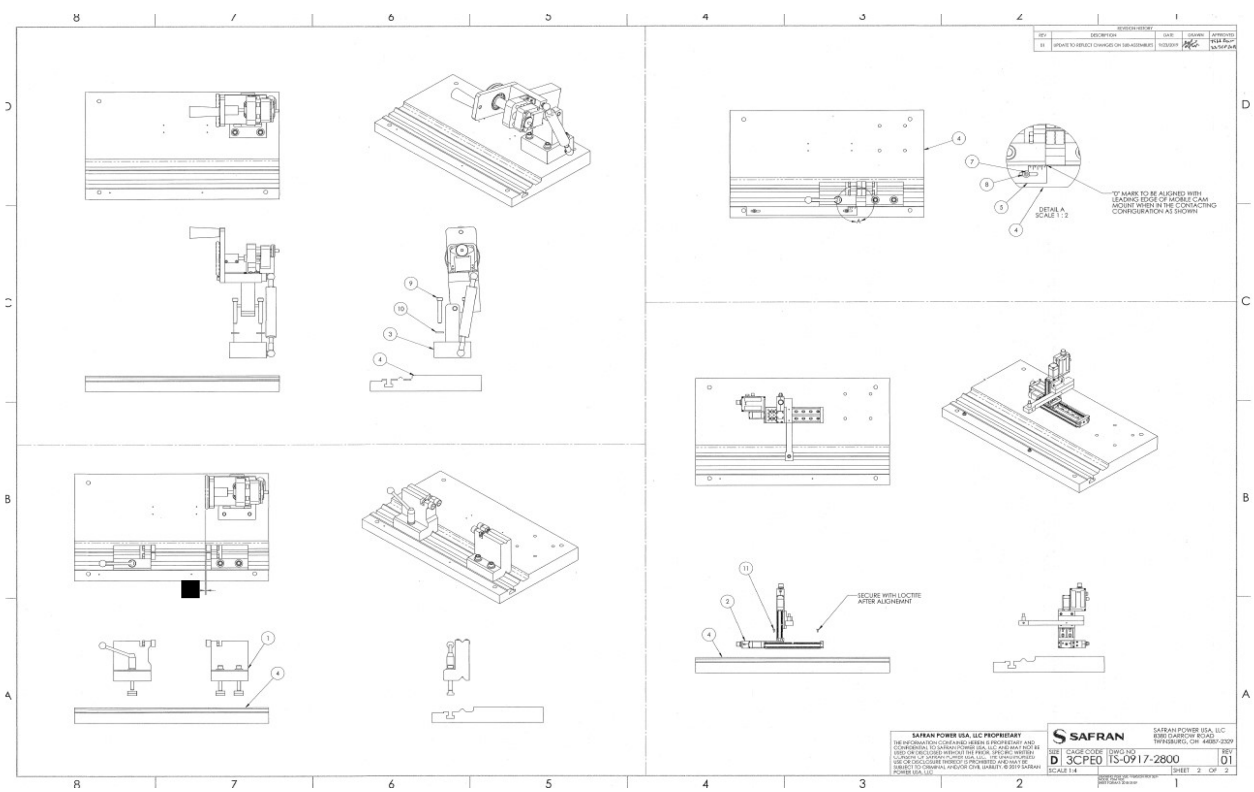


Figure 24. The top level drawing of the tool.

TS-0917-2801 Machine Table

The machine table is manufactured by the American Grinding and Machine Company. Many dimensions are omitted from the drawing to allow the supplier to use as much of their standard parts and tooling as possible.

This table weighs over 300 pounds and has soft rubber feet. This serves to damp out almost all high frequency vibrations that could interfere with the measurements.

A pair of holes are drilled in the lower struts to secure the table to the floor.

A series of holes are drilled in the top of the table to both secure the tool to the table and provide passage for cables to access the controller electronics below.

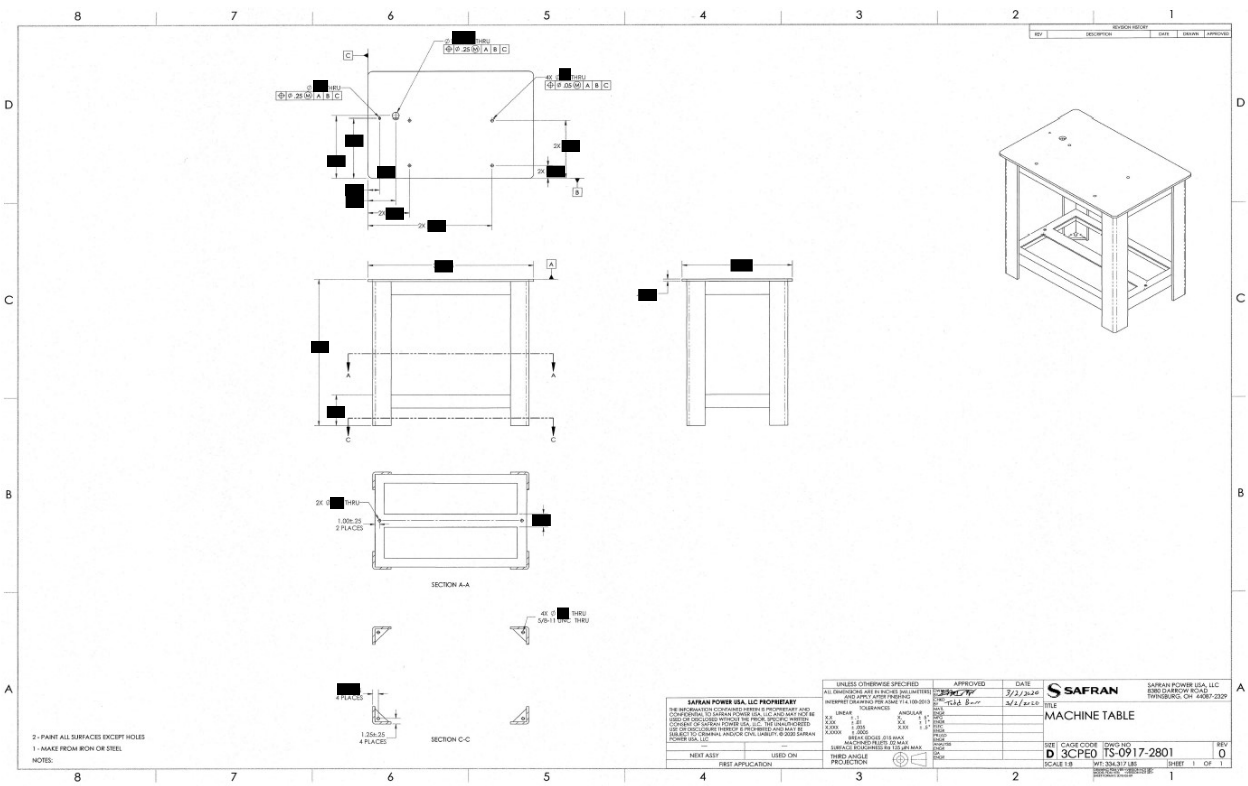


Figure 25. A drawing detailing the machine table the tool will be mounted to.

TS-0917-2810 Armature Holding Assembly

This subassembly holds the armatures. The cam rollers are pressed into two opposing mounts. The bolts that pass through the mount have T-nuts to allow them to slide smoothly through the slot of the base plate when they are installed on the top level assembly.

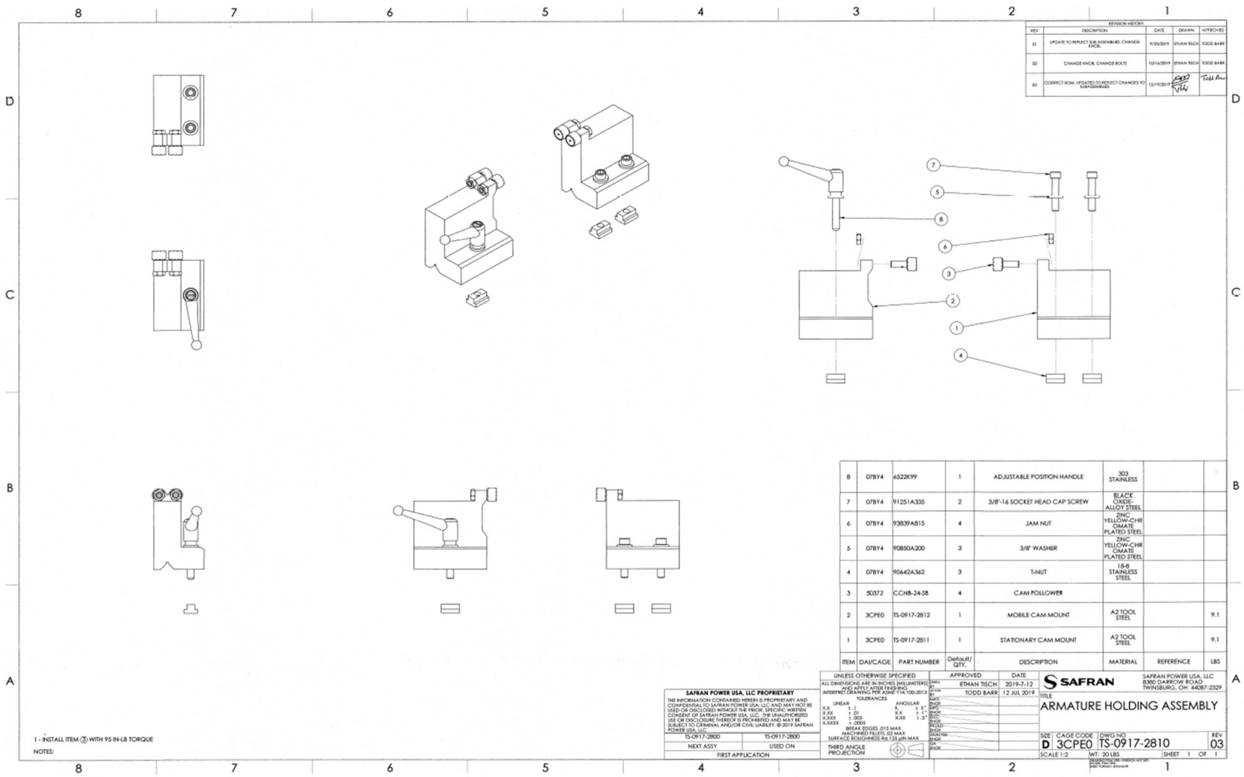


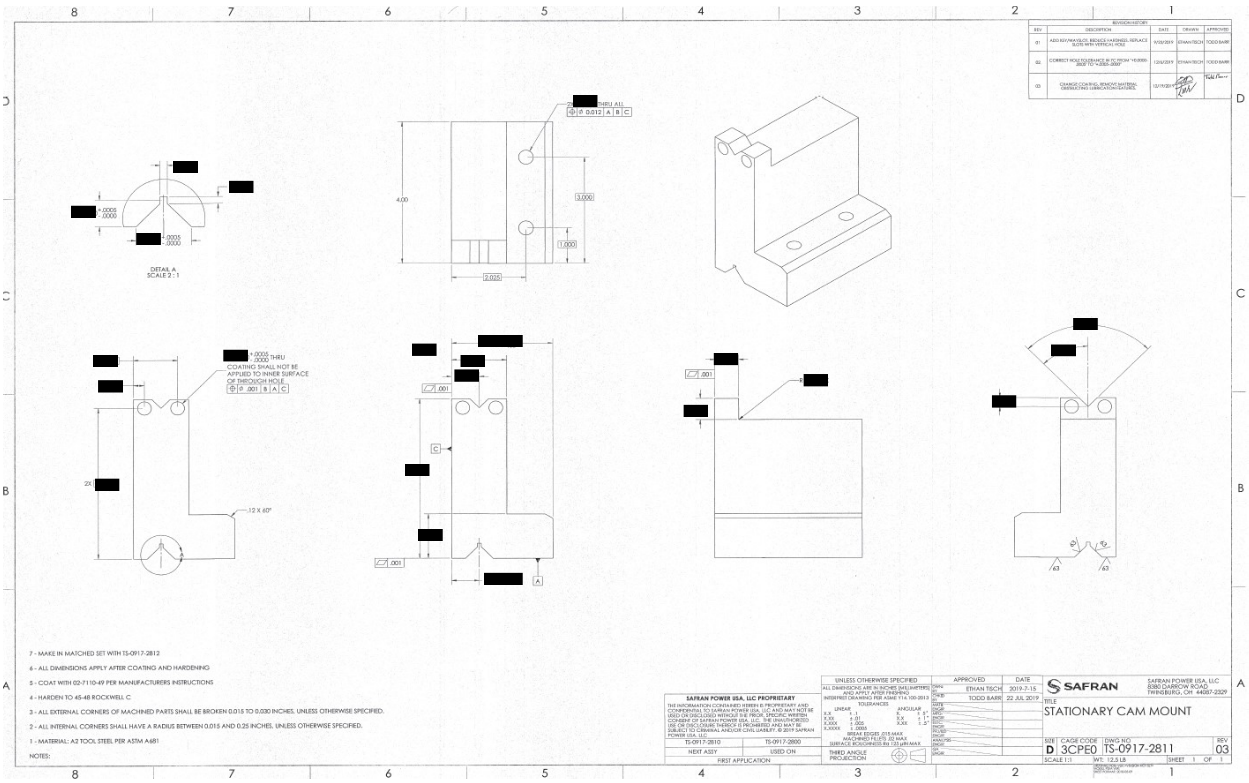
Figure 26. The datail drawing showing the assembly process of the armature holding assembly.

TS-0917-2811/2812 Stationary and Mobile Cam Mounts

These are the mounts that support the journals in the next level assembly.

The stationary mount has a pair of through holes that allow it to be securely bolted to the base.

The mobile mount has a single through hole to allow for quick adjustments while using the tool. The mobile mount also has a recessed face to allow for the slight overhang of the copper wires past the bearing shoulders on some armatures.


DETAIL A
SCALE 2 : 1
COATING SHALL NOT BE APPLIED TO INNER SURFACE OF THROUGH HOLE
7 - MAKE IN MATCHED SET WITH TS-0917-2812
6 - ALL DIMENSIONS APPLY AFTER COATING AND HARDENING
5 - COAT WITH 02-7110-49 PER MANUFACTURERS INSTRUCTIONS
4 - HARDEN TO 45-48 ROCKWELL C
3 - ALL EXTERNAL CORNERS OF MACHINED PARTS SHALL BE BROKEN 0.015 TO 0.030 INCHES, UNLESS OTHERWISE SPECIFIED.
2 - ALL INTERNAL CORNERS SHALL HAVE A RADIUS BETWEEN 0.015 AND 0.25 INCHES, UNLESS OTHERWISE SPECIFIED.
1 - MATERIAL: A2 TOOL STEEL PER ASTM A681
NOTES:
SAFRAN POWER USA, LLC PROPRIETARY
UNLESS OTHERWISE SPECIFIED
ETHAN TISCH 2019-7-15
TODD BARR 22 JUL 2019
SAFRAN
SAFRAN POWER USA, LLC
8380 DARROW ROAD
TWINSBURG, OH 44087-2329
STATIONARY CAM MOUNT
D 3CPE0 TS-0917-2811 03
SCALE 1:1 WT: 12.5 LB SHEET 1 OF 1

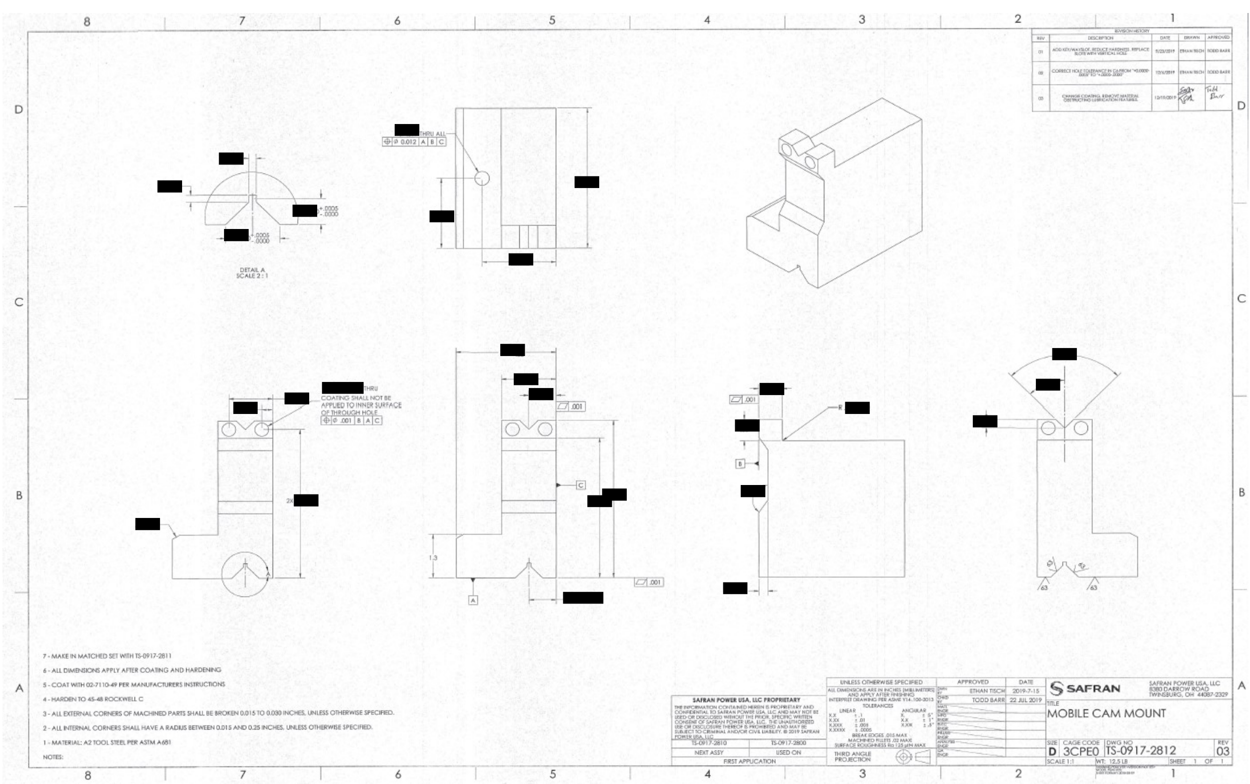

DETAIL A
SCALE 2 : 1
COATING SHALL NOT BE APPLIED TO INNER SURFACE OF THROUGH HOLE
7 - MAKE IN MATCHED SET WITH TS-0917-2811
6 - ALL DIMENSIONS APPLY AFTER COATING AND HARDENING
5 - COAT WITH 02-7110-49 PER MANUFACTURERS INSTRUCTIONS
4 - HARDEN TO 45-48 ROCKWELL C
3 - ALL EXTERNAL CORNERS OF MACHINED PARTS SHALL BE BROKEN 0.015 TO 0.030 INCHES, UNLESS OTHERWISE SPECIFIED.
2 - ALL INTERNAL CORNERS SHALL HAVE A RADIUS BETWEEN 0.015 AND 0.25 INCHES, UNLESS OTHERWISE SPECIFIED.
1 - MATERIAL: A2 TOOL STEEL PER ASTM A681
NOTES:
SAFRAN POWER USA, LLC PROPRIETARY
UNLESS OTHERWISE SPECIFIED
ETHAN TISCH 2019-7-15
TODD BARR 22 JUL 2019
SAFRAN
SAFRAN POWER USA, LLC
8380 DARROW ROAD
TWINSBURG, OH 44087-2329
MOBILE CAM MOUNT
D 3CPE0 TS-0917-2812 03
SCALE 1:1 WT: 12.5 LB SHEET 1 OF 1

Figure 27. The detail drawings of the subcomponents of the armature holding assembly.

TS-0917-2820 Sensor Positioning Assembly

This subassembly is responsible for positioning the sensor beneath the rotating commutator. It consists of two high precision linear stages equipped with linear encoders and the sensor mounted to an overhanging arm.

The stages are fixed to each other in an X-Z configuration. This allows movement along the length of the commutators and accommodates the size range of the commutators.

There is a matching set of magnets installed in the sensor arm and its mount. This, in combination with aligning tapers, pulls the sensor arm tight into place with exceptionally accuracy and repeatability. The magnets apply an amount of holding force that is less than necessary to damage any of the slides or other components. When the arm collides with an object for any reason, it drops from the assembly thus protecting the delicate hardware. The sensor is pressed in to a precision ground hole at the end of the arm and held in place with nylon set screws.

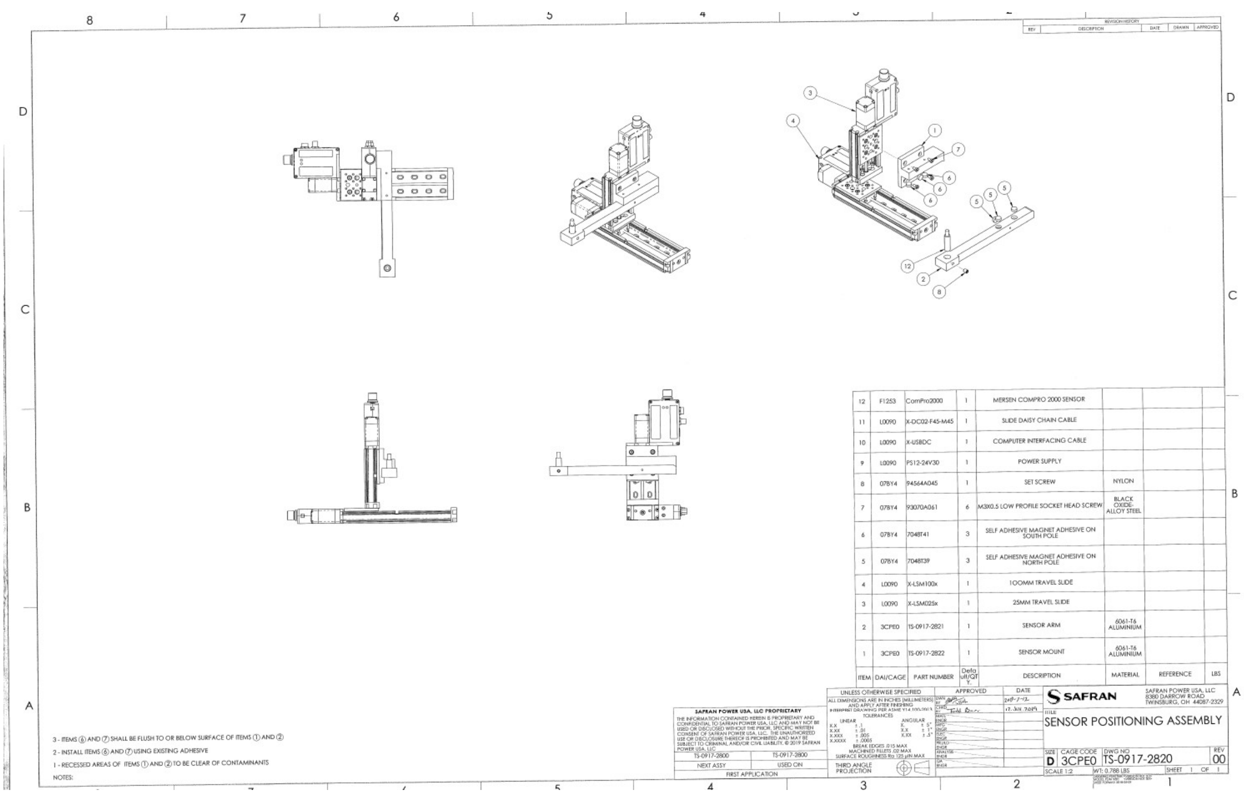


Figure 28. The assembly drawing of the sensor positioning assembly.

TS-0917-2821 Sensor Arm

This component holds the Eddy current sensor.

Three blind holes are made to allow magnets to sit flush to the surface. The blind holes have a small through hole that allows an ejector pin to drive the magnets out should they need replacement or reinstallation. The blind holes are also undercut to allow the self-adhesive magnets to sit flush with the bottom of the blind holes.

A precision sloped face is created at the back to match its mating part at the next level assembly. A generous chamfer is also created along the edge that mates with the next level assembly to allow the faces to sit flush.

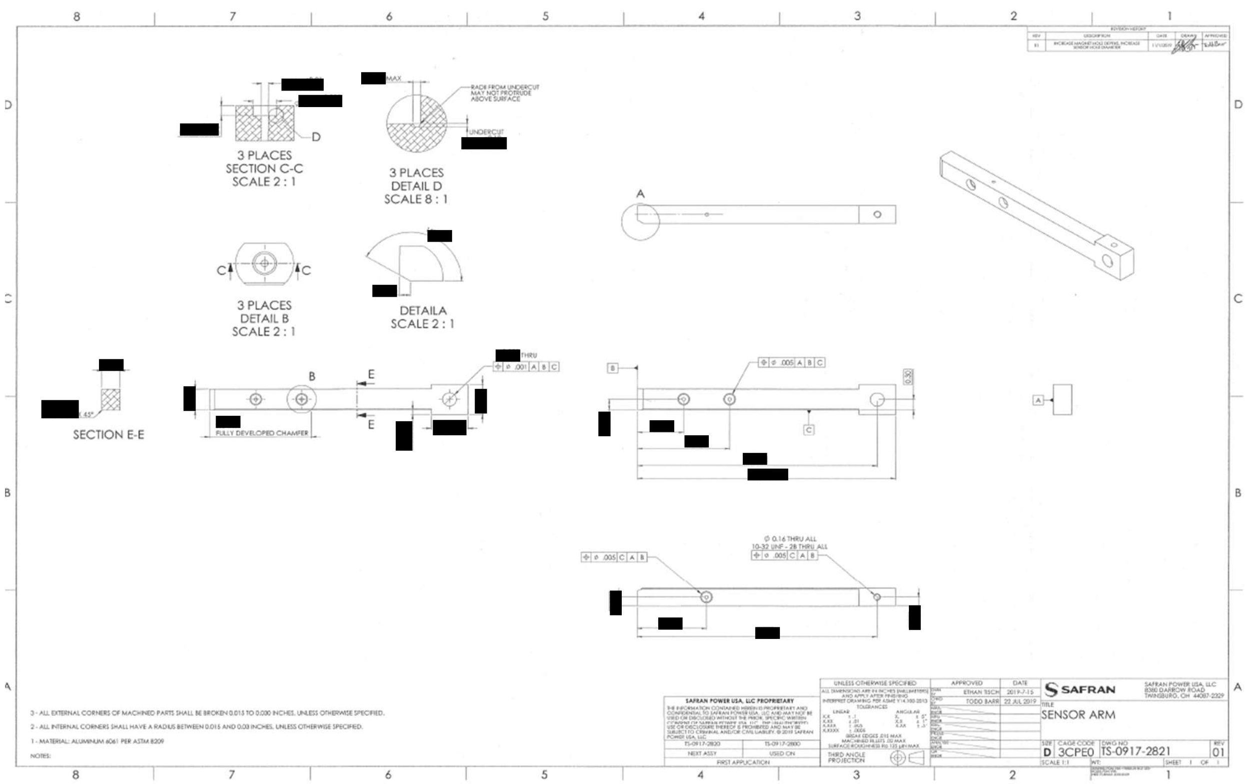


Figure 29. Detail drawing of the sensor positioning arm.

TS-0917-2822 Sensor Arm Mount

This is the component that connects the sensor arm to the linear stages.

A set of holes for magnets are made to match those on the sensor arm. These holes have the same countersinks and ejection features as those on the arm.

The matching precision sloped face is also created on this part.

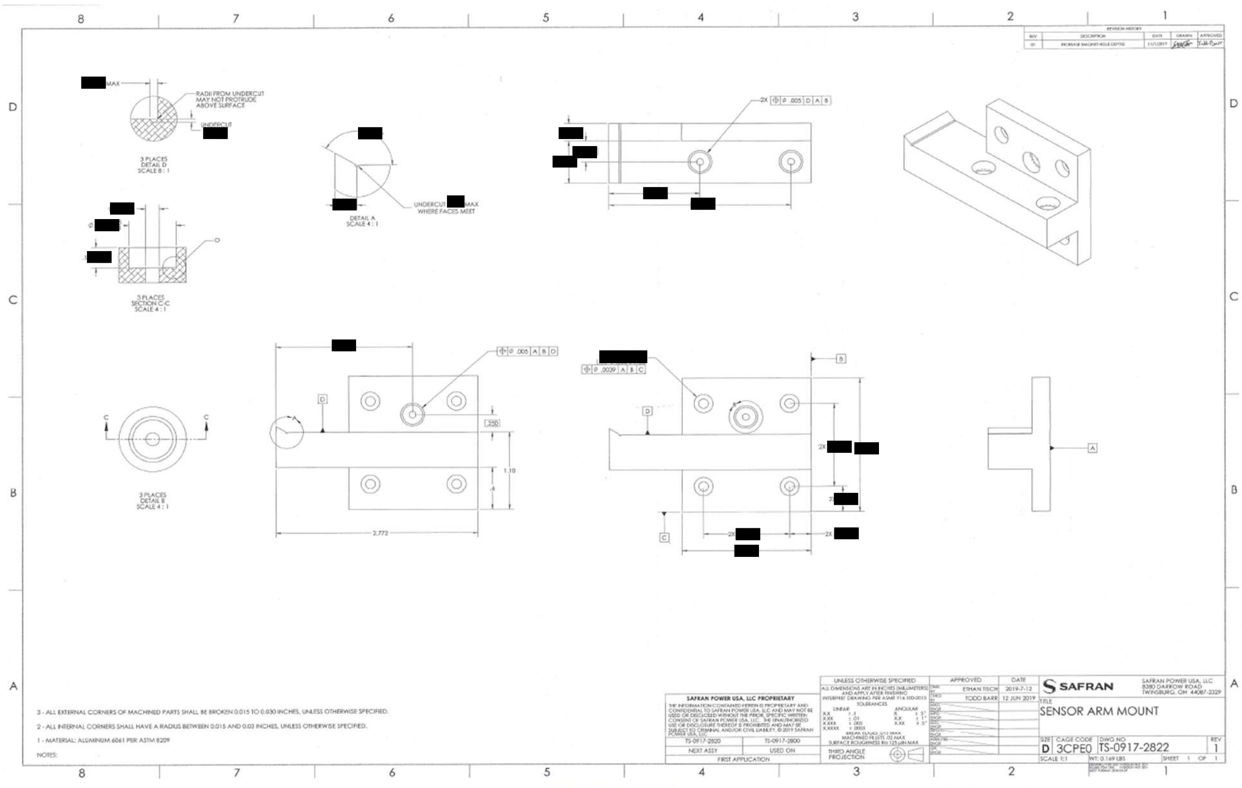


Figure 30. Detail drawing of the mount for the sensor positioning arm.

TS-0917-2830 Gear Motor Drive Assembly

This complicated assembly is responsible for rotating the armatures at a controlled and consistent pace. The assembly bends at the center to allow the operator to clear the drive wheel from the journals when exchanging armatures.

The hinging action is achieved by two precision drilled holes and a precision ground dowel pin. The dowel pin is secured by one end of the supporting stem having a slightly undersized hole that binds the pin in place.

An ergonomically considerate ball knob handle gives the operator ample leverage to operate the machinery.

A pulling gas spring provides a clamping force that increases the friction between the drive wheel and the journal. This spring also locks the arm securely in the upright position allowing the operator to safely exchange armatures.

The motor sized in the embodiment section of this report is mounted to the drive wheel through a flexible shaft coupling that prevents damage caused by misalignment. This coupling is rated for 300 hours of use at the maximum torque and speed of the motor.

The drive itself was supported by an oversized ball bearing pressed both over the wheels journal and into a hole in the drive assembly. The wheel contains a hardened steel core surrounded by a tightly wrapped Buna-N O-ring that makes a friction connection between the armature journals and the drive assembly.

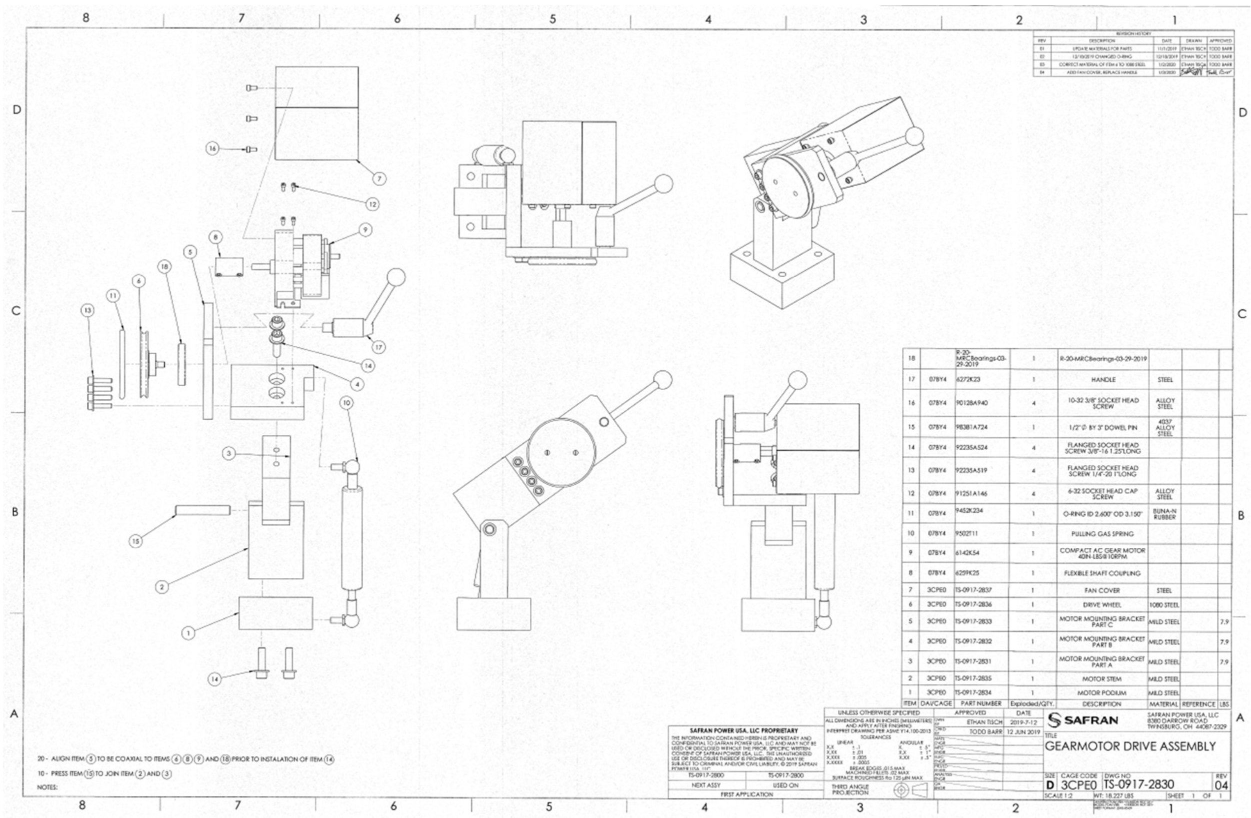
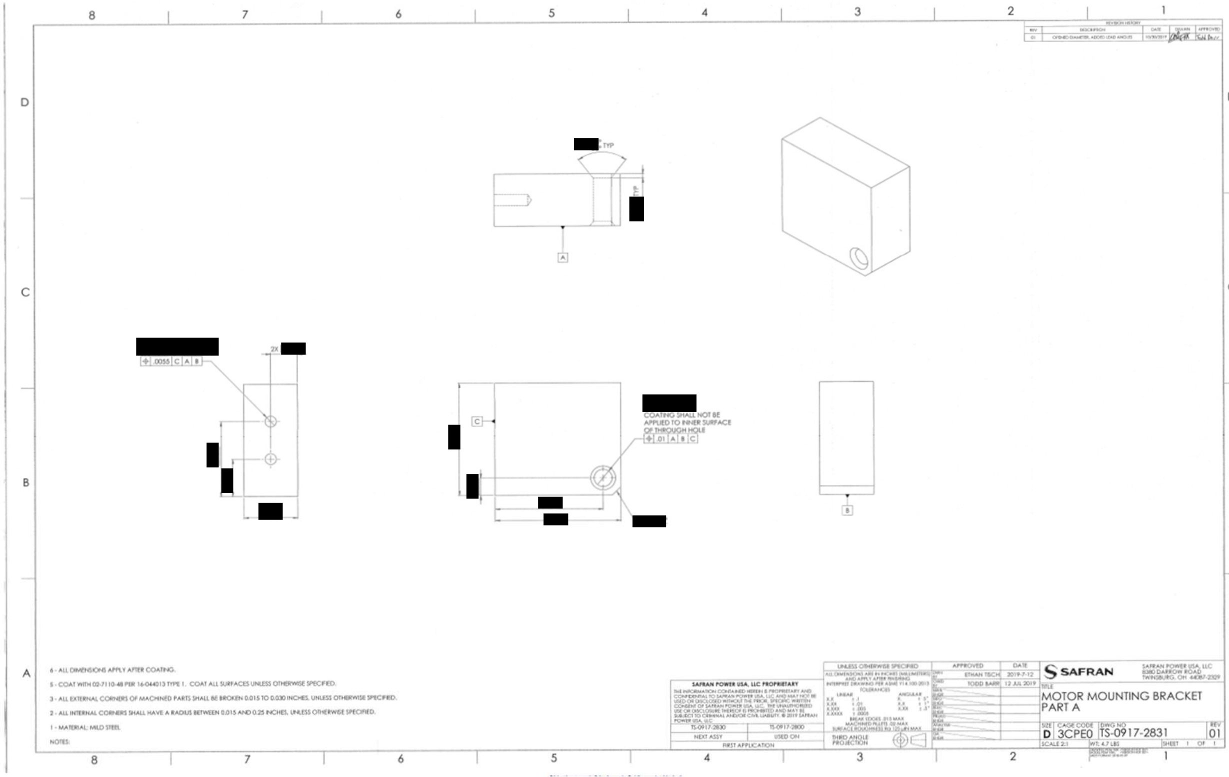


Figure 31. Detailed assembly drawing of the armature turning assembly.

TS-0917-2831/2832/2833 Motor Mounting Bracket Parts

These parts are the structural components used in the gear motor drive assembly.



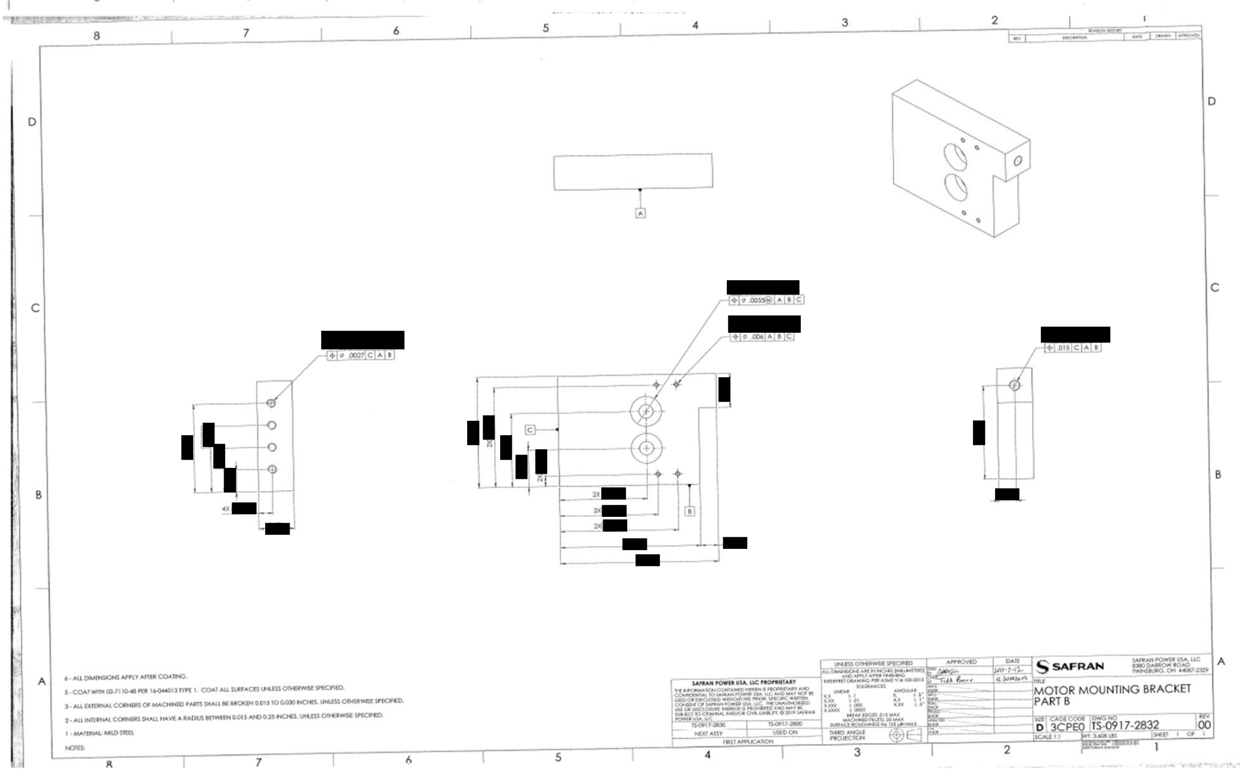
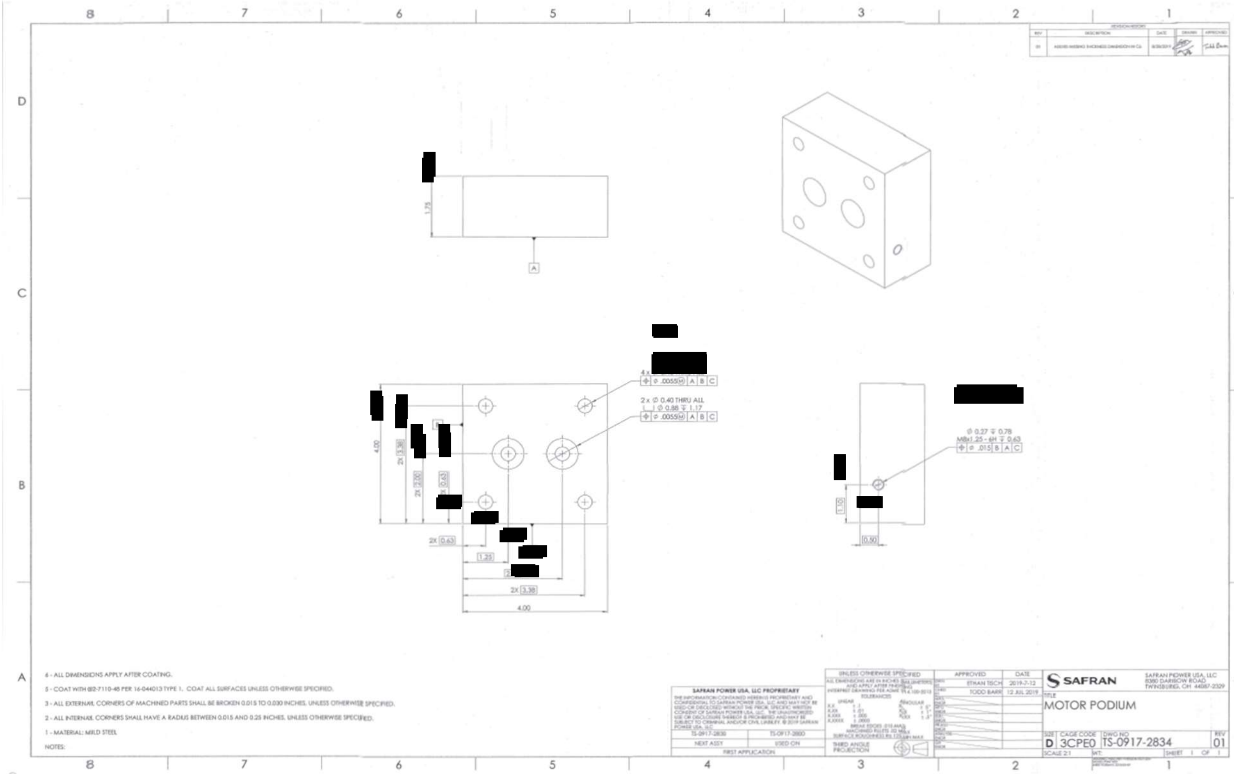


Figure 32 Detail drawings of the armture turning assembly subcomponents.

TS-0917-2834/5 Motor Podium and Stem

These are the parts that support the gear motor drive assembly and connect it to the baseplate.



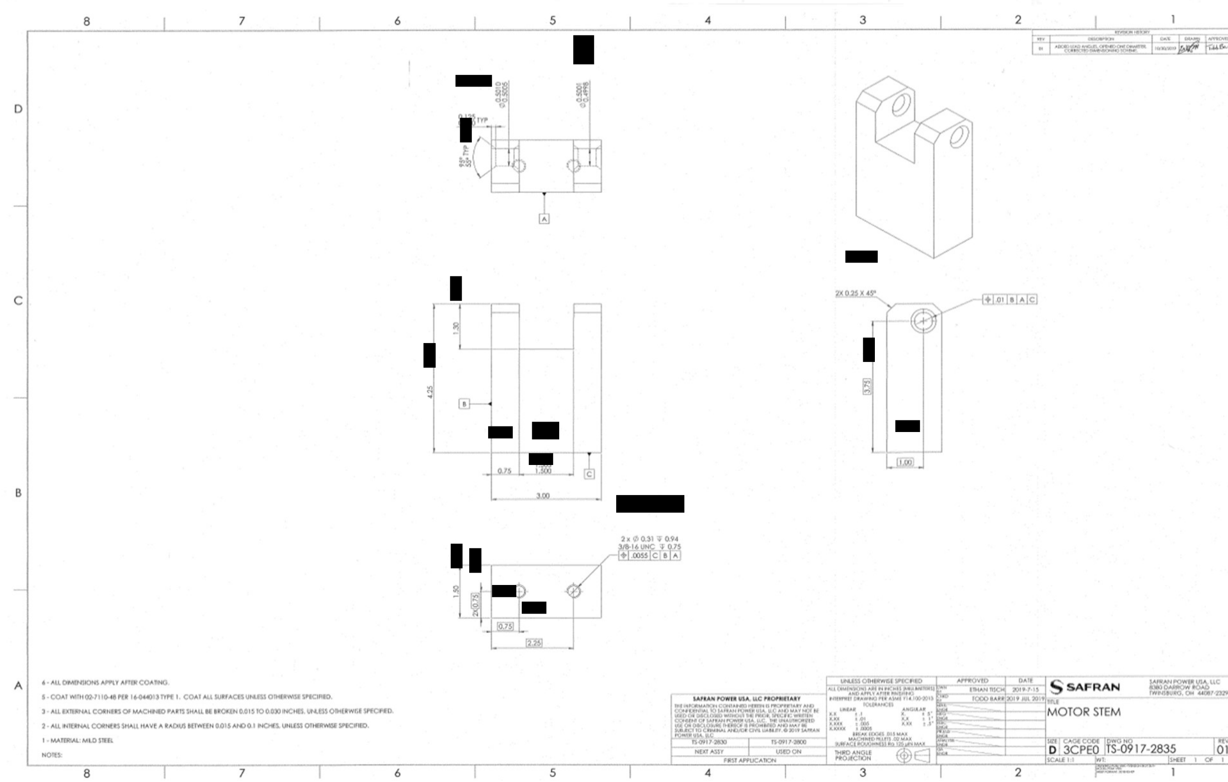


Figure 33. Detail drawings of the armture turning assembly subcomponents.

TS-0917-2836 Drive Wheel

The drive wheel is a turned carbon steel component that holds the O-ring in place.

Through holes were added just outside the bearing shoulder to allow the bearing to be forced off when it needs to be replaced.

An undercut was created at the back of the journal to allow the bearing to fully seat against the shoulder.

The roundness of this part was critical to its installation and operation. A multitude of GD&T control frames were applied to this drawing to assure the part would function correctly.

The nearing surface sand the groove for the O-ring are both highly polished to prevent damaging the bearing and the O-ring.

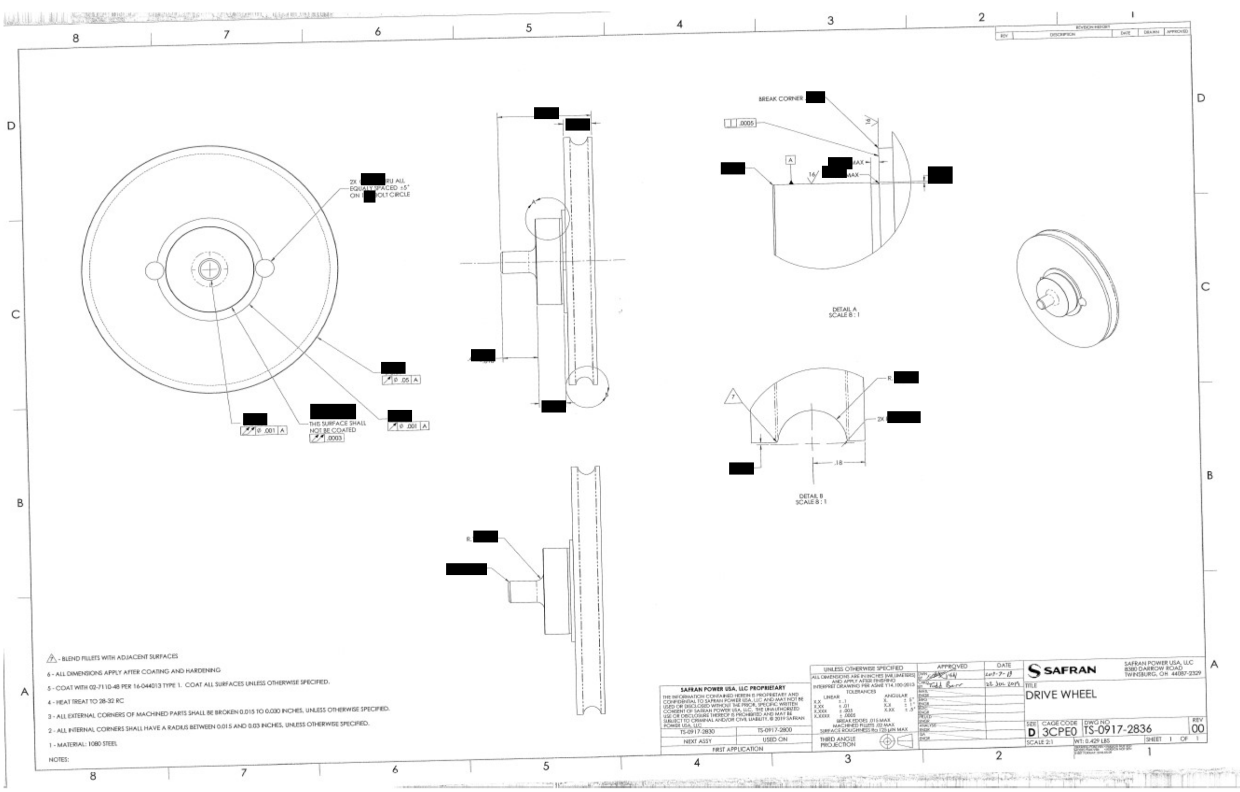


Figure 34. Detail drawings of the armture turning assembly drive wheel.

TS-0917-2837 Fan Cover

This simple folded sheet metal part protects the operator from the motors cooling fan. The permeable material is attached to the impermeable materials by welding at the seams.

It was designed to bolt on to the mounting holes already present on the gear motor.

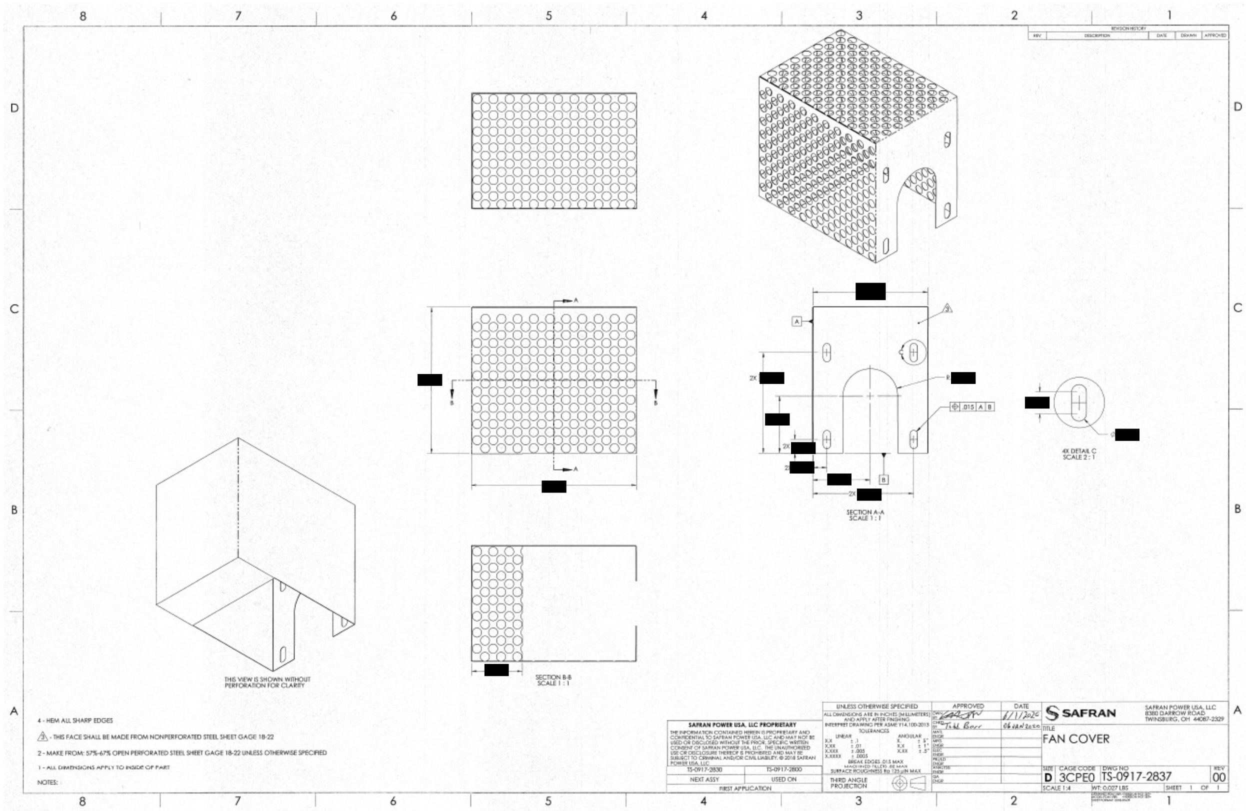


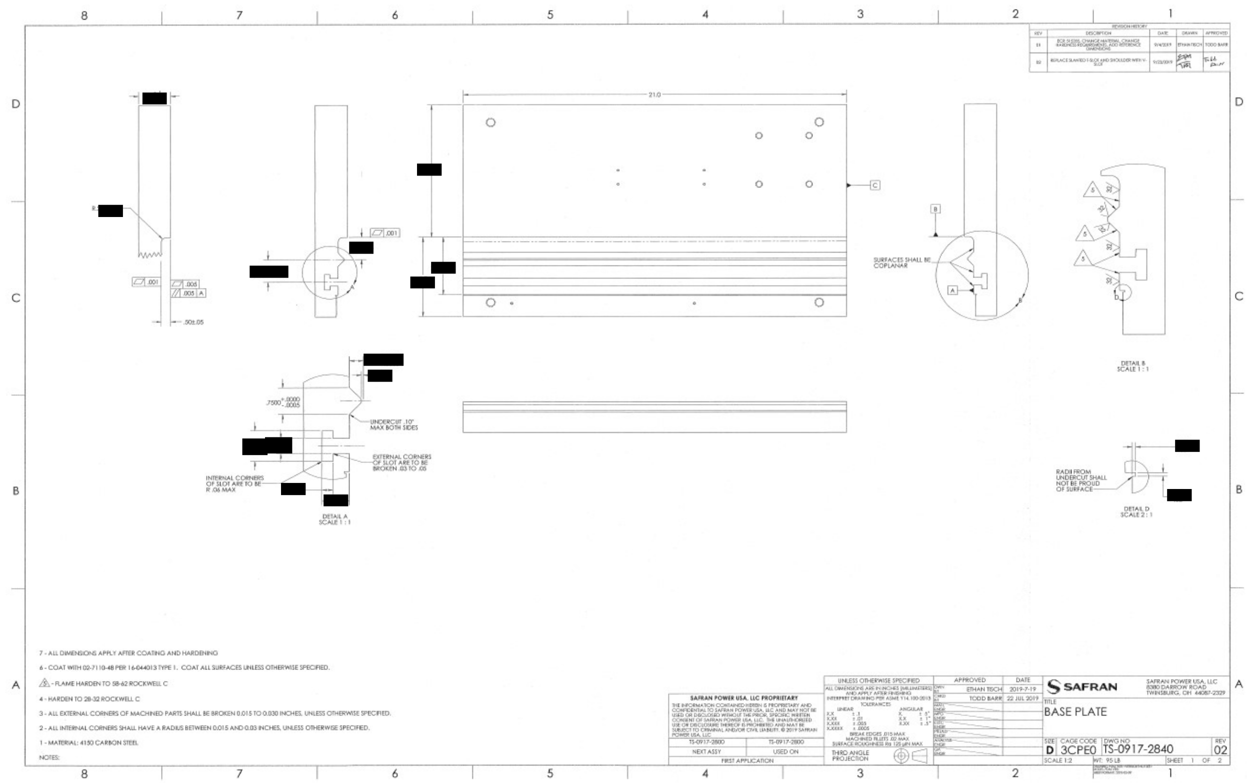
Figure 35. Detail drawings of the fan cover.

TS-0917-2840 Base Plate

The base plate is the heaviest part of the tool. This is the component that all subassemblies mount to.

A large ways is ground in to the tool with a straightness of one one thousandths of an inch over its full length. Running parallel to the ways is a T-Slot. The T-slot allows both the stationary and mobile cam mounts to be locked in any position along the length of the tool. In combination the T-slot and ways create a foolproof and repeatable way of aligning the cam rollers.

A number of holes were drilled and tapped to allow the subassemblies to bolt directly to the base plate and for the base plate to bolt to the table. These holes were tapped instead of made through because it allowed the subassemblies to bolt on without the assembler having to lift the 100 pound base plate to insert a nut.



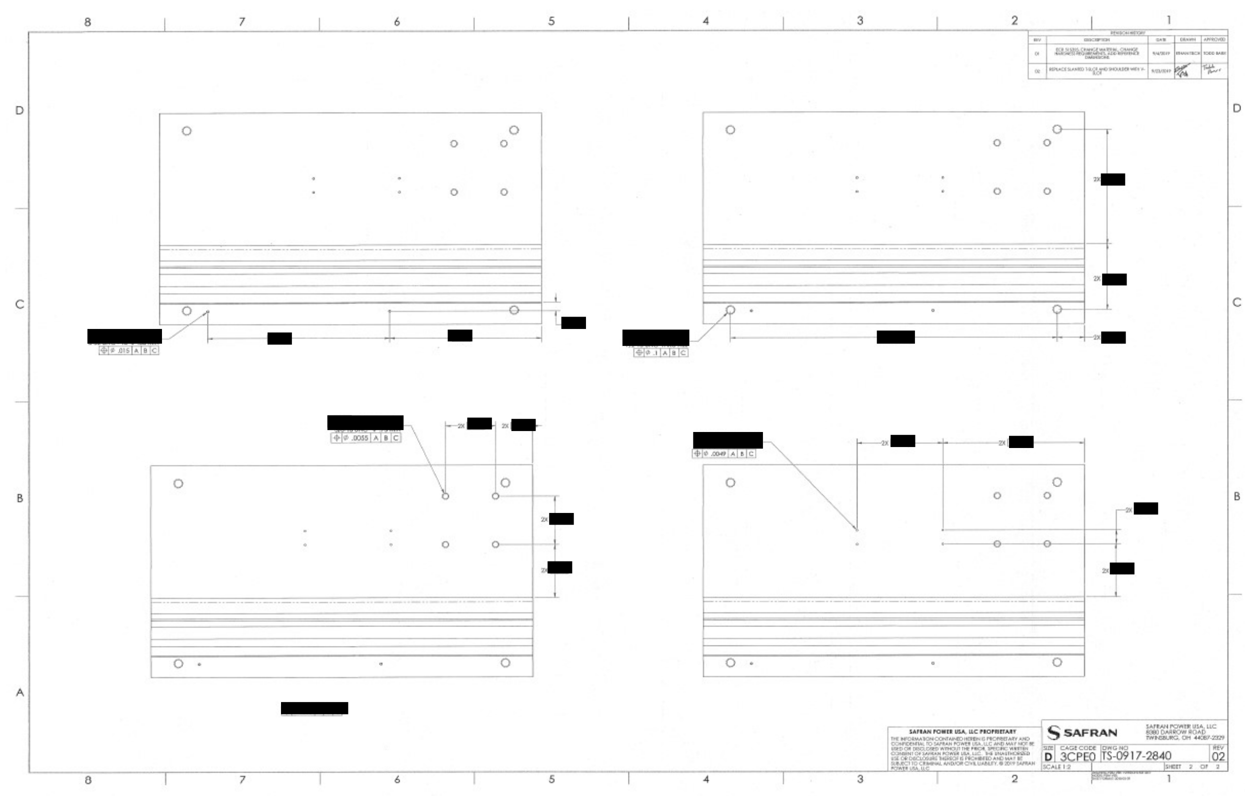


Figure 36. The base plate of the TIR tool that all other subassemblied will mount to

TS-0917-2843 Slotted Ruler

This final part is a conventional ruler with a slot cut into either end. The operator uses the ruler as a guide to align the mobile cam mount repeatedly when running the same part number.

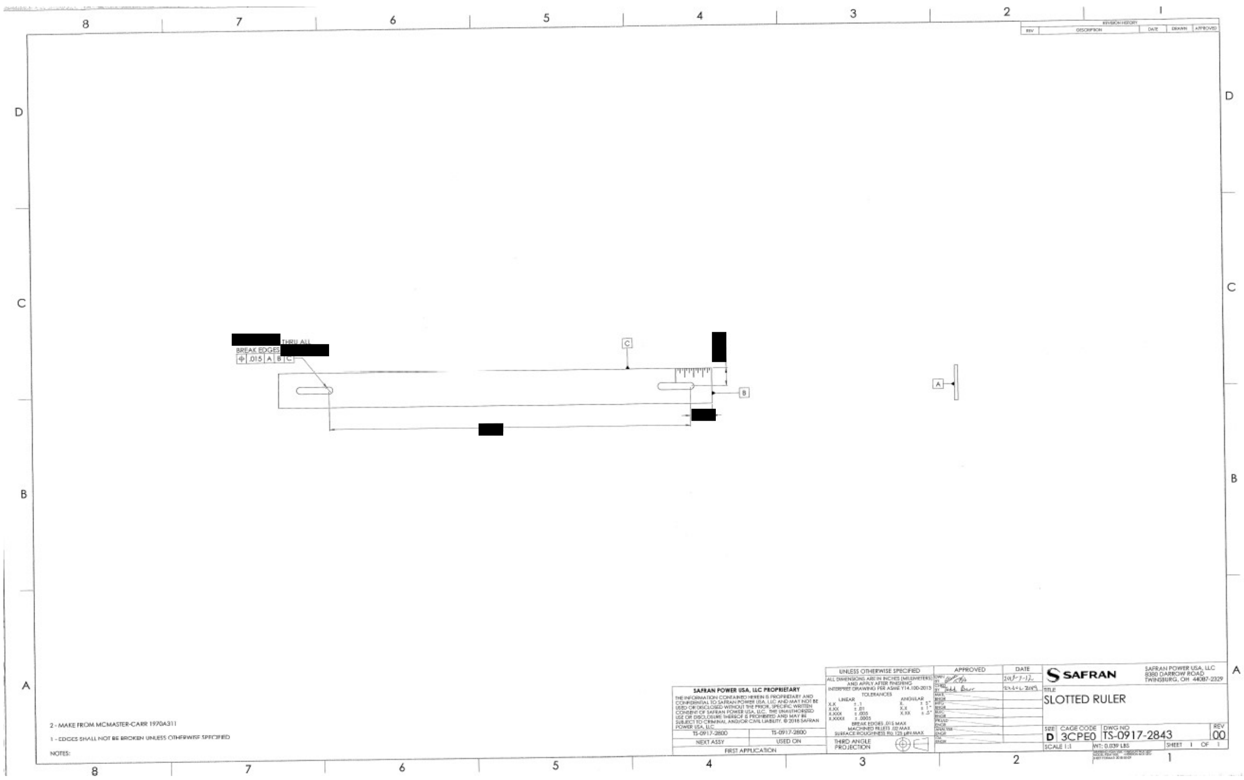


Figure 37. A detail drawing of the modified ruler.

8. Discussion

The discussions section of this report has been broken into two parts for clarity. The first focuses on the manufacturing and the lessons learned therein. The second part of the discussion focuses on the problems discovered while installing the tool in the manufacturing environment and the lessons learned while resolving them.

Manufacturing

Several lessons were learned and designs subsequently modified through the manufacturing process. The major design changes and their rationale are documented in this section.

Lead Angles and Material Drag

The hinge of the armature rotating assembly was originally designed without lead angles at the entrances to the though holes. This presented two major hindrances to assembly. The first problem noticed was the difficulty aligning the holes for the pin to be pressed in to. A series of smaller pins had to be inserted to perfect the alignment before the hinge pin could be pressed in. The second problem was material drag. As a pin is forced through a tightly fitting hole, it pulls along a small amount of material. This creates a raised area around the hole that completely seizes the hinge.

Both problems were rectified by adding a lead angle to either side of all mating holes allowing the parts to self-align during assembly and negating the effects of material drag.

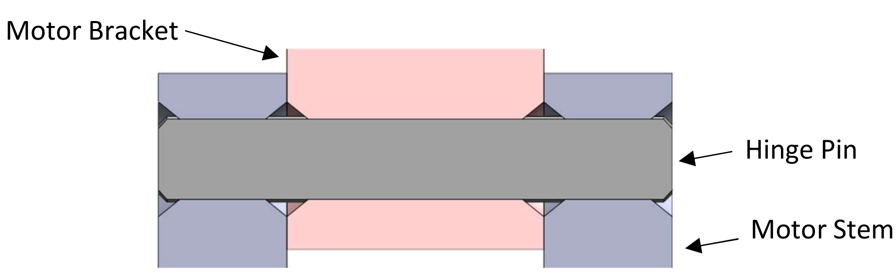


Figure 38. A cross section view of the hinge used in the gearmotor drive assembly.

Stress Concentrations During the Heat Treatment Process

The original prints for the base plate specified that it should be through hardened to 58-62 Rockwell C. Due to the thin section created under the T-slot and the sharp interior angles several manufacturers chose not to machine and harden it. Their fear was that these locations would concentrate stress in heat treat and cause the part to fracture or distort.

The sharp interior edges were eliminated by altering the design to allow a generous radius where possible. To minimize the possibility of distortion on such a large part, only the surfaces of wear features were hardened using flame hardening. This eliminated the risk of distortion caused by thin section or through hardening.

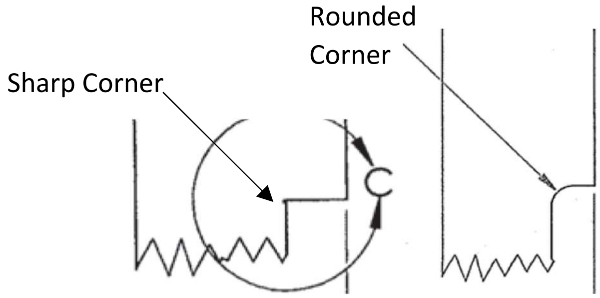


Figure 39. A drawing feature showing the change to add a radius to internal edges of the tool.

Difficulty of Machining Internal Geometries

An integral part of this tools design is a locking T-slot that securely hold the armature holding assembly in place. Originally, this was to be machined at a slight angle to pull the armature holders into a shoulder. This idea had to be revised as it turned out to be unreasonably difficult to cut.

With this knowledge in mind the morphological charts were updated and the alternate solution of using ways and a vertical T-slot was selected instead.

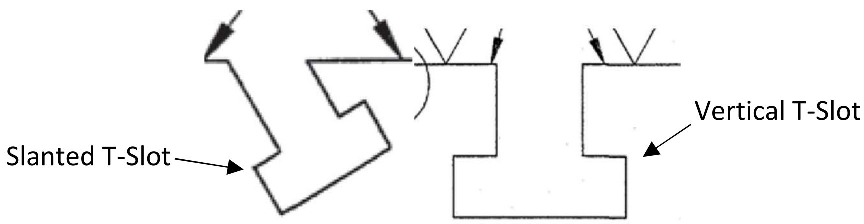


Figure 40. A drawing feature showing the change to ease manufacturing.

Weight Reduction for Assembly

Something overlooked in design was the physical labor required to assemble the parts. The overall weight of the assembled tool is above 150 pounds. This means to safely move it, someone must either disassemble it or use lifting equipment. Some of the subassemblies such as the armature turning subassembly were also difficult to lift and install by hand.

In future versions of the tool, large areas of the base plate will be cut away or have, their thickness reduced to allow it to be more easily carried. The armature holding podiums and the armature rotating assembly could also have some material removed to make handling and assembling easier.

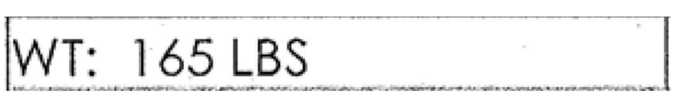


Figure 41. Them estimated weight of the top level assembly without the machine table.

Manufacturer Capability, Capacity, and Lead Times

A major lesson learned through this project was how unique each manufacturer is and how much information and time it takes for them to produce good parts. Part drawings of simple parts that we believed were clear and should not take long to manufacture ended up taking weeks or even months to complete.

The quality and lead times from manufactures vary wildly. Different tool houses have different equipment and different proficiencies. Knowing the right people to talk to before starting projects can save a tremendous amount of time and help guide a design quickly to completion under one roof. It was a manufacturer who was able to explain to us the risk of failure in heat treatment and suggested the vertical T-slot and the ways instead.

Many Simple Parts Vs One Complex Part

Several parts of this machine such as the red or gray parts of the below assembly were originally designed to be made from a single solid piece of steel. We received rapid feedback that this would drive the cost of machining beyond what was acceptable. The cost of these parts was a result of the complexity that ultimately increased the risk of scrap. Part ficturing for machining is also more difficult on complex geometries. The cost of manufacturing was greatly reduced by separating the parts into rectangular sections that could be bolted together.

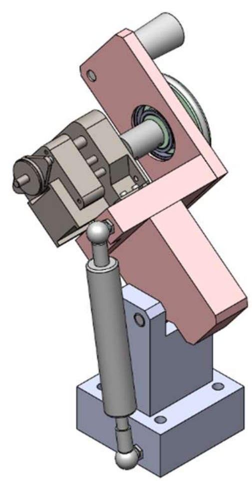


Figure 42. A computer rendering of the armature rotating assembly.

Transport and Safety Considerations

A dangerous accident occurred on February 3rd 2020 when the machine and the table it was being lifted on fell off the forklift and hit the floor. Had someone been standing in its path he or she would have been seriously injured. This fall also damaged some of the electronics. The cause of the fall was the way the tool and its table were being lifted. The machine is extremely heavy and was installed on top of a heavy-duty steel table to support its weight. Unfortunately, the table was much higher than it was wide which resulted in a dangerously top-heavy configuration when being lifted from the bottom.

To prevent similar accidents in the future, large stickers labeled “LIFT HERE” were affixed to the table just beneath the tool and above the center of gravity to assure that it is lifted safely in the future.

Implementation

Prior to shipping, several of the subassemblies were removed from the base plate to reduce its weight and profile. It was at this time that the corrosion proofing was applied to the individual parts.

The prototype of the tool arrived in the armature assembly facility on February 10th, 2020. To stabilize the tool and prevent it from falling over, it was studded securely to the floor in three locations.

Two problems became apparent when the tool was reassembled. Firstly, there is no obvious way to align the travel of the X-stage to be parallel to the axis of rotation of the armatures. Secondly, the sensor was occasionally giving erroneous readings.

If the X-stage is not parallel to the axis of rotation of the armatures it will not give accurate results. However, being off center or at an angle to the commutator reads a predictably conservative value of $Reading = TrueValue/Cos(Theta)$ where Theta is the angle between the sensors line of sight and the orthogonal axis of the commutators surface. Both requirements are maximums so this misalignment will possibly cause rejection of correctly manufactured parts and not acceptance of incorrectly manufactured parts. To reduce the number of false rejections, the drawings will be updated with requirements for setting the X-stage using gage blocks to assure it is both running parallel to and directly centered beneath the commutator’s axis of rotation. This was not a problem realized during protype testing as the group knew to align the slides using blocks without that information being on the drawings.

The source of the sensors erroneous readings is still unknown. The readings were not present at the domestic facility prior to shipping. Only three things had changed between testing and implementation of the tool. To prevent these readings from creating false rejections, software is being developed to filter out the incorrect readings.

Unfortunately, due to Covid-19, also known as coronavirus, I was not able to implement the tool myself at the end of March as we had originally planned. To prevent further serious delays, we are building the second and third units so that we may test and further develop the tool without travel complications.

9. Conclusion

The original design intents of this project were specified in the design brief of this report. A summarized version of the requirements and whether they were met is listed below.

- The new method should be standard across all sites and reproducible without specially trained operators.
    - This criterion was met. Three identical version of the machine were built, assuring that all sites have the same equipment. Additionally, the tool is easy to use and gives the operator feedback for rapid troubleshooting.
- The new method should reduce the time needed to examine an armature to less than half of its original time.
    - This criterion was met. The measurement time was reduced from over ten minutes to less than two.
- Human error should be mitigated in the new measurement system.
    - This criterion was met. The measurement quality is no longer dependent upon an operator's skill.
- Any new tools manufactured should avoid exotic machining processes.
    - This criterion was met. All parts can be manufactured on standard metal cutting machinery such as lathes, mills, and grinders.
- Any new tools manufactured should avoid exotic materials.
    - This criterion was met. All materials used were common alloys of steel and aluminum that are readily available from multiple suppliers.
- All tools developed should be easily repairable to assure they continue to function as they age.
    - This criterion has been met to a satisfactory degree. Most of the tools parts can be easily reworked or replaced with common hardware. Precautions have been taken to ensure that the few components that are not easily reworked or replaced are adequately protected.
- The tool should be able to fit all production units and any similar product developed in the future.
    - This criterion was met. several armatures that were not part of the original scope can also be inspected by the TIR tool without modifying the hardware.
- The necessary precision of the measuring method is to be 0.00001 inches or greater.
    - This criterion was met. The final tool is capable of reliably measuring to ten millionths of an inch

This tool met or exceeded all design requirements. As we roll out this tool to all locations, we expect to see a significant improvement in product quality and process control as well as a measurable reduction in lead times to our customers. We estimate a reduction in lead times of two weeks.

10. Acknowledgements

I would like to thank The University of Akron for the time and resources that it has invested in my peers and me. The university has given us a quality practical education that I will benefit from for the rest of my life. The other institution I would like to thank as a whole is Safran Electrical and Power. Safran has been very generous with their time, personnel and facilities. Without the sponsorship of Safran, I would have struggled tremendously to complete this project.

Bill Thomas from Willow Tool & Machining proved himself an invaluable resource. He provided a greater service than just a reliable and efficient machine house. He also gave our team valuable feedback on our designs from a manufacturing perspective. While other machine houses simply refused to quote our parts, Bill took time to explain why the parts were being turned away. On occasion, he even offered ingenious solutions to some of our design problems.

I would also like to thank Gopal Nadkarni from the University of Akron for his help with this project. He was very patient in working around my busy schedule and did a great job to assure we kept an open channel of communication. I greatly appreciate the independence he allowed me throughout this project.

I would like to thank Stefan Teufel for both his patience and his meticulous proofreading of my report.

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I would also like to thank Adam Brugmann, Terry McGlothlin, Dante Peruzzi, and Tom Katcher for their support throughout this project. They provided invaluable engineering guidance based on years of experience that I can only hope to possess in the future.

11. References

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12. Glossary of Uncommon Terms and Abbreviations

AC

Alternating Current is a type of electrical current that alternates direction.

APU

An Auxiliary Power Unit is a device that generates electrical or hydraulic power for uses other than propelling the aircraft. APUs can power everything from simple cabin lights to steering control surfaces.

Bar-to-bar

Bar-to-bar is a measurement expressing the radial difference between two adjacent commutator bars with respect to the axis of rotation. i.e. a bar-to-bar measurement of .001 inches implies that one commutator bar is .001 inches taller than its neighbor.

DC

Direct current is a type of electrical current that does not alternate direction.

T.I.R.

Total indicated run-out is a measurement of roundness. It represents the total deviation of a surface from perfect roundness about its axis of rotation. i.e. a 1 inch diameter disk rotating off center by .001 inches would read a radial low of .499 and a radial high of .501 inches. This would be read as a T.I.R. of .002 inches.

Ways

Ways are a form of basic guide rail often used on lathes. Ways are a raised V shape made on the base of a tool that other components may ride on.