Letter of Transmittal

4 December, 2019

University of Manitoba
Winnipeg, MB R3T 2N2

Dear Dr. Labossiere,

We, Group 21 – Dustbusters, are very pleased to present you with our engineering design report for a powder removal device. This fulfills one of the final deliverables of the MECH 4860 Engineering Design capstone course project received through the University of Manitoba IDEA Program. The report contains a detailed discussion of the device's capabilities, features, and components, including a parts list, cost breakdown and final CAD model.

Every effort was made to design a device which meets our client's needs and technical specifications outlined in the report. However, as a team of engineering students, Group 21 recognizes that all drawings for manufacture and assembly must be stamped by a licensed and practicing professional engineer, and that assembly of the device or future prototypes or variants from the original design including the operation thereof are carried out with the proper due diligence, care and appropriate expertise.

Due to the current limitations of industry standards and best practices associated with the safe handling, explosion mitigation and venting of titanium powder and/or its combustion products, we cannot guarantee that the device will operate safely and successfully at all times as intended. These limitations are made clear in the report where they apply. Some components are not intended for use with titanium powder but are included as part of a complete design.

In closing, we would like to express our thanks for your advice and support throughout this semester.

Sincerely,

Group 21 – Riley Anderson, Hannah Beynon, Atlanta Geleta, Daniel Gervai, Lukas Schulz

Faculty of Engineering
Department of Mechanical Engineering
MECH 4860 - Engineering Design - A01
Fall 2019

Design of a Powder Removal Device for Direct Metal Laser Sintered Parts

Phase III - Final Design Report

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4 December, 2019

Executive Summary

Precision ADM is a global engineering and manufacturing solutions provider that produces a variety of metallic 3-D printed parts for various sectors including the medical sector. The production of such parts involves sequentially sintering thin layers of metallic powder until a part is built. Upon completion of the printing process, the part is encompassed in loose powder and must be subjected to a post-print powder removal process. Precision ADM's current post-print powder removal process is time-consuming, labour-intensive, lacks repeatability, and exposes employees to safety risks. To address these issues, Precision ADM has commissioned a design project to a student engineering team through the University of Manitoba's IDEA Program. The project was completed over the course of a 4-month semester.

The goal of this design project was to design a device that improves the client's post-print powder removal process, an important step in the production of 3-D printed metallic parts. After parts are printed, they are first vacuum cleaned to remove the loose encompassing powder but some powder remains within the tight spaces and voids of the part. This powder must be completely removed for parts to meet the medical industry's stringent regulations.

The proposed solution to this challenge is a fully automated device with three modes of powder removal: gravity-assisted powder removal, vibration and impact, and blow-off air cleaning. The device rotates the build-plate about two rotational axes, allowing gravity to pull powder out of part voids at virtually any spatial orientation. Continuous vibration and forceful impacts are delivered to the parts by two vibration motors and a pneumatic impactor, respectively. Blow-off air cleaning is accomplished using an industrial air knife attached to a linear actuator. Automation and control of these systems is achieved via a PLC system and compatible sensors, switches and valves. Powder removal takes place in a sealed enclosure that is connected to a powder collection-and-recovery system. The device also features a blow-out panel which allows for excess pressure to be released from the enclosure into an adjoining vent in case of a powder explosion. The design of this vent is provided as a mitigation and is in no way intended to replace a properly rated commercial solution which was outside of the scope and budget of this project. Similarly, due to the relative infancy of the additive manufacturing industry, some components in the system are not rated specifically for handling these explosive metallic powders. Caution should therefore be taken when implementing this design. The total material cost of the device is $9,689.05 CAD.

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1 Introduction

Precision ADM is a global engineering and manufacturing solutions provider that utilizes direct metal laser sintering (DMLS) additive manufacturing (AM) in combination with conventional multi-axis machining to produce components for the medical, aerospace, energy, and industrial sectors [1]. DMLS AM produces 3-D parts by sequentially fusing thin layers of a metallic powder with a high-powered laser. The process results in a solid part encompassed in metallic powder. Precision ADM is committed to improving their DMLS post-processing and commissioned a student engineering team at the University of Manitoba to develop a solution for the removal of powder from printed parts [1].

The client's post-processing of builds involves the removal of metallic powder from DMLS parts after the printing process is complete. This removal occurs in three main phases: initial cleaning, on-plate cleaning, and final cleaning. During initial cleaning, the excess powder surrounding the on-plate parts is vacuumed away while the build is still inside the printer. During *on-plate* cleaning, an operator repeatedly impacts the build-plate with a dead-blow mallet to dislodge powder. This phase of powder removal also includes blow-off cleaning of builds on a downdraft table. During final cleaning, parts are removed from their build-plates and individually subjected to ultrasonic vibrations while submerged in ionized water. The main weakness of the client's current post-processing is the *on-plate* cleaning phase: it is time-consuming, lacks repeatability, and exposes employees to metallic powder.

The goal of this project is to design a device that improves the safety, effectiveness and powder reclamation of the current on-plate cleaning phase for medical implant parts. The client expressed a specific interest in gearing the device towards medical implant parts manufactured out of Ti-6Al-4V titanium alloy powder because the medical sector has the highest cleanliness standards. The device must improve current on-plate cleaning phase while also minimizing operator time spent performing manual labor by being semi or fully automated.

This report describes in detail the solution developed by the team for future implementation by Precision ADM. The presented design is intended to effectively satisfy the client needs.

1.1 Customer Needs

Table I lists the client approved needs and technical specifications, ranked by importance. The actual value column indicates the expected value of the final design for each metric in terms of it's specified units.

TABLE I
NEEDS AND TECHNICAL SPECIFICATIONS

No.	*Category* / Need / *Metric*	Unit	Target Value	Actual Value
1	***Operator Safety and Comfort***			
1.1	Protect operator from airborne powder			
	Use dust-tight enclosure	NEMA	5 [2]	N/A
1.2	Protect operator in case of explosion			
	Enclosure protects user from explosion	binary	yes	TBD
1.3	Minimize chance of powder ignition			
	Use rated fire safe components	UL	94 V [3]	maximized
1.4	Minimize operator strain, effort, exertion			
	Reduce # of operator actions needed	int	5	3
1.4	Minimize operator strain, effort, exertion			
	Level of strain on operator	subj	minimized	minimized
1.5	Safely contain powder throughout cycle			
	Carrying capacity of powder container by weight	kg	5	1.15
1.6	Inhibit powder accumulation			
	# of corners and pockets for material to accumulate	int	0	minimized
2	***Effectiveness***			
2.1	Remove powder consistently			
	Powder removed compared to current method	kg	TBD	TBD
2.2	Protect operator in case of explosion			
	Enclosure protects user from explosion	binary	yes	yes
3	***Efficiency***			
3.1	Reduce labour hours in post-processing			
	Cycle time from part loading to removed	minutes	20	TBD
3.2	Fully or semi-automated			
	# of operator actions required to complete process	int	5	2

TABLE I CONTINUED

No.	*Category* Need *Metric*	Unit	Value	Actual Value
4	***Reliability***			
4.1	Long service life			
	Length of service life	hours	10,000	TBD
4.2	Requires minimal operational maintenance			
	Time between maintenance intervals	hours	TBD	TBD
5	***Serviceability***			
5.1	Permits device maintenance and servicing			
	Mean time to repair any component (MTTR)	minutes	90	TBD
5.2	Can be maintained using standard tools			
	Unique tools needed for maintenance	list	none	0
6	***Manufacturability***			
6.1	Maximize use of standard components in design			
	% of standardized components	%	100	maximized
6.2	Custom parts are manufacturable in-house			
	% of custom parts manufacturable in-house	%	100	maximized
7	***Infrastructure Compatibility***			
7.1	Interface with client's existing utilities			
	% of compatible interfacing components	%	100	100
7.2	Occupy a minimal amount of workspace			
	Volume of shop workspace	m^3	1.5	0.6
8	***Budget***			
8.1	Stay within client's budget			
	Cost of device manufacture and assembly	CAD	5,000	9,689.05

The table above shows that the initially established needs and metrics were not easily quantifiable when applied to the final design. A large portion of the needs require that the device be built and tested in order to come up with a reasonable value. Rather than using the customer needs and their target values as rigid acceptance criteria for the design, the needs and their rankings helped to make important design decisions. The top needs categories of operator safety and comfort, effectiveness, and efficiency were particularly influential on the design, as you will see in the following discussion of the detailed design.

2 Detailed Design

The final design is shown in Fig.1. The design features three different methods of powder removal, a powder separation and containment mechanism, an electrical system, and appropriate safety features. The central mechanism of the device removes powder by reorienting the printed parts. Vibration is the second mode of powder removal and vibration sources are mounted to the rotating assembly. Lastly, an actuated air knife has been mechanized to remove lingering powder from parts. Once powder has been removed a downdraft and cyclonic separator are used for powder collection. These functions are structurally supported by an extruded aluminum frame which is sealed around the cleaning assemblies to form a dust enclosure. The device is easily operable from a user interface and will run automated cleaning cycles with minimal user input. The device is also fitted with a blowout panel which vents though a secondary containment unit and filter in the event of a powder deflagration.

Figure 1: Master assembly of powder removal device

This section of the report breaks down the description of the device by its functionality, secondary features and its operation and construction.

Sections 2.1 to 2.3 focus on the three powder removal functionalities. Sections 2.4 to 2.6 cover the secondary device features: structural and powder handling. Lastly, sections **??** and 2.7 explain the device's operation and construction including a bill of materials.

2.1 Build-Plate Motion

The build-plate mounting and rotation assembly is capable of moving the build-plate into every orientation useful for gravity assisted powder removal. This is accomplished by a two-axis rotational positioning system. Figure 2 shows the assembly, including the clamped build plate, supporting structure, secondary rotation motor, chain drive, and coupled drive shaft. The vibration assembly is attached to this system and was a significant consideration for material and fastener selection. It is also critical that the component materials do not introduce powder contaminants as they are located inside the dust tight enclosure. The following sections detail the operation of the build-plate motion assembly as well as the component design and selection.

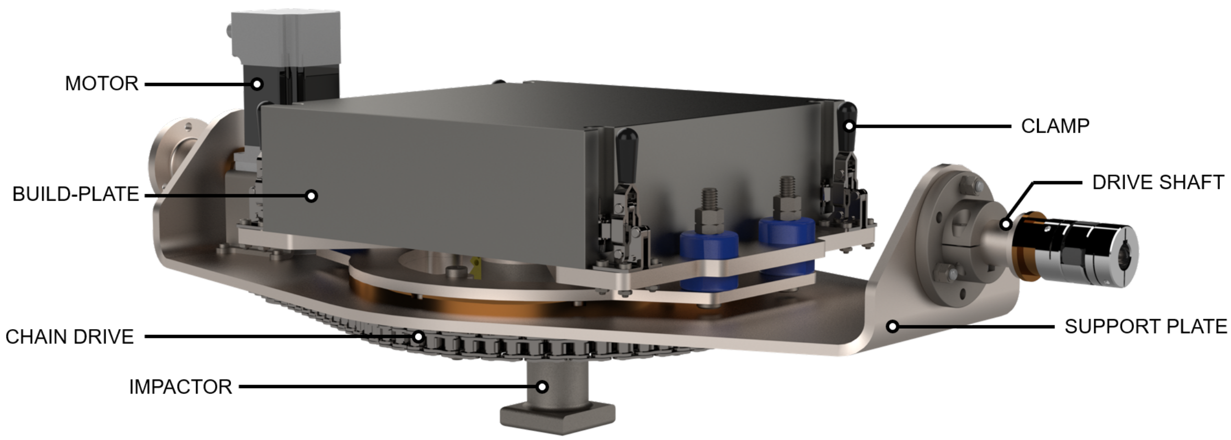

Figure 2: Build-plate motion assembly

Figure 3 outlines the two rotational degrees of freedom of the mounted build-plate. Axis A provides rotation capable of inverting the build-plate, and is directly driven by a stepper motor and worm gearbox (not shown). Rotation in this axis is limited to 180 degrees from its home position to prevent the pneumatic lines and electrical wires from wrapping. Axis B is driven by a stepper motor and planetary gearbox that transmits torque to the chain drive which permits up to 360 degrees of rotation.

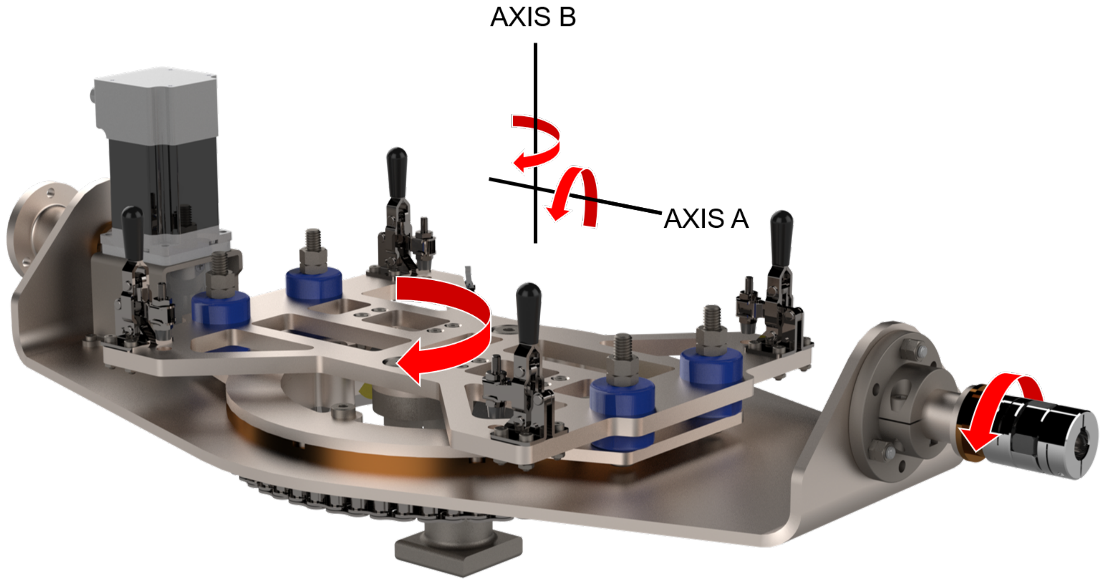

Figure 3: Axes of rotation of build-plate motion assembly

Axis B's rotation mechanism interfaces directly with the build plate. Figure 4 shows an exploded view of its subsystems.

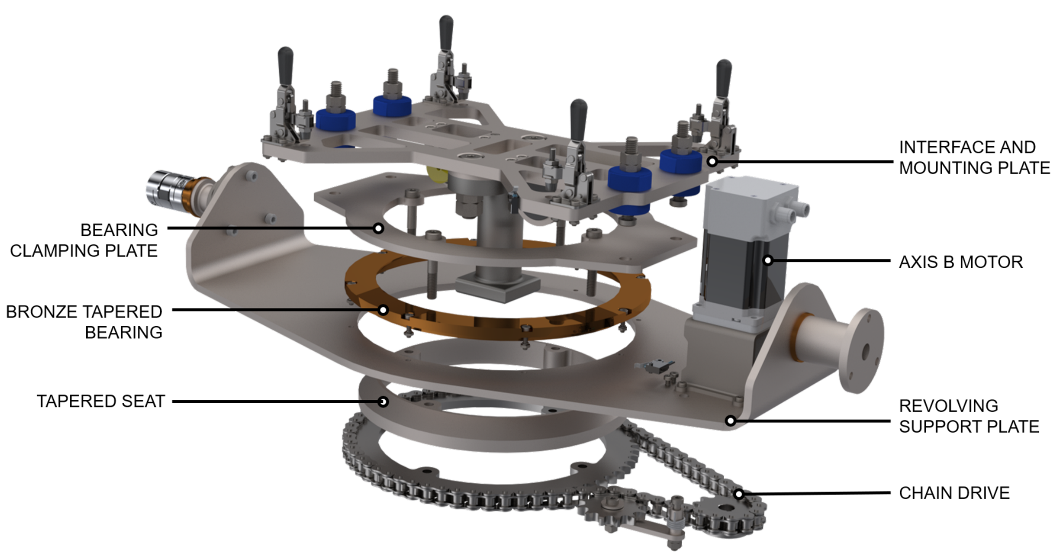

Figure 4: View of axis B rotation mechanism

2.1.1 Interface Plate

Figure 5 shows the interface plate responsible for securing the build-plate, transferring vibrations from the impactor and vibration motors, and allowing for isolation from the rest of the assembly. The build-plate (not shown) is fixed to the assembly by four hold-down toggle clamps with modified rubber plugs. Quick clamping is convenient for the operator, and removes any chance of fasteners being dropped into the powder collection system during setup. The interface plate is machined out of Grade 416 stainless steel plate with counter bore holes for vibration equipment mounting. Grade 416 stainless steel was selected because it is machinable, can be used without hardening, will not dampen the transmitted vibration, and is resistant to corrosion which would contaminate the collected powder [4].

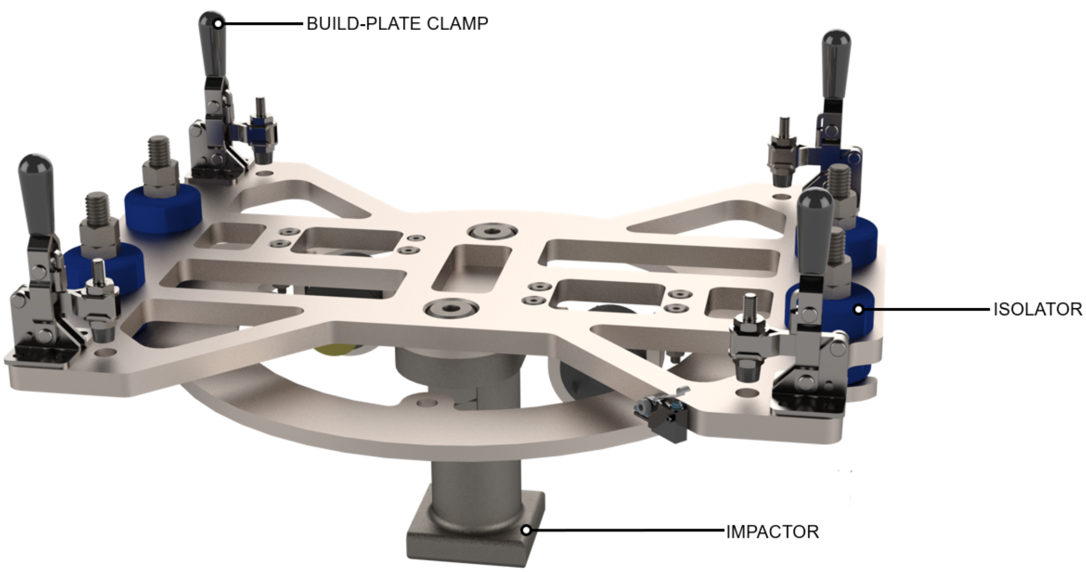

Figure 5: Interface and mounting plate assembly

2.1.2 Bearing Assembly

The custom tapered bearing shown in Fig. 6 seats into the support plate and facilitates smooth movement on both the conical face and top surface. The large diameter bearing helps to protects the assembly against any thrust forces or bending effects caused by vibration, gyroscopic inertia, or weight imbalance. The bearing assembly is bored out to accommodate the vibration generation components, resulting in a more compact and balanced distribution of weight. A simple bearing was chosen over a rolling contact bearing due to the unavoidable vibrations which will be transmitted through the system. The bearing is manufactured out of AMPCO 18, an aluminum-bronze alloy sourced from AMPCO Metal. This alloy has good sliding properties, wear resistance, fatigue resistance, toughness, and will not promote pitting [5]. Eventual wear on the bearing surfaces from contact with abrasive titanium powder is unavoidable, but they can be re-machined and resurfaced along with the steel seat once significantly worn. Surface finishes for the bearing are recommended in Appendix A, but maximizing the surface smoothness will prolong maintenance intervals.

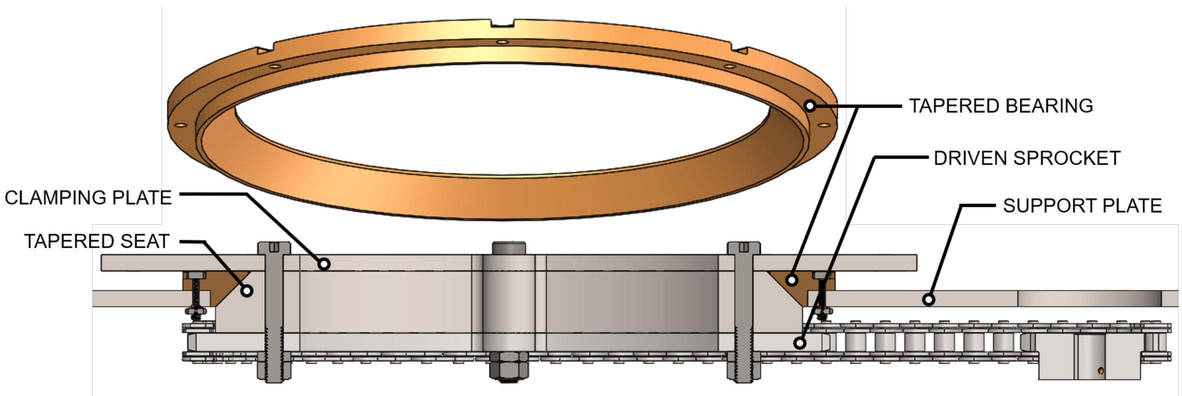

Figure 6: Axis B bearing design and integration

2.1.3 Chain Drive

Figure 7 shows the 5:1 chain transmission assembly which drives the slow rotation (approximately 2 rpm on the large sprocket) of the build-plate about Axis B. The chain drive is cost effective, permits a large reduction ratio, is operable in a dusty environment, and lacks the rubber contamination issues a belt drive would introduce. Furthermore, the sprockets' center-center distance is flexible, providing more room for other components than what is possible in a gear drive. The transmission consists of a driving sprocket, a idler sprocket, and a driven sprocket with a machined bore. The power is transmitted by an ANSI-40 lubrication free roller chain, which is tensioned by the spring loaded idling sprocket. The idler also increases the wrap angle around the driving sprocket to ensure no slippage can occur. Given the very low chain speed, the drive lacks a chain enclosure or guard. Implementing a guard would create a hidden area for powder to accumulate, increasing deflagration risk. Instead, the user is protected by electrical lockouts.

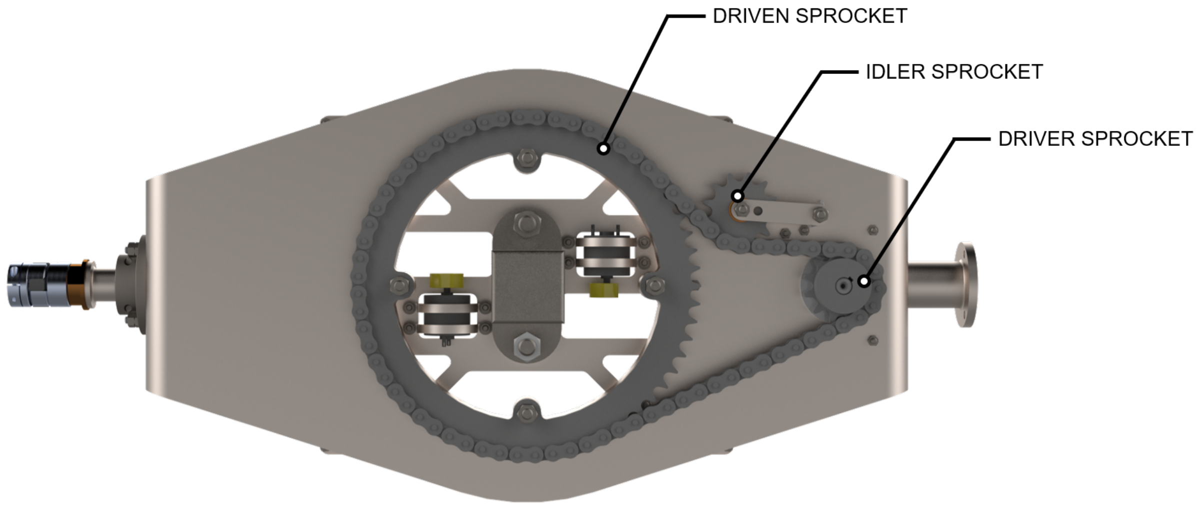

Figure 7: Axis B chain drive

Table II highlights the specifications for each sprocket.

TABLE II
AXIS B COMPONENT SPECIFICATION

Style	No. Teeth	Use
A Plate	60	Driven Sprocket
B Plate	12	Driver Sprocket
A Plate	12	Idler Sprocket

A large diameter sprocket was necessary to accommodate the bore required for impactor and vibration motor mounting. The smallest readily available chain for this sprocket size is ANSI-40. Consequently, the transmission is largely overbuilt for the low-torque, low-speed build plate rotation. This is further justified by ANSI chain sizing tables bottoming out at 50 rotations per minute, with ANSI-40 chains even lacking a power rating at sprocket speeds that low [6].

2.1.4 Revolving Support Plate and Shafts

The revolving support plate serves as the main mounting plate for the Axis B assembly, and is supported on either side by a set of shafts that provide motion about Axis A. The support plate is made out of 1/4 inch stainless steel plate to avoid corrosion contamination issues, which is folded on either side for connection with the shafts. Fig 8. shows an exploded view of the Axis A assembly.

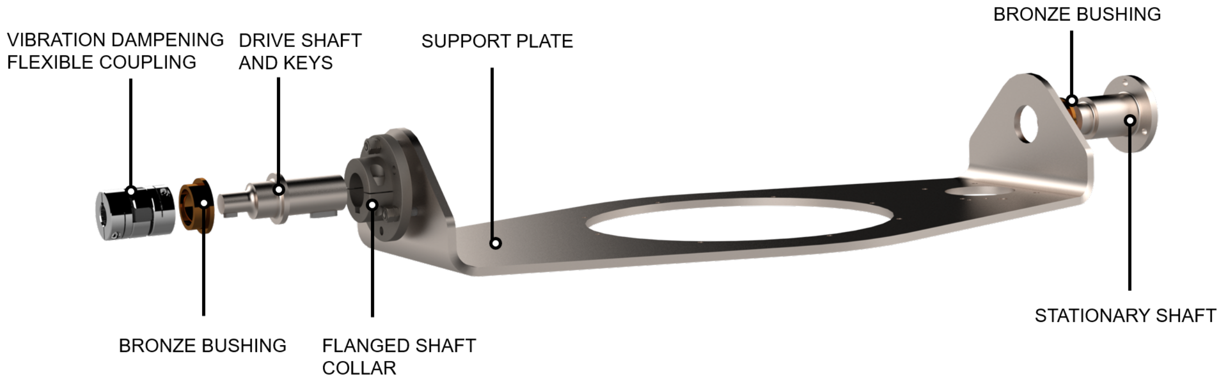

Figure 8: Revolving support plate and shafts assembly

The offset distance is set to keep the Axis B assembly's center of mass balanced, thereby reducing torquing on the driving motor. Complete elimination of the torque is impossible due to the varying weight of the build plate and parts, however a reasonable approximation can be reached by considering the maximum and minimum build plate thicknesses. Torque calculations for both minimum and maximum build-plate thicknesses can be seen in Appendix B.

Fig. 9 shows the driving shaft's side profile. The shaft is bolted to the plate through a keyed, flanged shaft collar. A set of keyways for simple round-edge keys are machined on each end, which allow for power transfer through the shaft. A flexible coupling between the shaft and motor provides vibration protection for the motor while also making shaft alignment easier during assembly. The drive shaft also requires a step down due to the difference in internal diameters on each end, which is filleted to avoid stress concentrations. The shaft extends out of the enclosure through a sealed hole in the side panel, and is supported by an external bearing mount. A simple aluminum-bronze bushing was selected over conventional roller-bearings for its resistance against vibration. The bushing seats into the mount, and is shouldered to fit against the mount's internal edge. The shaft features a similar shoulder for easy positioning. Shaft strength calculations can be found in Appendix C.

The other side of the support plate uses a fixed, stationary shaft fit into another aluminum bronze bushing. The shaft is shouldered to provide positioning against the bushing, which is pressed into the support plate for smooth rotation. The shaft passes through the enclosure wall and is bolted to an external mount. Sealing about the shaft is provided by a rubber grommet.

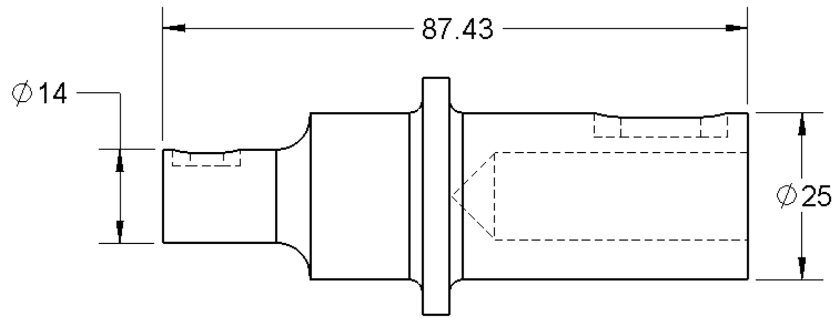

Figure 9: Drive shaft profile

Rotation about Axes A and B afford the build-plate a complete range of rotational motion: almost any orientation within 3-D space is achievable. This maximizes the device's powder removal effectiveness with respect to build-plate rotation. It should be noted that jam nuts were generally used in this assembly to lock the components which experienced vibration. Jam nut and, in some cases, spring lock washers were used in plate of nylon locknuts in order to avoid cantamination.

2.2 Vibration and Impact

The device employs continuous and forceful vibration for powder dislodgement, which are generated by two separate mechanisms. Continuous vibration is introduced using two vibrating motors , while the intermittent and more forceful impacts are delivered by a pneumatic impactor. Both mechanisms are mounted to the underside of the interfacing plate for direct vibration transmission. Rubber isolators are employed at several points to dampen unwanted vibration transmission, thereby preserving component life.

2.2.1 Vibration and Impact Generation

Vibration is generated using two Eccentric Rotating Mass vibration motors (ERM). The centrifugal force generated by the unbalanced rotating mass is transformed into vibration during operation of the motor. Each motor is capable of 125 g (g-force) of vibration amplitude, and have an adjustable frequency that can be achieved by varying the voltage input. The pneumatic impactor produces timed, intermittent impacts by converting a sudden release of compressed air into impact energy via a piston. Impact force and frequency can be varied by restricting air flow with a regulator. Force and frequency adjustability is desireable to provide modular systems of disturbance for printed parts.

2.2.2 Component Mounting and Isolation

The two ERM vibrating motors are mounted on either side of the pneumatic impactor, with balancing accomplished by mounting counter-directionally with respect to each other. Figure 10, shows the interfacing plate assembly.

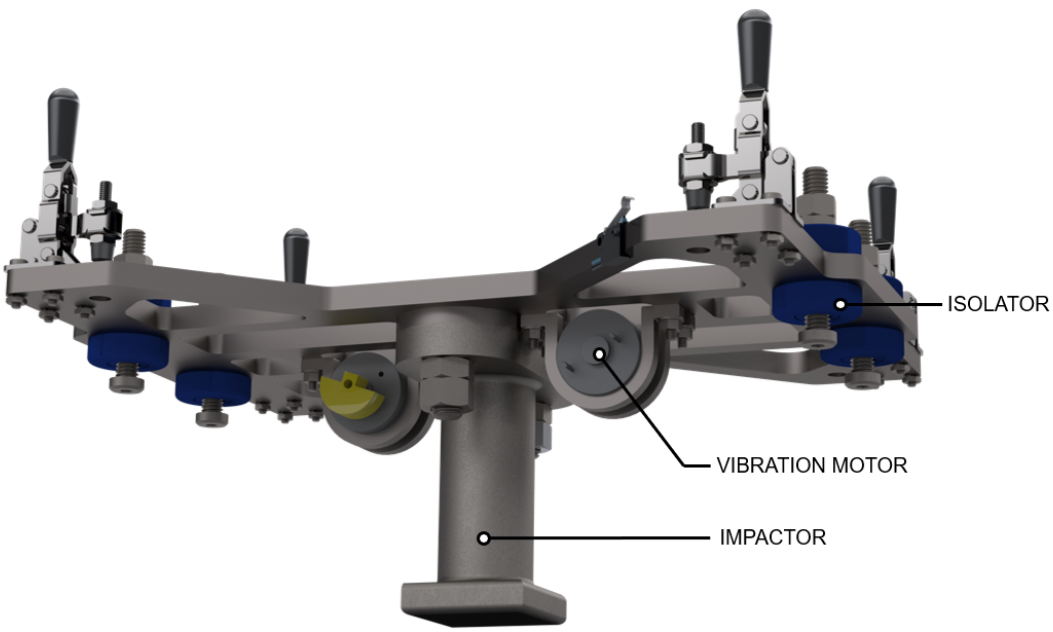

Figure 10: Interface plate assembly

Rubber isolators are placed at the four bolted connections between the interfacing plate and the thrust bearing. This dampens vibration from the interfacing plate before it passes on to the rest of the device through the build-plate assembly. With vibration decreased, component life can be extended substantially.

2.3 Blow-Off Cleaning

The device uses a shop air supply for automated build-plate blow-off cleaning. This step forces loose powder off the edge of the plate, which when combined with vibration and gravity complete the three-system powder removal function. Air usage can be very effective, but also introduce additional safety considerations. These are addressed in subsection 2.4.1 and involve the implemention of a forced downdraft.

2.3.1 Air Knife and Actuator

The device uses a commercially available 12-inch aluminum Full-Flow air knife from Exair®. The air knife is mounted to the end of a linear actuator capable of 12 inches of motion, which enables build-plate blow-off. The linear actuator is mounted to the enclosure roof as shown in Fig. 11, and can be manually repositioned closer or farther from the build-plate by lifting four cam handles, manually sliding the assembly to the desired position, and re-fastening the handles.

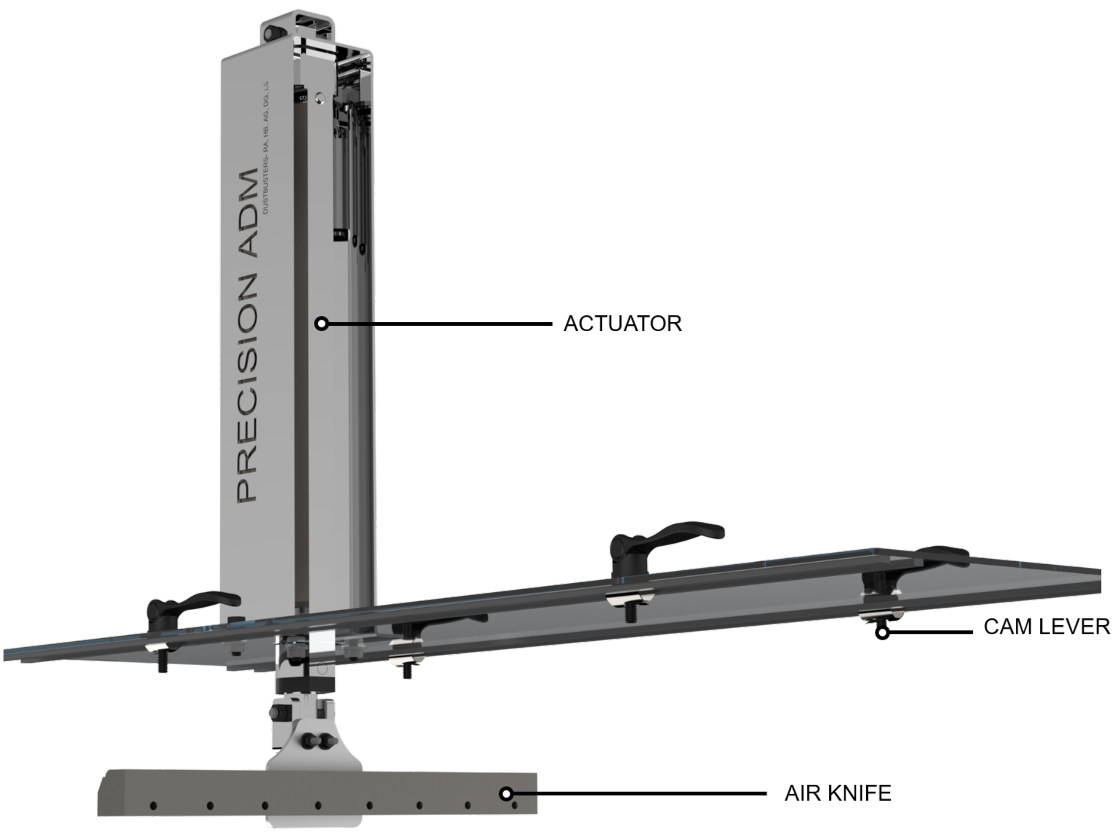

Figure 11: Air knife mounting assembly

An air knife was selected over a nozzle for two main reasons. Air knives offer the ability to clear an entire uninterrupted swath rather than a localized point, thereby increasing coverage without usage of additional nozzles. A multi-nozzle apparatus could feasibly achieve a similar result, but at greater expense and with less uniformity. The second advantage air knives offer is uniform sweeping minimal minimal powder loss. Air knives offer better control over powder dispersion by preventing particulates from passing through the air sheet. The air knife creates a barrier of high-velocity compressed and entrained air which will drag along a swath of powder as the air sheet impinges upon the build-plate. The advantage of powder dispersion control is exploited by only blowing air at the build-plate during the air knife's down-stroke. This forces the powder to the bottom of the enclosure rather than dispersing it upwards which would be both counterproductive and potentially hazardous due to increased deflagration risk.

Close proximity is a key factor in the blow-off effectiveness of air knives. As such, the air knife's back and forth position was made adjustable to allow the device to accommodate varying build-plate thicknesses and part geometries while maintaining a close proximity to the build-plate.

2.4 Powder Collection, Separation, and Containment

Safe collection, separation, and containment of dislodged powder is paramount to operator safety and comfort. Therefore, the key components comprising the powder collection and containment system required careful attention and are discussed in the following subsections.

2.4.1 Downdraft and Vacuum

The first step in promoting effective powder collection is through the use of a forced downdraft.

Vacuum The downdraft is induced by a standard industrial shop vacuum located outside of the enclosure. The vacuum draws ambient air into the enclosure, down through the dust catch basin and cyclonic separator, and into the vacuum chamber. The selected model for this design is the Dayton® Model 3VE21. This vacuum draws air at 155 cubic feet per minute and features a heavy-duty cartridge filter.

A standard industrial shop vacuum was selected because of its attractive features: sufficiently high volumetric flow rate and reasonable cost. This application does not require a high vacuum holding capability (i.e how much negative pressure the vacuum can maintain consistently) because its only function is to draw air through the enclosure. Therefore, the use of a commercially available shop vacuums is a viable option.

Downdraft Downdraft tables are commonly used to purify air of particulate matter. Precision ADM uses a downdraft table in their current powder-removal process. The purpose of the downdraft in this application is to prevent the formation of finely-dispersed powder clouds within the enclosure. These clouds constitute dispersion, one of the five key factors in powder deflagrations (sub-sonic explosions). These five factors (oxygen, heat, fuel, dispersion, and confinement) are collectively termed the “Dust Explosion Pentagon”; elimination of any one of these factors prevents an explosion from occurring [7].

The high volumetric flow rate of the downdraft is attractive because it increases the bulk velocity of the air leaving the enclosure allowing for rapid air cycling and a reduced chance of powder cloud formation. However, the high flow rate requires the device to allow fresh air from outside the enclosure to rush in to fill the vacuum. This is accomplished through the use of a pneumatic check valve.

Pneumatic Check Valve The roof of the device’s enclosure is equipped with a commercially available pneumatic check valve. The purpose of the valve is to relieve the vacuum created inside the enclosure by allowing ambient air to rush into the enclosure through the valve. This ensures there is always downward moving air inside the enclosure to prevent formation of finely dispersed titanium powder.

A check valve was selected instead of an open orifice in the enclosure because it allows air to rush into the enclosure while still maintaining a seal; the check valve only allows air flow in one direction: inwards. Therefore, the valve preserves an effective downdraft without compromising the containment and safety of the enclosure; powder and air will not be allowed to escape. This specific model of check valve was selected because of its high volumetric flow rate capability (130 cubic feet per minute) and very low cracking pressure (0.1 psi) — the pressure at which the valve opens to let air through. A low cracking pressure is important because the shop-vacuum cannot generate a strong vacuum pressure.

2.4.2 Dust Catch Basin

To further aid collection, a dust catch basin is fitted to the underside of the enclosure. The catch basin is constructed of a thermoplastic polycarbonate (PC) and Acrylonitrile Butadiene Styrene (ABS) alloy that is thermoformed into a pyramidal shape. ABS was chosen as the material of construction for its excellent anti-static property. Fig. 12. shows the funnel configuration along with the cylonic separator.

Figure 12: Powder collection and separation assembly

The funnel has a ridge on each face to facilitate material flow downstream. The end of the catch basin tapers down to a circular geometry to interface with the downstream cyclonic separator. The catch basin and the cyclonic separator are joined with piping that includes a 90 degree elbow. Copper tape is routed on the exterior of the cyclonic separator and funnel to prevent static build up in addition to the ground wire connected to one-third of the bolted connection in the assembly.

2.4.3 Cyclonic Separator

This section involves discussion of a component not intended for use with combustible titanium powder. All methods of titanium powder separation and containment incur a significant amount of risk, which is further increased by the presence of oxygen. Usage of this component goes against the manufacturer's safety recommendations and should only be implemented with a full understanding of the associated risks.

A gas cyclonic separator is placed between the dust catch basin and the vacuum generating the downdraft to collect the titanium powder into small collection container. A commercial cyclonic separator intended for use with shop vacuums is implemented.

Gas cyclonic separators are devices which remove entrained particulates from a gas stream using cyclonic flow. Heavy particles suspended in the air are pushed against the walls of the separator by centrifugal force and then forced downwards into a container by the airflow. Fig. 13 illustrates this process[8].

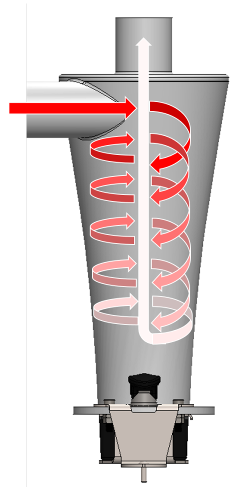

Figure 13: Cyclonic separator flow path

Due to the highly reactive nature of Ti6-Al4-V powder, it is undesirable to rely solely on the vacuum's internal cartridge filter (or any other filter) without further safety precautions. The client informed the team that replacing the powder-laden filters of their EOS printers posed heightened dangers to operators compared to most other tasks on-site, requiring specially trained personnel, protective equipment and strict procedure adherence. Therefore, the cyclonic separator is an important safety feature of the device. It also eliminates the need for filter consumables.

The selected separator (Dust Deputy®) is capable of capturing up to 99% of the dust in the air while consuming only 50 cfm of suction, which can easily be provided by a common shop vacuum. It is also made out of anti-static polyethylene which can be further improved with copper tape grounding to minimize static sparking risk [9].

While the benefits of the cyclonic separator are clear, its risks cannot be ignored. The separator funnels explosive, oxygenated, finely dispersed powder into a small enclosed high-flow container, which is ideal for explosions. Ultimately, the team was unable to source a cyclonic separator officially compatible with flammable powders. To reduce some of this risk, the collection container was designed to be as small as possible in order to limit the amount of powder present in the system. Further protection could also be achieved by paneling and sealing the frame around the separator.

2.4.4 Powder Containment

The powder container is mounted below the cyclonic separator using an adjustable metal bracket. Cam handles allow operators to quickly detach the container for powder disposal, with sealing achieved through flexible foam gaskets adhered to the container's top edge. When loosened, the cam handles create enough space for a thin sheet metal lid to be slid between the container and the separator, allowing for easy sealing of the container with minimal powder contact. The lid features several bent tabs for easy positioning against the container edge, with four rare earth magnets mounted inside the container providing the lid's necessary sealing pressure against the gaskets. Once covered, the container can be slid out of the clamping bracket for easy powder disposal. Fig. 14 shows the complete assembly in its sealed state (without the lid inserted), with a set of mounting brackets to the device enclosure.

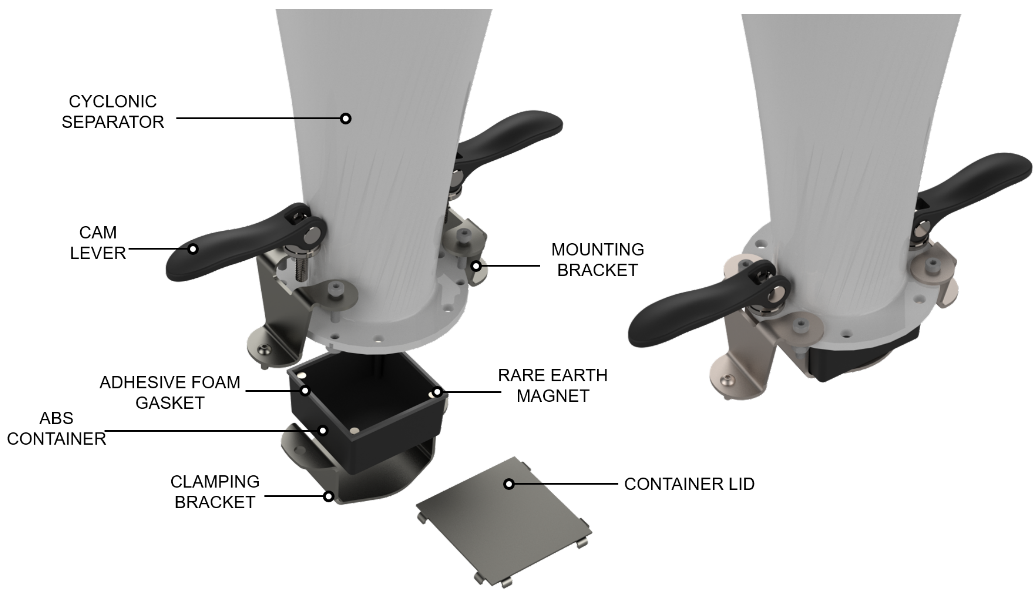

Figure 14: Powder containment assembly

The container was sized to be as small as possible while still sealing against the cyclonic separator output. This is to limit the accumulation of powder in the system, thereby reducing the risk of deflagration. Internal features were kept to a minimum to make emptying easy. The existing screw columns meant for screwing the container's original lid (unused in the design) can be re-purposed as mounting locations for the magnets. This avoids usage of brackets, which eliminates the need for extra holes in the container. Brackets would also create overhangs in the container, making it more difficult to empty.

The sourced container has a volume of 256 cubic centimeters which equates to roughly one kilogram of titanium powder (or six builds' worth based on test data provided by the client) [1][10]. However, the true capacity is less to avoid powder spillage when securing the lid. Implementing an operational restriction of 2-3 builds provides a safer amount of powder while also allowing the lid to be sealed in case of operation error.

2.5 Electronics and Automation

To effectively reduce processing times, the process is automated such that the operator simply inserts and fastens the build-plate to be cleaned, initiates the operation with a start button, and returns to a depowdered part. Per the client's request, the device allows the user to input custom angles into both the axes A and B of the machine for processing especially complex part geometries.

The automation of the depowdering process is achieved using a Programmable Logic Controller (PLC) which sends control signals to the impacting system, air-knife system, and both axis A and axis B motor controllers. Which signals to send and when to send them to each of these systems is determined by a variety of digital timers and limit switches. These switches, sensors, and an emergency stop button act as safety features capable of immediately halting and de-energizing the device in the case of a malfunction or operator error. Finally, a Human Machine Interface (HMI) provides operational and system diagnostic information and enables user input. Details of the component selection process, integration, and the suggested system program structure follow.

A schematic of the main electronic components and their connections is shown in Fig. 15. The details of each component in the figure and its connections are explained in the sections to follow.

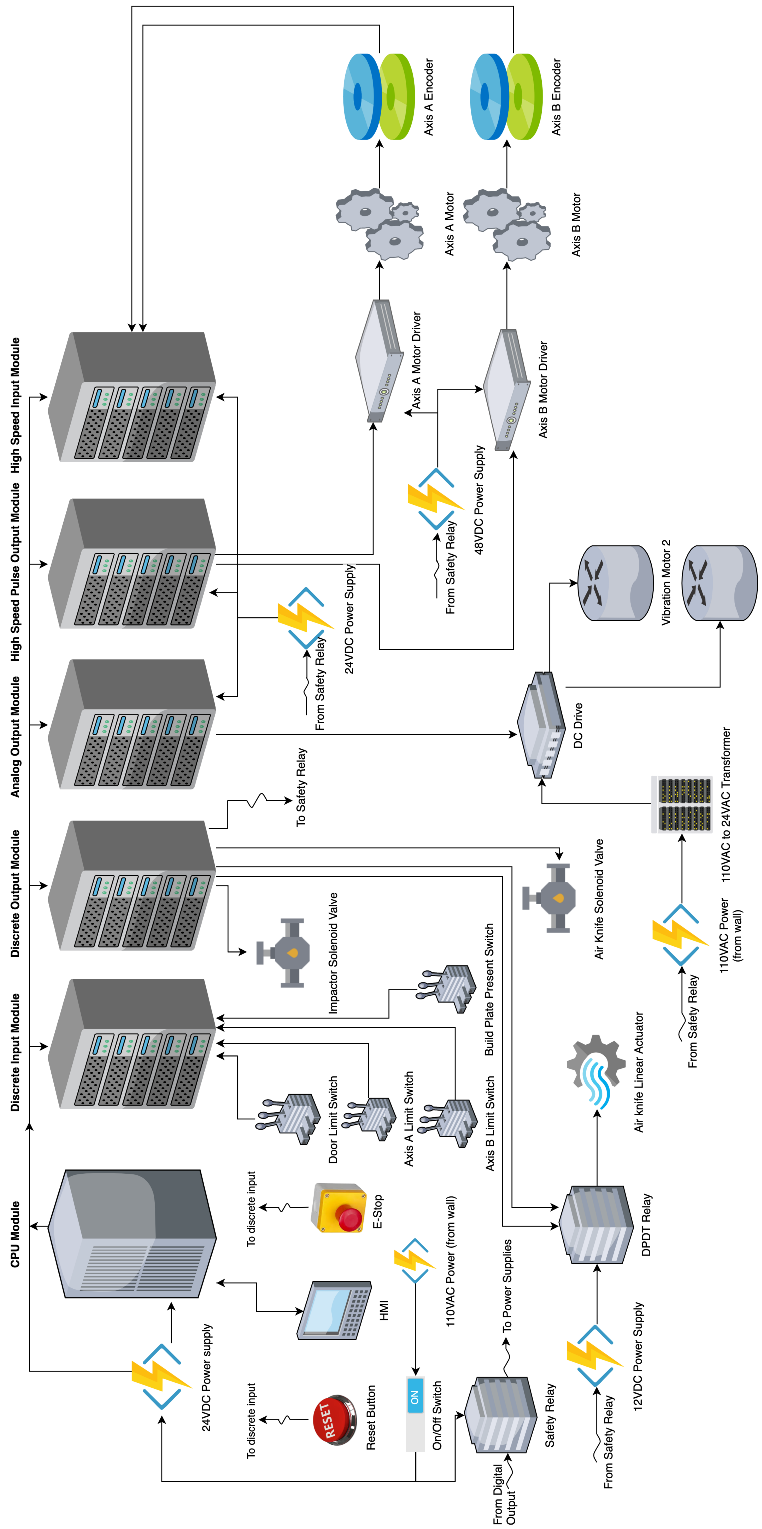

Figure 15: Schematic of electronics

2.5.1 PLC Selection

The selected PLC is the modular Productivity 2000 from Automation Direct,a render of which is shown in Fig. 16. The PLC has seven module slots, five of which are filled with necessary input and output (I/O) modules, leaving two open for future capability expansion. The chosen I/O modules are summarized in TABLE III.

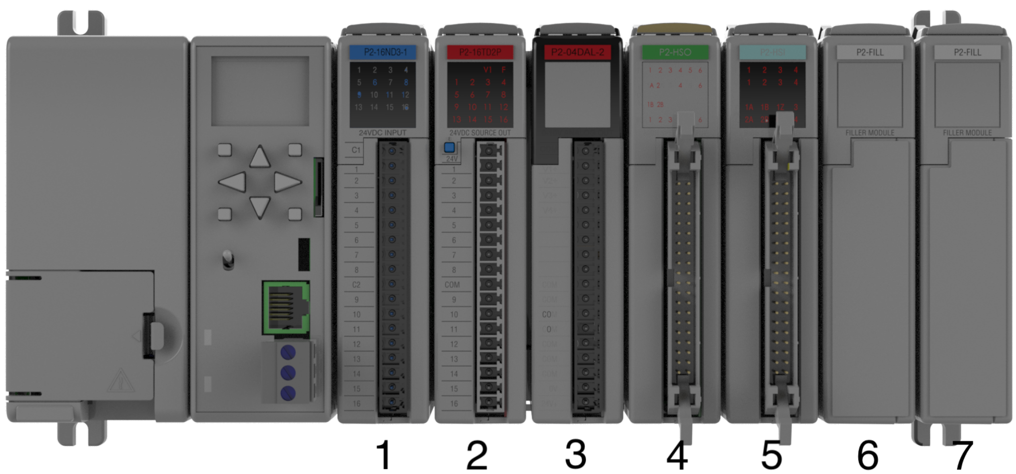

Figure 16: PLC with modules

TABLE III
PLC MODULES

PLC Module	Description	Slot
P2-16ND3-1	16 discrete inputs	1
P2-16TD2P	16 discrete outputs	2
P2-04DAL-2	4 ch. 12-bit analog output	3
P2-HSO	2 ch. high speed pulse output	4
P2-HSI	2 ch. high speed pulse input	5
P2-FILL	filler module	6
P2-FILL	filler module	7

The discrete input module receives binary signals from limit switches located throughout the device and the digital output module controls the system solenoid valves and relays. The analog voltage output module is used in combination with a DC drive to vary the frequency of the vibration motor. The high speed output module sends high frequency pulses to the stepper motor drivers to drive the motors. The high speed pulse input module receives pulses from the incremental encoders on the motors and the PLC interprets this to verify motor positioning accuracy.

2.5.2 User Interface

Figure 17: User interface of device

The user interface of the device is located on a panel of bent 11 gauge aluminum sheet metal located next to the main enclosure door as shown in Fig. 17. The user interface consists of a touchscreen HMI housed in the numeric keypad bezel, an e-stop button, a reset button, and an on/off switch.

A 3" C-more Micro EA1 series touch screen HMI is housed inside of a compatible numeric keypad bezel and communicates via an RS-232 serial port with the PLC, which also powers the HMI. The HMI screen displays prompts and error messages and its on-screen buttons are used to start and interact with the program. The inclusion of the numeric keypad simplifies the process of inputting custom angles into the machine.

The selected on-off switch is NEMA 1 rated to handle 30 amperes of current. The switch disconnects all device electronics from the wall power supply and features a sheet metal tab that enables machine lockout for servicing and maintenance.

The emergency stop button enables the user to stop the machine at any time by disconnecting the input wall power from all of the motor power supplies via an Omron safety control relay which is discussed further in section 2.5.5. The reset button is required to reset the safety relay after it has been triggered.

2.5.3 Motor Selection and Control

To determine motor size, approximate load and acceleration torque values were calculated and summed for each axis in the case of a 10 pound build on both a 3-inch and 1.5-inch thick build plate. Details of the calculations can be seen in Appendix B. The largest torque values from each scenario were considered with a factor of safety of two applied. These values were used to select appropriate motors and gearboxes. Ultimately, small motors with gearboxes were selected over larger direct drive motors for their larger weight to output torque ratio.

The selected drive motors are NEMA 23 dust tight IP65 rated stepper motors with integrated 24 volt direct current (DC) incremental encoders for position feedback. The IP65 rating ensures that titanium dust will not enter the motor during operation and the incremental encoder enables the system to verify that it reaches its commanded position.

The axis B motor is mated to a 20:1 reduction planetary gearbox which is connected to a 5:1 reduction chain drive that rotates the build plate about axis B. The axis A motor is mated to a 25:1 reduction worm gearbox which was selected for it's ability to self-lock. This self-locking action will prohibit the support plate from freely rotating in the case of a power outage, which could injure the operator, damage the device or damage the parts being processed. The calculated factor of safety for both primary and secondary axes of rotation is 2.2 and 5.2 respectively.

Each stepper motor is connected to an EM542S stepper drive which receives command signals in the form of a pulse from the high-speed pulse PLC output. The drive transmits an amplified high-voltage and high-current pulse to the motor corresponding to a proportional rotation angle of the motor. The number of pulses per revolution, or the resolution of the motor, can be varied using dipswitches on the stepper drive. Coincidentally, the incremental encoder attached to the stepper motor provides a feedback pulse signal to the high-speed pulse input module of the PLC to verify that the stepper reaches its desired position.

The vibration motor frequency is controlled using a GSD4-24A-5C DC motor drive and a compatible analog input module. The analog input module allows for the drive's output voltage to be varied from 0 to 24 volts by reading the variable 0 to 10 volt analog output signal from the PLC and converting it to a proportional control voltage between 0 and 24 volts. The optimal allowable vibration frequencies must be determined during device testing with the PLC programmed accordingly.

The linear actuator is driven using a 12 volt, 5 ampere DC power supply in combination with a double pole double throw (DPDT) control relay. The relay is controlled by two discrete PLC outputs, one of which enables a positive 12 volt signal that extends the actuator, and the other enables a negative 12 volt signal that retracts it.

Air flow to the air knife and pneumatic impactor is controlled by an inline air pressure regulator fitted and an electronically controlled solenoid valve, connected to a PLC discrete output.

A Rhino 48 volt, 10 ampere DC power supply will provide power to both the primary and secondary axis stepper motor drivers which have a maximum current draw of 4.2 amperes each. A Rhino 12 volt 5 ampere DC power supply will drive the identically rated 12 volt 5 ampere linear actuator. The PH50PG control transformer converts 110 volt alternating current (AC) power supplied by the wall into 24 volt AC power required by the vibration motor DC drive. Finally, an external 24 volt 2.5 ampere DC power supply is required to power the high-speed input and output, and analog output PLC modules.

Having a home position for both machine axes is necessary to prevent wire tangling, to guarantee process repeatability, and to indicate to the incremental encoders of both axes where the 0 degree rotation angle is. Omron D2HW-C233MR limit switches, selected for their small size and IP67 dust sealed rating, are located at locations shown in Figs. 18 and 19 for homing axis A and B respectively.

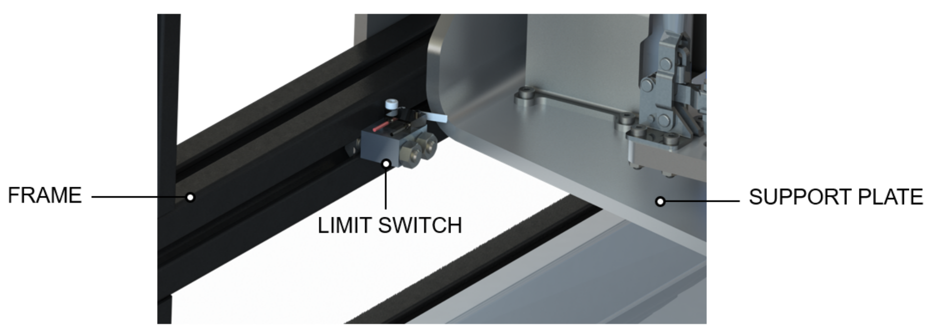

Figure 18: Axis A homing switch location

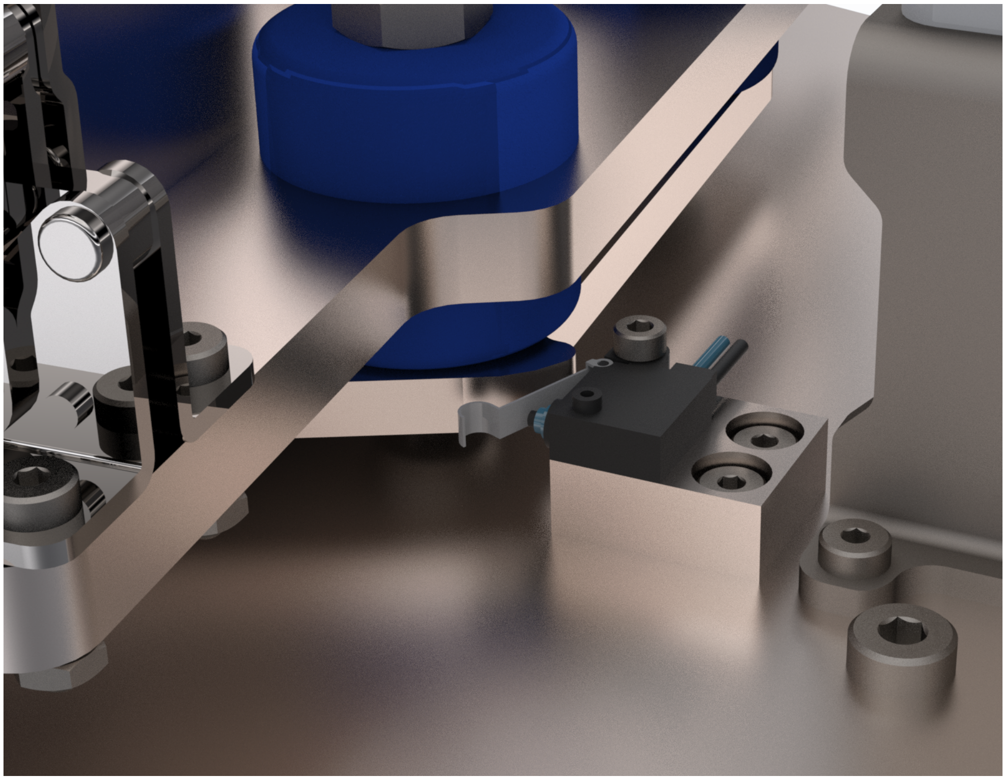

Figure 19: Axis B homing switch location

2.5.4 Electronic Enclosure

The PLC, power supplies, transformers, control relays, safety relays, and motor drivers are mounted within an 18×18×8 inch electrical enclosure box as shown in Fig. 20. To minimize noise in the control signals, power and control signal carrying wires are run separately out of the enclosure to their respective components.

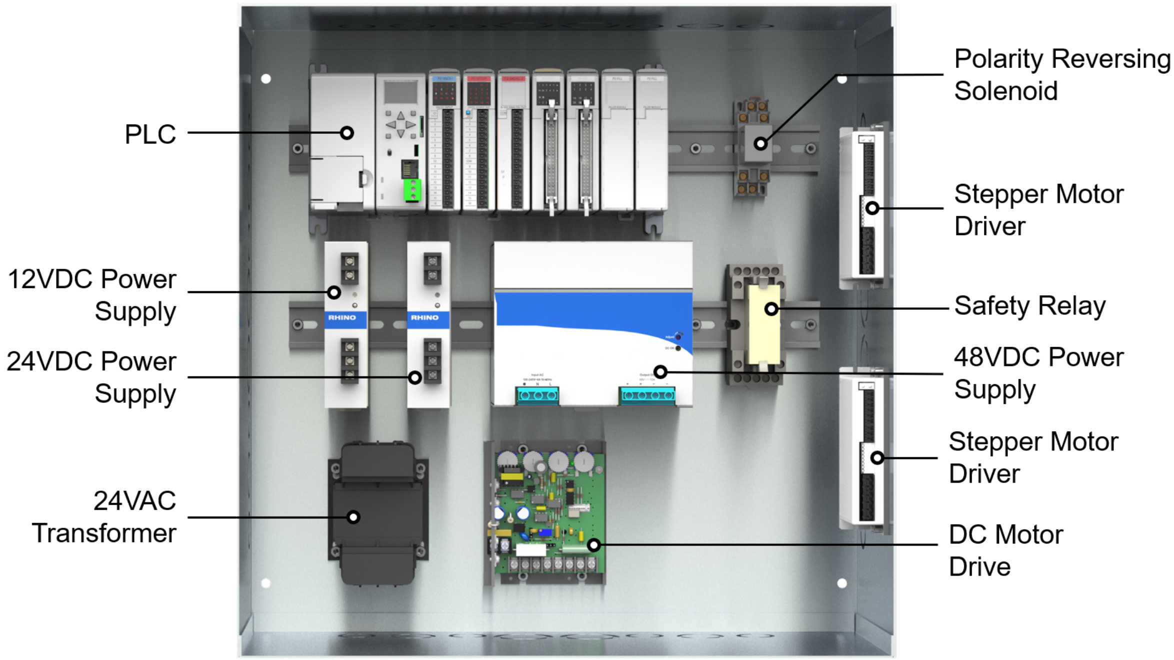

Figure 20: Electrical enclosure box

The control box is mounted to the base of the device frame and is located behind the user interface panel as shown in Fig. 21.

Figure 21: Enclosure box as viewed from the left

2.5.5 Electronic Safety Features

Safety features are integrated into the electronics of the device to protect the operator from prematurely starting the operation and to allow for halting of the operation in the case of a malfunction.

To mitigate operator complacency, a magnetic door switch which detects whether the door is closed or not before the homing process or depowdering process can begin. The chosen switch is an Adafruit magnetic door sensing system. The system consists of a simple magnet that is mounted to the door with an adhesive strip, and the sensor itself which will be mounted via an adhesive strip to the frame.

To prevent the process from being accidentally started without a build plate, a strategically located switch, as shown in Fig. 22, detects the presence of a build plate. This Omron D2HW-C233MR switch will not allow the depowdering process to start unless a build-plate has been inserted into the machine and the door is closed.

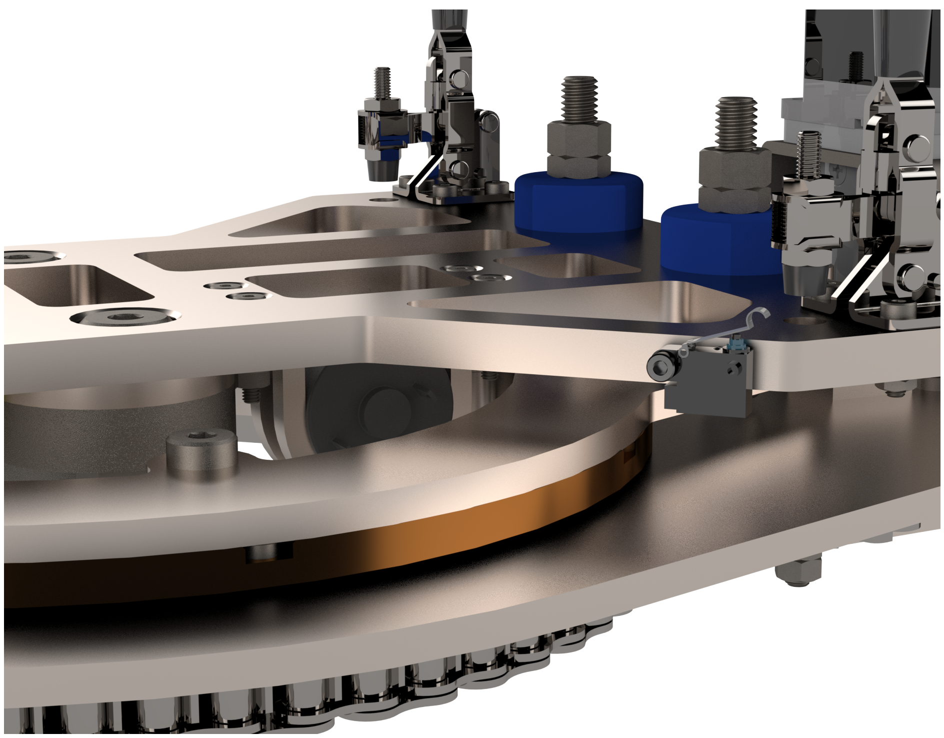

Figure 22: Build-plate detecting switch

The most critical electronic safety feature is the Omron G7S-3A3B-E DC24 safety control relay, which acts as a PLC controlled electronic disconnect between the external motor power supplies and their input wall power. The relay features six contacts, three of which are normally closed (NC) and three of which are normally open (NO). The external motor power supplies are hooked up in parallel to the three NC relay outputs, and during normal operation, power flows directly through the relay. The relay is controlled by a 24 volt DC input connected to a discrete output of the PLC. When this output is in it's energized state, the relay energizes and disconnects all power to the motor power supplies. The relay energizing the discrete output can be triggered by either pressing the emergency stop button, the enclosure door being opened after the depowdering process has started, or a large discrepancy between the commanded and measured motor position. To restart the machine after tripping the safety relay, the reset button must be pressed after all e-stop triggering issues have been resolved, only then can the process resume.

2.5.6 Programming Logic

The Productivity 2000 PLC is programmed using ladder logic in free software provided by the supplier. The supplier also offers extensive resources online for learning the program and its functionalities. Shown in Fig. 23 is a summary of the PLC program in the form of its main functional blocks followed by their descriptions. Per the client's request, the full functional block diagram logic for the automated process is provided in Appendix D.

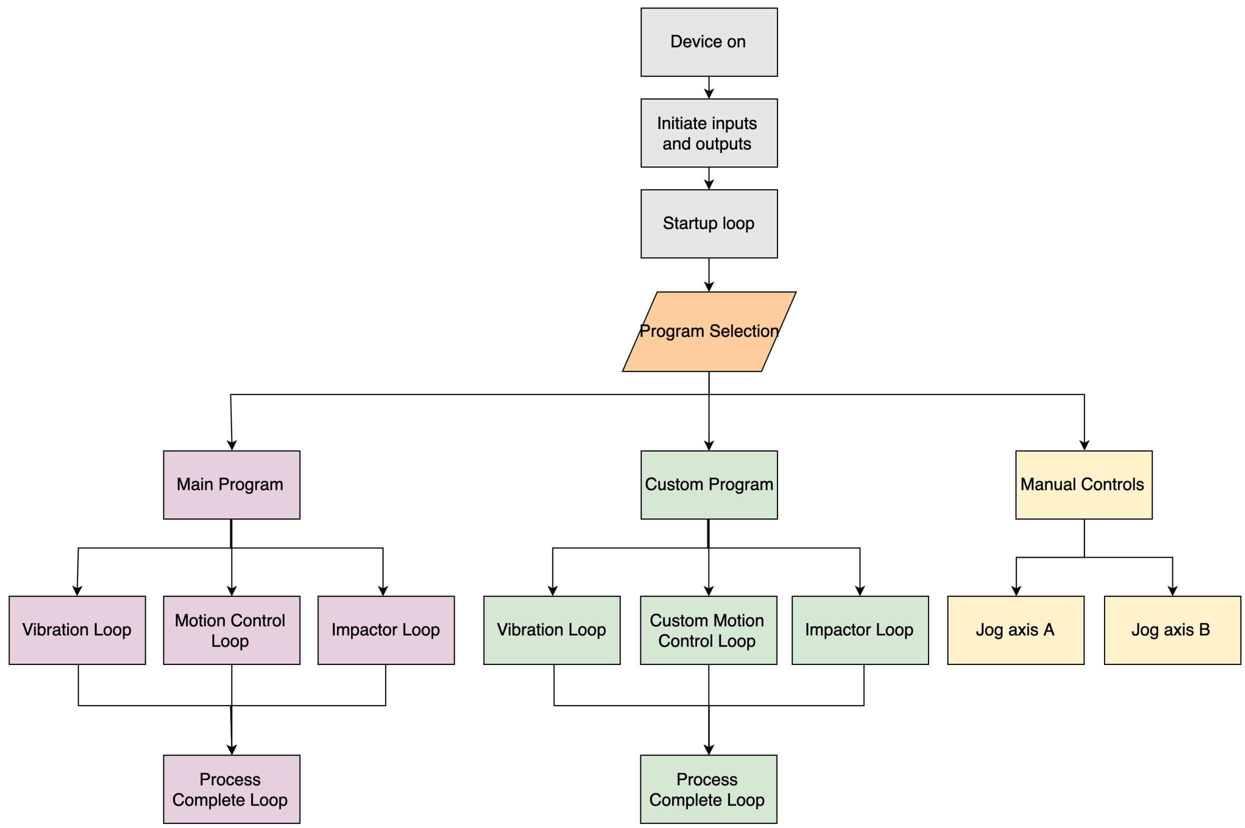

Figure 23: Summarized functional block diagram

Startup Loop The startup loop consists of a series of safety checks and prompts intended to aid the user in inserting the build plate safely. The program starts by checking the status of the door; if it is open the system buzzer is activated. Once the door is closed, both the primary and secondary axes are homed. The user is then prompted by the HMI to insert the build plate into the device. When a build plate is detected and the door is closed, the startup loop is complete.

Program Selection Immediately following the completion of the startup loop, the user is prompted to select a program using the touch screen interface of the HMI. The three program options are "Main Program", "Custom Program", and "Manual Controls".

Main Program This is intended to be the default program, suitable for most builds. The main program starts by simultaneously enabling the vibration motor loop, impactor loop, and motion control loop.

Vibration Loop The vibration loop sequentially commands the vibration motors to send low frequency vibrations for 2 seconds, followed by medium frequency vibrations for 3 seconds, and high frequency vibrations for 2 seconds. This loop runs in parallel with the motion control loop, and similarly repeats until counter 1 in the motion control loop is equal to 16 in the default program, and equal to "# of cycles" in the custom program.

Impactor Loop The impactor loop begins by momentarily engaging the impact solenoid, followed by a 5 second delay to allow for sufficient pressure to build up before another impact is made. This loop runs in parallel with the motion control loop, and similarly repeats until counter 1 in the motion control loop is equal to 16 in the default program, or equal to "# of cycles" in the custom program.

Motion Control Loop First, the axis A motor is driven clockwise 180 degrees, inverting the build plate. Next, the motor is rotated counter clockwise 90 degrees, such that the build plate is perpendicular to the air knife. The air knife is then turned on and driven downwards until the linear actuator is fully extended. The air supply is then turned off and the actuator retracts. Once the actuator is fully retracted, the build plate begins travelling counter clockwise back towards it's home position. Upon reaching home, counter 1 is incremented, and compared to a value of 16. If counter 1 is below 16, axis B is rotated counter clockwise by an angle of 22.5 degrees, and the motion control loop is repeated. If counter 1 is equal to 16, the motion control loop is exited.

Custom Program The custom program is largely similar to the default program in that it uses the same vibration and impactor loop. The difference comes in the form of custom motion control loop described below, which allows more control over the range of angles that the build is rotated through.

Custom Motion Control Loop First the user is prompted to enter the following parameters:

- **Max angle A:** Maximum angle of rotation of axis A
- **Max angle B:** Maximum angle of rotation of axis B
- **Min angle B:** Min angle of rotation of axis B
- **# of increments B:** The number of positions axis B should stop at
- **# of cycles B:** The number of times you want axis B to rotate through the min and max angle

The custom program rotates from 0 to max angle A, instead of going to 180 degrees. Then back to 90 degrees for air knife cleaning, and to 0 degrees after that. Similar to the default program, counter 1 is then incremented, but, in this program is compared to the user input "# of increments B". If counter 1 is not yet equal to "# of increments B", axis B is rotated by a degree increment equal to the range of allowable axis B angles divided by the "# of increments B", and the loop repeats. When the counter 1 comparison becomes true, a second counter called counter 2 increments and is compared to "# of cycles B". If the counter 2 is below "# of cycles B" the entire process repeats. When counter 2 is equal to "# of cycles B", the custom motion control loop is exited.

Process Complete Loop After exiting a motion control loop, axis B is driven clockwise towards home. As a precautionary measure, both axes are driven slowly away from home just until their respective homing switches are off. This allows for the system to detect the momentary on signal required for homing. Finally, a buzzer and HMI message indicate that the process is complete.

Manual Controls Upon selecting the manual controls on the HMI the user will be prompted to select the axis it is that they want to control. Once axis A or axis B is selected, the user is prompted by the HMI to select either the up or down arrow on the keypad. Each arrow press corresponds to a 5 degree increment in either clockwise or counterclockwise rotation of the selected axis motor. Safety checks are in place to ensure that neither axis can be driven past the machines minimum and maximum rotation angles.

2.6 Frame and Enclosure

The frame provides the overall support structure for the device and facilitates the spatial layout of the various components.The enclosure is an integral part of the frame, but refers primarily to the means of maintaining a sealed space within the device. This section covers the design features of the frame and enclosure.

2.6.1 Frame

The device frame is constructed out of black-anodized aluminum T-slot profile structural members. The specific T-slot model is the 40 series 40-4040 Ultra Light Black metric profile sourced from 80/20® Inc. The members have a 40×40 millimeter square profile and open T-slot on each side, as shown in Fig. 24. The T-slots allow for modular construction using a variety of compatible plates, gusseted brackets, and fasteners. The fully assembled frame requires no welding and can be easily customized for additional features. The lack of welds allows the frame to be assembled in-house by the client and may be modified or expanded, offering the client greater flexibility for future changes, if desired.

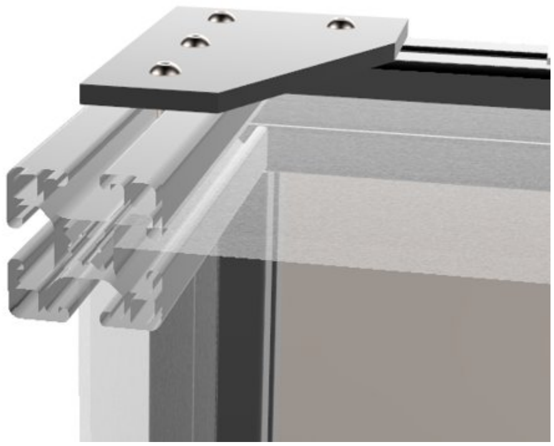

Figure 24: Metric 40 series aluminum T-slot profile

The frame was designed to be able to withstand major bending loads, with structural members analyzed on a beam by beam basis. Calculation details can be found in Appendix E. The 40 series of T-slot was chosen for its bending stiffness, aluminum 6105-T5 construction, light weight, and smooth surface finish.

Several different pieces of hardware, shown in Fig. 25, are used to join the frame's members together. All vertical to horizontal joints are achieved through the use of internal anchor bolt fastener assemblies (not shown), which slide inside the T-slot members and fasten them together using an anchor bolt. The bolt slides into a counterbore, connecting the two members together.

Gusseted corner brackets are mounted to most interior corners below the enclosure, helping to stiffen the joints between the legs and enclosure or legs and the base. Flat corner plates are used to fasten perpendicular members on outside surfaces. These plates are required specifically on the enclosure members where the presence of panels precludes the use of internal corner brackets. These plates support the horizontal load-bearing members on the left and right hand sides of the enclosure, which bear the weight of the entire shaft and support plate assembly. They are also used at each corner of the roof, as shown in Figs. 24 and 25.These components were chosen as they are specifically designed by the manufacturer as part of the framing and fastening system for the metric 40 series aluminum T-slot.

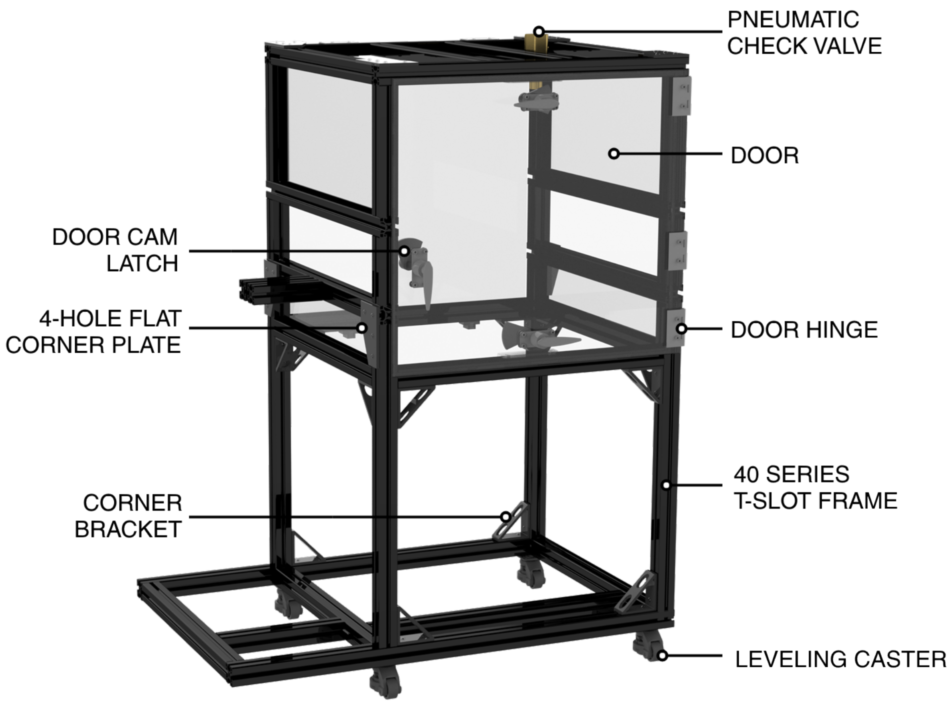

Figure 25: Frame with hardware

The device's overall width, depth, and height dimensions are 37×24×39 inches, respectively. This excludes the linear actuator which adds about 12 inches of height beyond the device's roof.

Casters The entire frame is supported by four, swiveling, leveling casters each load rated for 110 pounds. The leveling casters, shown in Fig. 26, feature anti-static rubber feet which are extendable and retractable using a thumb-screw. This allows the entire device to be made either mobile or stationary. When the wheels are lifted off the floor the device is stationary and the extended rubber feet provide vibration isolation, small level adjustments for uneven surfaces, and static build-up prevention. When the rubber feet are retracted, the wheels make contact with the ground and allow the device to be easily moved.

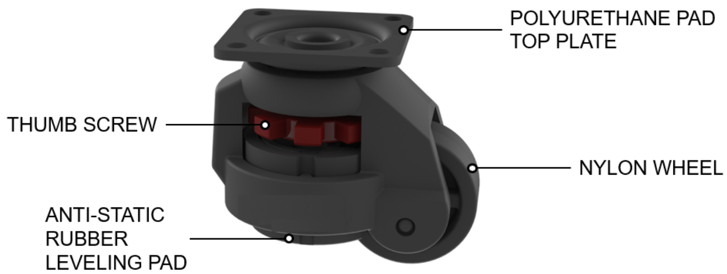

Figure 26: 7GD-40F-BLK model leveling caster

2.6.2 Enclosure

Most members comprising the enclosure frame are slotted with transparent polycarbonate (Lexan^{TM}) panels. These include the door, sides, and roof, with sheet metal being used only in smaller areas, where needed. The rear wall is a thin, hinged blow-out panel made of stainless steel, which serves as a safety device to mitigate powder deflagration hazards. Stainless steel was selected both to avoid corrosion contamination, and for its ferromagnetic properties, but could feasibly be replaced with black oxide steel.

Door The enclosure door is mounted on three large hinges with removable pins for easy detachment and maintenance. The door is fitted with three rotational compression cam latches which provide a strong seal and quick user access. Each latch has a corresponding sacrificial plate made of thin steel sheet metal, which mounts against the aluminum frame members to protect them against scoring by the latches. Sealing of the door is accomplished through the use of a 1/8-inch thick foam seal which adheres to the inside of the door panel. Some spacing is left in the bottom sacrificial piece to accomodate for the powder basin, while also eliminating a location where powder can accumulate. The full door assembly is shown in Fig. 25.

Lexan^{TM} was chosen because it is UL-94-V-0 standard rated for flame retardancy [11]. It is transparent, allowing for immediate visual monitoring of the powder removal process. Lexan has a high impact-strength and is commonly used for blast enclosures, making it capable of containing powder deflagrations.

Side Walls The side walls are each divided into three portions by two horizontal cross-members which bear the weight of the rotating support plate assembly. The top and bottom panels are made of 1/4-inch thick Lexan sheet and the middle panels are made of 1/8-inch thick stainless steel sheet metal. Sheet metal was used mainly for aesthetic reasons, as the shaft running through is heavily featured. Consequently it can easily be replaced with black-oxide steel or Lexan panelling.

The gaps between the enclosure frame and Lexan panels are sealed using black thermoplastic elastomer gasket stripping. The gasket stripping is inserted between the inner surface of the Lexan panels and the T-slot members to form a dust-tight, air-tight seal, as shown in Fig. 27.

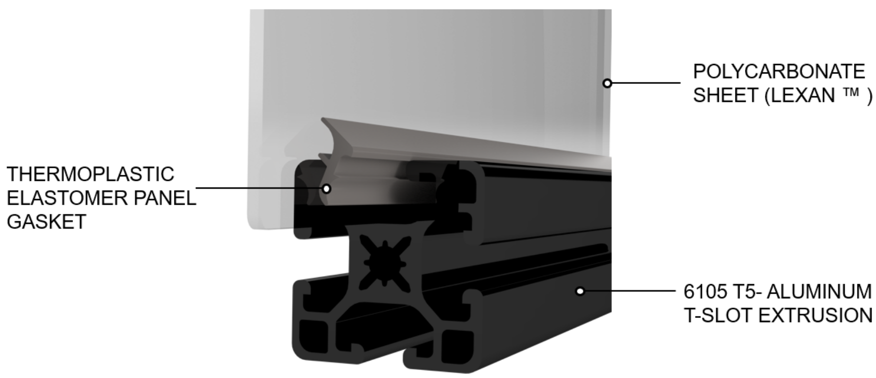

Figure 27: Gasket stripping between Lexan panel and T-slot

The sheet metal panels are sealed similarly, but with the addition of a second strip of gasketing outside the enclosure. This ensures a tight seal by compensating for the 1/8-inch difference in thickness between the Lexan and sheet metal panels. The shafts connected to the support plate pass through the metal side panels. Gaskets are used to the seal between the rotating shaft and the panels, while rubber grommets are used to seal the stationary shaft.

All T-slot grooves on the enclosure frame which are not occupied by a panel are fitted with dust plug strips. Snap-on end-caps are used to seal the ends of members. These two components ensure that dust cannot settle in the grooves of the T-slot profile and slowly migrate out of the enclosure over time. They also prevent foreign contaminants and debris from entering the enclosure.

Roof The roof is divided into three portions by two horizontal cross-members; each portion has a separate Lexan panel, sealed using the same gasket stripping as the walls. The middle panel has a rectangular cut-out which constrains the back-and-forth motion of the air knife assembly during adjustment. The air knife assembly is fixed to a 1/8-inch thick rectangular plate which sits on top of the two cross-members. When the cam handles shown in Fig. 28 are unlocked, the top plate is permitted to slide back and forth along the cross-members; this facilitates the air knife adjustment. The plate must cover the entire middle portion of the roof. Therefore, the plate will overhang the frame at the front or the rear or both, depending on its position.

As shown in Fig. 11, a polypropylene gasket is sandwiched between the cross-members and the sliding top plate. The gasket forms a seal between the top-plate and the members using the compressive force the cam handle exerts on the top plate when fastened. The Lexan roof panels on either side of the top plate are sealed using the same gasket stripping as the walls.

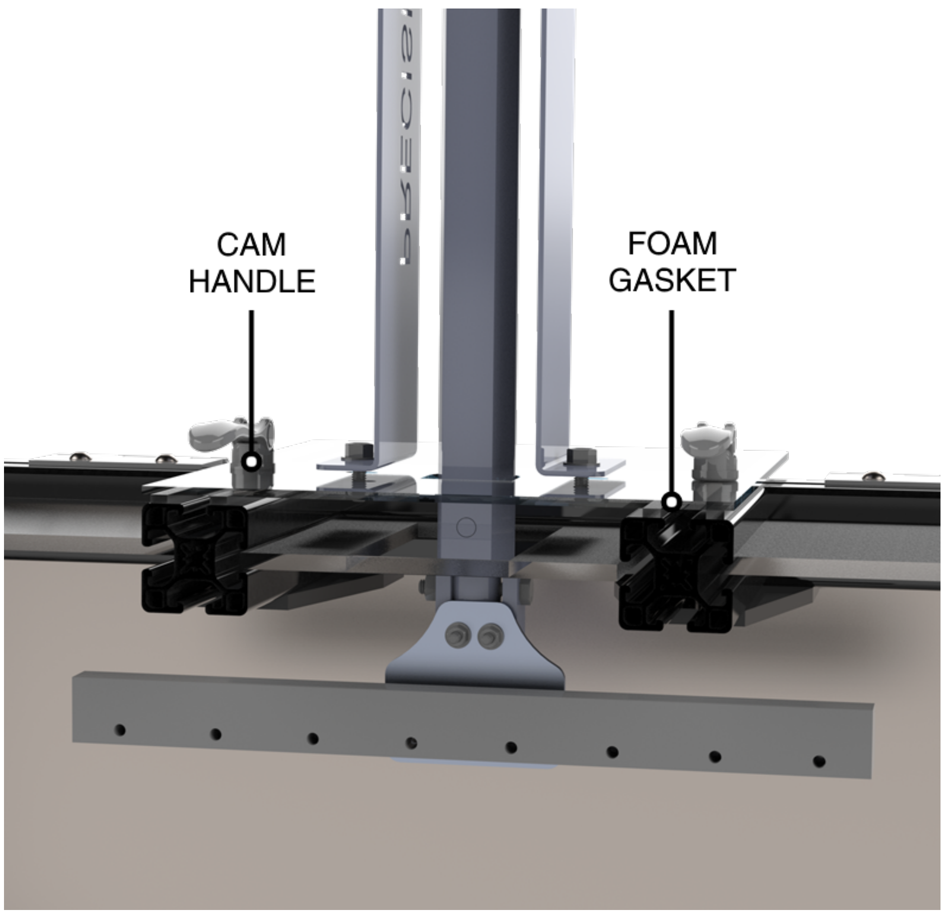

Figure 28: Gasket to seal sliding air knife panel

Blow-Out Panel and Expansion Duct The device features a sealed, stainless steel blow-out panel on the rear wall of the device enclosure held in place by permanent magnets. In the event of a powder deflagration, the sudden pressure increase will push the door open backwards against the sheet metal wall and vent pressure and combustion products into an expansion duct, shown in Fig. 29. This sheet metal duct will direct the deflagration away from the operator while confining combustion products to a safe location. The metal enclosure will absorb heat and greatly alleviate the pressure in the device. Hot gases will be allowed to vent through a flame-retardant filter at the end of the duct.

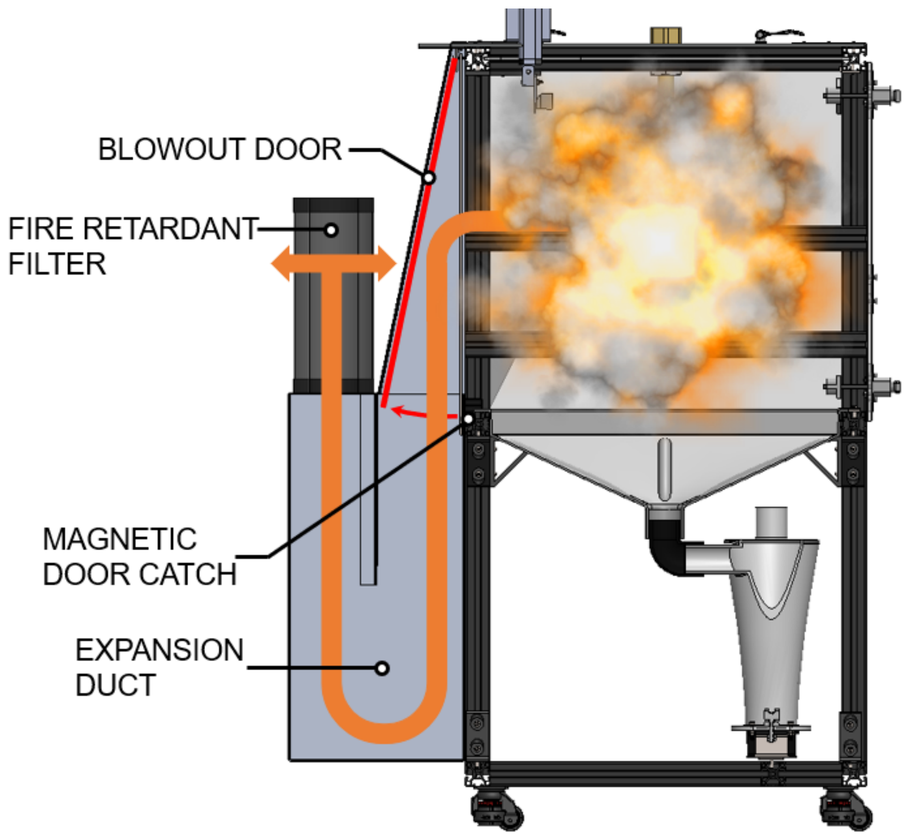

Figure 29: Blow-out door and expansion duct functionality

Dust Catch-Basin The dust basin makes up the bottom portion of the enclosure. It has a lip around its square perimeter which allows it to rest on the enclosure frame and form a dust-tight seal.

2.6.3 Component Mounting, Wiring and Pneumatics

Sourcing and routing of pneumatic hoses and wiring are not addressed in this report due to the time limited scope of this project. However, consideration was taken to ensure that routing can be easily implemented without engineering effort. T-slot compatible harness mounts are available on the market and the stationary shaft is hollow to permit entry to the enclosure. The device was designed with routing in mind and will not cause tangling of installed wires and hoses.

2.7 High-Level Cost Breakdown

A high-level cost-breakdown is given in Table IV. Cost categories are broken down by major functionality.

TABLE IV
HIGH-LEVEL COST BREAKDOWN

Section	Sub-Total (CAD)
Build-Plate Motion	$1640.74
Vibration and Impact	$279.61
Air Cleaning	$225.10
Main Enclosure	$2235.86
Powder Separation and Containment	$253.30
Electronics and Automation	$5334.06
Grand Total	**$9689.05**

This breakdown is based entirely on commercially available prices, and excludes manufacturing and assembly costs. Certain standard components require additional modification, such as extra mounting holes in the cyclonic separator, shortened metal components present in the build-plate hold-down clamps, and trimmed seals around the powder collection container. A full bill of materials can be found in Appendix F.

The client will be able to manufacture the device by following the provided drawings as well as referencing the associated CAD files. Manpower cost may be calculated based on manufacturing time estimates by the client.

3 Future Considerations

While the proposed design is the best version of the powder removal device that could be designed within the given time-frame, the team recognizes there is always room for improvement. The following sections detail some recommended future considerations which would serve to improve the device's performance, ease of use, safety, and automation.

3.1 Device Performance

A few recommendations for several components are given to further improve the performance of the device.

3.1.1 Impactor

Due to space and time constraints, the team decided the best option was to mount a single impactor to the underside of the build-plate. However, the team generated a concept involving multiple mechanically-driven impactors impacting at various locations on the build plate. This would have two key performance improvements: 1) vibrations from impacts would become more effective at the edges of the plate because the impactors are located in multiple locations instead of just at the plate's center; 2) moving from pneumatic to mechanically actuated impactors would the reduce the device's air consumption.

3.1.2 Cyclonic Separator

The current cyclonic separator is not designed to handle flammable powders, and should only be used with a full understanding of the risks involved. Reinforcing and sealing the underside of the device could potentially be an effective way to mitigate this risk, but a custom seperator designed with this in mind could be a better solution. The efficiency or effectiveness of a gas cyclonic separator depends upon its geometry and the volumetric flow rate of the gas passing through it. Past research on gas cyclonic separators indicate that for fine powders (powders with particle sizes below 100 µm), effective geometries for maximum powder removal are 1D3D and 2D2D [8]. The D's refer to the barrel diameter of the cyclone and the numbers preceding the D's refer to the length of the barrel and length of the cone respectively. So, 1D3D refers to a cyclone geometry with a barrel length of 1 barrel diameter and a cone length of 3 barrel diameters. The recommendation is to design a cyclonic separator which falls under one of these two geometries.

One improvement for the collection box assembly is to use small draw latches for a more robust lid seal. The sourced magnets collectively provide 10 pounds of pressure, which is sufficient for a strong seal but could potentially open if accidentally dropped [12]. Latches were not included due to the 1/16 inch lid thickness dictated by the cam lever motion, but custom or modified commercial latches could reasonably be made to fit.

3.2 Ease of Use

Implementing a dead-man's step switch to transition between the device resting on its casters to stationary legs. This would be the same type of switch used on rolling staircases. The added value in this is that the mobility of the entire powder removal device is preserved while also allowing it to be better isolated from the concrete floor; its stationary legs would be fitted with rubber isolators.

Another improvement would be to extend the frame to provide a moving platform for the shop-vac. This would permit movement of the device as a single unit.

3.3 Safety

The device features a simple expansion duct open to the ambient atmosphere. This is to relieve pressure in case of a powder deflagration. While this is better than no mitigation at all, it is not specially designed to handle titanium powder explosions nor does it fully contain the burnt titanium powder. Unfortunately, there are currently very few if any commercially available systems capable of handling titanium powder explosions. Some systems that do exist for other powders are very expensive and may not even be effective in this specific application. Titanium powder presents a unique hazard and this area of the design will require significant research and industry attention. One option is to vent the explosion directly outdoors.

3.4 Electronics and Automation Systems

Some recommendations for improving the electronics and automation aspects of the design include adding a pressure monitoring gauge that provides the operational pressure of both the air knife and impactor and feeds this data to the HMI display. This would allow for the operator to track which air pressures are optimal for different builds. Similarly, encoder angle data could be displayed on the HMI for the operator to track which combinations of axis A and B angles most effectively remove powder. As discussed with the client, a monitoring humidity sensor could be implemented to check that the device stays within the ranges acceptable for Ti-6Al-4V powder.

Since this area of the design is by far the most costly, further research could be done into more cost effective components capable of the same function. Due to the limited availability of worm gear drives that mate with stepper motors, the team was forced to select a highly inefficient and costly gearbox for the axis A drive system. It is recommended that alternative drive systems be explored for this axis. Costs could also be reduced by using standard (not ip65 rated) stepper motors and removing encoders, which would also negate the need for the high speed input PLC module.

The provided program is intended to be used as a skeleton for the development of the ladder logic program to be implemented into the device. Adjustments and alterations to the program and it's variables should be made to improve its effectiveness once more is known about which vibration frequencies, impacting frequencies, and air knife speeds are most effective. Finally, it is recommended that an electrician review the selected components to ensure their compatibility and safety before purchasing them.

4 Conclusion

The objective of this project was to improve Precision ADM's current on-plate powder removal process by designing a device which makes the process safer, more effective and less labor-intensive than current methods.

This objective was met with the proposed device, described in this report. The device improves the safety of the current process by confining the powder removal process to a dust-tight, air-tight enclosure. The risks this introduces have also been considered and are mitigated by providing a blow-out panel with an expansion duct as well as an air downdraft within the enclosure.

The device features three methods of powder removal which improve the effectiveness of the powder removal process. The device is able to rotate build-plates with a two-axis fixture which facilitates gravity-assisted powder removal. Secondly, impact and vibration aid the removal process with the use of a pneumatic impactor and two vibration motors. Thirdly, an industrial air knife provides blow-off cleaning functionality to maximize the effectiveness of the device. These functionalities exceed the current methods in several ways. Currently, the gravity-assisted removal is restricted to one axis, significantly limiting the orientations possible. With the proposed device, virtually any orientation is possible. Regarding impact and vibration, current methods only consist of repeated impacts with a mallet whereas the proposed device is capable of impacts in conjunction with added vibration. The current blow-off cleaning process utilizes a simple air nozzle which is not very effective. The proposed device is capable of cleaning the entire build-plate in one pass using an industrial air knife.

Finally, the device makes the powder removal significantly less labor-intesive by being heavily automated and greatly reducing the hours spent cleaning parts. Most importantly, employees are protected from handling risks associated with metallic powders. The device allows the operator to insert a built-plate and start the device with the push of a few buttons. Operators are no longer required to spend hours manually hitting or blowing off the build-plates in order to effectively remove all trapped powder.

5 References

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Appendices

List of Figures

List of Tables

A Drawings

B Torque Calculations

Torque calculations for both axis A and axis B are shown below. Note that calculations with both the 3 inch and 1.5 inch thick build plate were performed for only axis A because in this axis changing the build plate thickness shifts the center of gravity and the highest torque value can occur with either build-plate thickness. For axis B, only calculations were performed for the 3 inch thick build-plate because in this axis, changing build-plate thickness does not change the moment of inertia. Thus, only the maximum build-plate weight was considered. For both scenarios an assumed part weight of 10 pounds evenly distributed over the entire build plate surface was used. Moment of inertia values and assembly masses were pulled from SolidWorks data.

3 inch build plate - Axis A			
	Axis A - Acceleration Torque		
Acceleration Torque	**Ta**	**0.00020749**	***Nm***
Rotor Inertia	J0	0.000	*kg*m^2*
Total Load Inertia	JL	0.000	*kg*m^2*
Operating Speed (rpm)	N_M	10	*RPM*
Acceleration time (s)	t1	1	*s*
Gear Ratio	i	1	
Axis A - Load Torque (Fric.)	**Tf**	**4.3524**	**Nm**
Additional 90 deg loading torque	**TL**	**0.90552186**	***Nm***
	Safety Factor	2	
	Total Torque Req.	**10.5162587**	***Nm***

Static Torque - Axis A		
Material	**Static Coeff (mu)**	**Units**
Aluminized Bronze	0.46	-
Mass of rotating components	46.153	kg
Motor mass	2	kg
Gravity	9.81	m/s^2
Frictional Force	217.2952278	Newtons
Bushing radius	0.025	m
Frictional Torque	5.432380695	Nm

Figure B.1: Axis A - 3 inch build-plate

1.5 inch build plate - Axis A			
	Primary Axis - Acceleration Torque		
Acceleration Torque	**Ta**	**0.234629064**	***Nm***
Rotor Inertia	J0	0.000	*kg*m^2*
Total Load Inertia	JL	0.224	*kg*m^2*
Operating Speed (rpm)	N_M	10	*RPM*
Acceleration time (s)	t1	1	*s*
Gear Ratio	i	1	
Axis A - Load Torque (Fric.)	**Tf**	**4.3524**	**Nm**
Additional 90 deg loading torque	**TL**	**4.85647974**	***Nm***
	Safety Factor	2	
	Total Torque Req.	**18.88701761**	***Nm***

Static Torque - Axis A		
Material	**Static Coeff (mu)**	**Units**
Aluminized Bronze	0.46	-
Mass of rotating components	35.361	kg
Motor mass	2	kg
Gravity	9.81	m/s^2
Frictional Force	168.5952486	Newtons
Bushing radius	0.025	m
Frictional Torque	4.214881215	Nm

Figure B.2: Axis A - 1.5 inch build-plate

3 inch build plate - Axis B			
	Axis B - Acceleration Torque		
Acceleration Torque	**Ta**	**0.41466555**	***Nm***
Rotor Inertia	J0	0.000	*kg*m^2*
Total Load Inertia	JL	0.396	*kg*m^2*
Operating Speed (rpm)	N_M	50	*RPM*
Acceleration time (s)	t1	1	*s*
Gear Ratio	i	0.2	
	Axis B - Load Torque (Fric.)		
	Tf	**4.1944617**	*Nm*
	bushing rad	0.125	*m*
	large sprocket rad	0.15	*m*
	small sprocket rad	0.03	*m*
	Bearing Fric. Force	167.778468	*N*
	Safety Factor	2	
	Total Torque Req.	**9.218254499**	*Nm*

Static Torque - Axis B		
Material	**Static Coeff (mu)**	**Units**
Aluminized Bronze	0.46	-
Mass of rot. Components	37.180	kg
Gravity	9.81	m/s^2
Frictional Force	167.778468	Newtons
Bushing radius	0.125	m
Frictional Torque	20.9723085	Nm

Figure B.3: Axis B - 3 inch build-plate

Axis B	MOIz	0.396	kg*m^2
	z-components mass	37.180	kg
	Factor of Safety	2	
	Total Torque Req.	**9.218254499**	**Nm**
Axis A	MOIx	0.353815	kg*m^2
	x-components mass	46.153	kg
	Factor of Safety	2	
	Total Torque Req.	**18.88701761**	**Nm**

Figure B.4: Total torque requirement of each axis

Axis B				
Torque @ 200rpm	1.55	Nm	**FOS Axis B**	**5.247113215**
Selected gearbox	20	:1		
Gearbox efficiency	0.89			
Output Torque	27.59	Nm		
Axis A				
Torque @ 200rpm	1.55	Nm	**FOS Axis A**	**2.215807751**
Selected gearbox	25	:1		
Gearbox efficiency	0.54			
Output Torque	20.925	Nm		

Figure B.5: Factor of Safety of each axis

C Drive Shaft Calculations

The shafts mounted on either side of the rotating support plate experience both bending and torsional stresses during their operation. To ensure that the designed shafts would not fatigue from this cyclic loading cycle the modified Goodman approach was applied to simplified version for the shaft. This approch resulted in a high factor of saftey

D Electronics and Automation

The full functional block diagram program for the PLC controlled system is shown in Fig. XXX below.

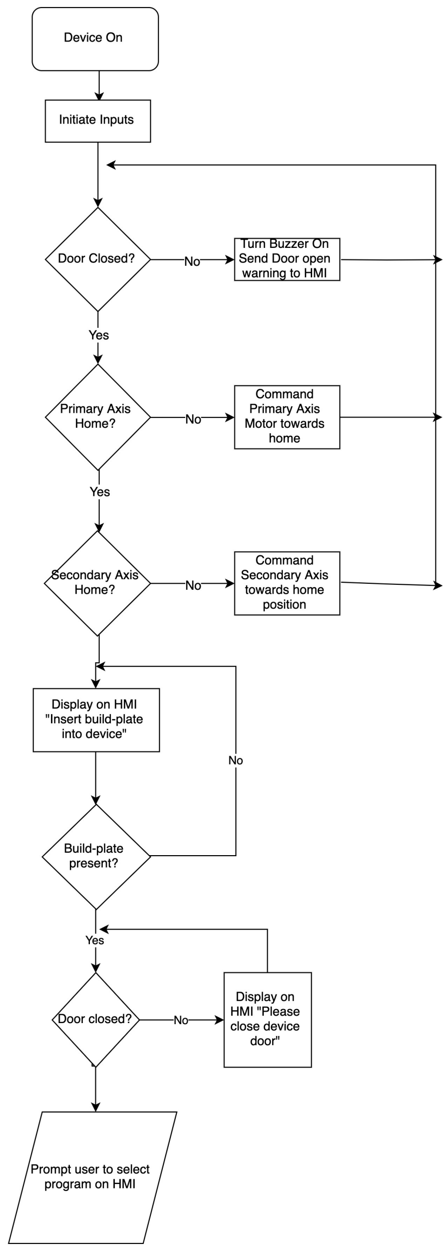


Figure D.1: Startup loop and program selection

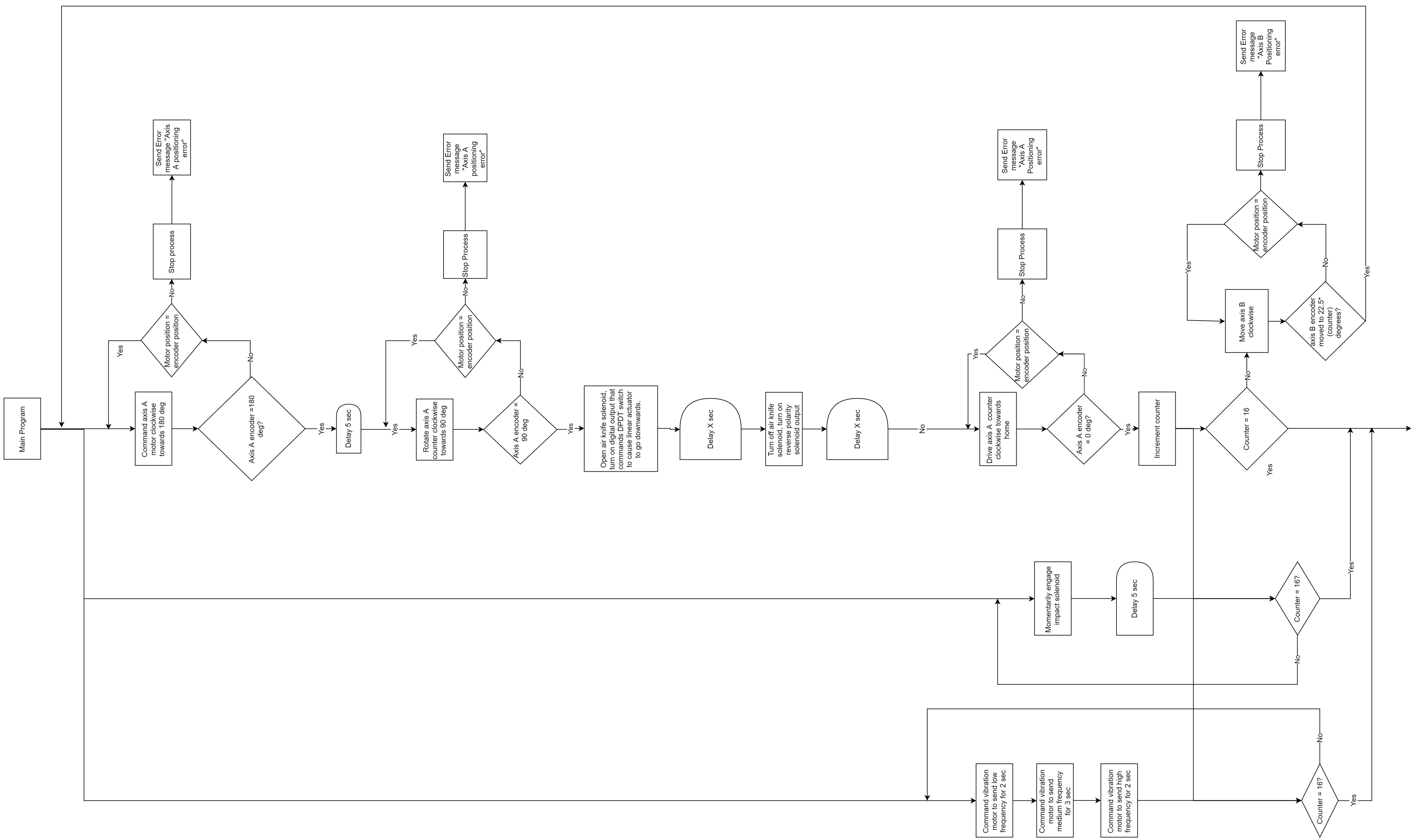


Figure D.2: Main Program

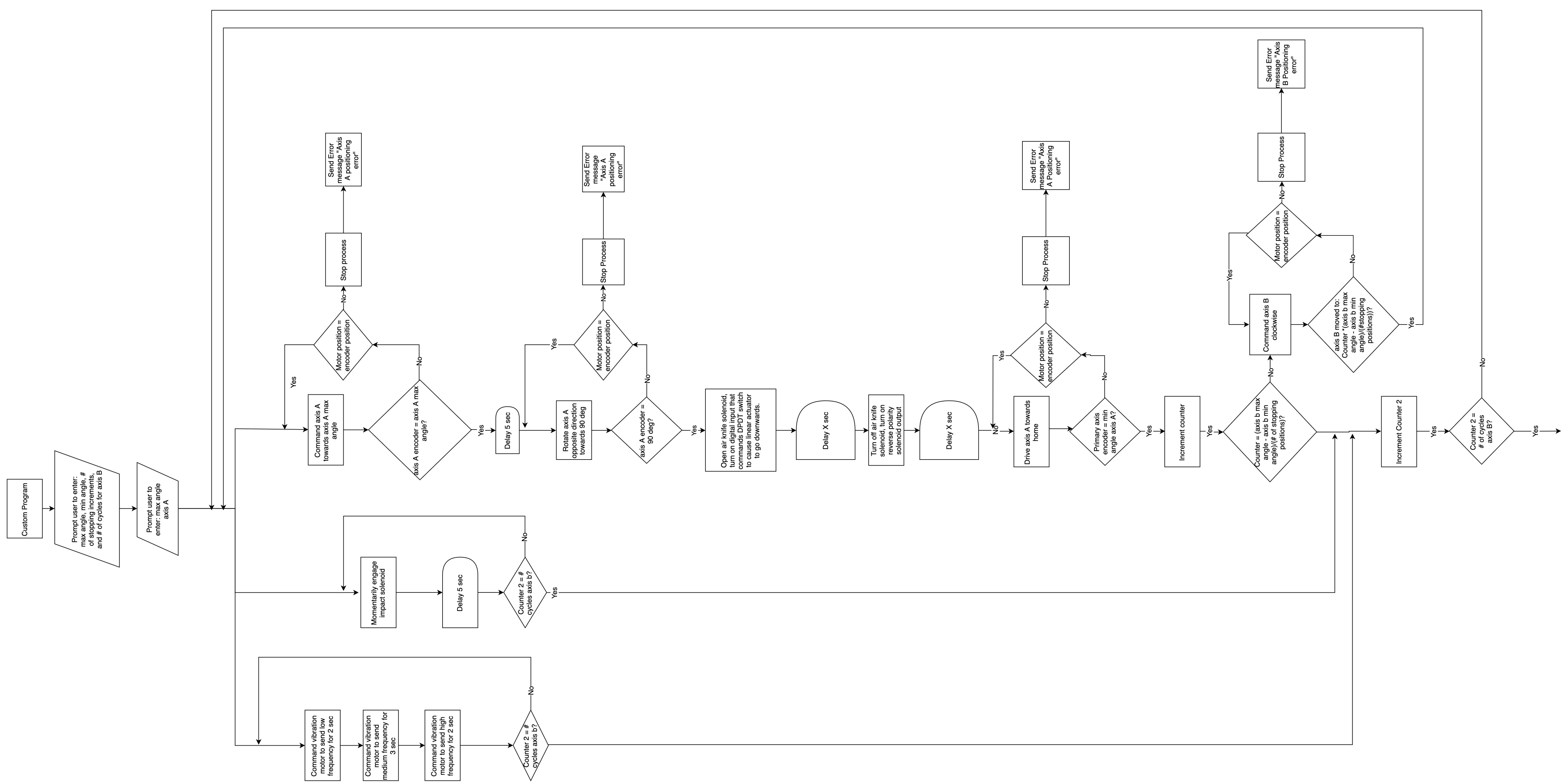


Figure D.3: Custom Program

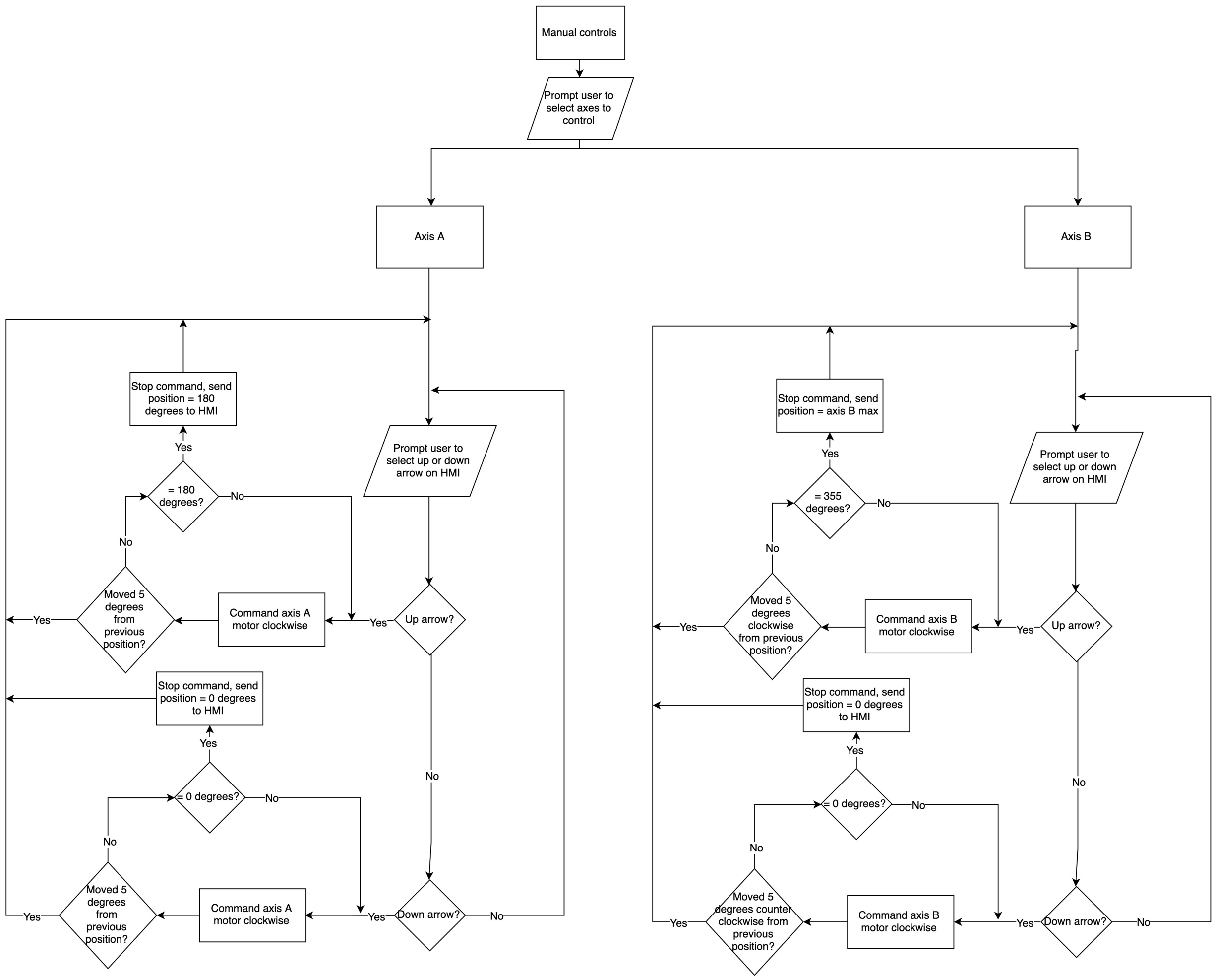


Figure D.4: Manual Controls

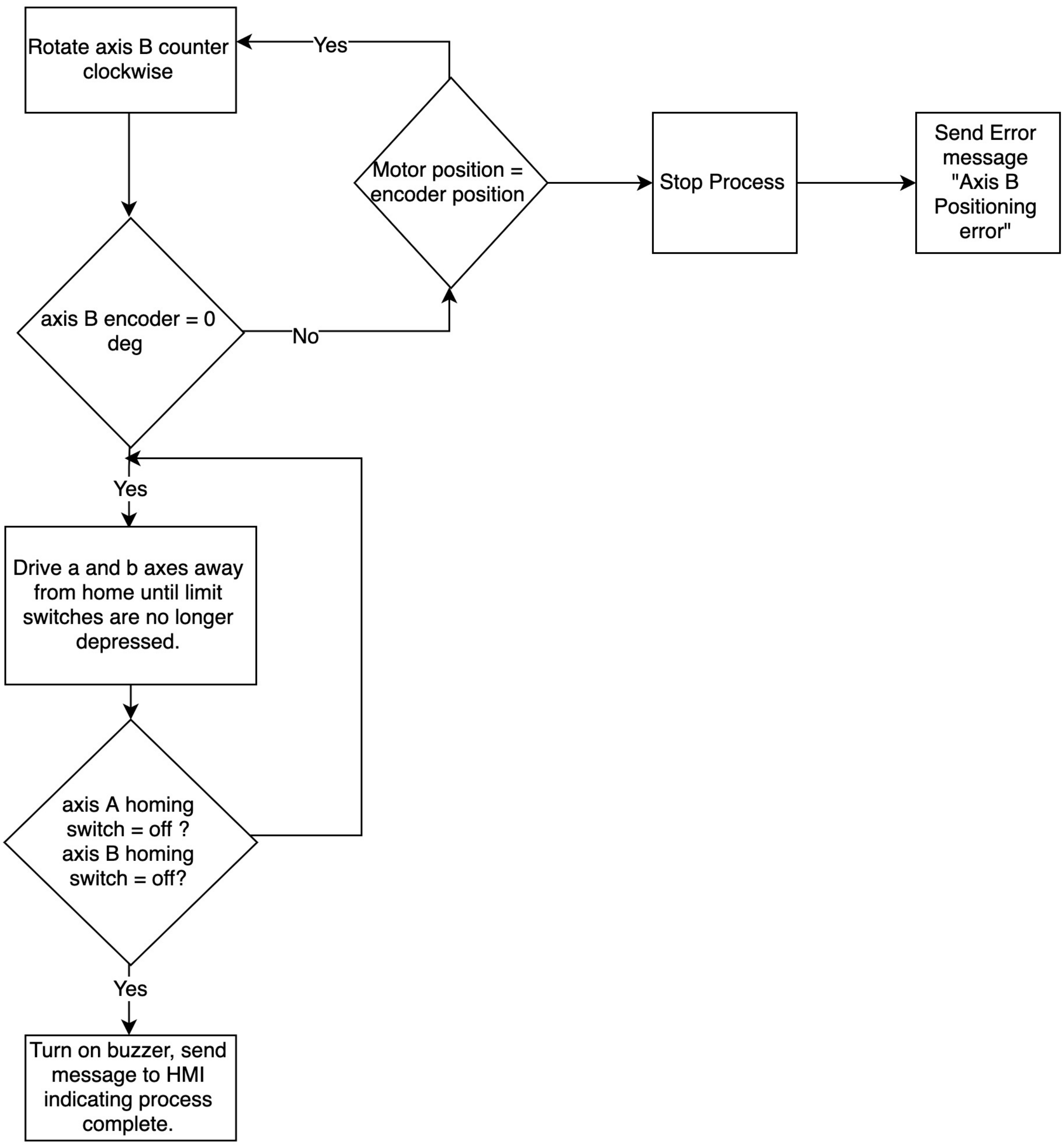


Figure D.5: Process Complete Loop

E Beam Calculations

The following section presents the material specifications of the frame material, bending moment and shear diagrams of various load scenarios that were investigated, and the results obtained by the deflection calculator from the aluminum T-slot extrusion supplier.

Material Properties The frame is made up of an Aluminum 6105-T5 extrusion which is a 6000 series aluminum alloy that is T5 tempered. and is mostly used in aluminum alloy extruded bars including aluminum T-slot. The following table (data adapted from [1]) presents the mechanical properties of aluminum:

TABLE E.1
ALUMINUM EXTRUSION MECHANICAL PROPERTIES [1]

Parameter	Value
Cross-sectional Area	6.035cm^2
Moment of Inertia X	8.706 cm^4
Moment of Inertia Y	8.706 cm^4
Modulus of Elasticity	68 GPa
Elongation at Break	9%
Fatigue Strength	130 MPa
Poisson's Ratio	0.33
Shear Modulus	26 GPa
Poisson's Ratio	0.33
Shear Strength	170 MPa
Tensile Strength (Ultimate)	280 MPa
Tensile Strength (Yield)	270 MPa

Front-Bottom support beam Approximating the load by the HMI panel to be 0.001kN/m and the weight on the two casters is 0.22kN each. Maximum deflection for the load scenario obtained using a deflection calculator provided by the aluminum T-slot supplier is 0.186 mm.

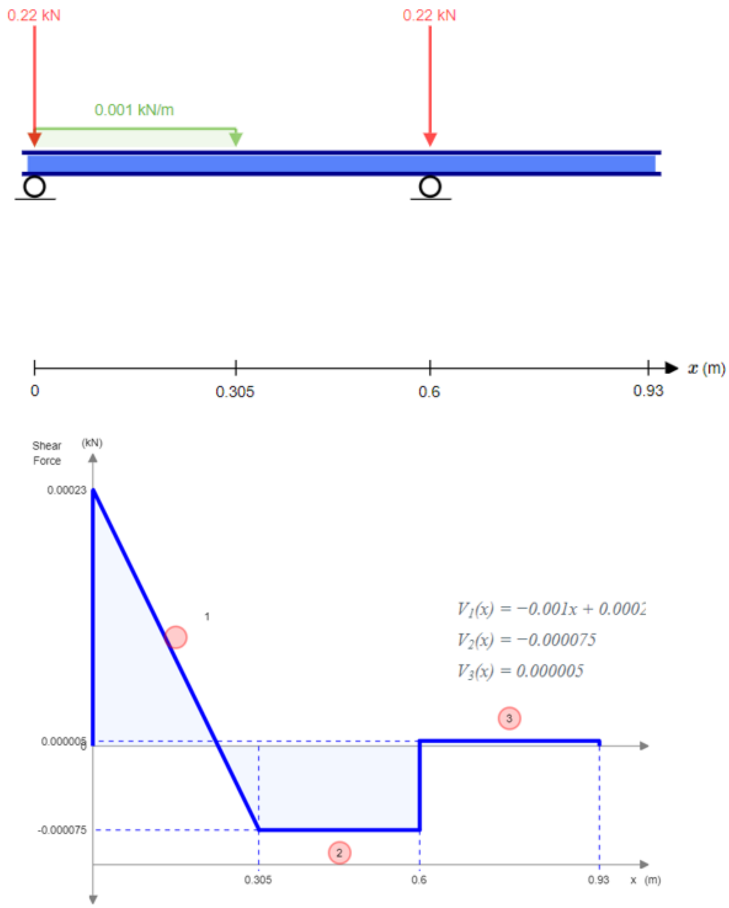


Figure E.1: Free body diagram (top), shear force diagram (middle) for front-bottom support beam

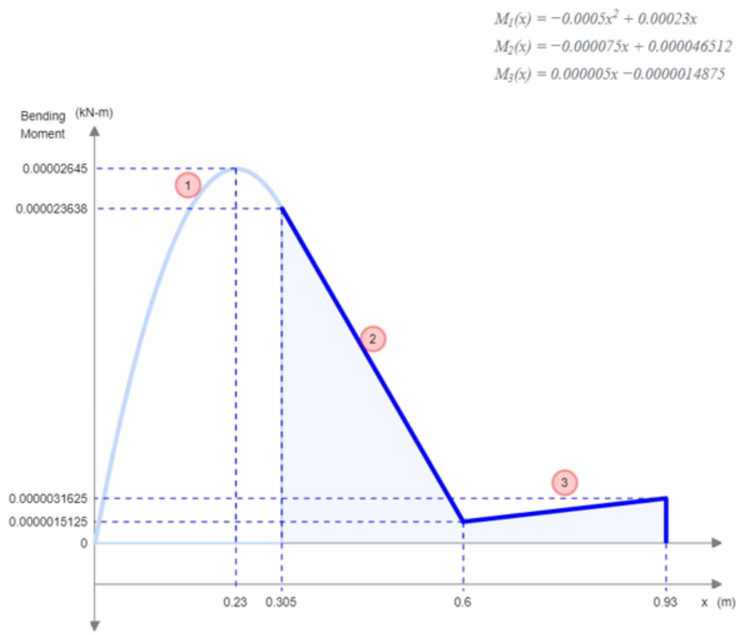
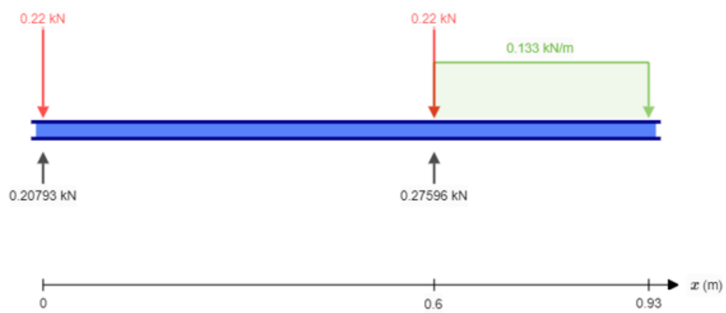


Figure E.2: Bending moment diagram for front-bottom support beam

Rear-Bottom support beam Approximating the load by the control box to be 0.133 kN/m distributed and the weight on the two casters is 0.22kN each. Maximum deflection for the load scenario obtained using a deflection calculator provided by the aluminum T-slot supplier is 0.6138 mm.



$V_1(x) = -0.01207$

$V_2(x) = -0.133x + 0.12369$

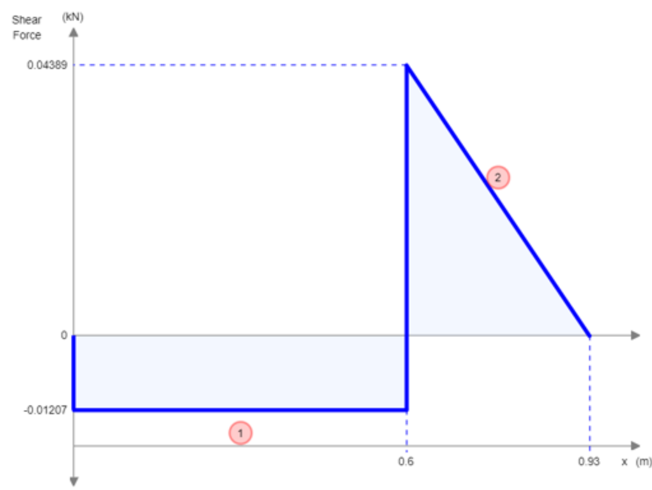


Figure E.3: Free body diagram (top), shear force diagram (middle) for rear-bottom support beam

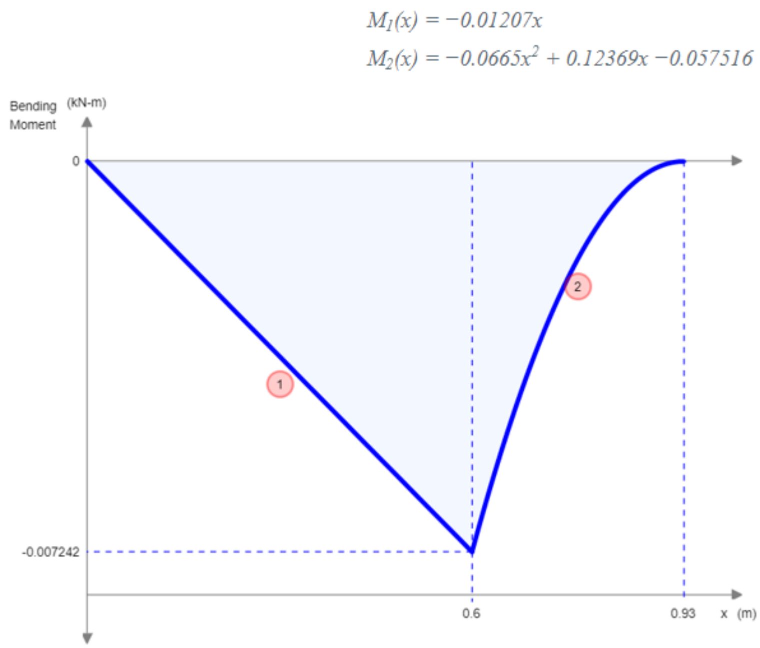


Figure E.4: Bending moment diagram of rear-bottom beam

Side-beam with cantilever motor mount Approximating the load of the motor and gearbox and if 50lb of the support shaft weight is supported by the side beam. Maximum deflection for the load scenario obtained using a deflection calculator provided by the aluminum T-slot supplier is 0.982 mm.

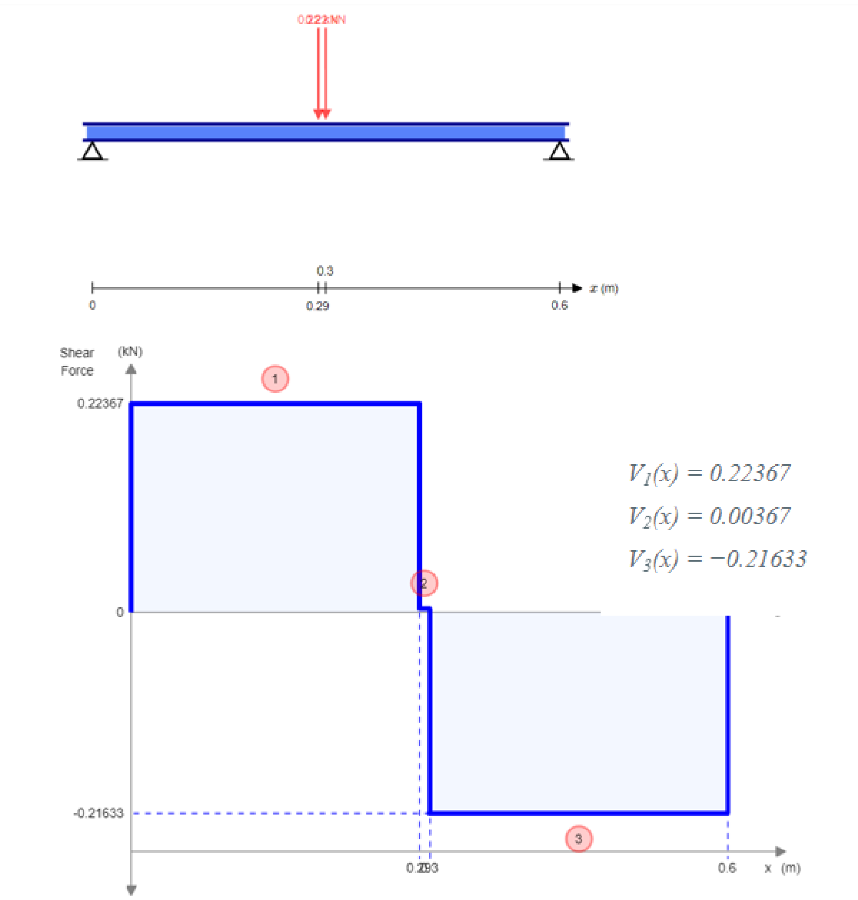


Figure E.5: Free body diagram (top), shear force diagram (middle) for side-beam with cantilever motor mount

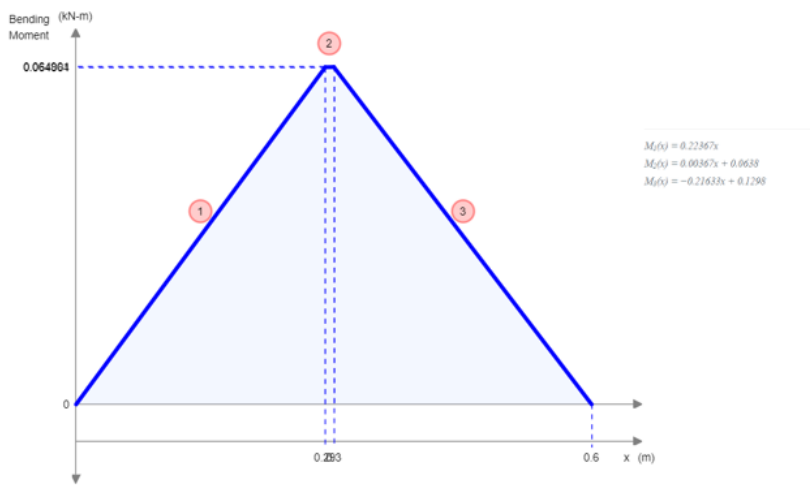


Figure E.6: Bending moment diagram for side-beam with cantilever motor mount

Cantilever beam for motor and gearbox mount Maximum deflection for the load scenario obtained using a deflection calculator provided by the aluminum T-slot supplier is 0.0155 mm.

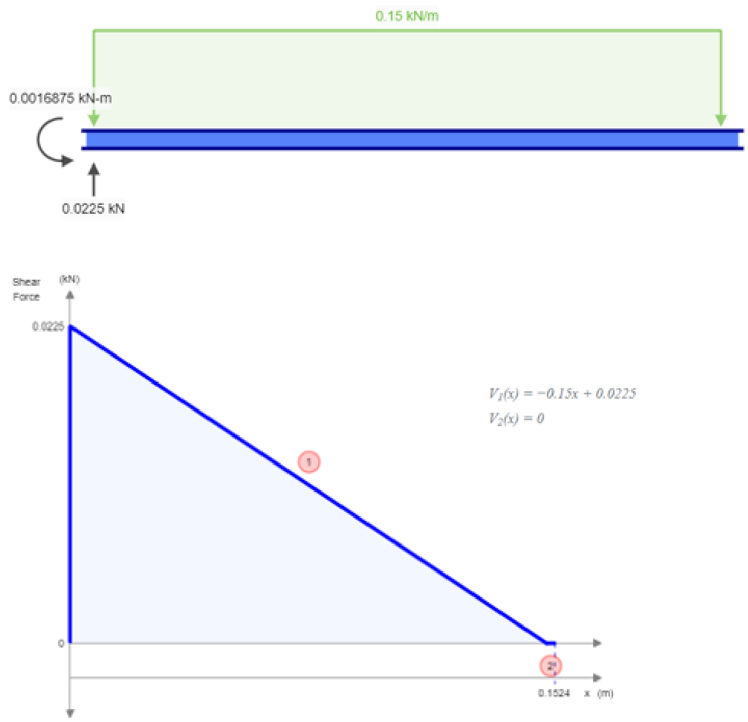


Figure E.7: Free body diagram (top), shear force diagram (middle) for Cantilever beam for motor and gearbox mount

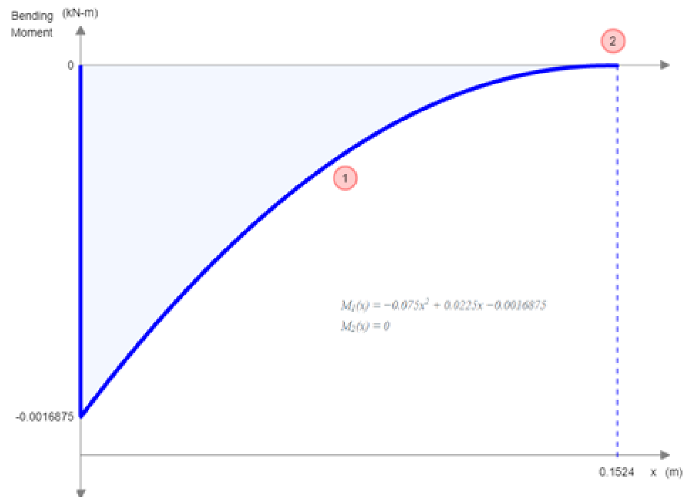


Figure E.8: Bending moment diagram for Cantilever beam for motor and gearbox mount

Top side support beam for motor mount Maximum deflection for the load scenario obtained using a deflection calculator provided by the aluminum T-slot supplier is 0.068 mm.

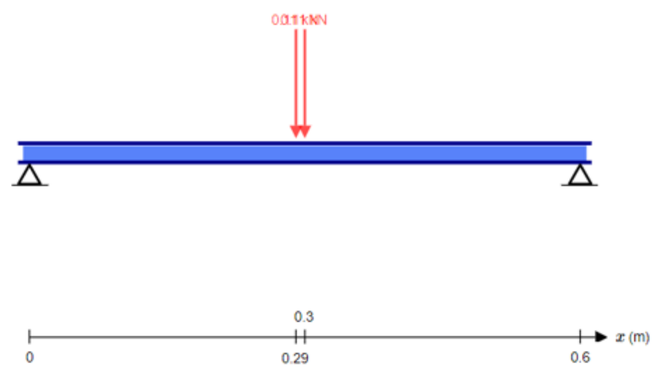


Figure E.9: Free body diagram (top)for top side support beam for motor mountt

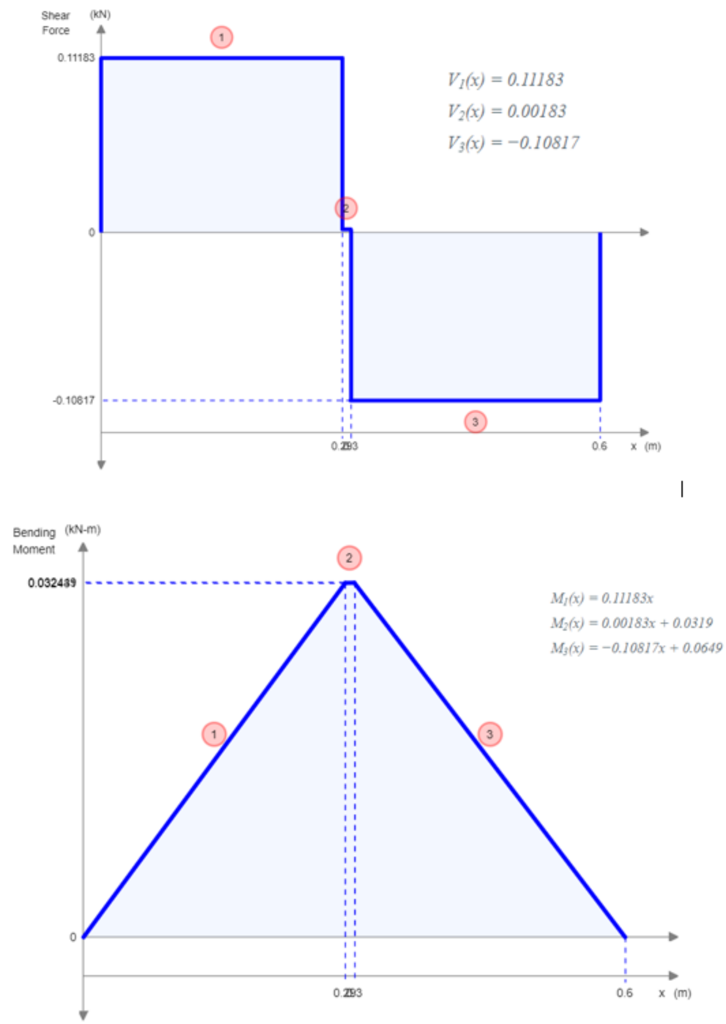


Figure E.10: Shear (top) and bending moment diagram (bottom) for cantilever beam for motor and gearbox mount

F Bill of Materials

Number of Parts:		Commercial:	2643.91		
Revision:	0	Fasteners:	434.32		
		Raw Material:	1155.15		
		Electrical:	5344.69	Total: $	9,689.05

Part No.	Part Name	Supplier Part Number	Purpose	Cost/Unit	Quantity	Cost USD	Cost	Part Type
1.0	Air Cleaning (AC)						$ 225.10	
	Exair Full Flow Air Knife (12" Alum.)	2612	Blowoff cleaning	$161.00	1		$ 161.00	Commercial
	Air Knife Pressure Regulator	9008	Blowoff cleaning	$54.00	1		$ 54.00	Commercial
	Shrink-to-Fit Sealing Grommet	5277T11	To seal actuator opening	$10.10	1	$ 6.73	$ 10.10	Commercial
2.0	Main Enclosure (ME)						$ 2,235.86	
	Estimated Cost of Custom Funnel		Powder Collection	$350.00	1		$ 350.00	
	Anti-vibration Support		Vibration Isolation		4		$ 38.00	Commercial
	Flame-Retardant Neoprene Foam Strip	1601N122	Frame Sealing	$26.87	1		$ 26.87	Commercial
	Steel Hinge without Holes Removable Pin, 3" x 1-1/2" Door Leaf, 0.093" Leaf Thickness	16175A65	Door Hinge	$5.37	3		$ 16.11	Commercial
	Tight-Hold L-Handle Cam Latch, for 2" Maximum Thickness	1337A37	Door Latch	$15.07	3		$ 45.21	Commercial
	80/20 Extruded Aluminum		Frame	$0.48	360		$ 172.80	Commercial
	Panel Gasket	40-2117	Enclosure Sealing	$106.35	1	70.9	$ 106.35	Commercial
	Dust Cover for T-slot Framing		Enclosure Sealing	$6.96	5	4.64	$ 34.80	Commercial
	Snap-on End Cap for T-slot Framing		Enclosure Sealing	$2.81	10	1.87	$ 28.05	Commercial
	Wide Backing Plate	40-2437	Frame Structure	$6.90	10	4.6	$ 69.00	Commercial
	Tall Gusseted Inside Corner Bracket	40-4336	Frame Structure	$11.52	20	7.68	$ 230.40	Commercial
	4-hole 90 Degree Flat Plate	40-4350	Frame Structure	$9.87	10	6.58	$ 98.70	Commercial
	4-hole Tee Flat Plate	40-4341	Frame Structure	$10.68	10	7.12	$ 106.80	Commercial
	Anchor Fastener Assembly	40-3359	Frame Structure	$5.55	20	3.7	$ 111.00	Fastener
	M5 Standard Drop-in T-nut	13116	Frame Structure	$1.11	40	0.74	$ 44.40	Fastener
	M5x16mm Button Head Cap Screw	11-5316	Frame Structure	$0.54	75	0.36	$ 40.50	Fastener
	M8x16mm Button Head Cap Screw + T-Nut	75-3422	Frame Structure	$1.01	16	0.67	$ 16.08	Fastener
	Fleetguard Air Filter	AF25308	Explosion vent filter	$70.67	1	$47.11	$ 70.67	Commercial
	Rubber Grommet (25-pk)	408M75	Enclosure Sealing	$4.37	1	$2.91	$ 4.37	Commercial
	Water- and Steam-Resistant Cork Gasket Material	9487K54	Shaft side enclosure sealing	$24.00	1	16	$ 24.00	Commercial
	Water- and Steam-Resistant Cork Gasket Material	9487K55	Shaft side enclosure sealing	$40.59	1	27.06	$ 40.59	
	Black Oxide 18-8 Stainless Steel Socket Head Screw - 25 Pack - Need 22	96006A692	Door Latch and Door Hinge Mounting Screws	$5.61	1		$ 5.61	Fastener
	Steel Sheet Metal 20 gage		Door Latch Catch (Sacrificial)	$2.63	10	1.75	$ 26.25	Raw Material
	18-8 Stainless Steel Serrated Flange Locknut - 50 pack - Need 22	93776A401	Door Latch and Door Hinge Nut	$5.64	1		$ 5.64	Fastener
	Vacuum Relief Valve	60256 60158	Vacuum Relief	$20.76	0	13.84	$ -	Commercial
	Adjustable Vacuum Relief Valve - 1/4in	48935K25	Vacuum Relief	$11.63	0	7.75	$ -	Commercial
	CHECK VALVE PIPE 1.25 IN X 1.25 IN	CTLP1212-1EP	Vacuum Relief	$89.21	1		$ 89.21	Commercial
	Sealing Washer Bonded	39WD84	Check Valve Sealing	$1.26	2	0.84	$ 2.52	Commercial
	Nylon Wheel Top Plate Leveling Caster	7GD-40F-BLK	Mobility and Support	$67.50	4	45	$ 270.00	Commercial
	24" x 24" - Clear Polycarbonate Lexan Sheet - 1/4" Thick	3002502424	Frame Structure	40.485	4	26.99	$ 161.94	Commercial
	Retractable Levelling Casters (4-pk)	TP-60F	Mobility and Support	$119.99	0	79.99	$ -	Commercial
3.0	Powder Separation and Containment (PSC)						$ 253.30	
	Dust Deputy	AXD000004A	Powder Separation	99.95	1		$ 99.95	Commercial
	Brass On/Off Valve with Lever Handle, 2 NPT Female x 2 NPT Male	47865K48	Isolating powder containment unit	98.6594	1	74.18	$ 98.66	Commercial
							$ -	
	Sheet Metal 12 Gage							Raw Material
	Rare-Earth Circular Magnets	99K3101	Rare Earth Magnets for Box Lid	$0.65	4		$ 2.60	Commercial
	Medium-Strength Steel Thin Hex Nut 100 pack need 4	94846A030	Double Jam NutsFor Clamping Handle	5.53	1		$ 5.53	Fastener
	Static Conductive 2.5" Tapered Vacuum Hose Elbow	#AXD600103	Connect Cyclonic Separator to Funnel	$10.85	1		$ 10.85	Commercial
	Medium-Strength Steel Thin Hex Nut 100 pack (included in BP motion section) Need 4	90695A038	Cyclonic Separator Holder Jam Nuts	3.3	0		$ -	Fastener
	Steel Hex Nut (included in Bp motion section) 100 pack need 4	90592A016	Cyclonic Separator Holder Nuts	2.59	0		$ -	Fastener
	Alloy Steel Low-Profile Socket Head Screw - 50 pack. Need 4, (included in BP motion section)	93070A149	Cyclonic Seperator Holder Bolts	10.79	0		$ -	Fastener
	Clamping Handle with Threaded Stud	5720K26	Powder Container Clamp	13.06	2		$ 26.12	Commercial
	Light Duty Blended EPDM Foam Strip	8694K117	Powder Container Seal	0.505	2.5		$ 1.26	Commercial
	Plastic Enclosure	TW8-4-8B	Powder Container	8.33	1	6.27	$ 8.33	Commercial
4.0	Build-Plate Motion (BM)						$ 1,640.74	
	ANSI 40 Lambda roller chain, cut to length to 48 pitches (1/2P)	40LAMR72P	Axis B Rotation Chain Drive	$65.67	1		$ 65.67	Commercial
	ANSI 40 A plate, Machinable Stockbore 1" , 60 teeth, hardended teeth	40A60	Axis B Rotation Chain Drive	$34.10	1		$ 34.10	Commercial
	ANSI 40 A plate, Machinable Stockbore 1" , 12 teeth, hardended teeth	40A12	Axis B Rotation Chain Drive	$13.20	1		$ 13.20	Commercial
	ANSI 40 B plate, finished bore 1 1/4 max. keyway, 2 set Screws, 15 tooth	40B15F-1G	Axis B Rotation Chain Drive	$13.20	1		$ 13.20	Commercial
	Continious cast C954 aluminum bronze (7"ID 10"OD X1.5") for bearing	AMPCO 18	Axis B Rotation Bearing	$415.00	1		$ 415.00	Raw Material
	Hold-Down Toggle Clamp	5126A24	Build-Plate Mounting	$12.59	4		$ 50.36	Commercial
	Alloy Steel Low-Profile Socket Head Screw (X2)	92220A264	Impactor Mounting	$12.72	1		$ 12.72	Fastener

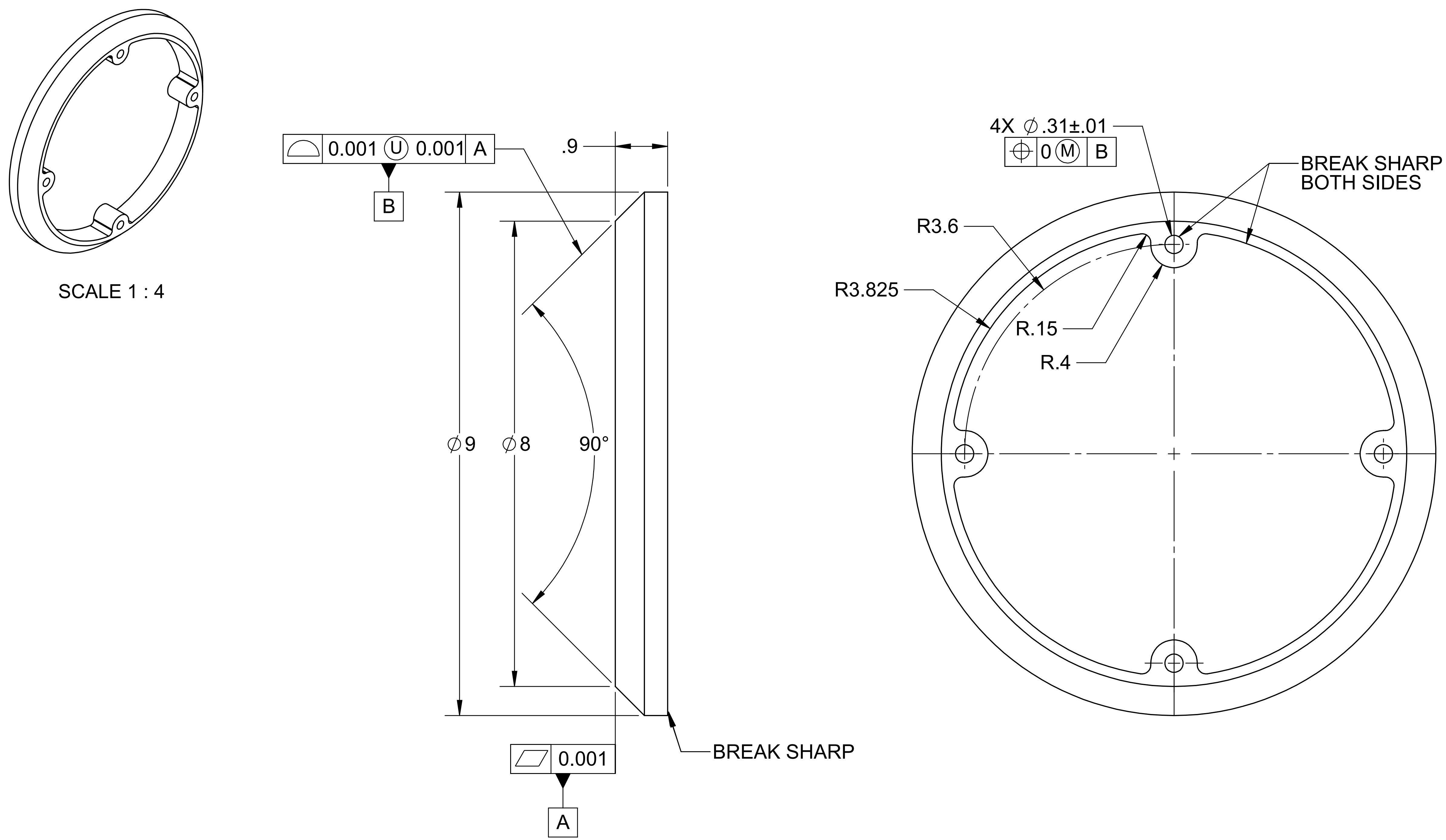
Part No.	Part Name	Supplier Part Number	Purpose	Cost/Unit	Quantity	Cost USD	Cost	Part Type
	Medium-Strength Steel Thin Hex Nut (X2)	94846A523	Impactor Mounting	$7.23	1		$ 7.23	Fastener
	Medium-Strength Steel Hex Nut (X2)	95462A033	Impactor Mounting	$16.58	1		$ 16.58	Fastener
	Alloy Steel Low-Profile Socket Head Screw (X4)	93070A183	Axis B	$14.24	1		$ 14.24	Fastener
	Medium-Strength Steel Thin Hex Nut (X4)	90695A040	Axis B	$5.30	1		$ 5.30	Fastener
	Steel Hex Nut (X4)	90592A022	Axis B	$5.09	1		$ 5.09	Fastener
	Alloy Steel Low-Profile Socket Head Screw (X4)	92220A266	Interface Plate Mounting	$13.37	1		$ 13.37	Fastener
	Medium-Strength Steel Thin Hex Nut (X4)	94846A031	Interface Plate Mounting	$8.63	1		$ 8.63	Fastener
	Medium-Strength Steel Hex Nut (X4)	95462A031	Interface Plate Mounting	$8.79	1		$ 8.79	Fastener
	Alloy Steel Low-Profile Socket Head Screw (X28+8)	93070A105	Axis B Bearing, Clamps, Motor Mount, Vibration Motor Mount	$15.01	1		$ 15.01	Fastener
	Medium-Strength Steel Thin Hex Nut (X28)	90695A035	Axis B Bearing, Clamps, Motor Mount	$2.26	1		$ 2.26	Fastener
	316 Stainless Steel Split Lock Washer (X28)	92147A415	Axis B Bearing, Clamps, Motor Mount	$2.50	1		$ 2.50	Fastener
	18-8 Stainless Steel Serrated Flange Locknut (X8)	97400A380	Vibration Motor Mount	$9	1		$ 9.00	Fastener
	Black-Oxide Alloy Steel Socket Head Screw (X3)	91290A330	Axis A Flange	$7.92	1		$ 7.92	Fastener
	Medium-Strength Steel Thin Hex Nut 100 pack (included in BP motion section) Need 4	90695A038	Axis A Flange, Chain Tensioner	3.3	1		$ 3.30	Fastener
	Steel Hex Nut 100 pack need 5	90592A016	Axis A Flange, Chain Tensioner	2.59	1		$ 2.59	Fastener
	Alloy Steel Low-Profile Socket Head Screw - 50 pack. Need 5	93070A149	Chain Tensioner	10.79	1		$ 10.79	Fastener
	Alloy Steel Low-Profile Socket Head Screw (X1)	93070A155	Chain Tensioner	$10.87	1		$ 10.87	Fastener
	Flange-Mount Shaft Collar	9604T18	Axis A Rotaion	$70.28	1		$ 70.28	Commercial
	Rounded Machine Key (X1)	96717A144	Axis A Rotation	$6.06	1		$ 6.06	Commercial
	Rounded Machine Key (X1)	2977N22	Axis A Rotation	$8.95	1		$ 8.95	Commercial
	Vibrate-Damping Precision Flexible Shaft Coupling	9845T311	Axis A Rotation	$34.86	2		$ 69.72	Commercial
	Durometer 98A Spider for 1-5/16" OD Clamping Vibrate-Damping Precision Flexible Shaft Coupling	9845T17	Axis A Rotation	$11.59	1		$ 11.59	Commercial
	Black-Oxide 18-8 Stainless Steel Pan Head Phillips Screws pack 10	95836A688	Mounting motor side support plate	$12.52	1		$ 12.52	Commercial
	12 X 36 X 0.25" 416 SS		Support plate and isolator mounting plate	$487.01	1		$ 487.01	Raw Material
	12 X 24 X 3/8" 146 SS		Interface plate	$226.89	1		$ 226.89	Raw Material
5.0	Vibration and Impact (VI)						**$ 279.61**	
	Mounting Plate				1		$ -	
	Pneumatic Piston Vibrator			214.5	1		$ 214.50	Commercial
	Model No. 334-800 34mm Vibration Motor - 30mm Type			30	2		$ 60.00	Electrical
	Routing Clamp Steel with 2 Mounting Points, 1-5/16" ID, 4-3/4" Long		Vibration Motor mount	2.5536	2	1.92	$ 5.11	Commercial
							$ -	
6	Electronics and Automation (EA)						$ 5,334.06	
	PLC Base module	P2-07B		$152.95	1		$ 152.95	Electrical
	PLC Power Supply	P2-01AC		$105.07	1		$ 105.07	Electrical
	PLC CPU module	P2-550		$363.09	1		$ 363.09	Electrical
	Discrete input module	P2-16ND3-1		$98.42	1		$ 98.42	Electrical
	Discrete output module	P2-16TD2P		$98.42	1		$ 98.42	Electrical
	Analog output module	P2-04DAL-2		$146.30	1		$ 146.30	Electrical
	High speed output module	P2-HSO		$279.30	1		$ 279.30	Electrical
	High speed counter input module	P2-HSI		$279.30	1		$ 279.30	Electrical
	Filler module	P2-FILL		$15.96	2		$ 31.92	Electrical
	Axis B motor	AS5918M2804-E		433.846	1	326.2	$ 433.85	Electrical
	Axis B motor driver	EM542S		61.845	1	46.5	$ 61.85	Electrical
	Axis A and B driver power supply	PSB48-480S		239.4	1	180	$ 239.40	Electrical
	Axis B gearbox + assembly fees	GP56-S2-20-SR		309.491	1	232.7	$ 309.49	Electrical
	Axis A motor	AS5918L4204-E		433.846	1	326.2	$ 433.85	Electrical
	Axis A motor driver	EM542S		61.845	1	46.5	$ 61.85	Electrical
	Axis A gearbox + assembly fees	GSGE60-25-1		593.313	1	446.1	$ 593.31	Electrical
	HMI	EA1-S3MLW		284.62	1	214	$ 284.62	Electrical
	HMI keypad bezel	EA-MG-BZ2		121.03	1	91	$ 121.03	Electrical
	Vibrational Motor	334-800		34.1012	2	25.64	$ 68.20	Electrical
	Vibration motor controller transformer	PH50PG		57.855	1	43.5	$ 57.86	Electrical
	Vibrational motor controller	GSD4-24A-5C		109.06	1	82	$ 109.06	Electrical
	Vibrational motor control analog module	GSDA-AI-V4		114.38	1	86	$ 114.38	Electrical
	Impactor pneumatic solenoid valve	AVS-3313-24D		46.55	1	35	$ 46.55	Electrical
	Air knife pneumatic solenoid valve	AVS-3313-24D		46.55	1	35	$ 46.55	Electrical
	Pressure regulator for impactor	AFR-3333		49.21	1	37	$ 49.21	Electrical
	Pressure regulator for air knife	AFR-3333		49.21	1	37	$ 49.21	Electrical
	Solenoid muffler	SBC-38R		5.32	1	4	$ 5.32	Electrical
	Polarity switching relay for linear actuator	QL2N1-D24		14.63	1	11	$ 14.63	Electrical
	Socket for QL2 relay	SQL08D		5.6525	1	4.25	$ 5.65	Electrical
	Linear actuator	PA-14-12-35		136.24	1		$ 136.24	Electrical
	Power supply for actuator	PSB12-060		52.535	1	39.5	$ 52.54	Electrical
	Power supply for HSI, HSO, Analog output modules	PSB24-060		48.545	1	36.5	$ 48.55	Electrical
	Steel DIN 3 Rail, 7.5mm Deep, 1m Long	8961K15			1		$ -	Electrical
	Build plate present switch, axis b homing switch	D2HW-C233MR		9.66	2		$ 19.32	Electrical
	E-stop legend plate	AHX720-5A		10.64	1	8	$ 10.64	Electrical
	Illuminated E-stop push button	AR30V0L-01E3RZC		47.215	1	35.5	$ 47.22	Electrical
	E-stop relay mounting socket	P7S-14F-END DC24		72.72	1		$ 72.72	Electrical
	E-stop relay	G7S-3A3B-E DC24		88.64	1		$ 88.64	Electrical
	On/off switch	30102D	Overall power disconnect for entire machine	44.555	1	33.5	$ 44.56	Electrical

Part No.	Part Name	Supplier Part Number	Purpose	Cost/Unit	Quantity	Cost USD	Cost	Part Type
	Reset Button	GCX1123	Reset button required to reset safety relay	10.9725	1	8.25	$ 10.97	Electrical
	Male-Female Threaded Hex Standoff - 18-8 Stainless Steel, 4.500 mm Hex, 5 mm Long, M3 x 0.50 mm Thread (X1)	93655A091	Mounting DC drive analog input module to DC drive	4.256	1	3.2	$ 4.26	Fastener
	18-8 Stainless Steel Socket Head Screw - M3 x 0.5 mm Thread, 12 mm Long (X9)	91292A114	For fastening to standoff nut, supporting DC drive analog module, and stepper drivers	6.6101	1	4.97	$ 6.61	Fastener
	316 Stainless Steel Split Lock Washer - for M3 Screw Size, 3.4 mm ID, 6.2 mm OD (X8)	92153A416	Washers for M3 socket head screws used above	3.2452	1	2.44	$ 3.25	Fastener
	18-8 Stainless Steel Serrated Flange Locknut - M3 x 0.5 mm Thread (X8)	97400A135	Nuts for m3 screws	10.6134	1	7.98	$ 10.61	Fastener
	18-8 Stainless Steel Socket Head Screw - M5 x 0.8 mm Thread, 8 mm Long (X20)	91292A191	Fastening DIN rail and other components to junction box	12.7946	1	9.62	$ 12.79	Fastener
	Medium-Strength Steel Serrated Flange Locknut - Class 8, M5 x 0.8 mm Thread (X20)	94920A300	Nuts for fastening DIN rail and other components to junction box	11.8503	1	8.91	$ 11.85	Fastener
	D2HW Sealed Ultra Subminiature Basic Switch - with long lever handle	D2HW-C223M	axis A limit switch	9.87	1		$ 9.87	Electrical
	MAGNETIC CONTACT SWITCH (DOOR SE)	1528-1907-ND	Door closed sensor	5.67	1		$ 5.67	Electrical
	18x18x8 Enclosure	SC181808	Electrical junction box	77.14	1	58	$ 77.14	Electrical

Figure F.1

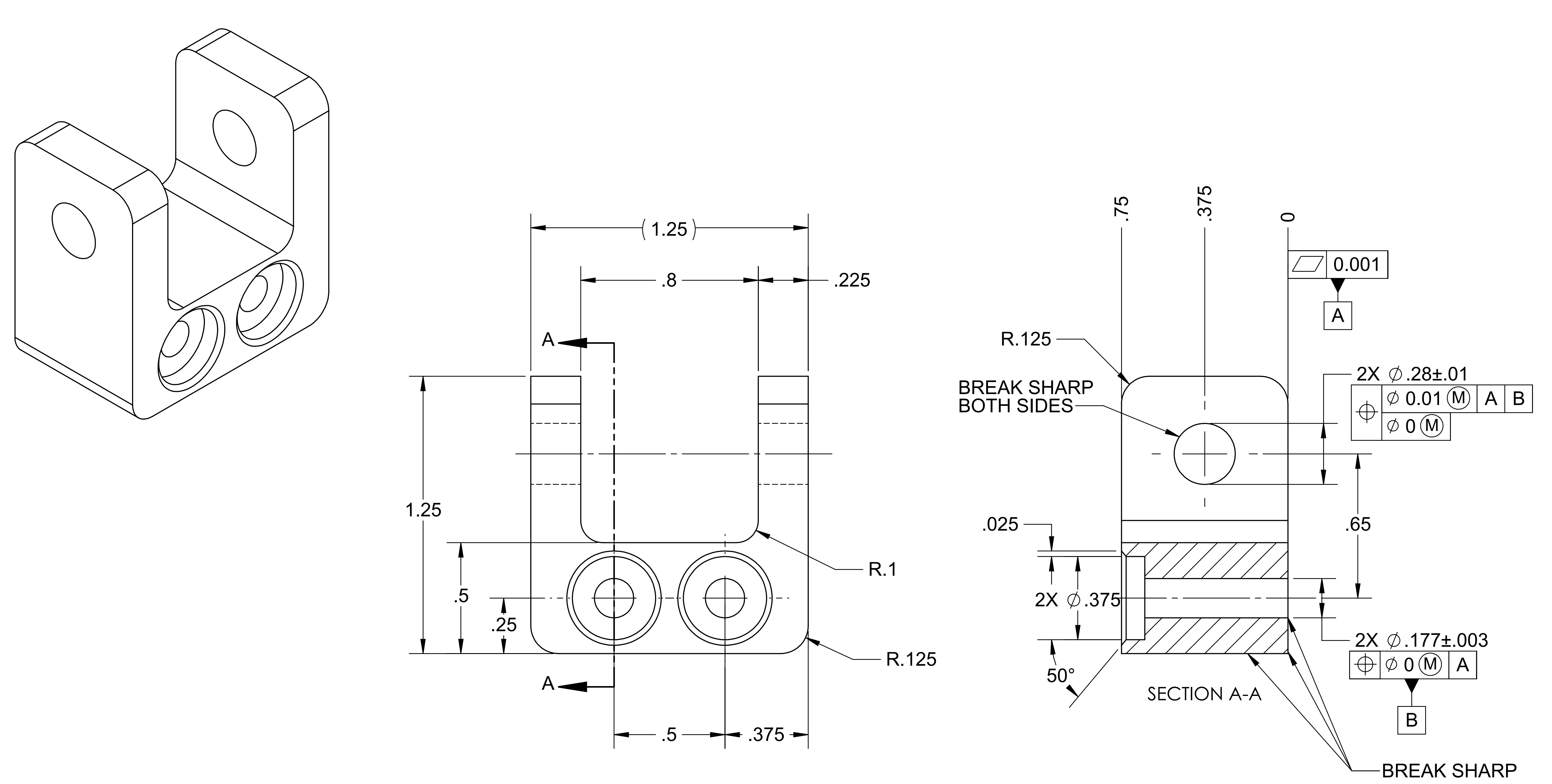
References

[1] MakeItFrom.com. (). 6105-t5 aluminum, [Online]. Available: https://www.makeitfrom.com/material-properties/6105-T5-Aluminum.



DWG. NO. BM_CRANKSHAFT_BAXISSEAT_R0 REV 0

UNLESS OTHERWISE SPECIFIED GD&T PER NONTOLERANCED DIMENSIONS ARE BASIC CAD MODEL IS BASIC NONDIMENSIONED GEOMETRIES PER CAD MODEL	**DIMENSIONAL UNIT:** INCH	**EDUCATIONAL AND PROPRIETARY** THE INFORMATION CONTAINED IN THIS DRAWING IS PROPRIETARY AND MAY NOT BE USED WITHOUT THE WRITTEN CONSENT OF A UMSAE FORMULA REPRESENTIVE..	University of Manitoba — PRECISION ADM POWDER REMOVAL DEVICE
GENERAL TOLERANCE 0.003 A B **THREADED FEATURES** EXTERNAL THREADS AT ⌀MAJOR INTERNAL THREADS AT ⌀MINOR	N/A = NOT APPLICABLE **CHAMFERS** N/A **FILLETS** N/A **BREAK SHARP** R0.001 ± 0.0005 **OR** 0.001 ± 0.0005 X 45° ±2° **SHARP** R MAX **OR** X 45° MAX WITH NO BURR PERMISSIBLE	MATERIAL 4340 STEEL FINISH	TITLE: AXIS B SEAT BUILD-PLATE MOTION
		DO NOT SCALE DRAWING	SIZE B — DWG. NO. BM_CRANKSHAFT_BAXISSEAT_R0 — REV 0 SCALE: 1:2 — WEIGHT: KG — SHEET 1 OF 1



DWG. NO. AIR_AIRKNIFE_MOUNTING2_R1 REV 0

UNLESS OTHERWISE SPECIFIED
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NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES
PER CAD MODEL

DIMENSIONAL UNIT: INCH

N/A = NOT APPLICABLE

GENERAL TOLERANCE
0.003 | A | B

THREADED FEATURES
EXTERNAL THREADS AT ∅MAJOR
INTERNAL THREADS AT ∅MINOR

CHAMFERS N/A
FILLETS N/A
BREAK SHARP ±
OR ± X 45°±2°
SHARP R MAX **OR** X 45° MAX
WITH NO BURR PERMISSIBLE

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MATERIAL
4340 STEEL

FINISH

DO NOT SCALE DRAWING

University of Manitoba

PRECISION ADM POWDER REMOVAL DEVICE

TITLE:
AIR KNIFE MOUNT
AIR

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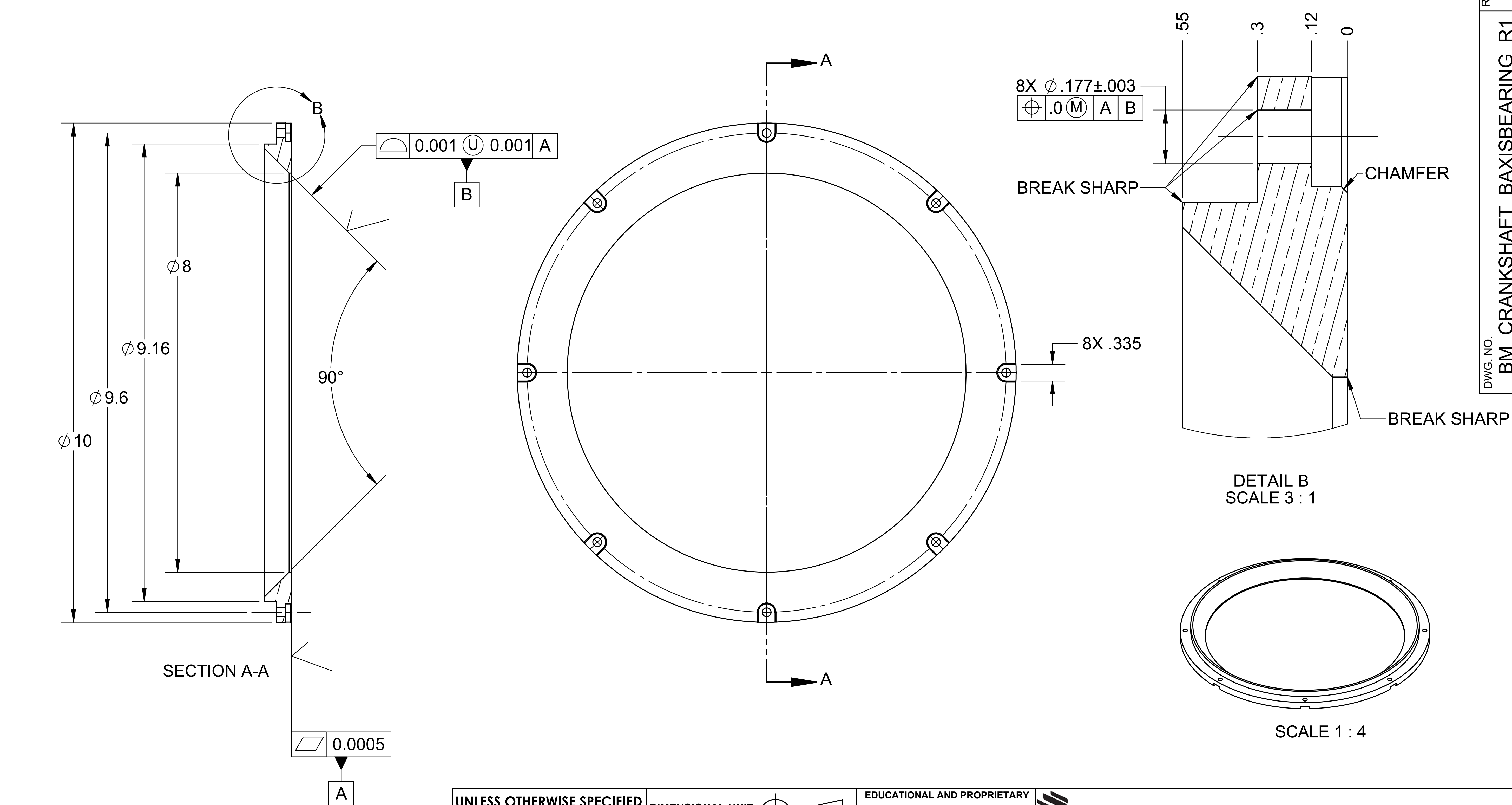

REV 0

DWG. NO. BM_CRANKSHAFT_BAXISBEARING_R1

UNLESS OTHERWISE SPECIFIED GD&T PER NONTOLERANCED DIMENSIONS ARE BASIC CAD MODEL IS BASIC NONDIMENSIONED GEOMETRIES PER CAD MODEL	**DIMENSIONAL UNIT: INCH**	**EDUCATIONAL AND PROPRIETARY** THE INFORMATION CONTAINED IN THIS DRAWING IS PROPRIETARY AND MAY NOT BE USED WITHOUT THE WRITTEN CONSENT OF A UMSAE FORMULA REPRESENTIVE..	University of Manitoba — PRECISION ADM POWDER REMOVAL DEVICE
GENERAL TOLERANCE 0.003 A B **THREADED FEATURES** EXTERNAL THREADS AT ∅MAJOR INTERNAL THREADS AT ∅MINOR	N/A = NOT APPLICABLE **CHAMFERS** 0.02 ± 0.003 X 45° ±2° **FILLETS** N/A **BREAK SHARP** R0.001 ± 0.0005 **OR** 0.001 ± 0.0005 X 45° ±2° **SHARP** R MAX **OR** X 45° MAX WITH NO BURR PERMISSIBLE	MATERIAL ALUMINUM BRONZE	TITLE: BEARING BUILD-PLATE MOTION
		FINISH	SIZE **B** — DWG. NO. BM_CRANKSHAFT_BAXISBEARING_R1 — REV 0
		DO NOT SCALE DRAWING	SCALE: 1:2 — WEIGHT: KG — SHEET 1 OF 1