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PRODUCT INSERTION FIXTURE PROJECT

A Major Qualifying Project Report

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by

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Abstract

The sponsor utilizes a manufacturing process that requires the insertion of a product into a housing slot. This stage of the assembly has been a source of scrap; however, the primary cause is undetermined. This project focuses on the design of a testing fixture to simulate the product insertion process and to induce a variable offset between the tooling and housing to determine the effects of misalignment on the success of assembly attempts. The tooling is actuated using a linear servo motor to simulate the tooling path used in the assembly machine. The nest holding the housing is mounted to a two-axis, micrometer-driven linear stage that is used to induce an adjustable offset between the housing and tooling in the plane perpendicular to the tooling approach direction. Sensors are used to align the product with the housing slot and to measure the geometric characteristics of the product prior to the assembly attempt. The nest and tooling are mounted on modular intermediate plates that allow more than one product line to be accommodated.

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Jeremy Donatell	Aerotech, Inc. area manager
Dennis Chepulis	Qioptiq Inc. sales manager
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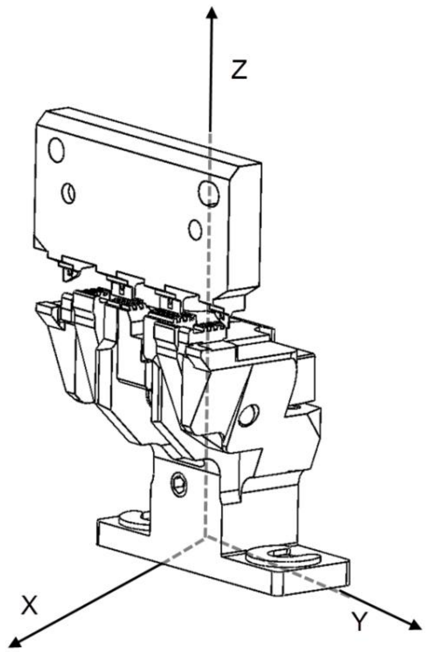


Figure 1: Definition of Coordinate Axes Used

Razor Blade Assembly Machines

There are two main categories of assembly machine used in the assembly of razor blades and housings. The first is a continuous motion machine, in which the product is worked on while still in motion. The second is an indexing machine in which the product is moved along an indexing conveyor or carousel that stops for the product to be worked on and then indexes to the next work station.

In processes on continuous motion machines the product is transferred between feeders and tooling stations; at each station the tooling and product move together as the product is worked on. The product is then transferred to the next station for further work. However, it should be noted that at each station the product and tooling remain stationary with respect to each other in the XY plane because they move together.

Conversely, indexing machines have stationary tooling and the product is moved along an indexing mechanism between tooling stations. The product is stopped at each tooling station to be worked on. There may be some variation in the positioning between the tooling and product from stop to stop, so it is a common practice to have either the product or tooling able to float in the direction of indexer motion to accommodate this variation. The tooling generally comes into contact with a positioning device which aligns the tooling and product precisely at each tooling station.

Problem Introduction

Misalignments between the tooling inserting a blade and the slot in the blade housing may lead to the blade not being properly inserted. These result in the housing and all blades inserted up to that point being discarded. As a result of the blade manufacturing process, all blades have a slight curvature along the length of the blade known as blade bow. Better understanding how blade bow and errors between tooling and housing locations result in such failures may allow the reduction of the overall scrap resulting from missed blade insertions. The purpose of this project is to develop a test fixture that varies the offset between tooling and nest to evaluate the potential effects offset has on the ability of the machine to correctly insert the blade, and to measure the critical blade geometry. The test apparatus adjusts the relative positions of the nest and tooling in the X direction, while still keeping the possibility of adding a degree of freedom in the Y direction. Blade insertion is attempted at various relative positions to determine if induced offsets have a significant effect on the ability to successfully load blades. The aim is to be able to predict if a given offset between housing and blade prior to loading will cause a failed loading attempt and, ideally, to induce an offset that will cause insertion failure and then automatically calculate the change in position that is necessary for the blade to be successfully loaded. This project designed the test fixture using a specific product, but the fixture also accommodates the tooling, nests, and tooling velocity profiles of other products.

Goal Statement

To design a test apparatus to be used in the measurement and analysis of a blade insertion process in order to minimize failure rate.

Background Research

Definition of Sub-Systems

In order to correctly understand the various sub-systems of the testing apparatus, research was conducted into available technologies that could be implemented in the design. The main sub-systems tasks identified were the actuation of the nest, the actuation of the tooling, the pressure and vacuum system, sensors and other detection components, the control of timing of each electrical component, and the structural design of the frame and sliding components. Options identified to accomplish the tasks in each sub-system are discussed in the following sections.

Actuation

Z Axis

There are three main design options for the vertical motion (z axis) mechanism. The rack and pinion set up shown in Figure 2 can be purchased through Atlanta Drive Systems Inc. (1) , which also provides an ultra-high precision rack and pinion, with the pitch accuracy up to 0.012 mm per meter traveled (0.012mm/meter). This precision meets the project's requirement. To help control the z direction motion of the rack and eliminate the movement other axes, the rack would be mounted to the carriage of a rail slide using the mounting holes that are on the rack.

A major concern with any rack and pinion driven system is backlash. Even in high precision rack and pinions, the backlash cannot be completely eliminated. This results in some positional inaccuracy and reduced smoothness of motion when starting, stopping, or changing direction of motion of system. This is of particular concern in this application, because the tooling would be changing direction as it interacts with the housing, which is the most critical part of the test.

Figure 2: Tooling Position and Z-axis Movement (30)

Figure 3: High precision ball screw used on CNC Router (11)

An alternative to the rack and pinion solution is a ball screw; Nook Industries provides high precision ground ball screw with ±0.0417 mm/meter of travel precision. The ball screw can be directly driven by a servo motor and the can achieve a linear output up to 30m/min (500mm/s). The tooling can be directly attached on the nut, as shown in Figure 3

Back-driving in ball screws is the result of the load pushing axially on the screw or nut to create rotary motion. All ball screws, due to their high efficiency, will back-drive. The resulting torque is known as “back-driving torque” and is the torque required to hold a load in position. When considering ball screws for an application, the need for a brake is an important consideration.

The third possible form of linear actuation being considered is a linear servo. These motors are very precise and powerful and ensure a near perfect simulation of the velocity profile of the machine tooling. This idea virtually eliminates back-lash in the system. It is also very versatile and accurate. Unlike some of the other options considered, a linear servo does not have any mechanical advantage so the motor must be sized to supply the force and acceleration needed.

Additional considerations for a linear servo that is vertically mounted include the overturning moment caused by the tooling, which has a center of gravity that is cantilevered 37 mm of the servo motor cart. The resulting moment may necessitate a counterbalance system. If the motor lost power it could crash, so a breaking, power backup, or decelerating system should be considered in this orientation.

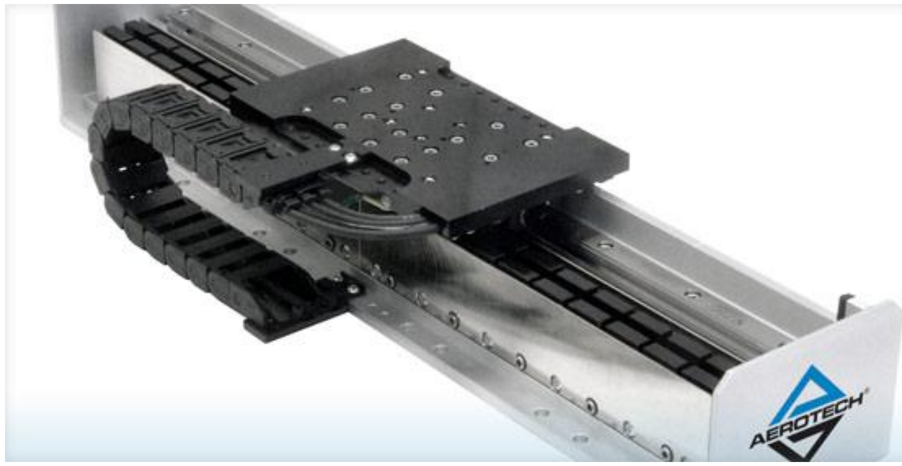


Figure 4: Linear Servo Motor (33)

<u>X and Y Axes</u>

Micrometers are one possibility to drive the stage to travel to the desired x and y positions. The micrometer resolution must be better than the stage's resolution to be a valid option. Two of the best options are shown in Figure 5.

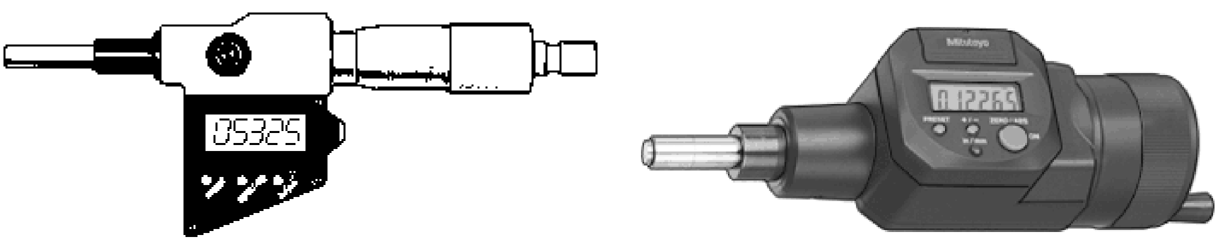


Figure 5: Electronic micrometer heads style A and B (2)

(A&B) Electronic micrometers have LCD displays, inch/metric conversion, auto shut-off (unless noted), and SPC data output so they can be connected to a Mitutoyo processor using an SPC data output cable (sold separately), or to a PC using the SPC data output cable and an input tool. They also have position memory, also known as absolute (ABS) positioning, that can set the display on the micrometer head to zero at any point and store the position in memory for the life of the battery. Additionally, the micrometer heads can "freeze" a reading to keep it displayed even if the measuring face is repositioned. Display in 0.00005" (0.001 mm) increments. Two batteries are required. Style A has an accuracy of ±0.0001 inches (±0.0025 mm) and Style B has an accuracy of ±0.00015inches (±0.003 mm).

The nest and housing are mounted to a surface on a linear guide, collectively known as the stage, and the stage position is controlled by micrometers. The resolution, stage size, range of travel, load capacity, micrometer thrust capacity, weight of the stage and price are listed in the table below as factors for comparison.

Table 1: Precision Stage Comparison Chart (3), (4)

Model #	Resolution	Stage Size	Travel	Load Capacity	Weight	Price
NT55-461	± 0.001mm	44.4mm x 44.4mm	25.4mm	48.93N	450g	$599.00
1203MM-XY	± 0.00052mm	79.2mm x 79.2mm	25mm	133.4N		$626.00
NT55-282	± 0.000127mm	45.0mm x 45.0mm	25mm	107.9N	230g	$319.00
NT56-357	± 0.000127mm	32.5mm x 32.5mm	13mm	13N	78g	$249.00

According to the task specification, the x and y directions offset adjustments must be able to be accurately measured to ±0.015mm. All models meet this requirement. The project also requires a stage that is able to support the nest, housing, and a mounting apparatus for the nest without exceeding the load capacity. The NT56-355 Model has a load capacity of 13N, which may be a concern due to the combined weight of the nest, housing, plate the nest is mounted on, and tooling forces; this is especially a concern because future designs may have tooling forces different from those seen in the product lines currently being used. Overall, the NT55-283 is inexpensive compared with the rest options, and it meets all the requirements.

Qioptiq Inc. offers several pre-assembled micrometer driven stages that have two axes of travel such as the one in Figure 6. Because these stages are sold as two-axis systems rather than stackable one-axis stages, there can be a higher assurance that the directions of travel are orthogonal to one another. This is desirable in the event that testing is performed with an offset in more than one direction. These stages are available in 25 mm and 200 mm of travel and offer the option of digital micrometers to measure offset. The model being considered for this application is the XY 85-25 with digital micrometers. This model has an 85mm x 85mm stage with 25mm of travel measured by digital micrometers. It has a load capacity of 150 N, which is sufficient for this application and an orthogonality of 30 arc seconds. The digital micrometer features storage of the last value, variable zero point and an automatic display turn off when not in use (5).

Figure 6: Qioptiq Inc. stage (5)

Pneumatic System

As shown in the Figure 7, the tooling requires a –8.00 psig negative pressure at the ports to pick up the blade, and then switch to a +4.5 psig positive pressure to push the blade into housing. The signs on the pressure values indicate the direction of the flow. The task specs dictate that the testing pressure/vacuum system should be able to adjust the magnitude between –10 psi (–69kPa) to +10 psi (69kPa).

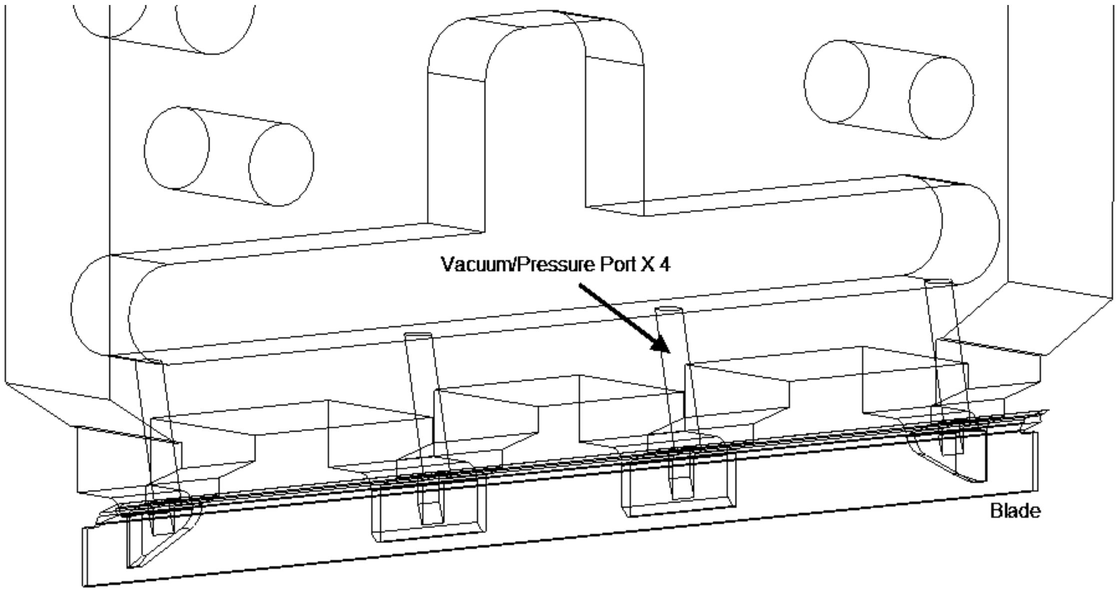


Figure 7. Blade Pick and Place Tooling

The total area of the ports is $0.048cm^2$. When the blade is picked up by the tooling applying –8psig pressure, the force applied on the blade is 0.267N.

Based on the pressure requirements, two designs are proposed. The first design uses a pressure source to provide pressure, a regulator to regulate the pressure to a desired magnitude, a solenoid valve to control the timing of the pressure, and a P3010 vacuum pump to generate constant negative pressure based on the Venturi effect. The Venturi effect is the reduction in fluid pressure that results when a fluid flows through a constricted section of pipe. The vacuum pump also consists of a cassette with integrated nozzles, non-return valves, silencers and filters for compressed air and vacuum, and it comes with different modules such as vacuum switches and quick-release module.

The second design uses a compressed air accumulator to store the compressed air at the required pressure magnitude, and provide the pressure whenever the valve is open to deliver pressure to the tooling. Meanwhile, a vacuum pump is also used to provide constant vacuum to the tooling whenever the testing apparatus is on.

The flow diagrams for both designs are shown in Figure 8 and Figure 9.

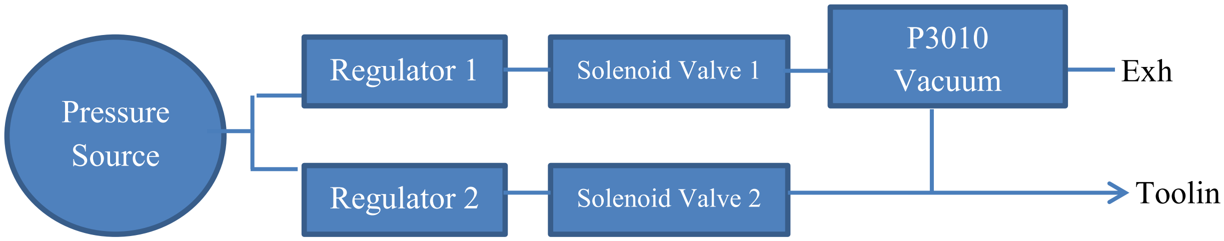


Figure 8: Pneumatic System Design 1

The first design uses a single pressure source to provide both positive pressure and vacuum. The pressure source supplies pressure to two hoses, one that directly supplies pressure to the tooling and one that runs through a vacuum generator. The venturi vacuum pump P3010 generates a controlled level of vacuum based on the regulated input pressure. A 2-way solenoid valve is placed between regulator 1 and the P3010 vacuum pump to switch the vacuum output on and off. The vacuum is directly applied at the tooling end. When the vacuum line is shut off, the solenoid valve 2 is opened to allow the air to flow through regulator 2 to supplied the tooling end with pressure.

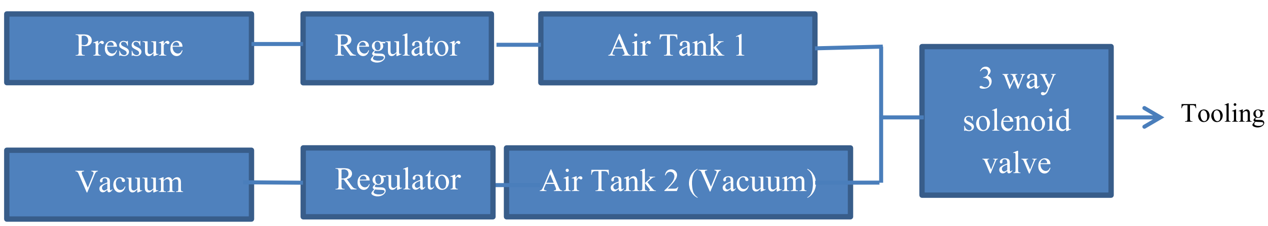


Figure 9: Pneumatic System Design 2

The second design consists of separate vacuum and pressure sources and a three way solenoid valve. The vacuum pump is directly connected to the normally open port of the solenoid valve. The inlet pressure of the pressure source is adjusted by regulator 1 and the air is stored in the pressure accumulator. this system is connected to the normally closed port of the solenoid valve, which is turned on by an electrical signal when the blade need to be blown off. The third port of the solenoid is the output port which is connected to the tooling to provide vacuum or pressure to the blade ports.

The 9888K13 compressed air/vacuum accumulator from McMaster-Carr Supply Company is a good option for the second design. It is able to withstand a pressure ranging from

29.9'' Hg vacuum to 200 psi pressure, which is within the range of vacuum to pressure requirement.

Besides the –10psi to +10psi controllable pressure, the maximum flow rate is 2.9 cfm. Therefore, the 4246K41 tamper-resistant quick-response air regulator is selected for regulator 1 and 2 in design one. The selected air regulator can be connected to a ¼" pipe, and has a 86 max scfm at 100 psi, with a 0–140 psi range. The air regulator for the second design option can be a 4246K43 tamper-resistant quick-response air regulator, which can be connected to a ½" pipe, and has a 210 max scfm at 100 psi and a 0–140 psi range.

The 9901K64 vacuum pump was selected to produce 26" Hg vacuum. The oil-free electric high-vacuum vacuum pump is able to produce maximum vacuum of 26" Hg, and a 4.5 cfm flow rate. However flow rate is not a serious concern because it is assumed that the blade completely covers the holes, so there is no leakage and therefore no flow rate.

Sensor Detection

The ability to detect the position of the blade within the tooling and the housing with respect to the tooling is necessary to properly align them and obtain a zero point for testing. Additionally, it is also beneficial to be able to measure the amount of curvature in the blade out of the YZ plane. Finally in an attempt to understand the mechanisms that cause the process to fail it is likely to be helpful to be able to see what happens during the insertion attempt, for this a high speed camera is needed to record the test.

Blade Bow Detection

Blades are slightly bowed along the Y axis as a result of production; it is possible that the degree of curvature could affect the assembly process being examined by this test fixture. As such, it should be possible to measure the amount of curvature in each blade on the tooling prior to testing. Several methods were considered for this application. Below 1 dimensional and 2 dimensional laser displacement devices, spectral interference measurement tools, and linear variable displacement transformers (LVDTs) will be discussed. One concern that still exists is the possibility that the vacuum pressure applied to the blade while it is on the tooling may deform the blade. It is currently unknown if the blade shape is deformed by the tooling; furthermore there is no information examining if the shape on the tooling or the shape without the applied pressure has a more pronounced effect on the blade insertion.

1D Laser Displacement

A 1D laser displacement device functions by reflecting a laser spot off of the surface and the location of the reflected spot on a CCD is analyzed to determine the distance of the object (6). The LK-G series seen in Figure 10 made by Keyence Corporation was considered for this type of sensor. This sensor is available with two spot types: wide spot and small spot. The wide spot uses a diffuse beam to find an average distance to the surface, whereas the small beam detects the distance at much smaller points, making it better for taking the profile. Several of the sensors within this family are being considered with repeatability ranging from 0.01μm to 0.2 μm. Because this is a one dimensional sensor and its size prevents multiple sensors from being mounted along the length of the blade, the sensor would have to be mounted to a precision rail and then driven along the length of the blade either manually, or preferably by a small actuator that would provide a more regular travel speed. The reflective properties of the target would enable the sensor to operate at a lower power and with a shorter emission time than needed for a less reflective target, which leads to a faster sampling rate. These sensors have been quoted at $5,000-$6,000 for the models considered. For additional specifications please see sensor matrix comparison and sensor schematics in Appendix D.

Figure 10:LK-G series sensors (2)

Figure 11: LK-G sensors mounted (2)

2D Laser Displacement

A 2D laser displacement device functions by reflecting a laser line off of the surface and the location of the reflected profile is projected on an E^3-CMOS sensor and analyzed to determine the distance of the object (7). The LJ-G series seen in

Figure 12: LJ-G Series application example (3)

Figure 12 made by Keyence Corporation was considered for this type of sensor. Because this is a 2D sensor it would eliminate the need for a rail and allow the sensor to remain stationary while still providing a full profile of the blade. These sensors have been quoted at $17,000-20,000 for a complete system. For additional specifications please see sensor matric comparison and sensor schematics.

Spectral Interference

The spectral interference device also uses a reflected laser beam to measure distance, however it can achieve much higher resolution than the methods discussed previously: on the scale of 1-10 nm (8). As a result of this accuracy it is more likely to be susceptible to interference from the movement in a rail, so it is preferable to have them mounted stationary to the blade at the time of measurement. This requires multiple sensor heads in an arrangement similar to that in Figure 13. It is also preferable to have as many heads as possible to accommodate along the blade, but three may be considered the minimum with one mounted in the middle and one near either end of the blade. The controller accommodates two sensor heads, and an expansion can be added to accommodate a third (additional expansions may be added until the total sensor heads is six). The sensor heads themselves are small enough to allow multiple heads to be mounted along the length of the blade, however depending on model it may be necessary to add a means of moving the sensor in the X axis to get the sensor heads sufficiently close to the target. The additional equipment and multiple sensor heads required in this application may drive the price up. For additional specifications please see sensor matrix comparison and sensor schematics in the appendix.

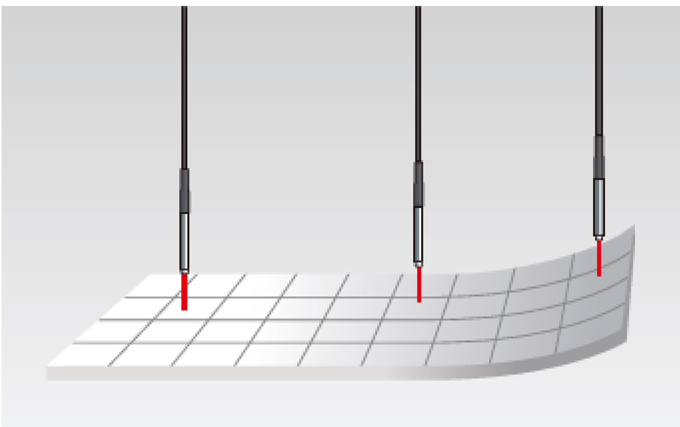


Figure 13: SIF Series measuring warpage (4)

LVDT

An LVDT is a ferrous rod used as a core within a primary coil and two secondary coils. Alternating current is driven through the primary coil and this induces a current along the center of the coil. As the rod is displaced the voltage in one of the secondary coils increases while the voltage in the other secondary coil decreases; by measuring the voltage difference between the secondary coils, the distance the center rod has been displaced can be calculated. Keyence Corporation's GT2-air push sensors seen in Figure 14 are being considered in this application with a low stress head (9). The spindle is actuated using an air supply of pressure 0.25- 0.5 MPa with a 4mm diameter hose. Although this model is moved by the air pressure, the measuring force is unaffected by the amount of air pressure supplied. This is likely to be the least expensive option but it has the risk of moving the blade during measurement because it is a contact sensing method. At least 0.3 N of force is required to measure blade location; however, it cannot be guaranteed that this will not move the blade, especially if the blade is bowed off the surface of the tooling. For additional specifications please see sensor matric comparison and sensor schematics in the appendix.

Figure 14: GT2 Air Push type LVDT (5)

Housing Position Detection

Automated Optical Inspection

One option for detecting the location of housing is to use a machine vision or Automated Optical Inspection (AOI); this is a process used for inspection in a variety of industries including automotive and in the production of printed circuit boards and LCDs. AOI systems take an image of the product, scan for imperfections and take measurements. In this application those measurements can be used to determine if the part is positioned incorrectly and possibly determine where it should be located in comparison to current location. Possible drawbacks of an AOI system in a continuous motion machine may be the sacrifice of the quality of images. Additionally, these systems require software that uses complex algorithms to analyze the position; this can make the systems expensive to implement.

Manual Optical Inspection from the Side

One way to implement the kind of visual inspection seen in and AOI system at a reduced cost is to eliminate the software that is used to analyze the image. This idea led to the development of a type of 'manual optical inspection' system. This system uses a camera that is aimed at the housing and tooling the same way the camera in an AOI system; however, the image is displayed on a screen or computer monitor and the machine operator uses that image to position the housing rather than the image being analyzed by the AOI software. This manual inspection and alignment process introduces concerns about the resolution and accuracy of the system. To help reduce errors in alignment a reference plate with vertical lines is mounted behind the tooling and housing, these vertical striations would serve as a guide to aid the operator when adjusting the position. Ideally, the camera will also magnify the image, making it easier to see the position of each component. Additional considerations for selecting and manufacturing parts for this system include the depth of field on the camera and precision manufacturing and mounting of the reference plate. The camera needs a sufficient depth of field to keep the housing, tooling, and reference plate in focus; otherwise, the accuracy of the system would be greatly diminished. However, the camera does not need to be a high speed camera; the primary function of this camera is alignment, not observation. The lines on the reference plate must be precise and the plate must be mounted with the lines correctly aligned with the z axis to ensure that the housing and nest can be lined up with as much accuracy as possible.

Manual Inspection From Above

An alternative is to inspect the nest and housing from above. The nest and tooling is first aligned using a gage fixture to be designed by the project sponsors. A high resolution camera is positioned so it looks down on the nest. The housing is then inserted into the nest; there is a mark of known position on the nest that can be used to measure the relative position of the housing slot. If the measurement varies from the expected distance, then an adjustment can be made so the housing slot is in the correct location.

Consistent Slot Location Assumption

Other sensor types may require the assumption that the slots are placed in the same location in every housing of a given product line. Sensors can then be used to measure the location of the outside of the housing and calculate the location of the slots based off the product geometry. This option encompasses a number of options, primarily those technologies discussed in the measurement of the blade bow. The LVDT may be a much more practical option for this application than the blade measurement because the housing should be less susceptible the measuring forces. An alternative model of the GT2 series that would be more suitable for this application because of its longer stroke is listed in the sensor matrix.

High Speed Cameras[1]

A high speed camera is used to observe the results of the insertion test because of the speed of the tooling. However, these systems are costly. The most logical system to be used on test fixture like this is a camera similar to those used on production lines, one such camera is the FASTCAM MH4 seen in Figure 15, which is a four camera system that would allow the test to be viewed from a variety of perspectives (10). Alternatively, a single camera with a much higher frame rate and resolution could be used to get a clearer image (11); however, this degree of fine resolution may be more than is needed in the application at hand.

Figure 15: FASTCAM MH4 (6)

Structural Design

It is essential that the structural integrity of the frame does not reduce the precision of the testing apparatus motion or the sensor measurements. As a result, the material selected must provide a rigid enough frame for the system to be stable and reliable. A user-friendly system that offers dependable structural strength and simple assembly is T-Slot extruded aluminum framing from 80/20 Inc. These systems are known as the "Industrial Erector Set" that can create strong, rigid structures and allow versatility in design.

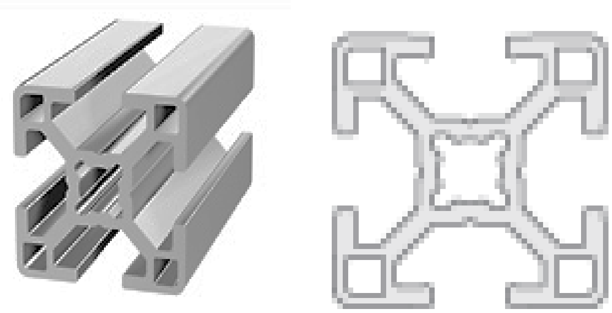


Figure 16:80/20 Extruded Aluminum T-Slot Framing with highlighted cross-section (23)

The unique T-slot structure shown in Figure 16 allows for limitless possibilities in orienting the frame structure, thus providing a suitable platform for the apparatus. A cart structure can be built to act as a support for the housing platform and to increase the portability of the test apparatus by adding self-leveling casters to the cart.

[1] High speed camera will be supplied by the project sponsor

Because of the many fasteners needed in an 80/20 frame, it may not provide the rigidity and precision that is wanted in the internal frame. The frame should not deflect more than 0.01mm under normal loading. A steel frame may be preferable for this application. In considering the frame design it is desirable to minimize the number of connections, alignment pins, and high tolerance surfaces to minimize the stack up errors in the system. Cantilevers should also be avoided wherever possible because they require more material to have a comparable stiffness to other support types. Additionally, support gussets and pockets may be incorporated to lighten the apparatus if it is more stiff than required.

Additionally, a cage structure was implemented around the testing fixture and safety panels added to the box to act as a shield between the test area and the operator. These panels are available from 80/20 Inc. distributors as are all necessary fasteners and accessories for framing. A cage structure can be built around the apparatus to act as supports for the motor and tooling that needs to be above the housing area. The strength of these systems has been tested in various industrial applications already and can be shown to provide the structural rigidity necessary for this application.

Procedure

Design

This project aims to identify key elements in the insertion process and design a test fixture that can vary them. The various sub-systems established are required to complete an assembly, so they must meet all the criteria necessary for an accurate and precise apparatus. The main three goals that must be achieved in this design are structural stability, modularity, and accurate adjustability. These are each addressed below and possible applications to maximize performance are suggested.

Z Direction Actuation

Three of the most promising z-direction actuation methods were the ball screw, rack and pinion, and linear servo. Each of these concepts, their advantages, and possible mounting orientations were investigated.

Ball Screw

A ball screw is an efficient means of converting rotary to linear motion. The ball screw has good precision and less backlash than a rack and pinion. Nook Industries provides a high precision ground ball screw with ±0.042 mm/m precision, and is able to be directly driven by rotary servo motor. As shown in Figure 17 on the right.

To choose a ball screw and mounting kit, the precision requirement, dynamic load, driving torque, back-driving torque, end machining, mounting options, life expectancy, length, critical speed, and column strength of the screw must all be determined. The following steps help the user to determine if the selected ball screw (Nook-0750-0200 SGT RA) meets the design requirements.

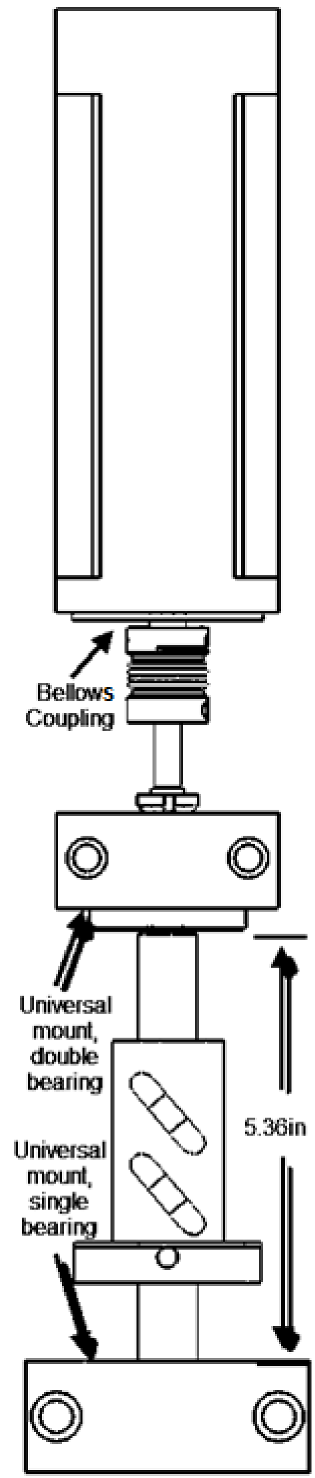


Figure 17 Ball Screw Assembly

Step 1: Find the Load

The static load is the maximum thrust load – including shock – that can be applied to the ball nut without damaging the assembly. The dynamic load is the thrust load in pounds. The static load on the ball screw nut is the total weight of each component driven by the nut.

$$\text{Load} := (2 \cdot 0.5534 lbm + 0.9299 lbm + 0.0961 lbm + 0.048 lbm) \cdot g = 2.181 lbf$$

Also, under high acceleration conditions, the inertia load must be determined and included in the calculation.

Step 2: Determine the Length of Travel

In order to simulate the blade insertion process on different product lines, the length of travel needs to be considered. Based on the sponsor's current machine designs, the ball screw has a maximum length of travel of 2in, with an overall length of 5.7in, and an overall travel of 2.36in. However, 14in ball screw is more suitable in the model because it provides enough stroke for sensor measurement and blade loading.

Step 3: Determine the Average Travel Rate and Maximum Travel Rate

From the indexing machine profile, the average speed and the peak speed are determined.

$\text{travel} := 2.36 in$ Total unsupported length is 2.36in

The average travel rate is 276in/min in the sponsor's current machine design.

Assume the peak velocity is twice as large as the average velocity in this simulation. V.peak=560in/min

The maximum travel rate is:

$$V_{peak} := 560 \frac{in}{min}$$

Step 4: Determine the End Fixation

End fixation refers to the method used to support the ends of the ball screw. The degree of end fixation is related to the amount of restraint of the ends of the screw. A type D end fixation is when both ends are rigidly mounted with angular contact bearings that are spaced 1.5 times the diameter of the mounting journal or more.

Step 5: Determine the axial force required to move load

The axial force is determined by multiplying the coefficient of friction of the guidance system by the load. The coefficient of friction for lubricated Nook Linear Bearings is 0.0013.

$$\mu := 0.0013$$

$$F_{axial} := \mu \cdot Load = 2.835 \times 10^{-3}\,lbf$$

Therefore, the axial force the screw must produce to move the load is 2.835*10^-3 lbf.

Step 6: Check the critical speed based on screw

The speed that excites the natural frequency of the screw is called the critical speed. Resonance at the natural frequency of the screw occurs whether the screw is set horizontally or vertically.

The critical speed can be avoided by using the Critical Speed Chart in Appendix A. Based on the system travel rate, machine ends and the length between bearings, the maximum travel rate can be determined.

In current the design, the Nook-0875-0200 SGT RA ball screw has a type D mounting and a length smaller than 19in. Therefore, the maximum rate of travel is above 2000in/min, when the screw length is 10 inches long.

Step 7: Check Column Strength of screw

From the chart in Appendix B, the maximum column load can be determined. The maximum column load in current design is around 9,000 lbs, which is far higher than current project requirement.

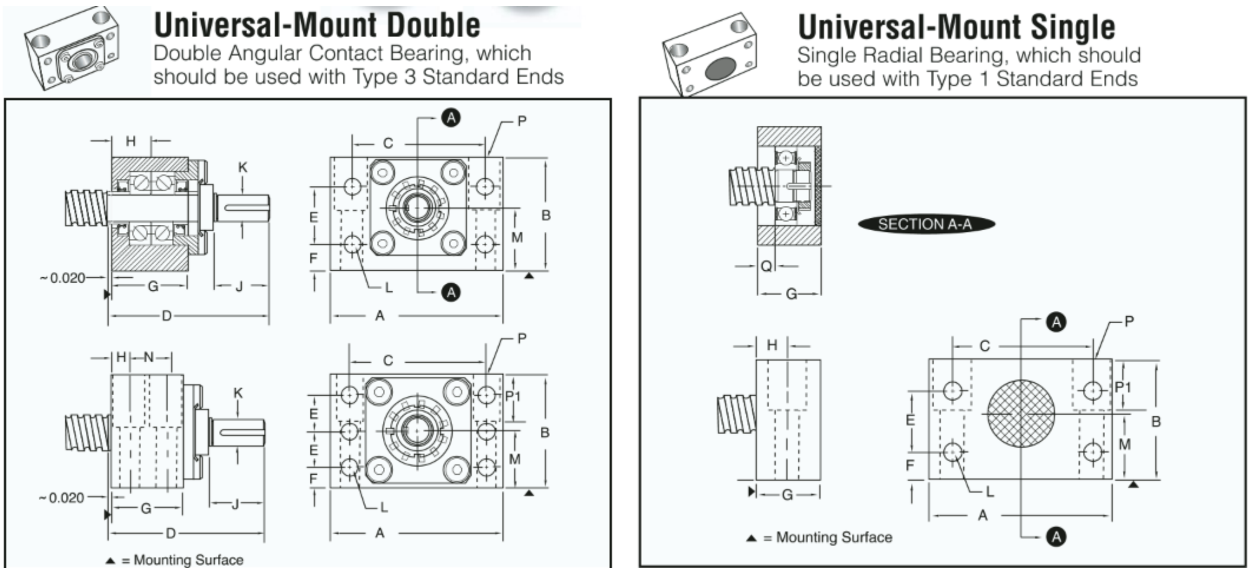
Step 8: Determine/Check the Driving Torque and Back-driving Torque

Driving torque is the amount of torque required to move the load. The load on the ball screw generates a back-driving torque that causes the ball screw to move when it should be stationary. An opposite torque needs to be applied to prevent this back-driving.

$$T_d := \frac{Load \cdot travel}{2\pi \cdot 90\%} = 0.103\,N \cdot m$$

$$T_{backdrive} := \frac{Load \cdot travel \cdot 90\%}{2\pi} = 0.083\,N \cdot m$$

The next step is to find the suitable mounting kits for the ball screw. Nook Industries offers EZZE-MOUNT precision bearing blocks, which can be assembled to precision machined screws. The selected mounts are shown Figure 18.



DOUBLE Part No.	SINGLE Part No.	A	B	C	D	E	F	G		H	J	K Shaft Dia.	L Thru (4 or 6)	M	N	P				Q	END CODE
								Single	Double							Bolt Size (2 or 4)	Thru	C'Bore	P1		
EZM-3010	EZM-4010	2.75	2.00	2.00	2.50	1.38	0.31	1.19	1.19	0.56	0.69	0.312 0.311	0.28(4)	1.000	—	5/16 x 2(2)	0.34	0.50	0.56	0.38	10
EZM-3015	EZM-4015	3.50	2.52	2.75	3.50	1.25	0.80	1.38	1.38	0.69	1.30	0.500 0.499	0.28(4)	1.438	—	3/8 x 2 1/8(2)	0.41	0.62	1.00	0.33	15

Figure 18 Universal-Mount for Double and Single Bearings (12)

A Nook-EZM-3010 was chosen for the Universal-Mount Double Bearing to hold the top screw, and a Nook-EZM-4015 was chosen for the Universal-Mount Single Bearing to support the bottom. When selecting the bottom bearing for the application, the axial load limitation was considered and the capacities of the bearings and locknuts were checked. From Figure 19, the EZM-3010 locknut max axial load is 4100 lbs.

EZM Part#	Bearing	LOCKNUT NO.	LOCKNUTS MAX AXIAL LOAD LB
EZM-1007* EZF-1007	627-2RS1	1/4"-20	1800
EZM-1008* EZF-1008	608-2RS1	5/16"-24	2300
EZM-1009* EZF-1009	609-2RS1	5/16"-24	2300
EZM-3010* EZF-3010	6000-2RS1	N-00	4100

Figure 19: Axial load limitation for Universal Single Bearing (12)

Based on the mounting selection, the machined ends can be determined. The Universal-Mount Double Bearing requires a Type 3 Standard End, and the Universal-Mount Single Bearing requires a Type 1 Standard End. As shown in Figure 20.

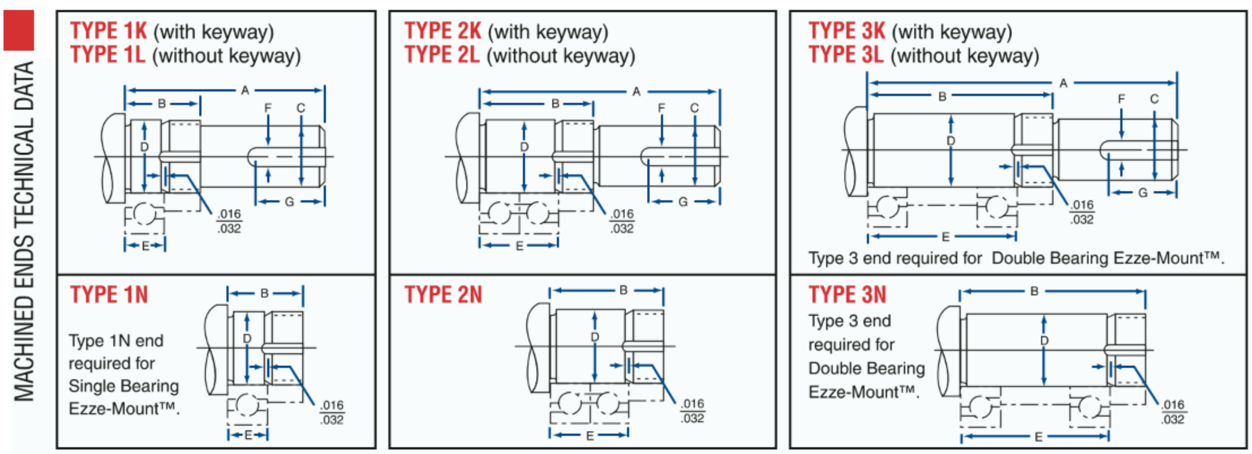


Figure 20 Machined Ends Technical Specifications (12)

The dimensions for these two types of machined ends are listed below in Figure 21.

MACHINE END CODE	TYPE 1 (K, L, N) Typical Journal for Single Bearing			TYPE 2 (K, L, N) Typical Journal for Duplexed Bearings			TYPE 3 (K, L, N) Typical Journal for Multiple Sets of Duplexed Bearings			COMMON DIMENSIONS FOR TYPE 1, 2 & 3 (K, L, N)					
	A	B	E	A	B	E	A	B	E	C	D	F	G	LOCK NUT	LOCK WASHER
10	1.37	.69	.315	1.67	1.00	.630	2.50	1.81	1.438	.312 / .311	.3939 / .3936	.125	.50	N-00	W-00
15	2.15	.84	.433	2.59	1.27	.866	3.50	2.18	1.732	.500 / .499	.5908 / .5905	.125	1.00	N-02	W-02

Figure 21: Machined End Dimensions (12)

Bellows Coupling

A BKL-2-30 bellows coupling was chosen to connect the motor and the screw machined end.

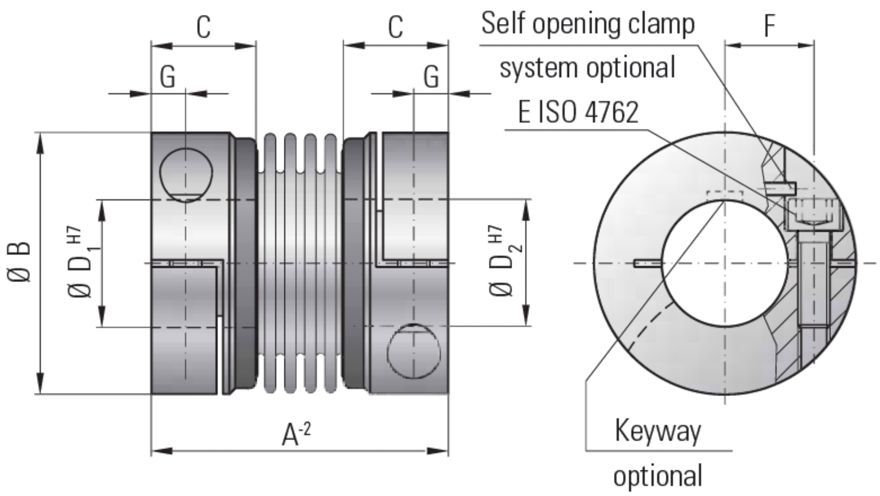


Figure 22 R+W | Metal Bellows Couplings | BKL (13)

BKL Series		2
Rated torque (Nm)	T_{KN}	2
Overall length (mm)	A^{-2}	30
Outer diameter (mm)	B	25
Fit length (mm)	C	10,5
Inner diameter possible from Ø to Ø H7 (mm)	$D_{1/2}$	4-12,7
Inner diameter possible from Ø to Ø H7 (inch)	$D_{1/2}$	0.187" 0.500"
Fastening screws ISO 4762	E	M3
Tighting torque of the fastening screw (Nm)	E	2,3
Distance between centers (mm)	F	8
Distance (mm)	G	4
Mass moment of inertia (10^{-3} kgm^2)	J_{ges}	0,002
Hub material (standard) (steel on request)		Al
Approx. weight (kg)		0,02
Torsional stiffness (10^3 Nm/rad)	C_T	1,5
Axial (mm)	max.	0,5
Lateral (mm)	max.	0,20
Axial spring stiffness (N/mm)	C_a	8
Lateral spring stiffness (N/mm)	C_r	50

Figure 23 Specs of R+W | Metal Bellows Couplings | BKL (13)

Linear Servo

The linear servo motor is one of the most accurate and efficient ways of actuation in any axis. Compared to the rack and pinion system and the ball screw the linear servo has the highest precision and virtually eliminates backlash in the system. Similar to the process involved in determining the appropriate ball screw mentioned earlier, several criteria need to be considered in picking the right servo motor. The current model features a custom counter-balanced Chicago Electric Linear Shaft Servo system as seen in Figure 24. When sizing the linear servo, it is important to consider the load, load location with respect to the motor, length of travel, average rate of travel, and peak accelerations. The load bearing capacity must be sufficient to hold the rotational forces and linear forces that the tool mounted on the vertical rail would induce. The length must also be sufficient to accommodate the stroke to have a blade measurement mode located above this insertion position and a blade loading position. With the current arrangement, an overall stroke of approximately 300mm.

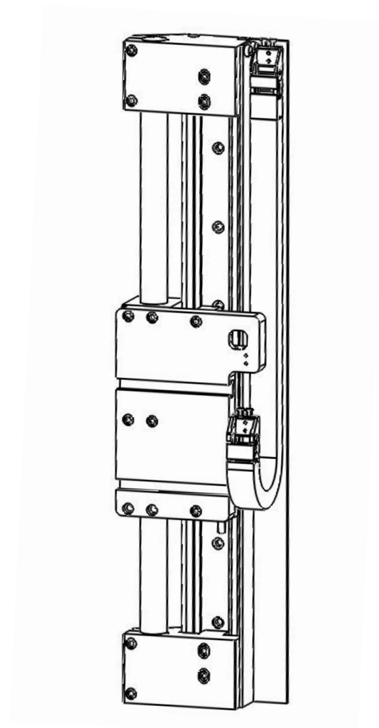


Figure 24: Chicago Electric Custom Counter-balanced Z-actuated linear servo system

Generally a servo motor is designed for use in a horizontal configuration, such as lying flat on a countertop or floor. In this orientation the moment about the axis perpendicular to the line of motion is not usually a significant factor of wear on the motor. After consulting with several engineers experienced in vertically mounted linear servo systems at several companies such as Aerotech Inc., Chicago Electric and ALIO Industries, it became apparent that in vertically mounted applications the moment resulting from the force of gravity on the cart can cause excessive wear on the motor. In the proposed set-up the tooling is positioned so it is cantilevered off the cart causing a moment to result from the force of gravity acting downward on the cart and the acceleration the motor must achieve. Once the other forces caused by the fast acceleration of the motor are taken into account, the need for a counterbalance to counteract the moment is even greater. As a result, a system must be created to ensure these moments are counteracted and a motor must be specified to be able capable of moving this mass of the tooling and counterbalance system accurately. Many of the counterbalanced systems used in traditional style linear servos use pneumatic or mass and pulley systems; however these systems may have problems being effective at the stroke length and accelerations that must be achieved in this test fixture.

Structural Stability

As mentioned earlier, the framing should not compromise the validity of the test results. Therefore the frame must be sturdy enough to support the fixture without distorting. Additionally the structure should be designed to limit the transmission of vibrations to the test fixture. As a result, appropriate materials must be chosen to ensure rigidity and proper mechanisms such as sub-frames and self-leveling casters were implemented to make for a constant system with minimal influence from any outside vibrations or discontinuities. The frame must deflect less than 0.01mm and not be excited by natural frequencies of the system. It should minimize fasteners and cantilevered components where possible.

An 80/20 frame may lack the stability to act as a structural support and has numerous fasteners and connections. It is preferable to use a frame that is made of a few pieces of metal that are properly manufactured to be square and then fastened. 80/20 would primarily serve as a protective frame surrounding the apparatus without any structural loads involved. Additional sub stages may be incorporated to support sensors or the blade loader

An L-shaped internal frame is proposed with an additional cantilevered shelf to support the blade loader and Cognex camera as shown in Figure 25.

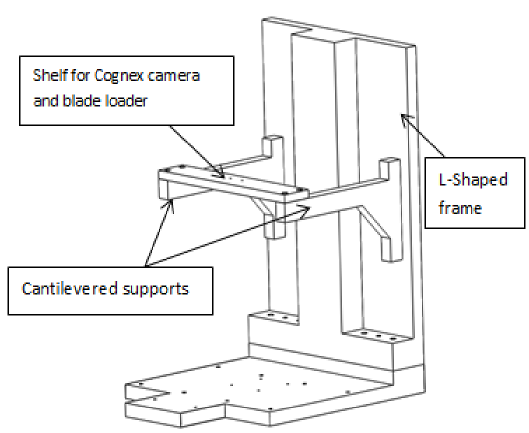


Figure 25: Frame Structure

The frequencies excited by the motion of the servo motor were found using Fast Fourier Transform (FFT) analysis. The natural frequencies of the extended stage composed of the shelf and cantilevered supports were analyzed using Blevins Formulas (14). The natural Frequency of the cantilevered support arms of the stage is 243 Hz, the natural frequency of the shelf holding the blade loader is 618 Hz. The largest peak in natural frequency is at the 2nd harmonic of the end effector; however it does not come near exciting the system until beyond the 14th harmonic. Full calculations can be found in Appendix G

The frame also has to be very rigid: it must not deflect more than 0.01mm at any point in testing. The main back plate of the frame and cantilevered shelf were analyzed for expected loading. Singularity functions were used; full calculations can be seen in Appendix H. The maximum deformation of the frame occurs during the insertion attempt, at this time the frame back deforms a maximum of $4.587*10^{-3}$mm, the shelf deforms a maximum of $8.373*10^{-3}$mm. It may be desirable to stiffen the cantilevered shelf further; however, the deflection is less when the tooling is interacting with the blade loader and when the nest is being aligned.

<u>Modularity</u>

A modular design is desirable because it promotes the interchangeability of various parts, which allows the test apparatus to be used to study many different product lines.

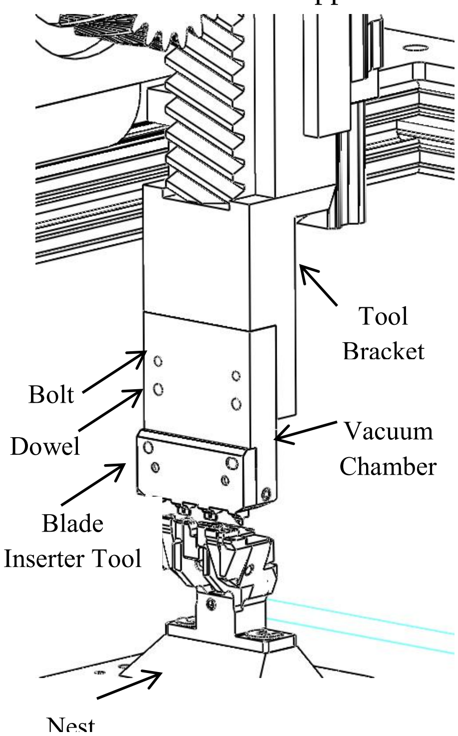


Figure 26: Modular Tool Design

One way of achieving modularity is using a dowel-bolt configuration. The dowels provide precise and repeatable location of the part being mounted and the bolts secure the part so it does not slide off the dowels. A pattern of dowels and bolt like the one shown in Figure 26 allows the location of the part to be the same whenever it is remounted after being removed for cleaning or other maintenance. A dowel-bolt configuration can be implemented to accommodate alternate tooling heads, vacuum chambers, tooling brackets, and vertical slider brackets as show in Figure 29 and Figure 26.

For a servo motor or ball screw the tooling must be cantilevered. Therefore, a mounting bracket was designed to carry a variety of tooling on the same linear servo or ball screw. The mounting bracket has a constant pattern of bolts and dowels used to mount itself to the adapter plate. The bolt pattern for the tooling needs to be customized based on the pattern of tooling in different product lines. The mounting bracket also has a ¼’’ port for the pneumatic hose to attach to and an internal cavity that transfer vacuum and pressure to the ports on the tooling.

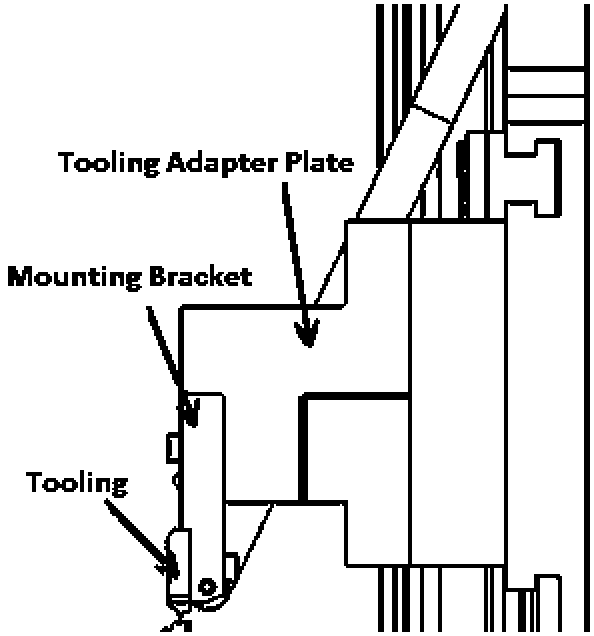


Figure 28: Profile of Tooling Mounting

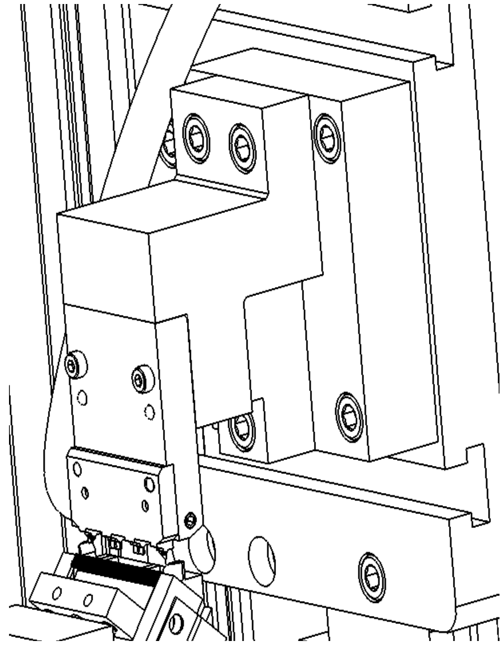


Figure 27: Isentropic View of Tooling Mounting

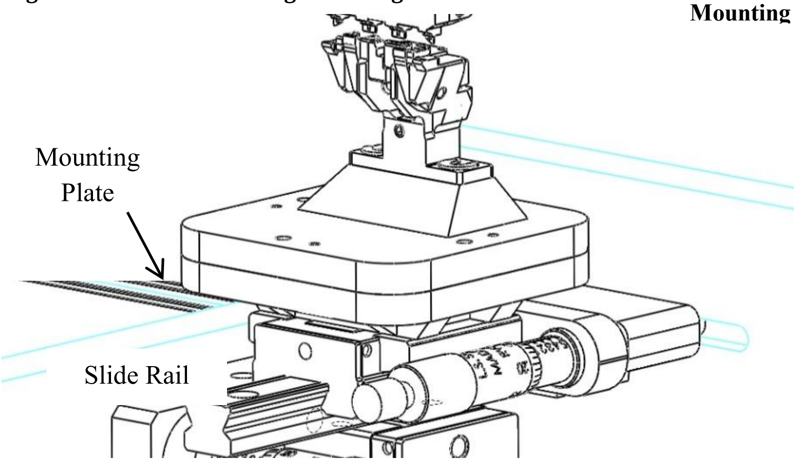


Figure 29: Custom Modular Nest Stage Design

Because one of the main goals of the project is to ensure the apparatus can work accurately for other similar product designs and future products, modularity is a major component of the design. The adjustable stage base has a specific bolt and dowel configuration to ensure proper fitment, and a new template piece is made for each new product to correctly fit this base configuration and have the correct positioning for the new nest. After proper fitment on the base, a simple re-calibration needs to be done to find the correct zero-position for the adjustable base, but once this is found all testing should be able to occur in the same manner as any other product.

Another modularity option being investigated is the use of a modular clamping mechanism like the one shown in Figure 30. This mechanism has two clamps actuated with adjustment screws. This adjustability enables the system to account for nests with any unique angles on the side. Because the angle of rotation about the z axis can be varied, tests investigating the effects of angular misalignment may be able to be conducted.

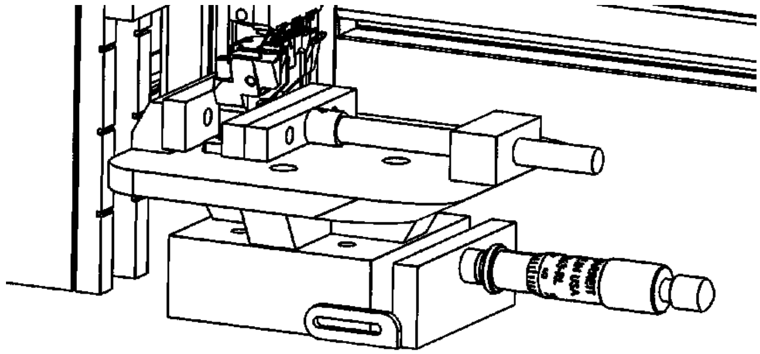


Figure 30: Modular Clamping Mechanism

The above design does not incorporate any kind of mounting plate. The nest is held by the clamp alone. Because the nest is held by friction on flat surfaces, it cannot be guaranteed that the clamp will be able to securely hold all shapes of nest without interfering with any parts of the nest that move during loading.

The third concept for a modular plate was developed by combining aspects from the previously discussed two designs. This design is comprised of five major parts: a modular plate for the product nest to be mounted to, a base plate with a precision-ground top surface to be mounted on the XY-stage and provide a precision surface to place the adapter plate on, a precision bracket with two precision-ground sides to act as walls for the adapter plate to be aligned against, and two clamp plates to ensure that the adapter plate is constrained in all axes.

When a new nest is necessary to be added to the fixture, a new adapter plate must be custom made out of standard aluminum to a given specification that is necessary to securely mount the nest in a way that simulates its current orientation in the production line most accurately. Once this plate is made, it is placed in the modular well and aligned with the precision-ground L-bracket walls. The two clamps are then screwed in placed and the nest is accurately aligned for calibration in the fixture. Additionally, shims may be used between the modular plate and precision backing to adjust the positioning of the nest with respect to the tooling.

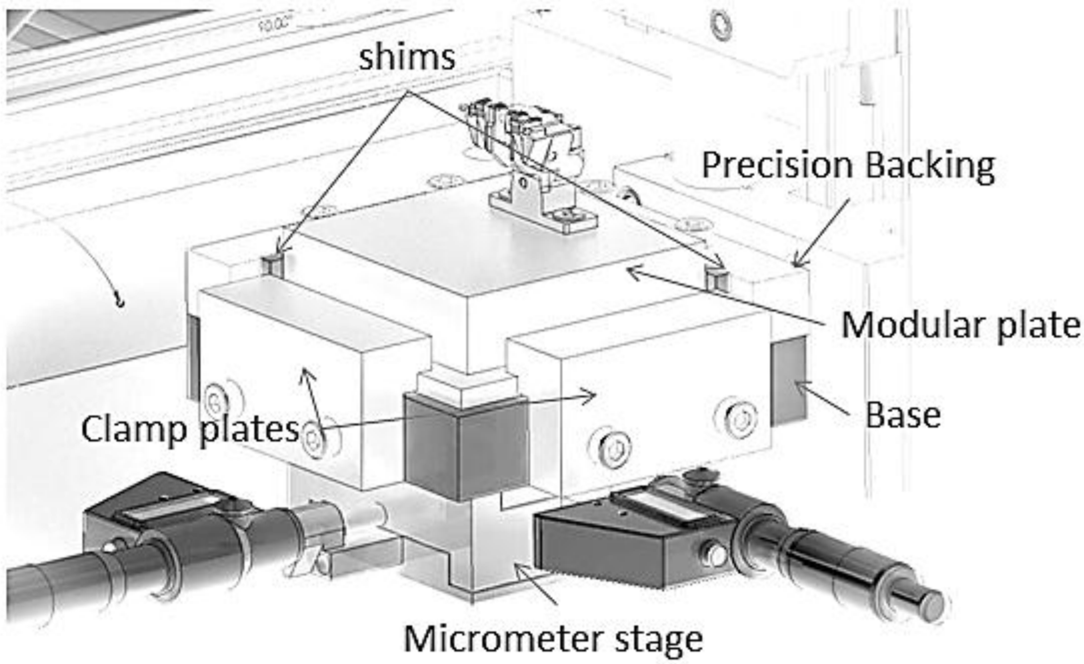


Figure 31: Modular Base Plate and Clamp

Accurate Adjustability

It is necessary to induce and control an offset between the tooling and housing in the X direction. By controlling the relative positioning between the tooling and nest, the apparatus is able to adjust to a zero point and ensure the blade and the housing slot are correctly aligned. An offset in the X direction can then be induced and an insertion test preformed to study maximum allowable offset in successful attempts. Additionally, it is crucial that the offset be controllable and measurable; Because of the scale it is reasonable to use a micrometer adjustment device.

A micrometer driven one-axis stage is capable of creating and accurately measuring offsets that would be called for in this fixture. There are a variety of commercially available products that would be acceptable; however, it is necessary to take into account several factors about these stages including accuracy, load bearing capacity, and total range of motion. One commercial option is the Edmund Optics Inc. translation stage shown in Figure 32 featuring stackable stages for X- and Y-axis motion if required for future applications.

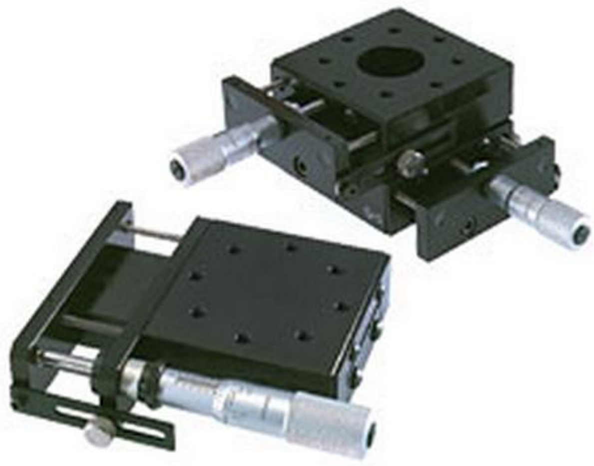


Figure 32: Edmund Optics Inc. Metric Center Drive Single Axis Translation Stages (15)

The accuracy is a concern because offset increments are very small. The position must be known as exactly as possible for the data collected to be useful in determining allowable errors in positioning of nest with respect to tooling. Both load capacity and range of motion are taken into account partially because of accuracy of measurements. Accuracy is generally measured per distance of travel. This prompts the use of a range that is large enough to encompass the test range plus an amount that allows for accommodation of testing for other product lines, but does not have a large over all range of motion. There are some stages available that have a very high accuracy but load capacity of only13-18 N; conversely there are ones that can withstand larger loads, but with some reduction in accuracy. The latter option is preferable because it allows for the weight of the nest and mounting plate as well as forces from tooling.

An alternative to the stackable stages that are discussed above is a single unit has two axes of movement. These stages are available from Qioptiq Inc. and include digital micrometers as a readout option. These stages are available in 25 mm and 200 mm of travel and offer the option of digital micrometers to measure offset. Because they are a single unit they have a specification for the orthogonality between axes of travel whereas the stackable stages do not.

Defining a Workspace

A workspace was defined to ensure the user could access and manipulate the various components required for loading, adjustment, and modularity purposes. The working envelope was designed with consideration to the size of an average person's hand and the space required to manipulate tools for each of the components. This workspace was defined as the region from the doors of the safety frame to the tooling and approximately a foot of clearance in the perpendicular axis as well as the z axis. This should allow the user to manually place a blade housing in the nest with a hand, to manipulate the required tools to replace an adapter plate for the modular well design or modular tooling design, and to access the micrometers used to induce offsets. A second workspace was also defined to ensure the user has sufficient space to load the blade loader with blades or replace the blade loader if necessary.

This work space guides the design of the frame and placement of components, including the sensors because the operator must have clear and easy access to the area. If a sensor is within this area, it must be able to be easily removed from the area to allow access for operation or maintenance.

Design of Blade Loading

A blade feeder was designed to precisely load the blade on the tooling. A spring was preloaded to push a pile of blades onto the tool. The advantage of the blade feeder is that it can guarantee the loading is the same every time when the suction force is applied by the tooling. The walls must be precisely machined to house and constrain the blade to move only toward the tooling. Fully loading the chamber with blades can cause the spring to have a force of 7lbf, which could be sufficient to deform the blades. This force may also cause the friction of between the blades to be enough for it to be difficult to remove a single blade for loading without moving the adjacent blade. To reduce the force on the blades, it is recommended that not more than ten blades are loaded at once, a spring with lower stiffness be used, and more features be added to the design to guarantee the single blade can be reliably extracted without causing the others to move. The device is shown in Figure 33 and the alignment between the blade loader and tooling can be seen in and Figure 34.

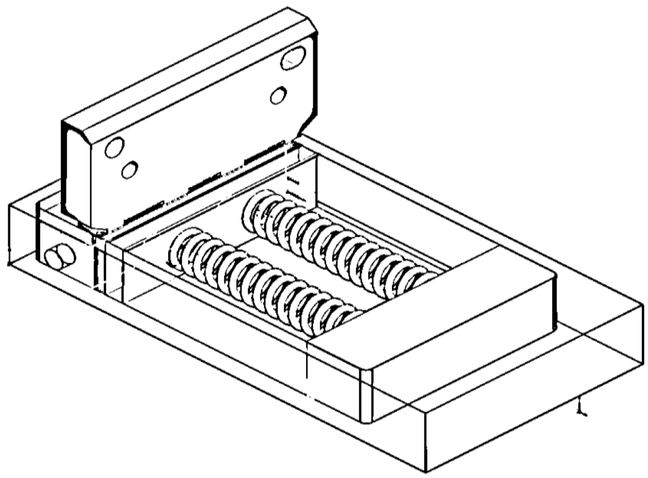


Figure 33: Isometric view of the initial blade feeder

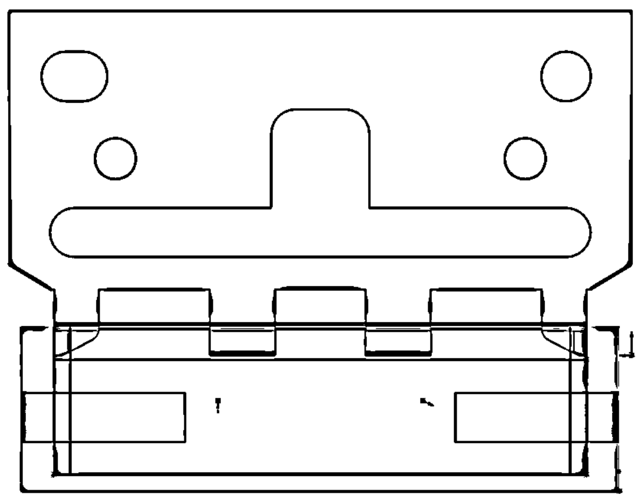


Figure 34: Front view of the blade feeder

A blade loader as shown in Figure 35 was designed to load the blade on the tooling. Two springs are preloaded to push a pile of ten blades to their pick-up position. The advantage of the blade loader is that it can guarantee the blade to be loaded at the same position on the tooling each time, and no part of the blade loader or human hand does not touch the blade's top edge. The springs have a low stiffness ratio of 0.24lbs/inch (0.042N/mm), and only ten blades are loaded each time so the springs are not fully compressed. The maximum force exerting on the blade from the spring is 0.24N. The current designed blade loader is for a specific product line, and its dimensions may need to be modified in order to be used in other product lines.

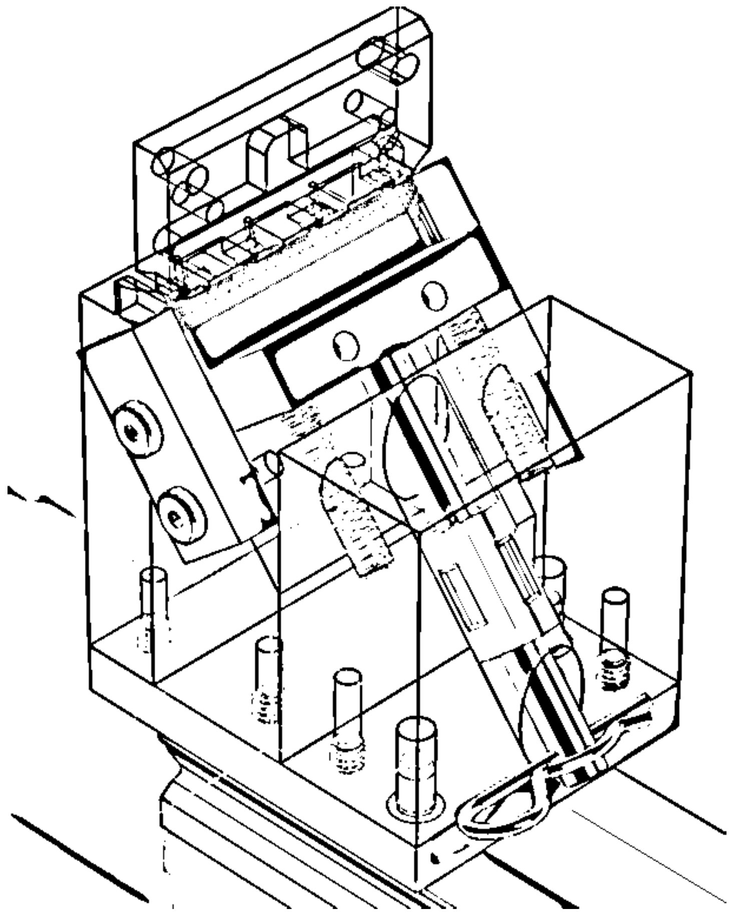


Figure 35 Blade Loader Isometric View

Because the pusher sits on top of the slanted surface, the weight of the pusher, rod, and handle creates a downward force that compresses the springs at the initial position. The free body diagram shown in Figure 36 was used to analyze the force applied on springs and calculate the initial compression of two springs. The initial compression is 0.84mm, which is small compared to the blade thickness and can be considered as zero displacement.

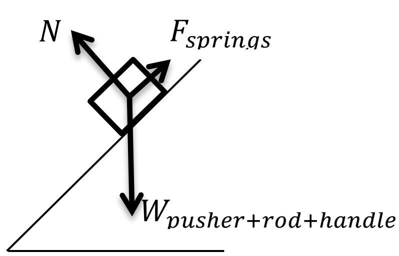


Figure 36 Free Body Diagram of Pusher, rod, and handle

$$M := \frac{6.44\,kg}{1000} + 2.53\frac{kg}{1000} + \frac{0.29\,kg}{1000} = 9.26 \times 10^{-3}\,kg$$

$$W := M \cdot g = 0.02\,lbf$$

$$k := 0.24\,\frac{lbf}{in}$$

$$\alpha := 50.62\,deg$$

$$Fx := W \cdot \sin(\alpha) = 0.016\,lbf$$

$$\Delta X_{initial} := \frac{Fx}{2k} = 0.835\,mm$$

Because the compressed spring can buckle if it is too slender, the aspect ratio and the deflection ratio of the spring were analyzed to guarantee the springs are stable against buckling.

In this design, the springs are constrained on parallel ends and the expected compression is 2.84mm. The ratio of deflection/free length is 0.12, and the ratio of free length/mean diameter is 4.99. According to the Critical Buckling Condition Curves in Figure 37, the spring will in a stable position.

$$Compression := 2.84\,mm = 0.112\,in$$

$$F_{blade} := 2 \cdot Compression \cdot k = 0.054\,lbf$$

$$Freelength := 0.938\,in$$

$$Dia := 0.188\,in$$

$$\frac{Compression}{Freelength} = 0.119$$

$$\frac{Freelength}{Dia} = 4.989$$

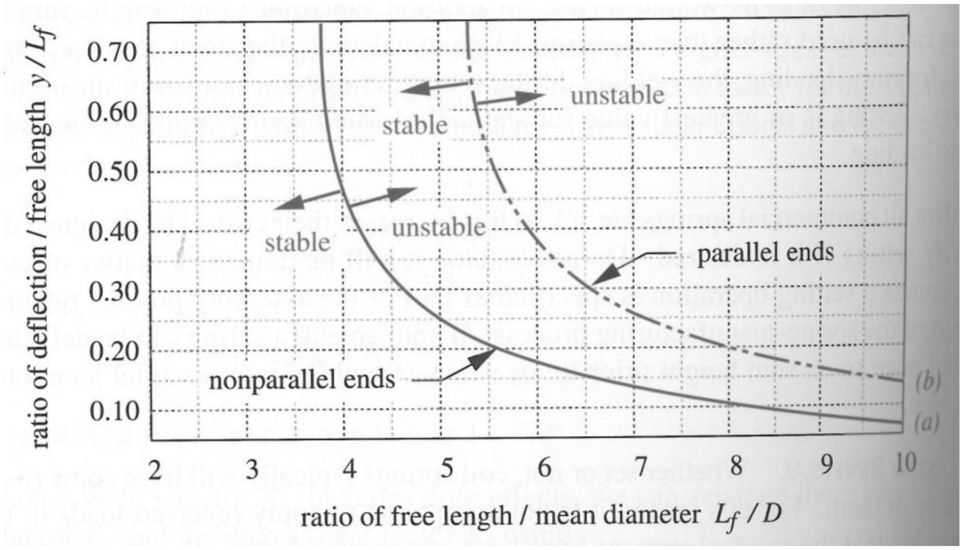


Figure 37 Critical Buckling Condition Curves (15)

To prevent the second blade being pulled out by friction when the tooling picks up the first blade, two side plates were designed to hold the blade ears. As shown in Figure 38 and again in Figure 39. The side plates are attached on both sides to use their overhanging parts to constrain the z axis movement of the rest of the blades. The side plates also provide guiding of the blades when moving toward the tooling.

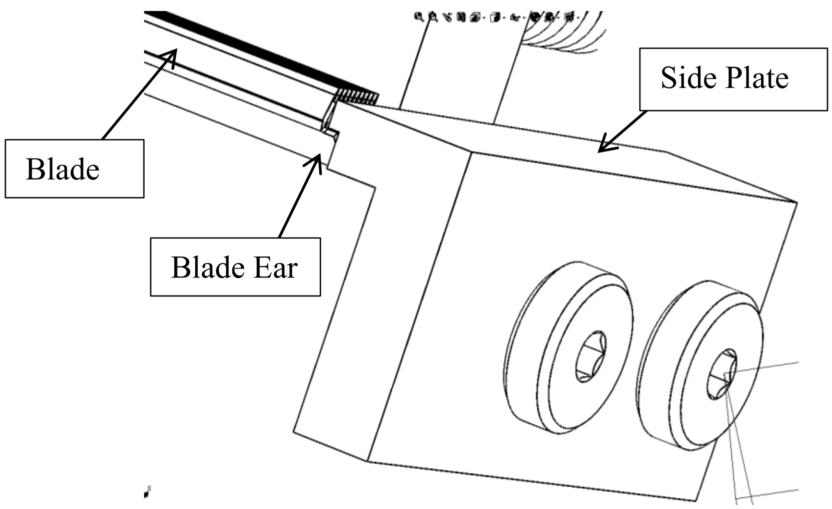


Figure 38 Side Plate

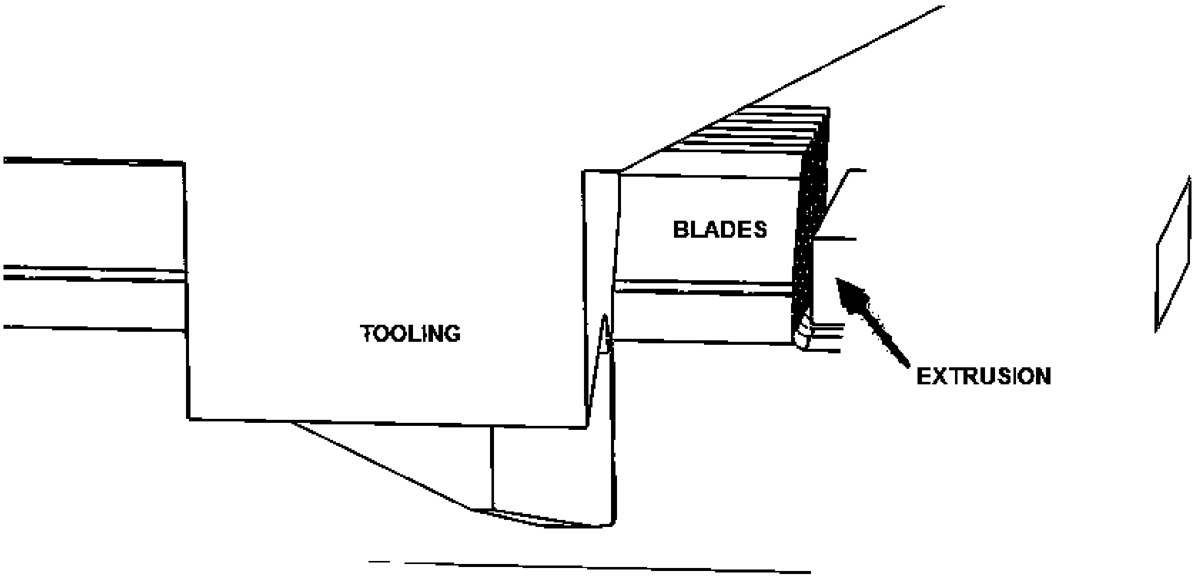


Figure 39: Blade Ear Restriction used to guide

The blades are loaded into the blade loader from the side. One piece of the side plate was mounted on a hinge that is attached to one side, as shown in Figure 40. The hinge is spring loaded in the middle. The operator can open the hinge to load the blade and the hinge closes the side plate back into position.

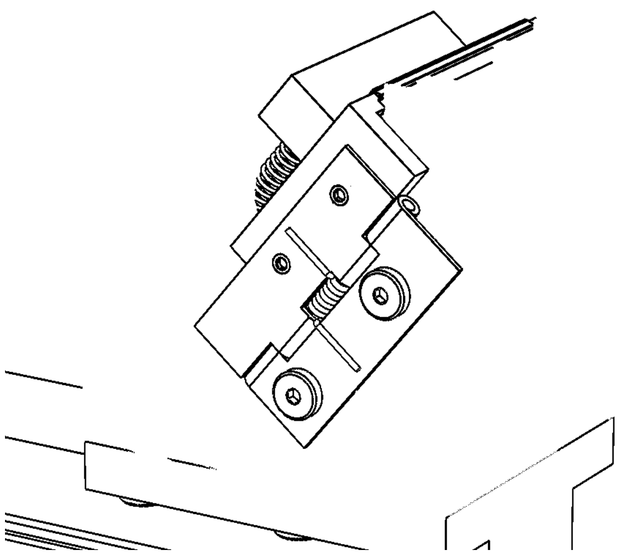


Figure 40 Spring-loaded hinge

Two ball-nose spring plungers as shown in Figure 41 are selected from the McMaster-Carr Supply Company. They are screwed in the pusher as shown in Figure 41 to keep the pusher's bottom away from the slanting surface. This reduces the undesired friction force thus make the pusher travels smoothly with less spring force that is required.

Figure 41 Ball-nose Spring Plunger (31)

Another alternative approach to load the blade is to pull the rod and pusher all the way to the back and load the blade from the back. However, that requires a longer stroke of the rod and that may cause interference between the rod and the bottom slide. It also requires the size of the side plates to be reduced so there is more room to load the blades. But this allows the side plates to be mounted by one screw on each side. Eventually, the side loading approach was selected.

It is preferable to have this apparatus operated from outside the safety frame so the operator is not put at risk from the possibility of the Z-actuation or pneumatic system failing and the tooling or blade falling. Therefore, the blade loader may be mounted to a slide rail such as those seen below in Figure 42

Figure 42: THK LM Series Slide Rails (16)

THK Company's Caged Ball LM Series slide rails have several models that accommodate small and large loads and offer the option of slides of various bolt configurations and surface areas for easier mounting. The slide rails shown in Figure 42 have mounting holes in the top of the slide and grease screws on the side. Other models include wider bodies with different mounting-hole configurations, slides made to carry larger loads, and slides that should be mounted in the vertical or horizontal position for maximum performance. A rod mounted to the rail extends though the safety frame making it possible to actuate the blade loader from outside the safety frame.

The rod is guided by a self-aligning linear ball bearing, which can be purchased from McMaster-Carr Supply Company, as shown in Figure 43. It is used to reduce the friction between the rod and the hole, and provide self-alignment when needed. The overall length of the bearing is 9/16", and its inner diameter is 3/16". Thus, the bearing ratio is $BR = \frac{9/16"}{3/16"} = 3$. This design guarantees the bearing ratio is larger than 1.5, which makes the motion along the slide smoother.

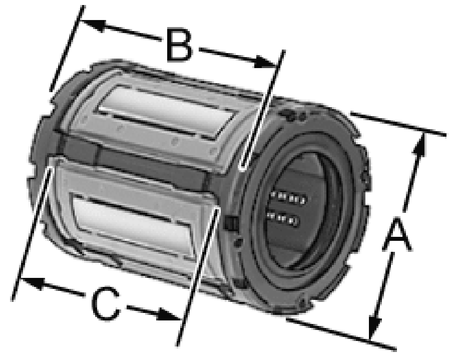


Figure 43 Self-aligning linear ball bearing (32)

Task Specifications

1. Design must accommodate the nest and blade insertion tooling (blade inserter) for product lines other than the one tested in this project with potential of a unique mounting device being made for each product line
2. Changeover time between product lines should no more than one hour by trained mechanic.
3. Load blade of 0.006 mm thickness into a slot of X width
4. Offset of blade inserter with respect to nest should be adjustable to at least ±0.45mm on the X Axis
5. Offset adjustments must be accurately measured to ±0.015mm
6. Velocity of Adjustment Mechanism[2] should be adjustable between at least -0.5m/s and 0.5m/s
7. Adjustment mechanism must not be back-drivable
8. Fixture[3] positioning may be manually adjustable
9. Fixture must not move more than ± 3μm once it is secured in a testing location due to forces from insertion process.
10. Testing apparatus[4] will be contained within a fixture frame no larger than 900mm x900mm x900 mm
11. Testing apparatus and frame will be mounted to a cart on casters
12. Total size of the cart and fixture combined will not exceed 1m X1m X2m or sit on a standard size lab bench
13. The structure of the housing and blade will not be modified
14. Motion of the blade inserter must be able to simulate the final insertion velocity of a given process for the assembly of a specific product
15. A single blade will be loaded into the blade inserter at a time
16. A single blade will be loaded into the housing within one cycle[5]
17. The blade inserter will complete one cycle and then stop
18. A pressure of 6psi and a vacuum of -10psi must be produced at the blade inserter venting port

[2] Adjustment mechanism will be the linear actuation mechanism used to produce the motion in the z direction
[3] The fixture will be defined as the housing and summation of components connecting the housing to ground
[4] The testing apparatus will be defined as the summation of the fixture, tooling, linear actuator, sensors and components connecting those subsystems.
[5] One cycle will be considered one repetition of the fall-dwell-rise motion defined in the production process being considered

19. Sliders used must be of precision grade
20. Blade inserter that comes in direct contact with blade will not be modified
21. The frame structure holding the motor must not deflect more than ±0.01mm in X- Y-, and Z-directions in normal use
22. Blade inserter must be equipped with a vacuum port capable of applying the specified suction and pressure from Task Specification 18 to the blade
23. Adjustment mechanism must be able to accurately locate to 0.03 mm of the true position
24. Blade must be loaded on blade inserter manually.
25. Housing must be loaded on the nest manually.
26. Before blade insertion, the blade and housing position should be adjusted to zero offset ± 10 µm.
27. The blade inserter x, y directions must be constrained to move less than 1 µm, whereas the housing position should be adjustable on x direction using the slide.
28. Blade position in the x direction should be able to be measured to position ± 5 µm

Initial Concepts

Based on the background research and the task specifications, several initial conceptual designs were made as shown below. The designs consist of 4 sub-systems including the Z direction actuation, the X direction actuation, sensor measurement, and the nest modularity.

Z direction actuation

Rack and Pinion

Z-axis actuation is fulfilled by using a pinion on the servo motor to drive the rack attached on the slide rail. The rack and pinion has relatively low precision, but is accurate enough for the purpose of the blade insertion project. The servo motor is used to program the output velocity profile of the blade insertion for a given product.

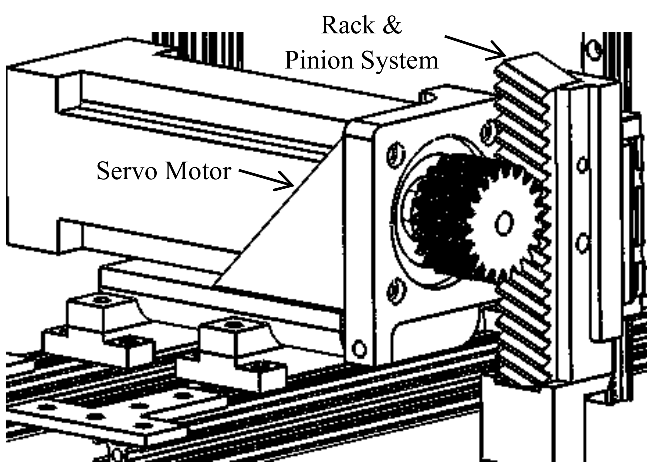


Figure 44: Rack and Pinion System

Ball Screw

Z-axis actuation is fulfilled by using a ball screw with a servo motor to drive the blade insertion tooling attached on the nut. The ball screw has relatively high precision. The servo motor was used to program the output velocity profile of the blade insertion for a given product.

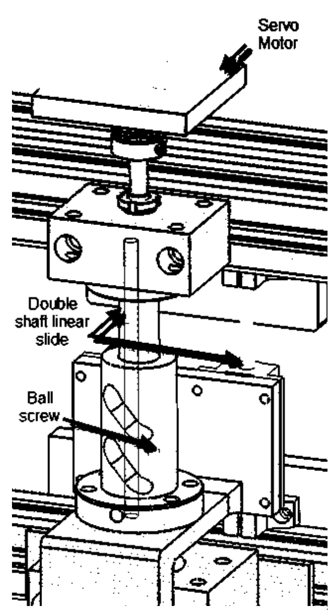


Figure 45 Ball screw and slider rail system

Linear Servo

Z-axis actuation is fulfilled by using a linear servo motor to drive the blade insertion tooling attached to the loading plate. The precision and repeatability of the servo is dependent on the encoder but is very high, generally ranging between 1 – 2 µm depending on the encoder used. The servo motor is used to produce the output velocity profile of the blade insertion for a given product and can be adjusted to meet any necessary end effector profile.

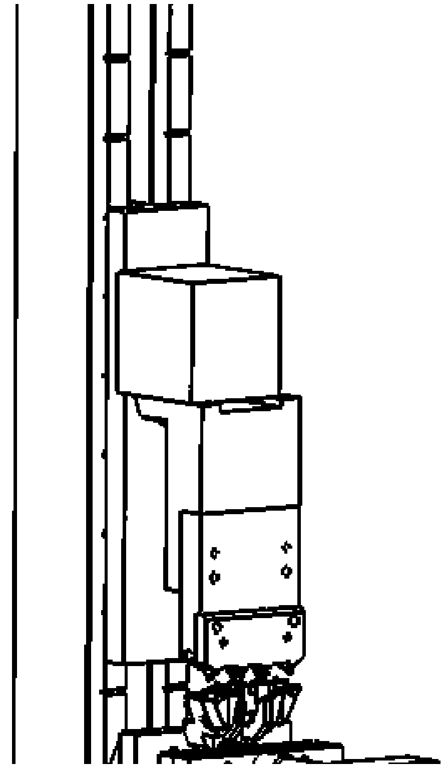


Figure 46: Linear Servo Motor Driven Mechanism

X Direction Actuation

Linear Slide Rails

Custom THK Co slide rails could be used to actuate the x-axis. This could be achieved by simply mounting a cart to the precision slide rail. After manufacturing a securing plate and a means to hold a micrometer in an accurate fashion like Figure 47, the cart could be adjusted to a measured distance and then secured with a holding screw.

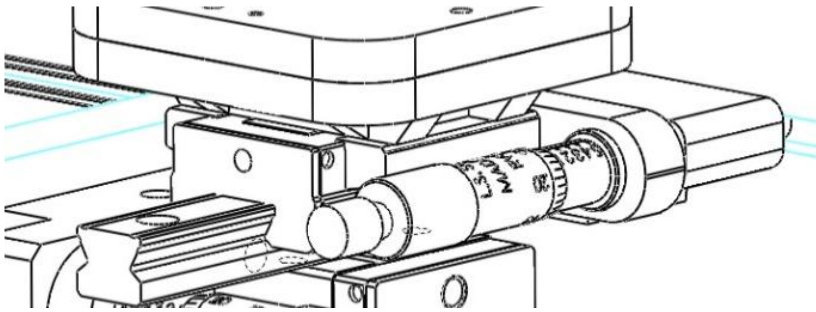


Figure 47: Custom Precision Slide Rails

Linear Stages

Edmund's Optical Inc. Linear stages are very precise linear actuation devices that would act in the same fashion as the custom slide rails. The main advantage is that these stages are pre-built and the overall cost is far less to buy them like this rather than making your own. The stages, as seen earlier in Figure 32, the stages can use a digital or manual micrometer and both fit compactly within the mechanism's boundaries.

Qioptiq Inc. Stage

In many ways the Qioptiq Inc. stages are very similar to the previously mentioned options; however, they have the advantage of coming as a single unit rather than separate units that get mounted together. This eliminates some assembly and potential for error while providing a specification for the orthogonality of the two directions of travel. This is important because unintentional offset in any given direction is undesirable in a high precision test fixture of this type.

Sensor Measurement

LJ-G Scanning Laser

These two dimensional laser sensors measure distance from the sensor using a line of laser light rather than a single point. This means that the sensor can be stationary and still measure the complete profile of the blade. However these systems are more cost prohibitive than the LK-G series.

LK-G Scanning Laser

As previously discussed this one-dimensional scanning laser would be able to accurately and reliably measure the blade bow by measuring the distance from the sensor to the blade along the length of the blade in the y direction. However, because it is a one-dimensional measurement the sensor would have to be on a linear guide that allowed it to move along the Y axis to collect data along the entire blade rather than at only one point.

SI-F Laser Micrometer

Spectral interference sensors offer very high resolution and sensor heads that are small enough to have multiples mounted along the length of the blade, which eliminates the need for a rail in the Y direction. However, they may also need to be much closer to the target being measured than is possible without a rail in the X direction. This still allows the system to be stationary at the time of measurement. Additionally, one expansion pack would have to be added onto the controller to accommodate the minimum three sensor heads that would need to be mounted along the blade to accurately estimate the bow.

LVDT Probe

The LVDT probe is the only contact sensor being considered. It is actuated by air causing the spindle to move until it contacts the target with a 0.3 N force. This sensor would also have to be on a y direction rail and take measurements at several locations, arguably making it the most time consuming method. The biggest concern with using a contact sensor is the possibility of deforming or moving the blade during measurement. As such, this technology may be more practical to implement in measuring the housing location rather than blade bow.

Manual Optical Inspection

Manual optical inspection is an option for housing alignment that would reduce the price compared to the an AOI system, however because it is a system that is being made rather than purchased and adjusted based on the operator's judgment it is difficult to ensure a specific repeatability or resolution. This option encompasses both the inspection from the side and from above methods.

Manual inspection from the side would involve a plate with vertical lines mounted next to the nest; these striations would serve as a guide that allowed the operator to visually line up a housing slot and the tooling. However this method is open to errors and no specification for the precision of this measurement can be made. Additionally, the space between the nest, plate, and view point would have to be minimized to minimize the amount that the view point can skew the alignment.

The inspection from above allows for more thorough adjustment to compensate for stack up errors. This method would first align the nest and tooling so it is correctly with the expected housing slot location. A housing is inserted and examined using a camera that looks down on the housing. The distance is measured against a known location on the nest using the camera and a computer. Any necessary adjustments can be made using the micrometer stages.

High Speed Camera

A high speed camera system is needed to observe the insertion test and may allow the methods of failure to be better understood. However this item will be supplied by the sponsor.

Nest Modularity

Customized Baseplate on Stage

As shown earlier in Figure 32 earlier, the use of a custom baseplate is one of the two main modularity concepts. This concept allows for the nest to have a custom securing plate designed for it to ensure accuracy in positioning in the x and y directions. This design would utilize dowel-bolt configurations to accommodate alternate nest plates precisely. The nest would simply be mounted on this plate and then recalibrated before testing. The one main disadvantage to this design is the fact that a new plate would be necessary for every new nest. This could prove costly and may lead to the usage of a different securing strategy.

Adjustable Clamping Mechanism

To avoid the cost of the first concept and approach the problem from a different angle, a modular clamping mechanism can be used to ensure the modularity of the design as shown in Figure 30 earlier. This mechanism would have two clamps that could be actuated using adjustment screws. This adjustability would enable the system to account for nests with any unique angles on the side as well as allow for rotation about the z-axis if testing the angle of the nest were to be conducted in the future.

Well and Plate Clamp

The third concept for a modular plate developed from combining aspects from the adapter plate design and the clamp design. This design is comprised of five major parts: an modular plate for the product nest to be mounted to, a base plate with a precision-ground top surface to be mounted on the XY-stage and provide a precise surface to place the adapter plate on, a precision bracket with two precision-ground sides to act as walls for the adapter plate to be aligned against, and two clamp plates to ensure that the adapter plate is correctly constrained in all three axes.

When a new nest is necessary to be added to the fixture, a new adapter plate must be custom made out of standard aluminum to a given specification that is necessary to securely mount the nest in a way that simulates its current orientation in the production line most accurately. Once this plate is made, it is simply placed in the modular well and aligned with the precision-ground L-bracket walls. The two clamps are then screwed in placed and the nest is accurately aligned for calibration in the fixture.

This design was even further developed to ensure simple manufacturing of each component and easy assembly. Strategic cuts and geometries were used to allow for easier precision-grinding of certain sides where necessary. The use of shims is also proposed to allow for the user to adjust the adapter plate within the fixture as well as provide for the option of inducing a rotational offset on the plate if requested.

Final Design

Overview

This project features intermediate plates that allow more than one product line to be accommodated both in the nest and tooling. The Z direction actuation is achieved using a linear servo motor that moves the tooling though several preparatory stages and then simulates the insertion profile of the end effector. The nest holding the housing is mounted to a two axis from Qioptiq Inc. micrometer-driven linear stage that is used to induce an adjustable offset between the housing and tooling in the plane perpendicular to the tooling approach direction. A gage fixture is used to line up the nest and tooling. A fixed mark is used as a reference point and the housing is examined from above using a Cognex Corporation camera. A custom blade loader is used to aid in placing the blade on the tooling. The blade is then examined using a LJ-G series 2D laser scanner from Keyence Corporation that measures the bow of the blade.

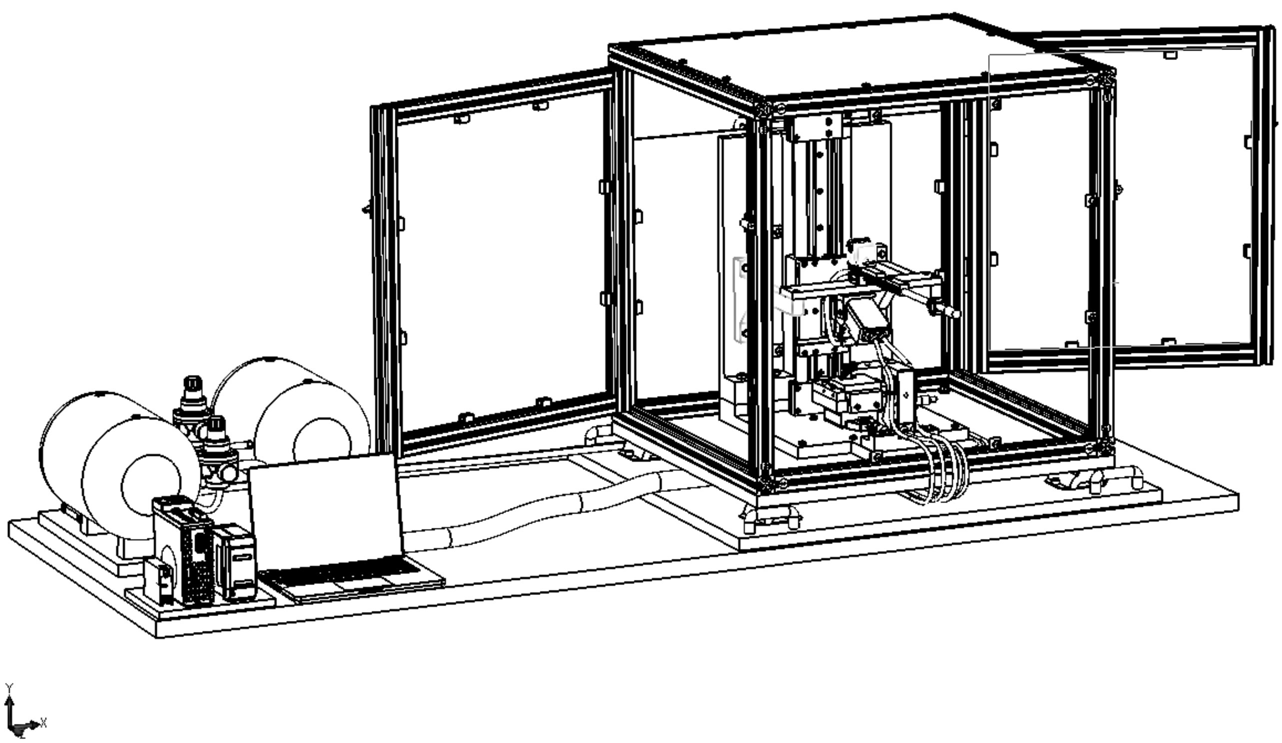


Figure 48: Full set up

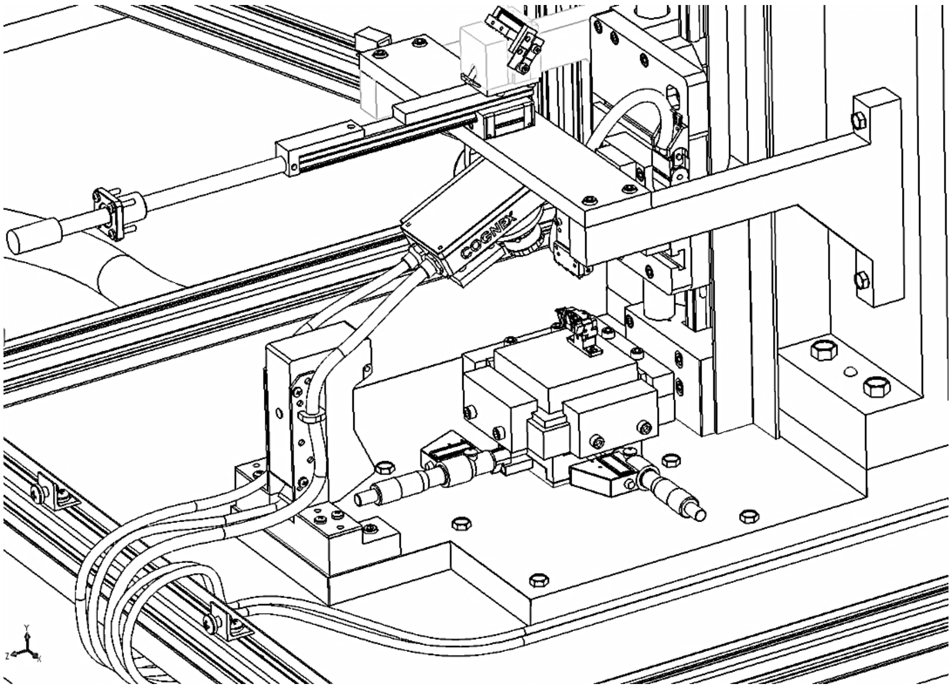


Figure 49: Test Fixture

Z Direction Actuation

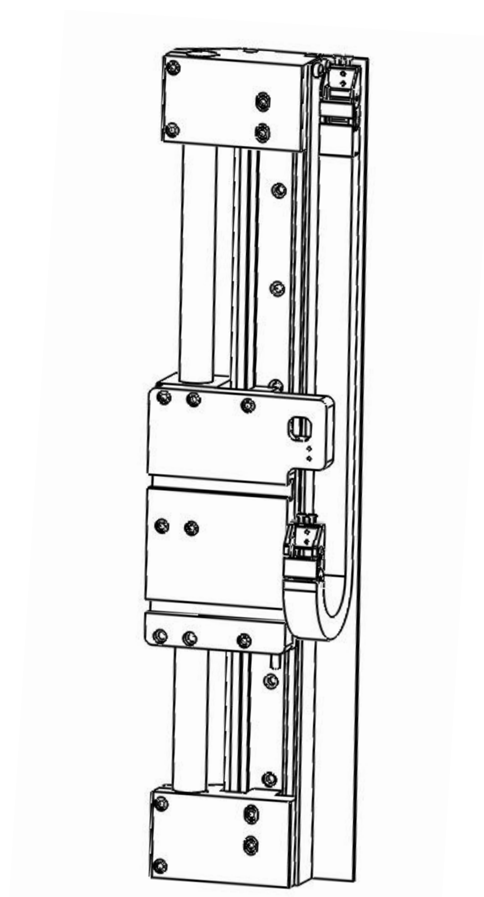


Figure 50: Linear Shaft Servo Set-up

Several linear servos were considered, including traditional style and shaft-style motors; after comparison of the motors and counterbalance system options Chicago Electric system using a linear shaft servo is recommended for this application. This complete system features several main components including a Nippon Pulse linear shaft motor, a precision linear slide rail and cart, a precision encoder capable of repeatability of 1-2μm, an energy chain, and the fasteners and end-caps necessary to hold the system together. The Nippon Pulse linear shaft servo motor consists of a metal shaft that has magnets enclosed within it and an electromagnetic motor that travels along the shaft. The motor is mounted to a stage that serves as a mounting surface for the tooling and also mounts to the cart on a precision slide rail that runs parallel to the shaft. This slide rail limits the motion of the motor to the desired one degree of freedom along Z-axis by preventing rotational motion around the axis of the shaft; additionally the cart can act as a counterbalance to counteract the moment that would be experienced without the use of the slide rail because the cart is rated for much higher overturning moments than are seen in use of the fixture.

Another concern with a vertically mounted linear servo is that the cart is held in position by an electromagnetic force rather than mechanical means. As a result the motor cannot maintain position if power is lost and unexpected power loss could result in a crash sufficient to damage the test fixture. This concern was addressed by implementing a braking system that clamps onto the side of the slide rail in the event of power loss. The break is regulated by a solenoid on the cart that has the break position as a default and then releases the break when electricity is applied. The motor may drop a few millimeters in the case of power loss. The motor would need to be re homed the next time it is turned on.

X and Y Direction Offsets

The Qioptiq Inc. stage is recommended because it is a single unit that minimizes the assembly and potential for error in the system. It offers five digit readout digital micrometers that make reading the offset easier to read and making it possible to reset the point set as zero. These stages can support up to 150 N, which is more than would be expected in normal use. The travel along each axis is 25mm, which would allow all slots of the housing to be tested.

Figure 51: Qioptiq Inc. Stage Selected

Sensor Measurement

It is recommended that the blade bow be measured by an LJ-G 200 Laser Scanning sensor from Keyence Corporation. This sensor allows for accurate measurement of the curvature of the bow by measuring variations in the distance of the blade from the sensor. This sensor was preferred in part because if its ability to measure the entire profile of the blade at once without moving. This is desirable because movement of the sensor could result in measurement errors. Additionally it is an optical sensor, so there is not a risk of displacing or deforming the blade as a result of measurement. The model selected was chosen because it can measure the entire profile at once and can be mounted far enough from the blade that it does not interfere with access to the workspace.

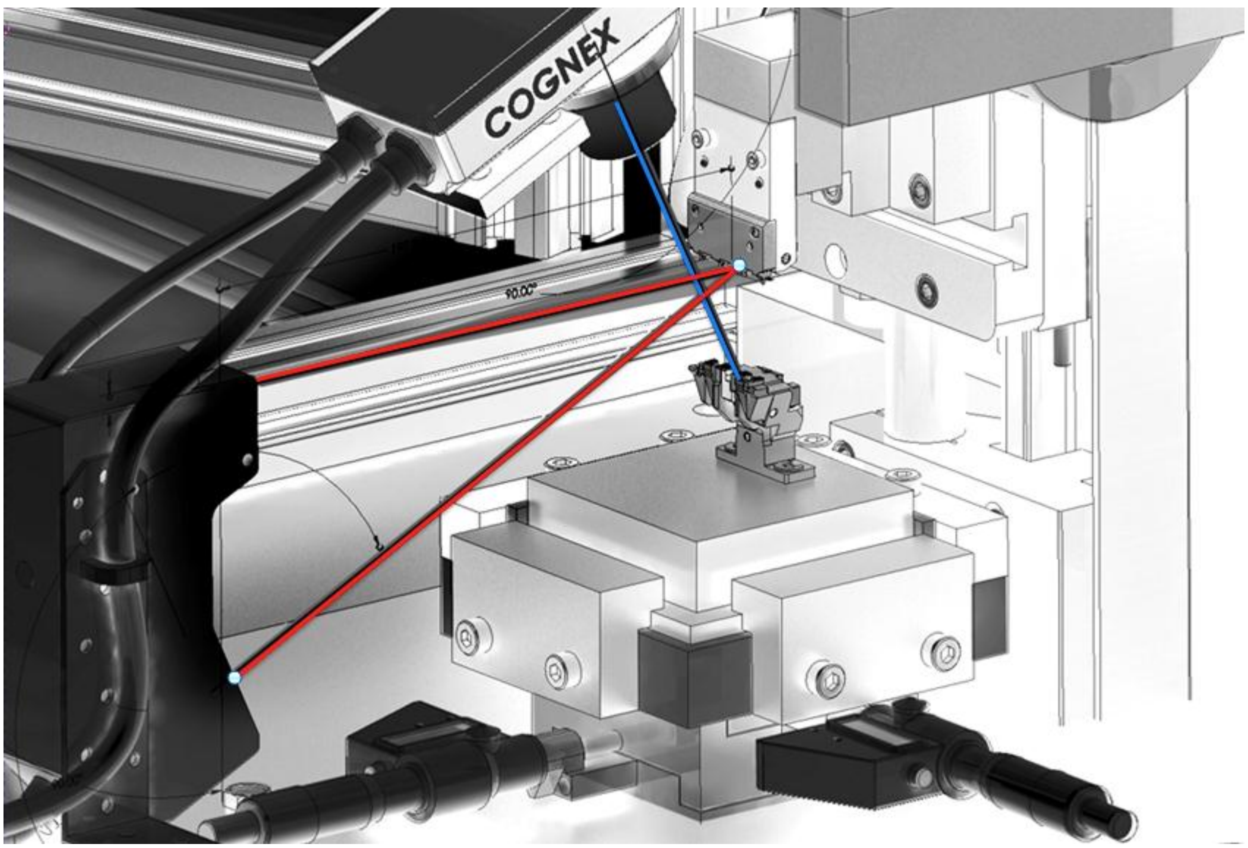


Figure 52: Sensor View Paths. Scanning Laser for Blade Bow Shown in Red. Cognex Camera for Alignment Shown in Blue

Housing Alignment

The manual inspection form above is recommended for aligning the housing. This is preferable over the use of laser sensors because the laser sensor would need to be moved to see the profile of the housing. Other methods such as using an LVDT require the assumption that all housings are exactly the geometry that is expected in that product line because they would measure only the outside of the housing but not the location of the individual slots. An AOI system is expensive and because time is not a constraint in this process the fast processing is not needed. Manual inspection from the side requires a back plate that would interfere with the working area and does not have as direct a view of the housing slots.

Aligning the housing to the correct starting position is a two part process. A gage fixture (to be designed) is first used as a physical contact method of aligning the nest and tooling before the housing is loaded. The micrometer stages can be used for course adjustments and the ground shims can be used to make fine adjustments. The gage fixture lines the tooling and nest up for the expected location of the housing slot based on product geometry.

A housing is then inserted into the nest and the Cognex 5605 High Resolution Camera is used to make any adjustments that are needed. This is done by taking a measurement between a known feature or mark on the nest with a known position and the slot in the housing. If this measurement is the expected distance for that product line, then no additional adjustments are needed. If the measurement varies from the expected distance then the offset can be accommodated by adjusting the stage by the difference from the expected.

Nest Modularity

The Modular Well concept is recommended for the nest adaptor plate because it minimizes the number and complexity of pieces that must be made for new product lines while maintaining the ability to hold any nest. As stated before, this design is comprised of five major parts: a modular plate for the product nest to be mounted to, a base plate with a precision-ground top surface to be mounted on the XY-stage and provide a precise surface to place the adapter plate on, a precision bracket with two precision-ground sides to act as walls for the adapter plate to be aligned against, and two clamp plates to ensure that the adapter plate is correctly constrained in all three axes.

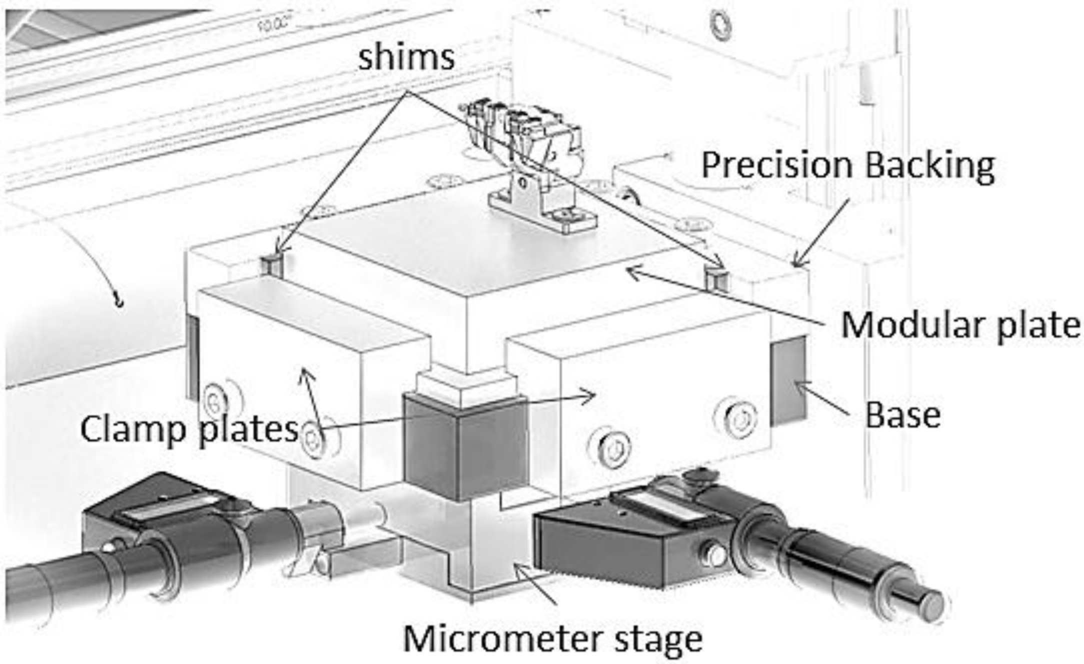


Figure 53: Nest Modularity Design

Though a new adapter plate must be manufactured for each product line, this design is the best way to ensure the blade insertion process is simulated as accurately as possible. The adapter plate can be made of standard aluminum to reduce cost and make manufacturing easier. Once an adapter plate is made, the nest is secured and the plate is placed in the modular well and aligned with the precision-ground L-bracket walls. The two clamps are screwed in placed and the nest is accurately aligned using the gage fixture.

Steps were taken to ensure simple manufacturing of each component and easy assembly. Strategic cuts and geometries were used to allow for easier precision-grinding of certain sides where necessary. The use of shims is also proposed to allow for the user to adjust the adapter plate within the fixture as well as provide for the option of inducing a rotational offset on the plate if requested.

Tooling

The tooling is also mounted through a modular plate. This plate has a bolt and dowel pattern between the modular bracket and the tooling adapter bracket that remains constant for every product line. The connection between the mounting bracket and tooling would be made so the mounting bracket attaches correctly to the tooling of a given product line. The mounting bracket also has an internal chamber that supplies pressure and vacuum to the tooling.

Framing

The L shaped frame seen in Figure 54 was implemented in the final design. It is made of two individual steel plates to provide sufficient rigidity and use the minimum amount of material. The plates are assembled using a bolt and dowel system. A cantilevered shelf provides mounting holes for both blade loader and Cognex Corporation camera. The overall structure stays outside of the natural frequency range that excites the system, and holds the servo motor firmly without any deflection greater than 0.01mm. The frame back deforms a maximum of $4.587*10^{-3}$mm; the maximum deflection of the shelf is $8.373*10^{-3}$mm. It may be desirable to stiffen the cantilevered shelf further, especially if the high speed camera is mounted on that shelf. If the camera is not mounted on this shelf, then there not any components on the shelf in use when the shelf experiences the maximum deflection.

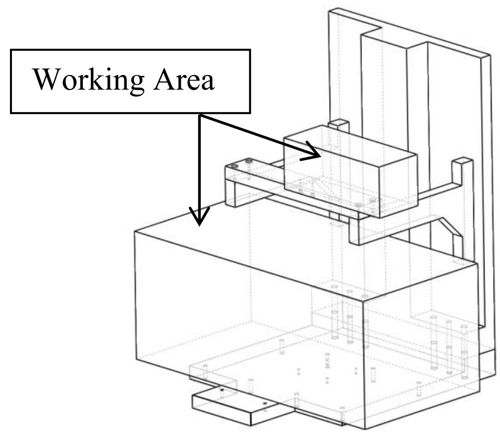


Figure 54:Frame and Work Space

The 80/20 frame and acrylic windows are installed around the testing fixture to prevent any part of the machine or blade from injuring the user. The 80/20 is also used to bound workspace so the operator is not at risk of injury when the servo is running. The blade loader is manually operable from the outside of the frame using a rod attached to a THK Co. slide rail. When manually loading the blade loader and adjusting the micrometer stage, the workspace provides enough space for the operator’s hand to reach both mechanisms from both right and left hand sides. However, the controls of micrometer stage and blade loader are oriented toward the right hand side to provide a more comfortable orientation for a right-handed person.

Pneumatic System

The design with a separate accumulator for pressure and vacuum is recommended for this project because it allows more control over the magnitudes of pressure and vacuum. Additionally, it allows the pressure and vacuum to be stored in the acuumulator tanks so the pumps do not need to be running during the test; conversly the pump must be running for the Venturi pump to generate vacuum producing both noise and vibrations that could interfere with the system. The following is an outline of the parts to be used in this system.

The pressure and vacuum pump can be purchased from McMaster-Carr Supply Company. Because the requirement for both vacuum and pressure magnitudes are relatively low, a small pump such as model 4176K11 fulfills the requirement. It is able to generate a maximum pressure of 60psi (414kPa), and a maximum vacuum of 25.5" Hg (-86kPa). The overall size of the pump is relatively small, and can be connected to 3/8" ID hose. The pump is powered by electricity, thus requires no oil. (17)

Figure 55 Oil-Free Electric Vacuum/Pressure Pump

Table 2: Oil-Free Electric Vacuum/ Pressure Pump

Oil-Free Electric Vacuum/Pressure Pump	
Model	4176K11
Max. Vacuum, Hg	25.5" (-86kPa)
Free Air, cfm	1.1
Max. psi	60 (414kPa)
dB Rating	68
hp	1/8
Overall Size Lg. Wd. Ht.	7 11/16" 5 1/4" 10 15/16"
Connections are barbed for use with 3/8" ID tubing	
Price	$415.03

To regulate the positive and negative pressure generated, two regulators are selected. The pressure regulator (SMC AR435-N04BG-NII) is able to regulate the pressure from 2.9psi

(20kPa) to 29psi (200kPa), and is capable of handling the maximum pressure output (414kPa) from the pressure pump. (18)

The vacuum regulator can control the negative pressure from –100 to –1.3kPa, and has an excellent knob resolution of 0.13kPa or less. Both regulators’ ports are 3/8", thus can be directly connected to air tank by hoses and barbed hose fittings. (19)

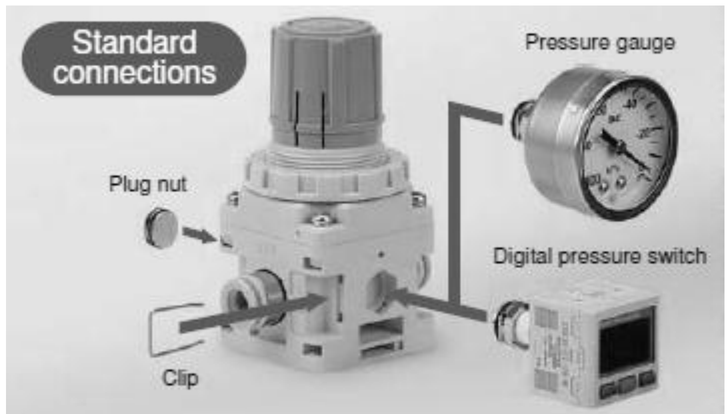


Figure 56 Pressure Regulator **Figure 57 Vacuum Regulator**

Table 3: Pressure Regulator

Pressure Regulator	
Model	SMC AR435-N03BG-NII
Port Size	3/8"
Fluid	Air
Proof Pressure	1.5MPa
Max. Operating Pressure	1.0MPa (145psi)
Set Pressure Range (MPa)	0.02 to 0.2 (2.9psi to 29psi)
Air Consumption (for bleed hole)	5l/min (ANR) (at maximum pressure)
Pressure Gauge Port Size	1/4"
Ambient and fluid temperature	-5 to 60ºC
Construction	Internal Pilot relieving type (pilot air is always bleeding.)
Mass (kg)	0.7
Price	$186.65

Table 4: ASME-Code Vertical Pressure Tanks

ASME-Code Vertical Pressure Tanks	
Model	9888K13
Cap. gal	5
Tank Dia. Lg.	10" 16"
NPT Female Openings	1" 3/4" 1/2"
Max. Pressure, psi	200
Max. Vacuum	29.9" Hg vacuum
Price	$281

Table 5: Vacuum Regulator

Vacuum Regulator	
Model	SMC IRV 20-Nil N11 L G
Fluid	Air
Set Pressure Range (MPa)	-100 to -1.3kPa
Atmospheric intake consumption	0.6l/min (ANR) or less
Knob resolution	0.13kPa or less
Ambient and fluid temperature	5 to 60ºC
VAC side tubing O.D.	3/8"
SET side tubing O.D.	3/8"
Mass (Without Accessories)	250g
Price	$186.65

Figure 58 Vertical Pressure Tank

Figure 59 SMC 3 Port Solenoid Valve

The 9888K13 ASME-Code Horizontal Pressure Tanks from McMaster-Carr Supply Company are a good option for the second design. They are able to withstand a pressure ranging from 29.9’’ Hg vacuum to 200 psi pressure, and the horizontal tank reduces the distance from he the outlet port to the solenoid valve, and thus reduce the pressure drop along the hoses. (20)

A 3 port solenoid valve was chosen as shown below. It is capable of switching between pressure and vacuum. And has a port size of Rc 1/8", small enough to connect to the tooling. A 6 or 12 DC rated voltage makes the control easy to power in most laboratory conditions with signal conditional or LabVIEW DAQ board. (21)

Table 6:3 Port Solenoid Valve

3 Port Solenoid Valve	
Model	SMC VKF334W
Operating Pressure Range (MPa)	-101.2kPa to 0.1
Fluid	Air
Port Size	M5 X 0.8, Rc 1/8
Type of actuation	Direct operated type 2 position single solenoid
Ambient and fluid temperature	Max. 50 ºC
Response Time	10ms or less (Standard)
Manual Override	Non-locking push type
Lubrication	Not required
Mounting Orientation	Unrestricted
Rated Voltage AC DC	AC: 100, 110, 200, 220, 240V. DC: 6, 12, 24, 48V
Price	$50

Figure 60 high pressure/vacuum air hose

All pneumatic components are connected using (High-Pressure/Vacuum Air) hoses with male fitting, Easy-install female fitting, or push-on fittings. The hose for push-on fittings has unique braid-reinforced structure so the push-on hose doesn’t require clamps or ferrules to stay put. In fact, the more you pull on the fitting, the tighter the hose grips. Pipe size are 1/8" and 3/8". Adapters are used. The hose for vacuum application has a vacuum rating of 29" Hg at 72° F, and reinforcement as aramid fiber yarn. (22)

The final pneumatic system design is shown below. Because most of the operators are right-handed, the system is located on the left side of the testing apparatus to get clearance on the right hand side.

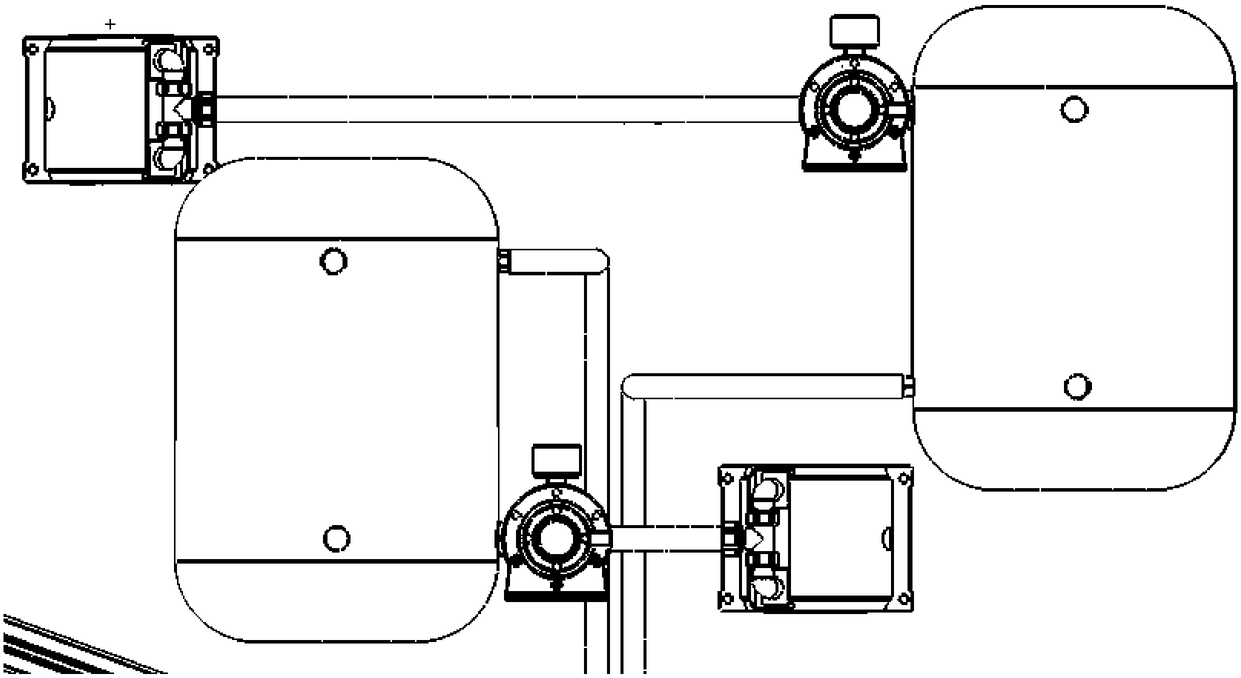


Figure 61 Final Pneumatic System Design (Solenoid Valve is not showing)

Blade Loader

The final design is able to feed one blade at a time to the exact same position on the tooling. Ten blades are loaded from the right hand side. The THK Co. rail guides the blade loader to move toward the tooling. After the loading is completed, the blade loader is drawn backward away from the tooling to provide enough clearance for the blade insertion testing.

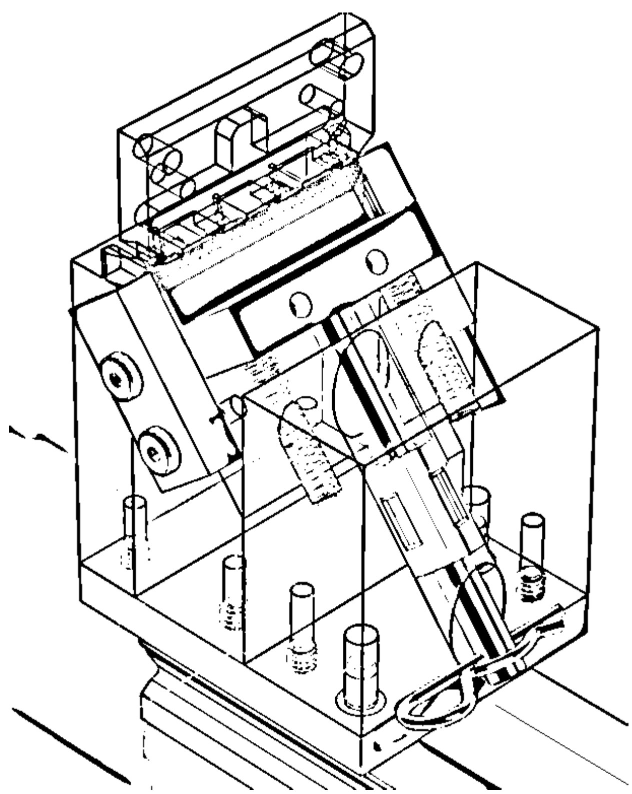


Figure 62: Blade Loader Final Design

Testing Procedure

To change from one product line to another the nest must be attached to the correct nest plate and the nest plate inserted into the modularity well. The correct tooling must be attached to the fixture and the pressure vacuum connection made. The blade loader can also be switched out for different product lines by mounting a new loader to the plate.

The nest and tooling is first aligned using a gage fixture, the micrometers should be used to make course adjustments in positioning and the shims in the well may then be ground to make fine adjustments in alignment. The electronic sensors should now be turned on. The housing is manually loaded into to the nest and the Cognex Corporation camera is used to make any adjustments needed due to inconsistencies in manufacturing of the housing.

Once these adjustments are made, the safety doors can be closed and the servo motor turned on. The motor first moves to the loading position. The blade loader is pushed in toward the tooling mounted on the motor and the vacuum source supplies vacuum to pick up the first blade. The motor backs off and the blade loader removed. The motor then drops to the measurement position and the blade bow will be measured. The motor then follows the appropriate insertion profile and apply pressure in the correct part of the cycle. The attempt is recorded and analyzed using a high speed camera.

A successful test is defined by the full up-down-up linear z-motion defined by the end effector motion provided by the sponsor, along with the proper release of the blade and a recording of proper data. Data points should include whether or not the blade insertion was successful and an analysis of relative position.

Control Programming

<u>Servo motor</u>

The servo motor being used to actuate the tooling must be able to be programmed to simulate the insertion speed and position/velocity profile of the tooling while it is interacting with the housing for a given product line. This profile varies depending on the line that is being studied and has to be re-programmed for each line independently. The Chicago Electric servo motor is controlled using a Rockwell Automation Kinetix 300 Controller.

<u>Sensors</u>

The sensors that have been selected from Keyence Corporation come with the software that is used to interpret the data collected by the sensor. The main task is going to be calibrating the sensors. For the scanning laser sensors the biggest calibration task will be finding the ends of the blade; this is seen as a change in distance that results from the end of the blade dropping off at the end. This sensor does not currently have a radius measure feature but it will allow the profile and height at any point to be seen.

Solenoid valve

The solenoid valve selected is VKF334W. The advantage of this three port solenoid valve is that it can switch between pressure supply and vacuum supply in one device. The valve is normally open during the testing to constantly provide vacuum source. When the tooling approaches the housing to insert the blade, a 6V, 12V, or 24V DC voltage signal is sent to the coil to shift the plunger inside, and the valve is switched from vacuum to pressure. After the insertion, the voltage drops to 0 volt to release the plunger and to switch the valve back to vacuum. The sponsor will program the timing control in accordance with the product line being tested. The standard response time for the solenoid valve is from 10ms to 15ms, and the time delay caused by the hoses needs to be considered during the calibration. A computer interface such as LabVIEW or a signal conditioner can be used to provide the appropriate power supply at the controlled timing.

Cognex Corporation

The Cognex camera also comes with its own software. The main component of the Cognex set up is physical positioning. From there one can use the software to take images and make measurements.

Electrical Requirements

Servo Motor-120/460 AC single/three phase

Solenoid—6, 12, 24 V DC

Vacuum pump -- 115VAC

Pressure generator -- 115VAC

LJ-G Sensor – 24 V DC

Cognex Camera—24 VDC

Micrometers -- battery operated

Operating System Requirements

Windows Vista 1.6 or later (Ultimate, Home Premium, Home Basic)

Conclusion

The fixture designed is able to accurately simulate the assembly process used by the sponsor in current machines and to be able to vary and measure several factors that could affect the assembly process. To accomplish this, several sub-systems were identified and investigated. A means of Z-direction actuation was needed to move the tooling up and down at the same rate and motion profile that is seen in the current machines. After analyzing several systems a vertically mounted linear servo motor was selected because it offered the precision and speed that the application required. To induce a known offset between the housing and tooling a digital micrometer-driven XY stage was selected; this stage allows the zero point to be reset to the position where the housing slot and tooling are correctly aligned and then allow very small offsets to be accurately measured in the plane perpendicular to the tooling approach direction. Additionally, the test fixture is capable of measuring geometric properties of the blade before it is inserted: a LJ-G 200 sensor from Keyence Corporation measures the amount of curvature of the blade while the vacuum force holds it on the tooling. A pneumatic system was implemented to supply the correct amount of vacuum and pressure to the tooling ports; regulators are included in the system so pressure and vacuum can be adjusted if necessary. A custom blade loader was designed to hold the blades and aid in placing a blade on the tooling; however, modifications may need to be made for product lines in which the blades stack at a different angle. The ability to test more than one product line is central to this design. To ensure that multiple product lines could be tested, modular attachments were designed to hold both the nest and the tooling. A frame structure was designed based off of the components that were needed in the system and a working envelope that was defined to make it easy for the operator to use the test fixture. The frame was analyzed for deflections and sized to limit deflection to less than 0.01 mm. The natural frequency of the frame was calculated and compared to the natural frequency range that the linear servo motor excites. The test fixture is enclosed within a safety frame made from 80/20 with acrylic panes.

This project outlines a test fixture that will vary and measure factors influencing the blade insertion process to identify potential problems. This fixture allows the variation of offset, tooling approach velocity, timing of the pneumatic system, and magnitude of pressure and vacuum applied; additionally, the geometry of the blade can be measured while on the tooling.

Because the design is modular, it can be used not only on current product lines, but also to test products which have not yet been put into production. By testing the factors affecting failure earlier in the design process, manufacturing tolerance can be better set and design changes can be made to the product to reduce the scrap rate. With further development, failures may be able to be understood enough that the likelihood of a given insertion failing may be able to be predicted and possibly corrected prior to the assembly.

Areas for Further Development

Emergency power backup

An emergency backup power supply may be considered in case of power loss to the system; however this is made less crucial by the incorporation of a power off break on the servo motor. The design of this system is left to the sponsor for further development because of the regulations and restrictions that govern such backup systems

Modular blade loader

The current design of the blade loader lacks modularity. The design may need to be revisited to make it more versatile and able to be used to multiple product lines. Redesign is very important if the stacking angle varies between product lines.

Gage Fixture

As previously discussed, a gage fixture needs to be designed to serve as a physical contact means of aligning the nest and the tooling. This fixture may need to be specific to each product line because of variations in tooling or nest geometries.

Automated stage

An automated stage could be used in place of the manually adjusted micrometer stage. This has the potential to reduce offset adjustment time and may make it more plausible to run tests back to back for multiple slots in one housing because the operator would not have to enter the safety enclosure. This means that the motor could stay running. Additionally such a stage may allow for automatic feedback between the Cognex camera and stage in initial adjustment.

Cart

Initially, it was proposed that this fixture could be on a cart so it was more portable; this is still a viable option. The controls and pneumatic system could be mounted below the fixture. This would make it easier to access to the inside of the fixture easier. However, if the cart were being moved it would have to be leveled and isolated from vibration each time for tests to be consistent.

Force measurement

Additional measurements could also be taken during the insertion attempt; one option initially discussed was a force measurement in the XY plane. This would collect data on the force being experienced by the tooling or nest during an offset attempt. This idea was not included in this version because it does not increase the likelihood of being able to predict failures. The force would not be experienced until an insertion is in progress whereas visual or offset measuring sensors may allow for predictions if an insertion is likely to fail prior to the execution of the process.

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Appendix

A. Critical Speed Chart

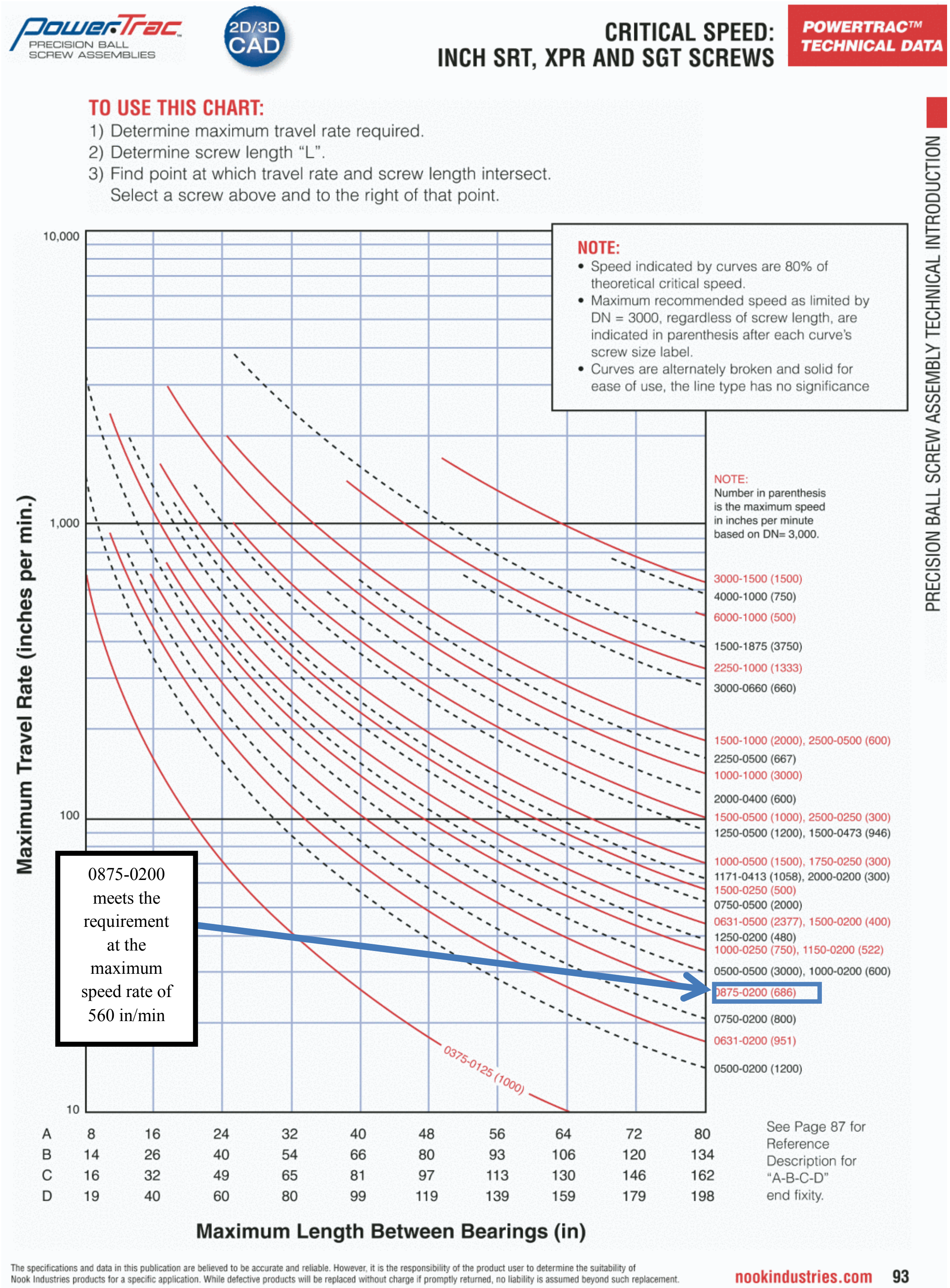


Figure 63: Critical Speed for 0750-0200 Ball Screw

B. Column Strength Chart

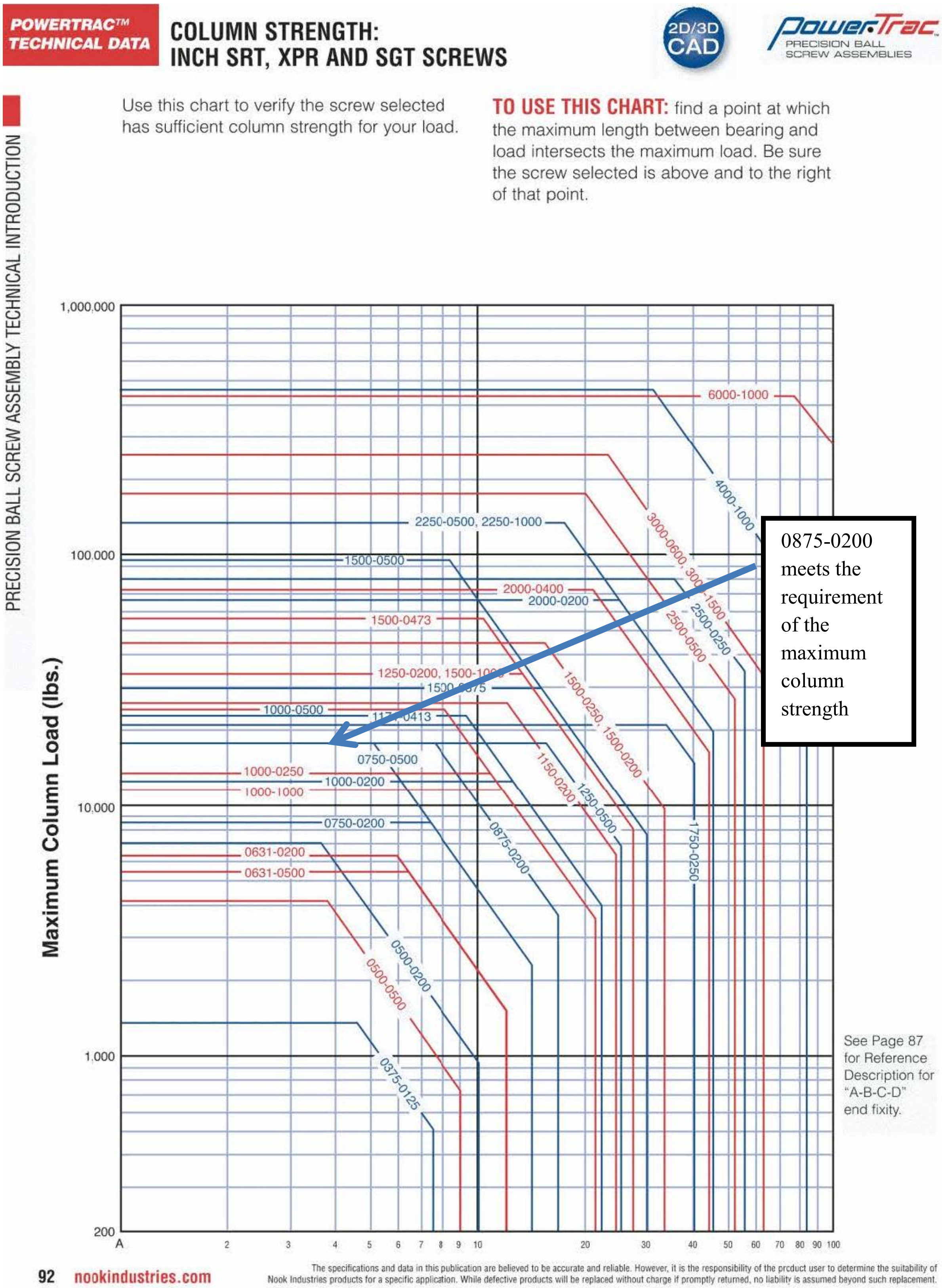


Figure 64: Column Strength for 0750-0200 Ball Screw

C. Pressure Pump Regulator Specifications

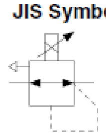
ITV1000

ITV2000

ITV3000

Fieldbus-compatible model

JIS Symbol



Standard Specifications

Model		ITV101□ Note 10) / ITV201□ / ITV301□	ITV103□ Note 10) / ITV203□ / ITV303□	ITV105□ Note 10) / ITV205□ / ITV305□
Minimum supply pressure		Set pressure +0.1 MPa		
Maximum supply pressure		0.2 MPa	1.0 MPa	
Set pressure range Note 1)		0.005 to 0.1 MPa	0.005 to 0.5 MPa	0.005 to 0.9 MPa
Power supply	Voltage	24 VDC ± 10%, 12 to 15 VDC		
	Current consumption	Power supply voltage 24 VDC type: 0.12 A or less Power supply voltage 12 to 15 VDC type: 0.18 A or less		
Input signal	Current type Note 2)	4 to 20 mA DC, 0 to 20 mA DC (Sink type)		
	Voltage type	0 to 5 VDC, 0 to 10 VDC		
	Preset input	4 points (Negative common)		
Input impedance	Current type	250 Ω or less Note 6)		
	Voltage type	Approx. 6.5 kΩ		
	Preset input	Power supply voltage 24 VDC type: Approx. 4.7 kΩ Power supply voltage 12 VDC type: Approx. 2.0 kΩ		
Output signal Note 3) (monitor output)	Analog output	1 to 5 VDC (Load impedance: 1 kΩ or more) 4 to 20 mA DC (Sink type) (Load impedance: 250 Ω or less) Output accuracy within ±6% (Full span)		
	Switch output	NPN open collector output: Max. 30 V, 80 mA PNP open collector output: Max. 80 mA		
Linearity		Within ±1% (Full span)		
Hysteresis		Within 0.5% (Full span)		
Repeatability		Within ±0.5% (Full span)		
Sensitivity		Within 0.2% (Full span)		
Temperature characteristics		Within ±0.12% (Full span)/°C		
Output pressure display Note 4)	Accuracy	±2%F.S. ± 1 digit		
	Minimum unit	MPa: 0.001, kgf/cm^2: 0.01, bar: 0.01, psi: 0.1 Note 5), kPa: 1		
Ambient and fluid temperature		0 to 50°C (No condensation)		
Enclosure		IP65		

Figure 65 Specifications for ITV1000

Standard Specifications

Stepless control of vacuum pressure in proportion to an electrical signal

Model		ITV2090	ITV2091
Power supply	Voltage	24 VDC ±10%	12 to 15 VDC
	Current consumption	Power supply voltage 24 VDC type: 0.12 A or less Note 6) Power supply voltage 12 to 15 VDC type: 0.18 A or less	
Minimum supply vacuum pressure Note 1)		Set pressure –13.3 kPa	
Maximum supply vacuum pressure		–101 kPa	
Set pressure range		–1.3 to –80 kPa	
Input signal	Current type Note 2)	4 to 20 mA DC, 0 to 20 mA DC	
	Voltage type	0 to 5 VDC, 0 to 10 VDC	
	Preset input	4 points (Negative common)	
Input impedance	Current type	250 Ω or less Note 3)	
	Voltage type	Approximately 6.5 kΩ	
	Preset input	Power supply voltage 24 VDC type: Approximately 4.7 kΩ Power supply voltage 12 VDC type: Approximately 2.0 kΩ	
Output signal Note 4) (Monitor output)	Analog output	1 to 5 VDC (Load impedance: 1 kΩ or more) 4 to 20 mA DC (Sink type) (Load impedance: 250 Ω or less) Output accuracy within ±6% (Full span)	
	Switch output	NPN open collector output: Max. 30 V, 80 mA PNP open collector output: Max. 80 mA	
Linearity		Within ±1% (Full span)	
Hysteresis		Within 0.5% (Full span)	
Repeatability		Within ±0.5% (Full span)	
Sensitivity		Within 0.2% (Full span)	
Temperature characteristics		Within ±0.12% (Full span)/°C	
Output pressure display	Accuracy	±2%F.S. 1 digit	
	Units	kPa Note 5) Minimum display: 1	
Ambient and fluid temperature		0 to 50°C (No condensation)	
Enclosure		IP65	
Weight Note 7)		350 g	

Figure 66 Specifications for ITV2090

D. Sensor schematics

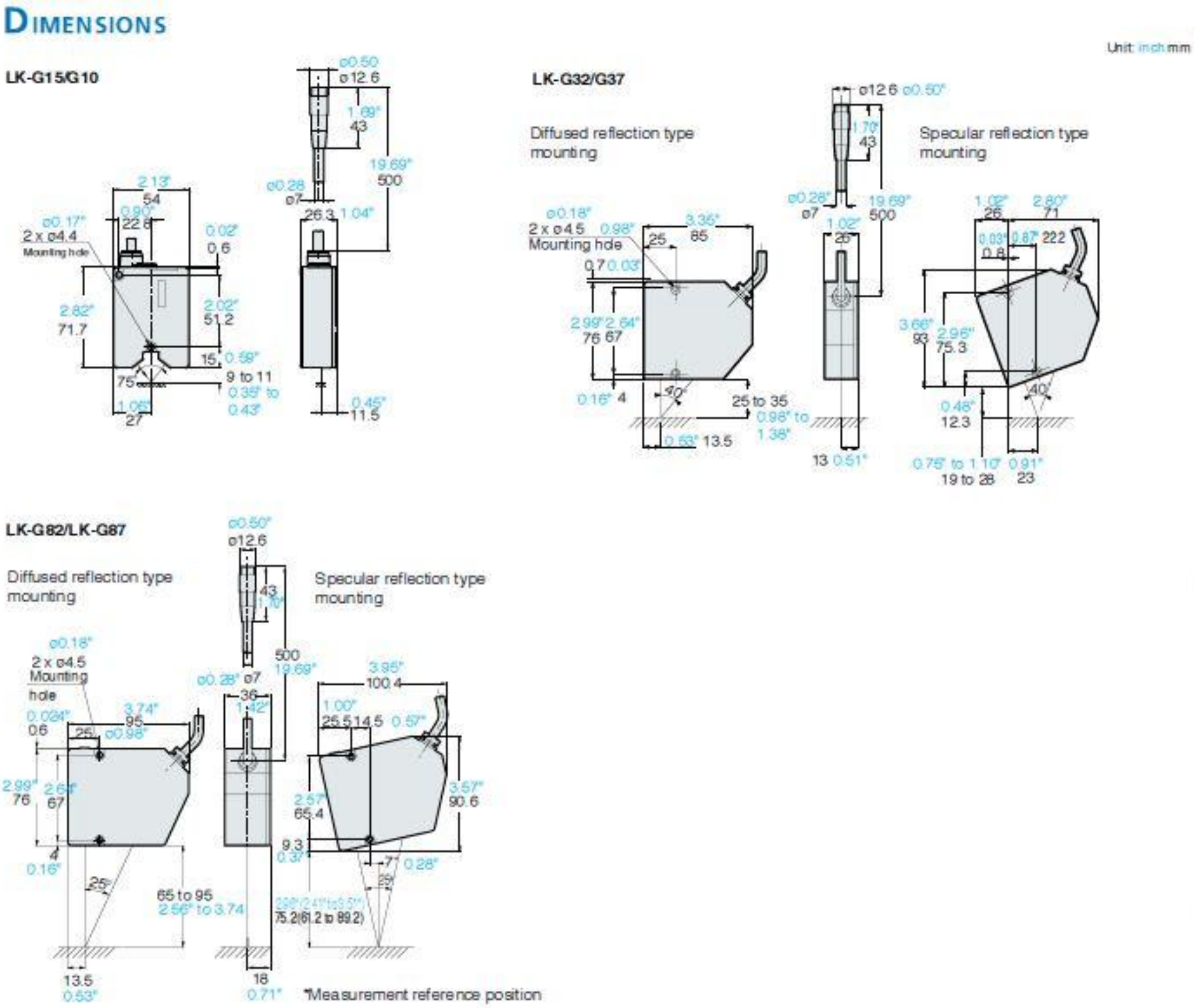


Figure 67: LK-G Model Dimensions (6)

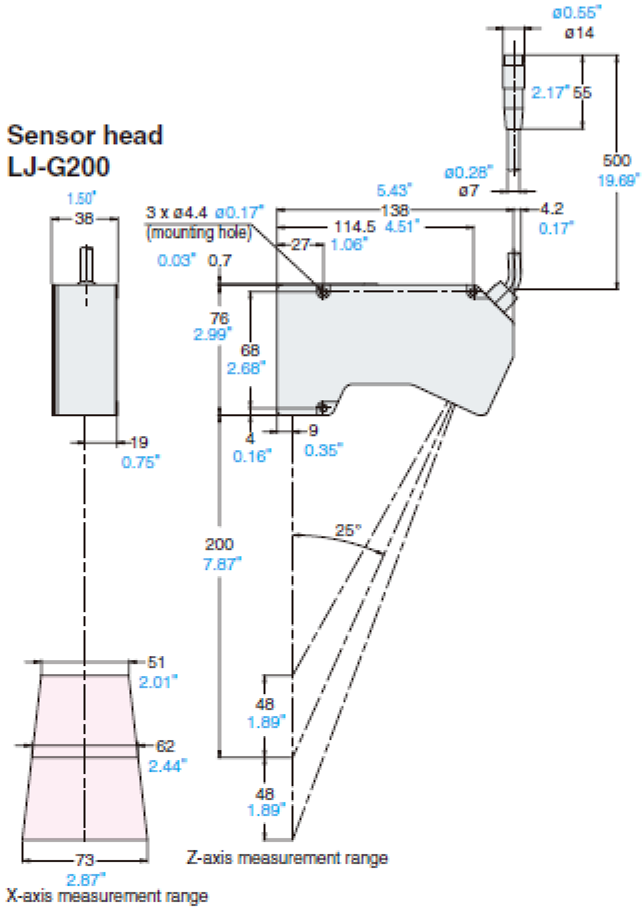


Figure 68: LJ-G Model Dimensions (7)

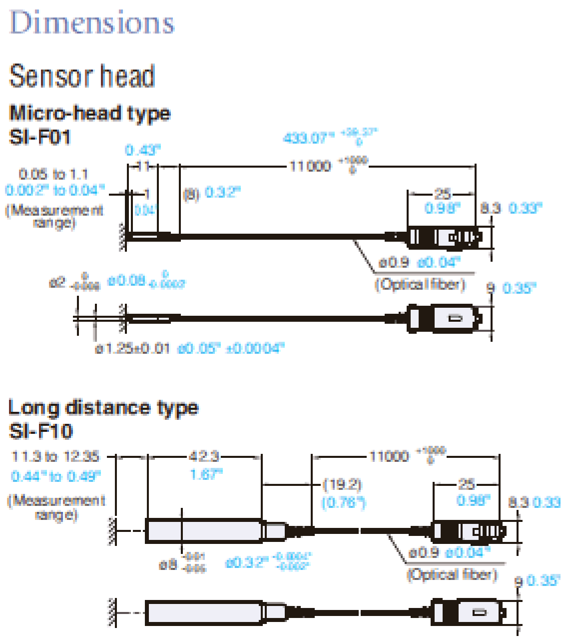


Figure 69: SIF Model Dimensions (8)

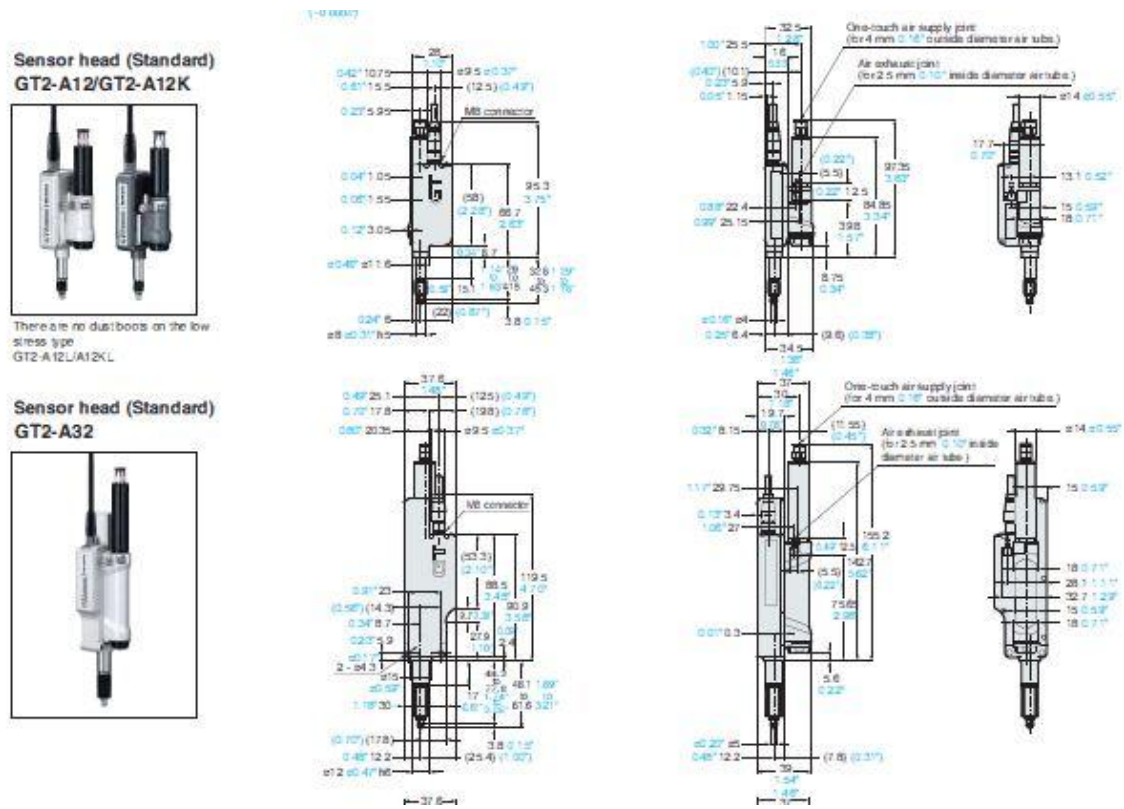


Figure 70:GT2 Model Dimensions (9)

E. Idea Matrix (Table of Possibilities)

	X and Y axis Actuation			Z axis Actuation				Motor
	Custom Stage	Stackable Stages	Qioptiq Stage	Rack and pinion	Ball screw	Linear Servo	Linkage	Servo Motor
Task Specifications	1. Offset of blade inserter with respect to nest should be adjustable to at least ±0.45mm on the X axis. 2) Offset adjustments must be able to be accurately measured to ±0.015mm			1) Z DIRECTION TOLERANCE: TRUE POSITION 0.03 mm6. 2) Velocity of Adjustment Mechanism should be adjustable between at least -0.75m/s and 0.75m/s				be able to actuate tooling at at velociies adjustable between at least - 0.75m/s and 0.75m/s
Repeatability/Accuracy	cannot be absolutly deermined without testing	5-digit LCD display	5-digit LCD display	±0.012mm/meter travel	±0.042 mm/m	±0.01mm	depends on manufacturing	N/A
Control / Approaches	Driven by micrometer	Driven by micrometer	Driven by micrometer	Servo Motor drives Pinion	Servo Motor directly	Is a motor	servo motor deives linkage	SERVOSTAR Amplifier
Advantage	design to loading and travel specs desired	Ultra Accurate; memory for the zero point, meets load and travel	Ultra Accurate; memory for the zero point, meets load and travel	High precision	Low backlash/backdriving; direct driven	No backlash; no back drive; high precision; high speed; high acceleration	high percision, limited mostly by motor	Max Speed of 7500RPM; Programmable; Accurate
Disadvantage	additional manufacutring, more tollerance stackup	potential errors in orthogonality because eof mounting	cost	Potential backlash, speed/acceleration limitation	speed/acceleration limitation	Vertically mounted linear servo requires customized counterbalance or a slide rail	more complicated to reprogram to new profiles, takes up more space	Heavy, may be unable to drive mechanisms at speed
Cost	$1,000	$1,516	$2,616	N/A*	$2,000.00	$10,000-$20,000	depends on linkage	$1,000
Feasibility	Unnecesarily Complicated	Feasible	Recommended	Feasible	Feasible	Recommended	feasable	Feasible

	Pressure/Vacuum/Switching System					
	ASME-Code Horizontal Pressure Tanks 9888K17	versatile air mini pump is BTC-IIS Series	3-way Normally Open solenoid valve	Venturi vacuum pump: P3010	Pressure/Vacuum Accumulator	Pressure/Vacuum Regulator
Task Specifications	A pressure of 6psi and a vacuum of -10psi must be produced at the blade inserter venting port					
Repeatability/Accuracy	Repeatable	Repeatable	Repeatable	Repeatable	Stable Source	0.13kPa or less
Control / Approaches		operate independently for a combination of pressure and vacuum	Switching between on and off at the tooling input	Control the pressure input to set the vacuum level	operate independently for a combination of pressure and vacuum	Electronically controlled from -1.3kPa to 1.0MPa
Advantage	ASME-Code Horizontal Pressure Tank w/o Top Plate, 10 Gallon Capacity, 12" Dia X 23" L	Four heads can be individually configured, sufficient pressure and vacuum	Easy to install, fast switching	Small in size, doesn't need any vacuum accumulator or vacuum regulator	Can provide continuous/constant pressure/vacuum supply. Large volume	Precisely controll the input vacuum/pressure magnitude
Disadvantage		N/A	N/A	Flow rate can be a limitation	Relatively large compared with P3010, requires a vacuum pump	Relatively more expensive compared with non-electronic regulator
Cost	$288	$250	$600-$800	$90	$250x2	$200x2
Feasibility	FEASIBLE	FEASIBLE	Recommended	Feasible	Recommended	Recommended

	2D Laser Sensors	SIF	LVDT	1 D
Task Specifications	1) Before blade insertion, the blade and housing position should be adjusted to zero offset. 2) The blade curvature needs to be measured before the insertion			
Rsolution	±2µm	±0.2µm to ±3µm	±0.1µm	±0.01µm
Control / Approaches	Laser measurement along a line	Spectral interference measurement	An electrical transformer used for measuring linear displacement	Laser Measurment at a Point
Advantage	High accuracy, enough blade curvature information, user friendly software	High accuracy	High accuracy	High accuracy
Disadvantage	cost	needs to be moved	Generate undesired force and contact during the measurement	needs to be moved
Cost	\$15,000-\$20,000	N/A*		\$5,000 to \$6,000
Feasibility	Recommended	feasible	feasible	feasible

	blade/housing loading onto tooling/nests		Nest Modularity			Camera
	Blade Loading	Housing Loading	Nest 1	Nest 2	Nest 3	Cognex In-Sight 5605 camera
Task Specifications	Blade must be loaded on blade loader manually	Housing must be loaded on the nest manually	Design must have the capability to accommodate the nest and blade insertion tooling (blade inserter) for product lines other than the one tested in this project with potential of a unique mounting device being made for each product line			Housing and Tooling Alignment
Control / Approaches	Loading blade by blade feeder, semi-automatic	Manually	Bolt and dowel	Clamp Design	Plate and clamp design	
Advantage	Load blade to the same position each timel; eliminate the chance of injury	Load housing at the correct location without complicated design	Easily mount the nest	simple and quick to change, no new parts	Shims can be ground for fine adjustments; Clamps in place	High resolution applications (5 MP) Specs camera lens
Disadvantage	A customized design that needs further testing	Not automatic	Cannot accurately locate the nest	may not hold all nests secure and square because it depends on geometry and friction	A new plate is made for nests	
Cost						
Feasibility	Recommended	Recommended	Not recommended	Not Recommended	Recommended	Recommended

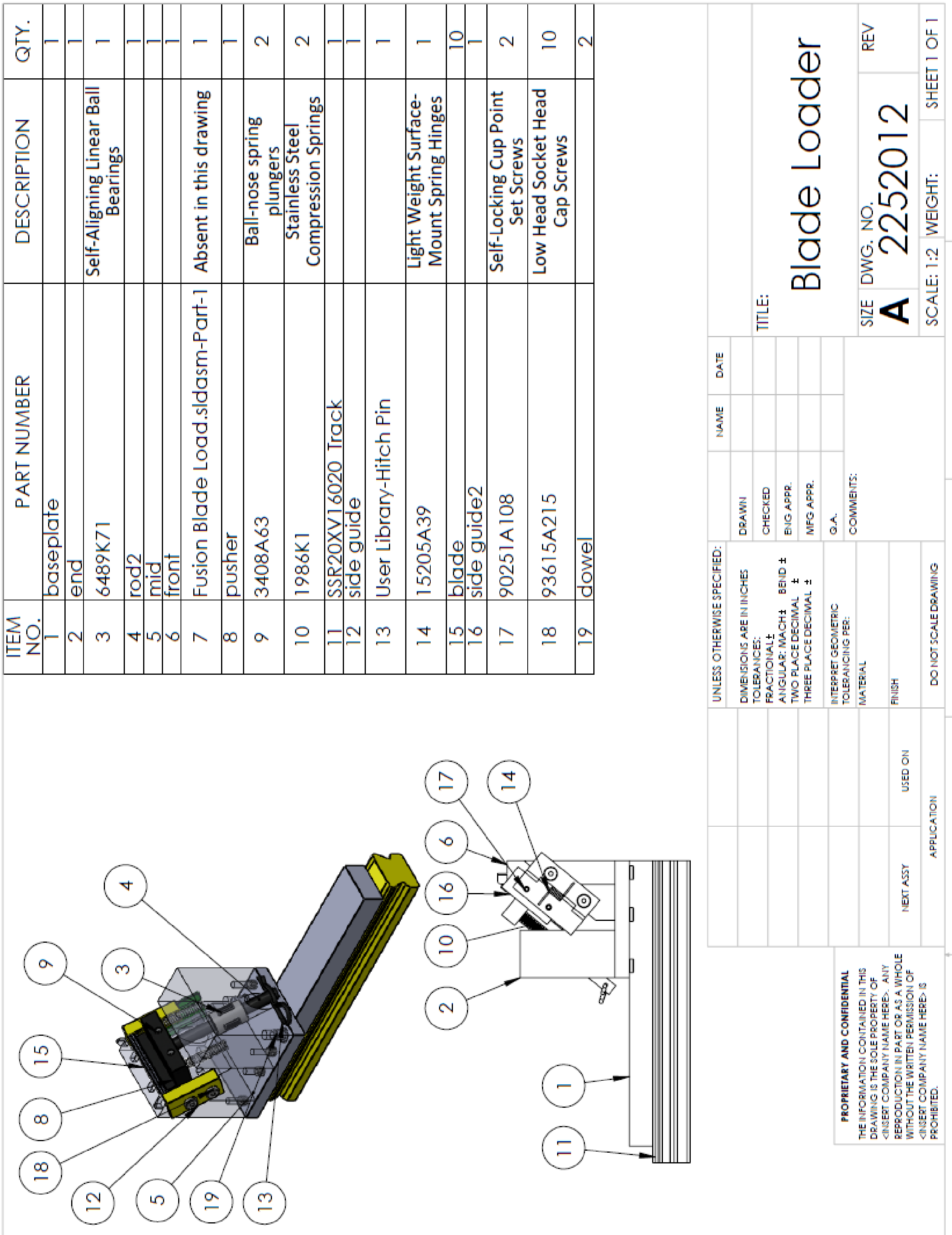
	Safety Frame
	80/20 Inc.
Task Specifications	The safety frame is used to protect operator from injured by the testing fixture
Repeatability/Accuracy	N/A
Control / Approaches	N/A
Advantage	Strong and rigid frame; easy to assemble and obtain; limitless orientation of the structure
Disadvantage	N/A
Cost	$650
Feasibility	Recommended

1D laser sensors							
model	distance from target	repeatibility	spot diameter	weight	cost	notes	
	mm	µm	µm	g	$		
LK-G10	10±1	0.01	20	190	5000-6000		
LK-G32	30±5	0.05	30	280	5000-6000		
LK-G82	80±18	0.2	70	380	5000-6000		
2d							
model	distance from target z	repeatibility z	repeatibility x	beam width	cost		
	mm	µm	µm	mm	$		
LJ-G080	80±23	1	10	32	17000-18000		
SIF	distance from target	resolution	linearity	head diameter	cost		
	mm	nm	±µm	mm	$		
SI-F01	0.05-1.1	1	0.2	2	waiting on quote	may require x axis slide to get to needed distance	
SI-F10	11.3 -12.35	10	3	8			
lvdt	range	resolution	accuracy	force side mounting	cost		
	mm	µm	µm	N	$		
GT2-A12L	12	0.1	1	0.3	waiting on quote		
GT2-A32	32	0.5	3	1.8		for housing	
high speed cameras	frame rate	horizontal res	vertical res	time		cost	
	fps			s		$	
FASTCAM MH4	250	512	512	16	1GB	not yet known	
	10000	512	96	2.2			
FASTCAM SA3	1000	1024	1024	1.36	2GB, 60K model		
	60000	128	16	11.6			
FASTCAM SA5	1000	1024	1024	5.46	8GB		
	75000	128	24	2.4			

Stages

stock number	total stroke	number of axis	normal load capacity	adjustment mechanism	repeatability	Straight Line Accuracy	weight	top type	cost
	mm		N		µm	µm/mm travel	g		$
NT55-461	24.5	1	48.93	digital micrometer	±1	2 per 25	450	solid 44.4x44.4 mm	599
NT56-357	13	1, stacks to 3	13.34	metric micrometer, 0.01mm graduations/0.5mm coarse	±1.27	2 per 25	78	solid top ball bearing	249
NT55-282	25	1, stacks to 3	107.91	Metric Micrometer, 0.01mm Graduations/0.5mm Coarse	±1.27	2 per 25	230	solid top ball bearing	339

F. Blade Loader



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	baseplate		1
2	end		1
3	6489K71	Self-Aligning Linear Ball Bearings	1
4	rod2		1
5	mid		1
6	front		1
7	Fusion Blade Load.sldasm-Part-1	Absent in this drawing	1
8	pusher		1
9	3408A63	Ball-nose spring plungers	2
10	1986K1	Stainless Steel Compression Springs	2
11	SSR20XV16020 Track		1
12	side guide		1
13	User Library-Hitch Pin		1
14	15205A39	Light Weight Surface-Mount Spring Hinges	1
15	blade		10
16	side guide2		1
17	90251A108	Self-Locking Cup Point Set Screws	2
18	93615A215	Low Head Socket Head Cap Screws	10
19	dowel		2

G. Natural Frequencies

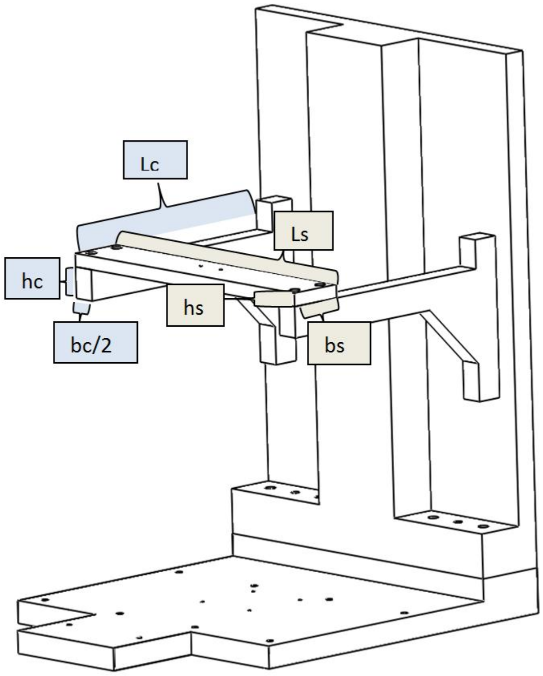


Figure 71: Natural Frequency Diagram

$E_c := 101 \cdot GPa$ youngs modulus of steel

$E_s := 69GPa$ youngs modulus of Al

Cantaliever

$b_c := 50mm$

$h_c := 50mm$

$L_c := 300mm$

$M_c := 2.5kg$

$$I_c := \frac{b_c \cdot h_c^3}{12} = 5.208 \times 10^{-7} m^4$$

$$k_c := \frac{3 \cdot I_c \cdot E_c}{L_c^3} = 5.845 \times 10^6 \frac{kg}{s^2}$$

$$f_{c1} := \frac{1}{2 \cdot \pi} \cdot \left(\frac{3 \cdot E_c \cdot I_c}{M_c \cdot L_c^3} \right)^{\frac{1}{2}} = 243.354 \cdot \frac{1}{s}$$

stage in between (clamped clamped)

$b_s := 62.5mm$

$h_s := 25mm$

$L_s := 350mm$

$M_s := 1.67kg$

$$I_s := \frac{b_s \cdot h_s^3}{12} = 8.138 \times 10^{-8} m^4$$

$$k_s := \frac{192 \cdot E_s \cdot I_s}{L_s^3} = 2.515 \times 10^7 \frac{kg}{s^2}$$

$$f_{s1} := \frac{4}{\pi} \cdot \left(\frac{3 \cdot E_s \cdot I_s}{M_s \cdot L_s^3} \right)^{\frac{1}{2}} = 617.582 \frac{1}{s}$$

$rps := \frac{185}{60s} = 3.083\,\frac{1}{s}$ $\frac{f_{c1}}{3} = 47.999\,\frac{1}{s}$

$2rps = 6.167\,\frac{1}{s}$

$3rps = 9.25\,\frac{1}{s}$

$4rps = 12.333\,\frac{1}{s}$

$5rps = 15.417\,\frac{1}{s}$

$6rps = 18.5\,\frac{1}{s}$

$7rps = 21.583\,\frac{1}{s}$

$8rps = 24.667\,\frac{1}{s}$

$9rps = 27.75\,\frac{1}{s}$

$10rps = 30.833\,\frac{1}{s}$

$11rps = 33.917\,\frac{1}{s}$

$12rps = 37\,\frac{1}{s}$

$13rps = 40.083\,\frac{1}{s}$

$14rps = 43.167\,\frac{1}{s}$

H. Deflections

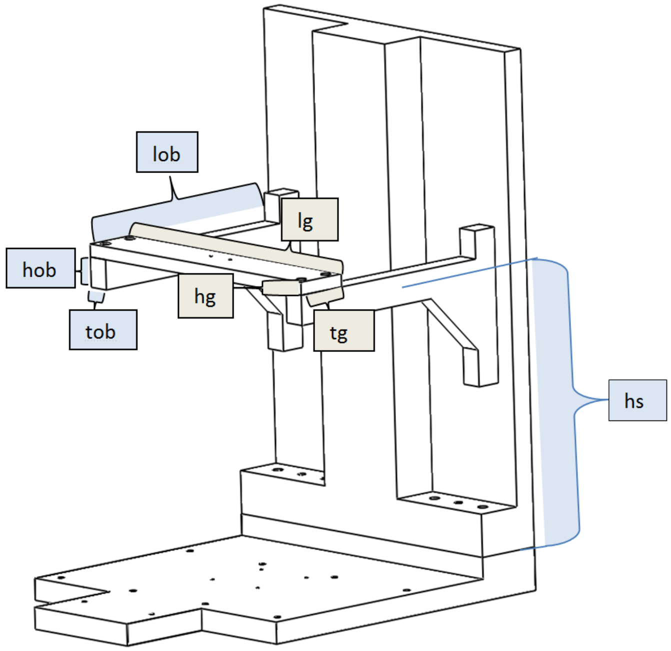


Figure 72: Labeling of Stage Dimensions for Deflection Analysis

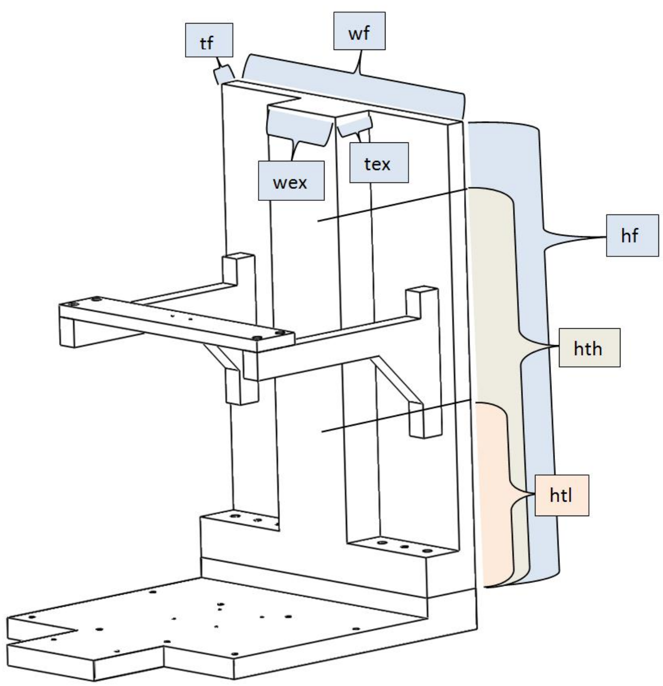


Figure 73: Labeling of Frame Dimensions for Deflection Analysis

FRAME

assumptions

slope of frame at base is 0

deflection of frame at base is 0

moment closes to 0

shear closes to 0

$t_f := 30mm$ thickness of frame

$w_f := 400mm$ width of frame

$h_f := 600mm$ total height of frame

$w_{ex} := 120mm$ width of extrusion holding motor

$t_{ex} := 95mm$ additionalthickness of extrusion holding motor

orange bars

$t_{ob} := 25mm$ thickness of one orange bar

$h_{ob} := 50mm$ height of orange bar

$l_{ob} := 300mm$ height of orange bar

$m_{ob} := 3.37kg$ mass of one orange bar

$h_s := 285.4mm$ height from base of frame to middle of orange bar

green shelf

$t_g := 62.5mm$ thickness of green shelf

$h_g := 25mm$ height of green shelf

$l_g := 350mm$ length of green shelf

$l_g := 350mm$ length of green shelf

$m_g := .87642kg$ mass of shelf

$m_{ad} := .74431kg + .93309kg = 1.6774\,kg$ mass of objects on shelf

tooling

$m_t := 2.6118kg$ mass of all moving parts on tooling

$cog_t := 135.11mm$ distance from COG to frame

$h_{th} := 484.3mm$ highest point

$h_{tl} := 205.56mm$ Point at insertion

moments of inertia in directions of loading

$$y_{cf} := \left(t_f + t_{ex}\right) - \frac{w_{ex}\cdot\left(t_f + t_{ex}\right)^2 + w_f\cdot t_f^{\,2} - w_{ex}\cdot t_f^{\,2}}{2\cdot\left[w_f\cdot t_f + w_{ex}\cdot\left(t_f + t_{ex}\right) - w_{ex}\cdot t_f\right]} = 0.0795513\,m$$

moment of inertia of the frame

$$i_f := \frac{w_f\cdot\left[\left(t_f + t_{ex}\right) - y_{cf}\right]^3 - \left(w_f - w_{ex}\right)\cdot\left[\left(t_f + t_{ex}\right) - t_f - y_{cf}\right]^3 - w_{ex}\cdot y_{cf}^{\,3}}{3} = -7.9643394\times 10^{-6}\,m^4$$

moment of inertia of the orange bar

$$i_{ob} := \frac{h_{ob}^{\,3}\cdot t_{ob}}{12} = 2.6041667\times 10^{-7}\,m^4$$

moment of inertia of the green shelf

$$i_g := \frac{h_g^3 \cdot t_g}{12} = 8.1380208 \times 10^{-8}\,m^4$$

moments applied to the frame

$$m_s := m_{ob} \cdot l_{ob} \cdot g + \left(m_g + m_{ad}\right) \cdot l_{ob} \cdot g = 17.4278488 \cdot N \cdot m$$ moment from the orange bars and shelf

$$m_{th} := m_t \cdot cog_t \cdot g = 3.4605736 \cdot N \cdot m$$ moment from the tooling at highest point

$$m_{tl} := m_t \cdot cog_t \cdot 4g = 13.8422943 \cdot N \cdot m$$ moment from the tooling at insertion (highest acceleration) point

moment base

$$m_{bh} := -m_{th} - m_s = -20.8884224 \cdot N \cdot m$$ reaction at the base when tooling is high

$$m_{bl} := -m_{tl} - m_s = -31.2701431 \cdot N \cdot m$$ reaction at the base when tooling is low

Define the range for x $x := 0 \cdot m, 0.005 \cdot h_f .. h_f$

$St(x,z) := if(x \geq z, 1, 0)$

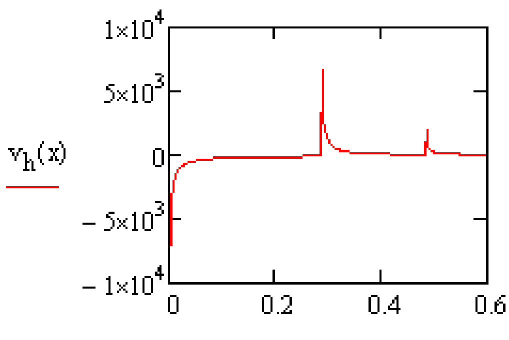
TOOLING IN HIGH POSITION

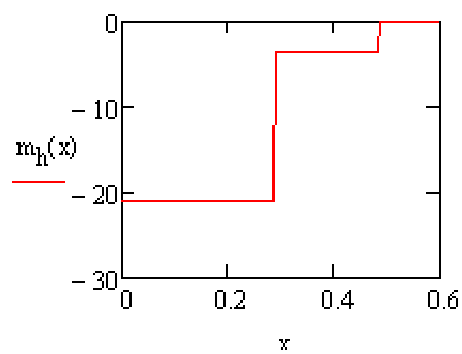
$$v_h(x) := m_{bh} \cdot St(x, 0m) \cdot (x - 0m)^{-1} + m_{th} \cdot St(x, h_{th}) \cdot (x - h_{th})^{-1} + m_s \cdot St(x, h_s) \cdot (x - h_s)^{-1}$$

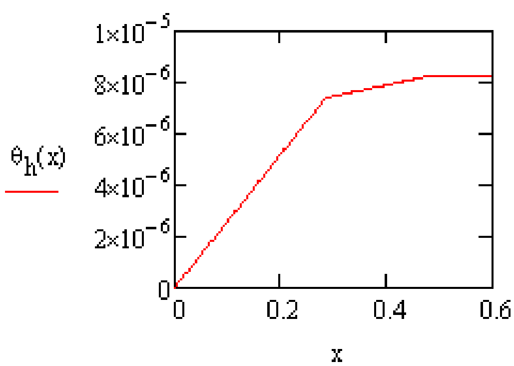
$$m_h(x) := m_{bh} \cdot St(x, 0m) \cdot (x - 0m)^{0} + m_{th} \cdot St(x, h_{th}) \cdot (x - h_{th})^{0} + m_s \cdot St(x, h_s) \cdot (x - h_s)^{0}$$

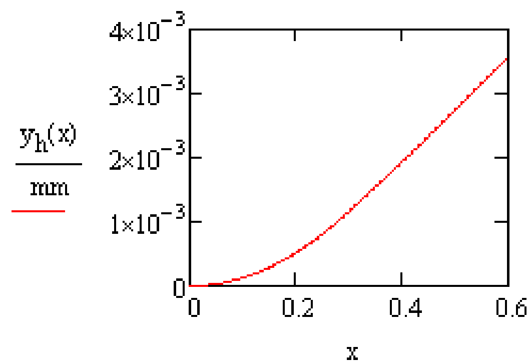
$$\theta_h(x) := \frac{1}{i_f \cdot e_s} \cdot \left[m_{bh} \cdot St(x, 0m) \cdot (x - 0m)^{1} + m_{th} \cdot St(x, h_{th}) \cdot (x - h_{th})^{1} + m_s \cdot St(x, h_s) \cdot (x - h_s)^{1} \right]$$

$$y_h(x) := \frac{1}{i_f \cdot e_s} \cdot \left[\frac{m_{bh}}{2} \cdot St(x, 0m) \cdot (x - 0m)^{2} + \frac{m_{th}}{2} \cdot St(x, h_{th}) \cdot (x - h_{th})^{2} + \frac{m_s}{2} \cdot St(x, h_s) \cdot (x - h_s)^{2} \right]$$









Slope at orange bar base

$\theta_h(h_s) = 4.2463042 \times 10^{-4} \cdot deg$

Deflection at top of frame

$y_h(h_f) = 3.573241 \times 10^{-3} \cdot mm$

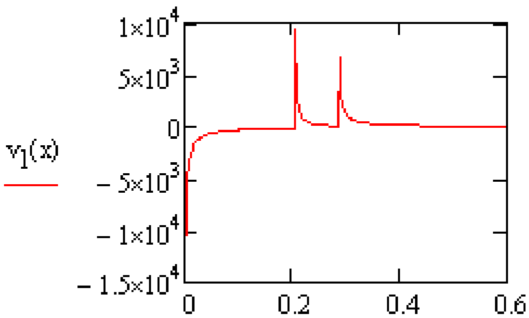
TOOLING IN LOW POSITION

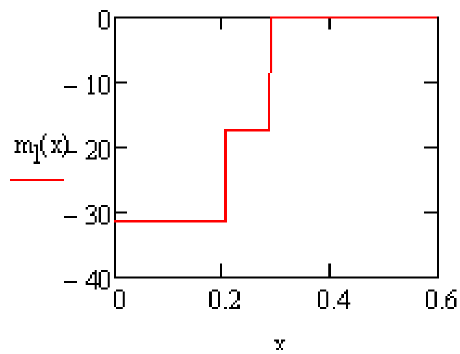
$$v_1(x) := m_{b1} \cdot St(x, 0m) \cdot (x - 0m)^{-1} + m_{t1} \cdot St(x, h_{t1}) \cdot (x - h_{t1})^{-1} + m_s \cdot St(x, h_s) \cdot (x - h_s)^{-1}$$

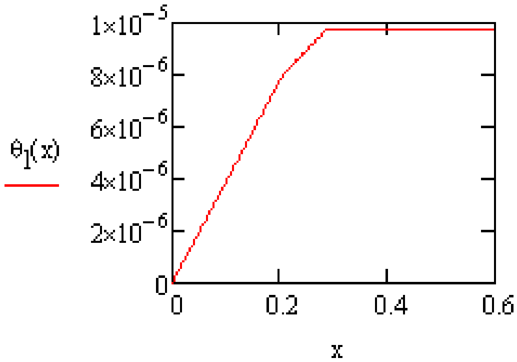
$$m_1(x) := m_{b1} \cdot St(x, 0m) \cdot (x - 0m)^{0} + m_{t1} \cdot St(x, h_{t1}) \cdot (x - h_{t1})^{0} + m_s \cdot St(x, h_s) \cdot (x - h_s)^{0}$$

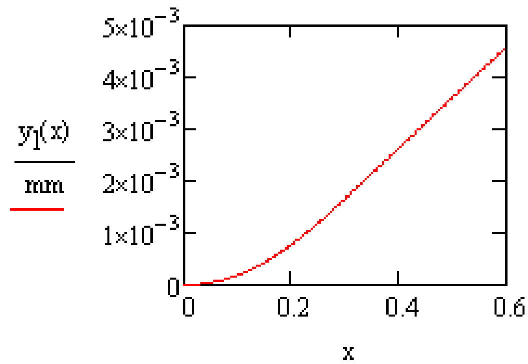
$$\theta_1(x) := \frac{1}{i_f \cdot e_s} \cdot \left[m_{b1} \cdot St(x, 0m) \cdot (x - 0m)^{1} + m_{t1} \cdot St(x, h_{t1}) \cdot (x - h_{t1})^{1} + m_s \cdot St(x, h_s) \cdot (x - h_s)^{1} \right]$$

$$y_1(x) := \frac{1}{i_f \cdot e_s} \cdot \left[\frac{m_{b1}}{2} \cdot St(x, 0m) \cdot (x - 0m)^{2} + \frac{m_{t1}}{2} \cdot St(x, h_{t1}) \cdot (x - h_{t1})^{2} + \frac{m_s}{2} \cdot St(x, h_s) \cdot (x - h_s)^{2} \right]$$









Slope at orange bar base

$$\theta_1(h_s) = 5.569562 \times 10^{-4} \cdot deg$$

Deflection at top of frame

$$y_{frame} := y_1(h_f) = 4.5864952 \times 10^{-3} \cdot mm$$

The dynamic loading situation resilts in greater deflection and will be used for analysis from here on

ORANGE BARS

displacment due to deflection of the main frame

$s_{con} := \theta_1(h_s) = 9.7207195 \times 10^{-6} \cdot rad$ slope at the base of the orange bar

$y_{\theta ob} := \sin(s_{con}) \cdot l_{ob} = 2.9162159 \times 10^{-3} \cdot mm$ deflection dues to the slope of the main frame

deflection of orange bars due to loading

Define the range for x $w := 0 \cdot m, 0.005 \cdot l_{ob} .. l_{ob}$

$St_1(w, z) := if(w \geq z, 1, 0)$

reaction at base

$r_{ob} := m_{ob} \cdot g \cdot 2 + (m_g + m_{ad}) \cdot g = 91.1412399\,N$ reaction at base of orange bar

$m_{obm} := m_{ob} \cdot g \cdot l_{ob} + (m_g + m_{ad}) \cdot g \cdot l_{ob} = 17.4278488 \cdot N \cdot m$ moment at end of orange bar

$w_{ob} := \frac{m_{ob} \cdot g}{l_{ob}} = 110.1613683 \cdot \frac{N}{m}$ distributed load from weight

$f_g := (m_g + m_{ad}) \cdot g = 25.0444189\,N$ point force from green shelf

assumptions

slope of bar at base is 0

deflection of bar at base is 0

moment closes to 0

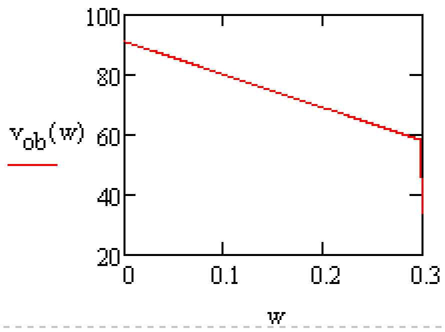
shear closes to 0

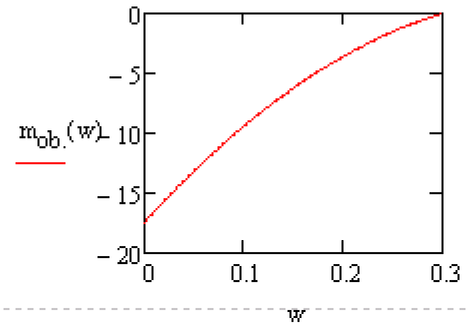
$$v_{ob}(w) := r_{ob} \cdot St_1(w, 0m)(w - 0m)^0 - f_g \cdot St_1(w, l_{ob})(w - l_{ob})^0 - w_{ob} \cdot St_1(w, 0m)(w - 0m)^1$$

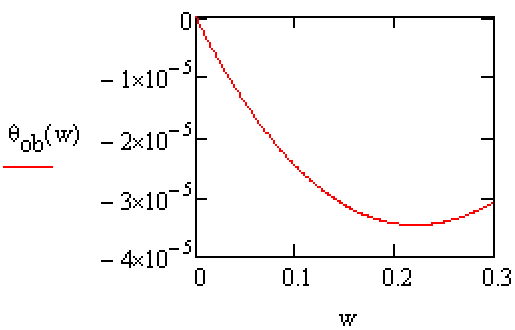
$$m_{ob}(w) := r_{ob} \cdot St_1(w, 0m)(w - 0m)^1 - f_g \cdot St_1(w, l_{ob})(w - l_{ob})^1 - w_{ob} \cdot St_1(w, 0m)(w - 0m)^2 - m_{obm} \cdot St_1(w, 0m)(w - 0m)^0$$

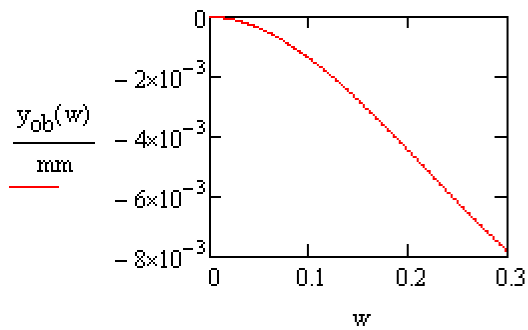
$$\theta_{ob}(w) := \frac{1}{2 \cdot i_{ob} \cdot e_s} \cdot \left[\frac{r_{ob}}{2} \cdot w^2 - \frac{f_g}{2} \cdot St_1(w, l_{ob})(w - l_{ob})^2 - \frac{w_{ob}}{6} \cdot St_1(w, 0m)(w - 0m)^3 - m_{obm} \cdot w\right]$$

$$y_{ob}(w) := \frac{1}{2 \cdot i_{ob} \cdot e_s} \cdot \left[\frac{r_{ob}}{6} \cdot St_1(w, 0m)(w - 0m)^3 - \frac{f_g}{6} \cdot St_1(w, l_{ob})(w - l_{ob})^3 - \frac{w_{ob}}{24} \cdot St_1(w, 0m)(w - 0m)^4 - \frac{m_{obm}}{2} \cdot St_1(w, 0m)(w - 0m)^2\right]$$









$y_{oend} := y_{ob}(l_{ob}) + y_{\theta ob} = -4.9025009 \times 10^{-3} \cdot mm$

GREEN SHELF

Define the range for x $\quad q := 0 \cdot m, 0.005 \cdot l_g .. l_g$

$St_2(q, z) := if(q \geq z, 1, 0)$

reaction at supports

$r_g := \frac{m_g \cdot g + m_{ad} \cdot g}{2} = 12.5222095\,N$ reaction at each support

$w_g := \frac{m_g \cdot g}{l_g} = 24.556412 \cdot \frac{N}{m}$ distributed load from weight

$f_{ad} := m_{ad} \cdot g = 16.4496747\,N$ force from blade loader and camera

assumptions
shear closes to 0
moment closes to 0

deflection at supports is 0

Given

$$0m = \frac{1}{i_g \cdot e_a} \cdot \left(\frac{r_g}{6} \cdot 0m + \frac{r_g}{6} \cdot 0m - \frac{f_{ad}}{6} \cdot 0m - \frac{w_g}{24} \cdot 0m + c_3 \cdot 0m + c_4 \right)$$

$$0m = \frac{1}{i_g \cdot e_a} \cdot \left[\frac{r_g}{6} \cdot (l_g - 0m)^3 + \frac{r_g}{6} \cdot 0m - \frac{f_{ad}}{6} \cdot \left(l_g - \frac{l_g}{2} \right)^3 - \frac{w_g}{24} \cdot (l_g - 0m)^4 + c_3 \cdot l_g + c_4 \right]$$

$$\text{Find}(c_3, c_4) \rightarrow \begin{bmatrix} \dfrac{4.0108816964285747142e\text{-}20 \cdot (1.0937497073897730171e27 \cdot kg \cdot mm^3 - 5.327527755944065201e24 \cdot N \cdot s^2 \cdot mm^2)}{s^2} \\ 0 \end{bmatrix}$$

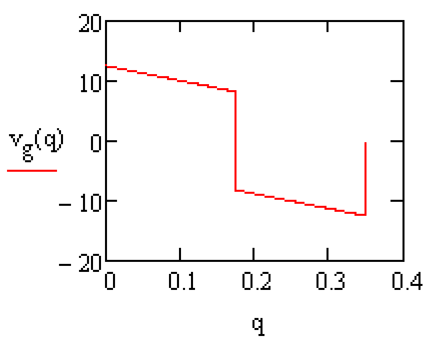
$$c_3 := \frac{4.0108816964285747142e\text{-}20 \cdot (1.0937497073897730171e27 \cdot kg \cdot mm^3 - 5.327527755944065201e24 \cdot N \cdot s^2 \cdot mm^2)}{s^2} = -0.1698118 \frac{m^3 \cdot kg}{s^2}$$

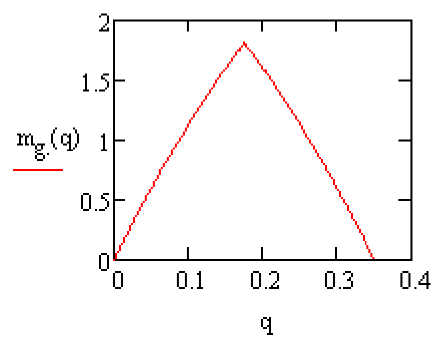
$$v_g(q) := r_g \cdot St_2(q, 0m) \cdot (q - 0m)^0 + r_g \cdot St_2(q, l_g) \cdot (q - l_g)^0 - f_{ad} \cdot St_2\left(q, \frac{l_g}{2}\right) \cdot \left(q - \frac{l_g}{2}\right)^0 - w_g \cdot St_2(q, 0m) \cdot (q - 0m)^1$$

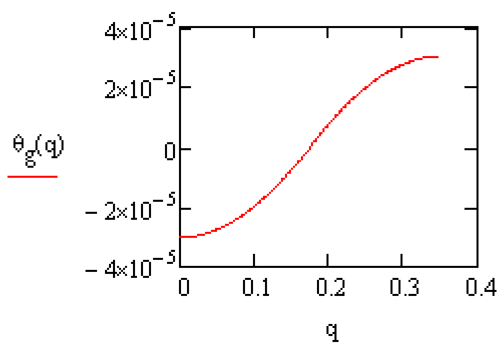
$$m_g(q) := r_g \cdot St_2(q, 0m) \cdot (q - 0m)^1 + r_g \cdot St_2(q, l_g) \cdot (q - l_g)^1 - f_{ad} \cdot St_2\left(q, \frac{l_g}{2}\right) \cdot \left(q - \frac{l_g}{2}\right)^1 - \frac{w_g}{2} \cdot St_2(q, 0m) \cdot (q - 0m)^2$$

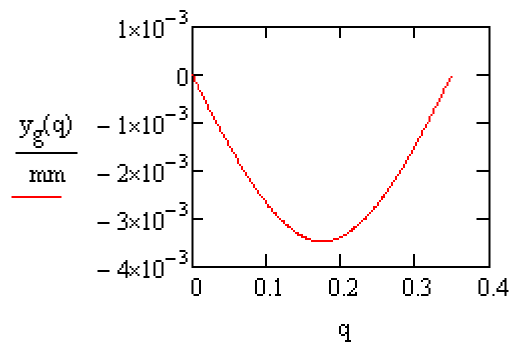
$$\theta_g(q) := \frac{1}{i_g \cdot e_a} \cdot \left[\frac{r_g}{2} \cdot St_2(q, 0m) \cdot (q - 0m)^2 + \frac{r_g}{2} \cdot St_2(q, l_g) \cdot (q - l_g)^2 - \frac{f_{ad}}{2} \cdot St_2\left(q, \frac{l_g}{2}\right) \cdot \left(q - \frac{l_g}{2}\right)^2 - \frac{w_g}{6} \cdot St_2(q, 0m) \cdot (q - 0m)^3 + c_3 \right]$$

$$y_g(q) := \frac{1}{i_g \cdot e_a} \cdot \left[\frac{r_g}{6} \cdot St_2(q, 0m) \cdot (q - 0m)^3 + \frac{r_g}{6} \cdot St_2(q, l_g) \cdot (q - l_g)^3 - \frac{f_{ad}}{6} \cdot St_2\left(q, \frac{l_g}{2}\right) \cdot \left(q - \frac{l_g}{2}\right)^3 - \frac{w_g}{24} \cdot St_2(q, 0m) \cdot (q - 0m)^4 + c_3 \cdot q \right]$$









deflection of the green shelf in the center

$$y_{gc} := y_g\left(\frac{l_g}{2}\right) = -3.4711822 \times 10^{-3}\ \text{mm}$$

deflection at center of green stage

$$y_{shelf} := y_{oend} + y_{gc} = -8.3736831 \times 10^{-3}\ \text{mm}$$

Summary of Deflections

end of frame

$$y_{frame} = 4.5864952 \times 10^{-3}\ \text{mm}$$

shelf total (stack up of orange bars and green shelf)

$$y_{shelf} = -8.3736831 \times 10^{-3}\ \text{mm}$$

I. *End Effector Profile*

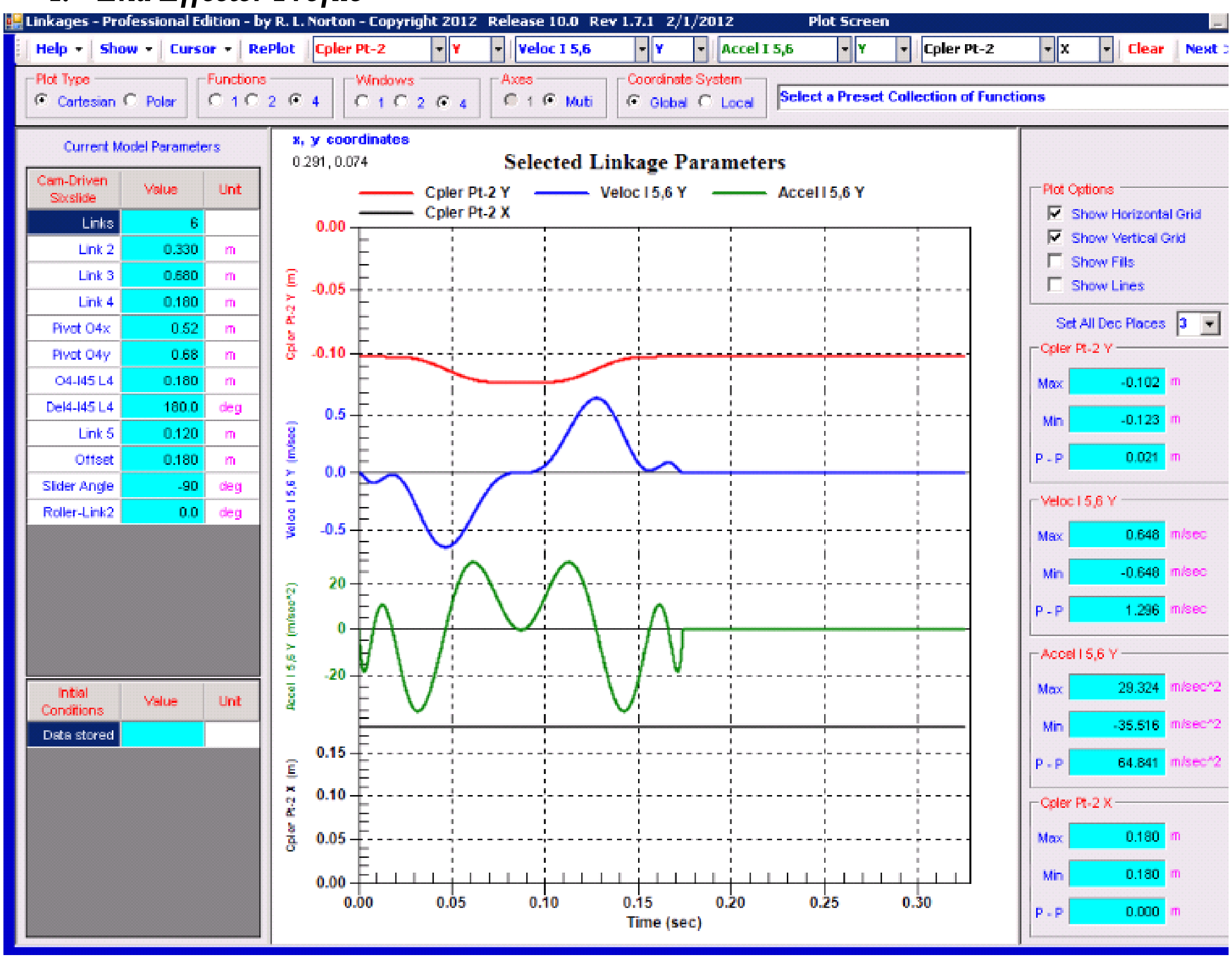


Figure 74: End Effector Profile from Linkages

J. FFT

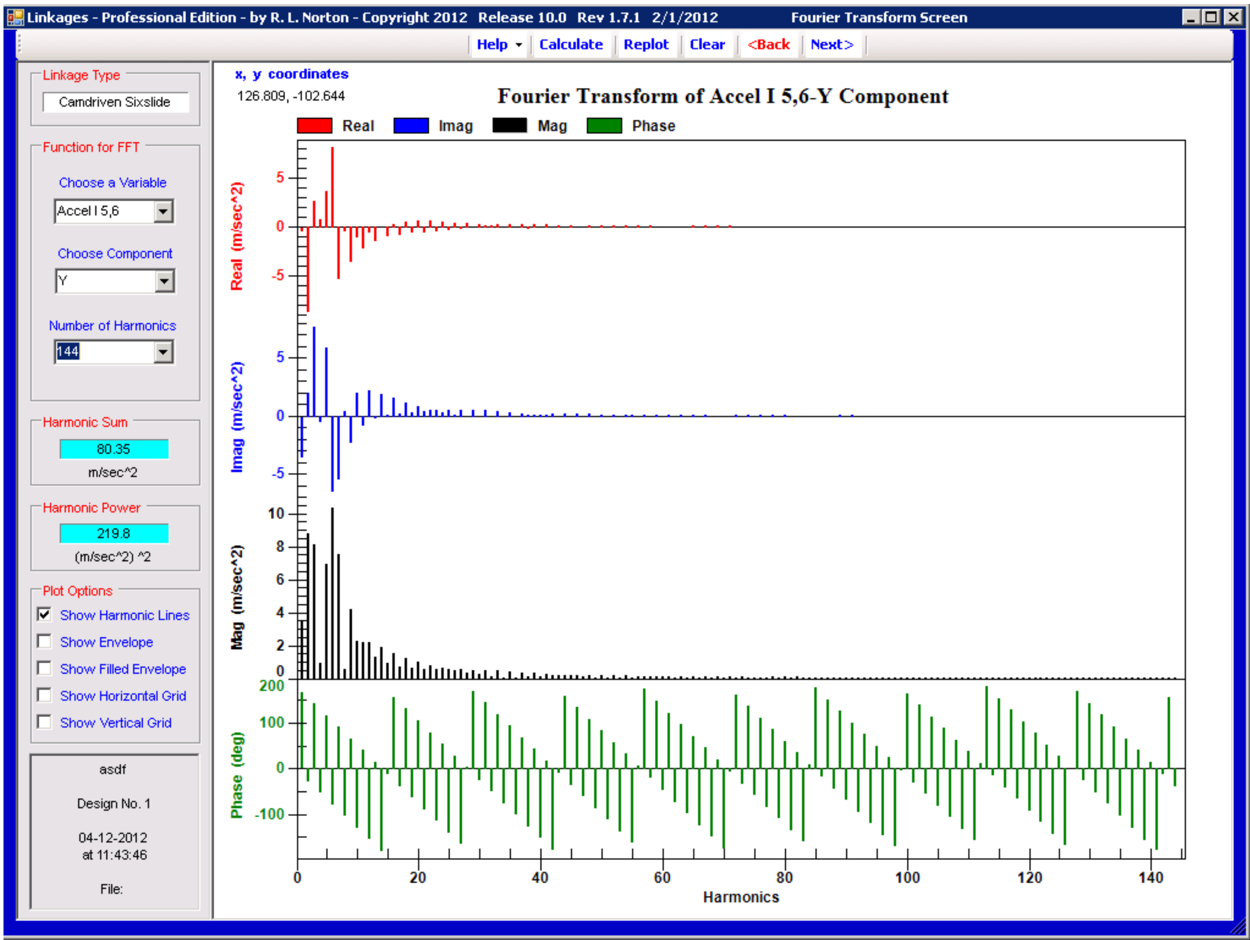


Figure 75: FFT of End Effector Vibrations

K. Bill of Materials

Red=Estimate				
Part No.	**Description**	**Price**	**#**	**Total Prices**
	SENSORS/VISION			
	Keyence LJ-G200 System	$20,000.00	1	$ 20,000.00
LJ-G200	LJ-G200			
LJ-H1W	LJ-navigator software			
LJ-G5001	LJ-Controller			
LJ-GC2	LJ-Cable			
	Cognex Insight 5100 System	$ 1,500.00	1	$ 1,500.00
	Insight 5100 Camera			
	Cognex Power Cable			
	Cognex Computer Cable			
	Cognex Visualizer Software			
FM3_2a_PTD	Foveal Mounts FM3_2a w/ Pan/Tilt Dials	$ 500.00	1	$ 500.00
NT58-000	Edmunds Optics 8.5mm Fixed Focal Length Lens	$ 295.00	1	$ 295.00
	XY ACTUATION			
G403337000	Qioptiq Inc. XY-Stage 85-25 Digital Micrometer	$ 2,616.00	1	$ 2,616.00
	Z ACTUATION			
	AeroTech Servo Motor	$10,000.00	0	$ -
	ALIO Servo System	$45,000.00	0	$ -
	Chicago Electric Servo System	$20,000.00	1	$ 20,000.00
	Nippon Pulse Linear Shaft Motor			
	Encoder			
	Linear Slide Rail			
	Emergency Brake			
	Kabelschlepp E-Chain			

2097-V31PR2	Rockwell Automation Kinetix 300 Controller			
	FASTENERS	$ 200.00	1	$ 200.00
	M3x0.5x25		4	
	Precision Baseplate to Qioptiq XY Stage (x4)			
	M3x0.5x10 Pan Screw Cross Head		2	
	Solenoid Bracket Plate to Solenoid (x2)			
	M4x0.7x10 Socket Head Cap Screw		6	
	Blade Loader to Side Guide (x2)			
	Blade Loader Base to Ends (x4)			
	M4x0.7x13 Pan Screw Cross Head		4	
	Keyence Bracket to Keyence LJ-G (x4)			
	M4x0.7x20 Pan Screw Cross Head		4	
	Linear Bearing to Panel (x4)			
	M4x0.7x25 Socket Head Cap Screw		2	
	THK Cart to Support Shelf (x2)			
	M5x0.8x16 Pan Screw Cross Head		6	
	Keyence Bracket to Keyence Bracket Adapter (x4)			
	Solenoid Bracket Plate to Back plate (x2)			
	M5x0.8x20 Socket Head Cap Screw		7	
	Tooling Adapter Extension to Servo Motor Cart (x4)			
	Tooling Adapter to Tooling Adapter Extension (x3)			
	M5x30 Dowel Pin		2	
	Tooling Adapter Extension to Servo Motor Cart (x2)			
	M5x0.8x45 Pan Screw Cross Head		6	
	80/20 Frame to Bottom Plate (x6)			
	M6x1.00x30 Pan Screw Cross Head		24	
	80/20 Hinges to 80/20 Frame (x16)			
	80/20 Locks to 80/20 Frame (x8)			
	M6x1.00x35 Socket Head Cap Screw		3	
	CUSTOM PARTS			
	General Parts			
	Bottom Mounting Plate	$ 400.00	1	$ 400.00
	Bottom-Bottom Mounting Plate	$ 450.00	1	$ 450.00
	Pneumatic Mounting Plate	$ 350.00	1	$ 350.00
	Controls Mounting Plate	$ 200.00	1	$ 200.00
	Blade Loader / Cognex Support Brackets	$ 300.00	2	$ 600.00
	Blade Loader / Cognex Support Shelf	$ 200.00	1	$ 200.00
	Blade Loader / Connecting Rod Bracket	$ 250.00	1	$ 250.00
	Keyence Bracket Adapter	$ 350.00	1	$ 350.00
	Solenoid Bracket Plate	$ 50.00	1	$ 50.00
	Steel Chassis Back plate + Baseplate (2 pieces)	$ 750.00	1	$ 750.00
	Modular Nest			
	Adapter Plate	$ 200.00	1	$ 200.00
	Precision Base	$ 450.00	1	$ 450.00
	Precision Sides	$ 500.00	1	$ 500.00
	L-Clamps	$ 200.00	2	$ 400.00

	Servo / Tooling			
	Extension Piece off of Servo Motor	$ 350.00	1	$ 350.00
	Blade Loading Vacuum Port	$ 350.00	1	$ 350.00
	Tooling-to-Servo Bracket	$ 500.00	1	$ 500.00
	Blade Loader			
	Baseplate	$ 350.00	1	$ 350.00
	End	$ 400.00	1	$ 400.00
	Front	$ 250.00	1	$ 250.00
	Mid	$ 400.00	1	$ 400.00
	Pusher	$ 400.00	1	$ 400.00
	Rod	$ 150.00	1	$ 150.00
	Side Guide	$ 200.00	2	$ 400.00

	SAFETY ENCLOSURE			
	80/20 System	$ 750.00	1	$ 750.00
40-2421	Quick Release Panel Fasteners		22	
40-2430	Panel Fasteners		16	
40-4040	Extruded Aluminum 40-Series (in meters)		15	
40-2833 / 40-2840	Hinges		4	
45-2107	Locks		2	
40-3897	Aluminum Securing Pieces		24	
	VACUUM / PRESSURE SYSTEM			
SMC VKF334W	3-Port Solenoid Valve	$ 50.00	1	$ 50.00
9888K13	ASME-Code Vertical Pressure Tank	$ 281.00	2	$ 562.00
4176K11	Oil-Free Electric Vacuum/Pressure Pump	$ 415.03	2	$ 830.06
SMC AR435-N04BG-NII	Vacuum Regulator	$ 186.65	1	$ 186.65
SMC IRV 50-Nil N07 L G	Pressure Regulator	$ 186.65	1	$ 186.65
5463K245	Nylon Single-Barbed Tube Fitting 1/4" Tube ID X 1/8" NPT Male	$ 5.26	3	$ 15.78
	Hoses (1/4" Diam.) (total)	$ 40.00	1	$ 40.00
	OTHER			
SSR-20XV1UU	THK Slide Rail	$ 117.00	1	$ 117.00
5190A8	McMaster-Carr 472lb Load-Rated Pull Handle	$ 12.18	4	$ 48.72
6483K63	McMaster-Carr Linear Bearing	$ 30.67	1	$ 30.67
17715A68	McMaster-Carr L-Bracket	$ 4.11	2	$ 8.22
633A-200	Barry Mounts Anti-Vibration Mounts	$ 35.00	4	$ 140.00
	RHINO Switching Power Supply (24VDC, 1A, 85-264VAC, 85-375VDC)	$ 59.25	1	$ 59.25
N/A	Computer	N/A	N/A	N/A

TOTAL
$ 56,836.00

L. AeroTech Servo Motor Quote

Dedicated to the Science of Motion

WORLD HEADQUARTERS
Aerotech, Inc.
101 Zeta Drive
Pittsburgh, PA 15238
Ph: 412-963-7470
Fax: 412-963-7459
Email: sales@aerotech.com

AEROTECH WORLDWIDE
United States • Germany • United Kingdom • Japan • China

www.aerotech.com

Company: **Worcester Polytechnic Institute (WPI)** **Quotation Number: B10214 9-00**
100 Institute Rd Date: 28-Mar-2012
01609 Worcester MA Expiration Date: 12-May-2012

Contact: **Catherine Shea** **Project Name:** Actuator
Title: Student:
Email: c.shea@wpi.edu

Dear Ms. Shea,

Thank you for your interest in Aerotech products. Aerotech is pleased to provide the following quotation for motion control equipment for your R&D assembly station:

QUOTE REVISION HISTORY:

-00 28-Mar-12 Original Quotation

PRODUCT INFORMATION:

General Information:	http://www.aerotech.com
Software Downloads:	http://www.aerotech.com/download.html
Manual Downloads:	http://www.aerotech.com/download.html
2D/3D Drawings:	http://www.aerotech.com/products/drawings/caddl.cfm
FAQ:	http://www.aerotech.com/FAQ.html

SYSTEM SPECIFICATIONS:
All specifications are per axis only.

Z

Travel: 500mm Vertical.

THE ACT115DL or ACT140DL IS BEING USED IN A VERTICAL APPLICATION. IT IS A STANDARD UNIT AND DOES NOT INCLUDE ANY COUNTERBALANCE OR SAFETY FEATURES FOR VERTICAL USE. THE CUSTOMER IS AWARE OF THE RISKS AND AGREES TO TAKE CARE OF THEM

ACTUATOR WILL BE TESTED IN HORIZONTAL POSITION ONLY.

Resolution: 0.020 um with LTAS and MXU
Accuracy: catalog spec
Repeatability: catalog spec
Load on Stages: 0.75 kg
Load CG: Centered, offset normal 64 mm from the carriage
Min / Max Velocity: 0.5m/s
Acceleration: 30m/s^2
Move Profile: See motor sizing calcs

SYSTEM COMPONENTS:

ITEM	QTY	PART NUMBER/DESCRIPTION	PRICE	AMOUNT
		Mechanical Components		
1	1	**ACT115DL-0500-TTM-AS-NCA-CMS0500-H-FC-EP-PLOTS** The **ACT115DL** is a high performance, cost effective linear servo motor driven actuator that is faster and more accurate than a ball screw or belt-drive without the costly, time consuming maintenance required. The ACT115DL is ideal for applications including assembly, pick and place machines, electronic assembly and qualification, packaging, vision inspection, dispensing, life sciences, image scanning and processing, and inject printing. The ACT115DL is configured as follows: **-0500:** 500mm travel linear actuator **-TTM:** Metric dimension mounting pattern and holes (standard) **-AS:** Linear optical encoder; 20 pm/Vpp output **-NCA:** Normally-closed end of travel limit switches with adjustable location. **-CMSxxxx-H:** Cable management system for [where xx = 50mm - 1500mm] single axis applications; Halls. **-FC:** Includes air cooling of linear motor forcer (20 psi compressed air supply required) **-EP:** End plates mounted on linear actuator base **-PLOTS:** Accuracy and repeatability plots http://www.aerotech.com/products/actuators/act.html	$5,525 $7,415	$5,525
2	0	**ACT140DL-0500-TTM-AS-NCA-CMS0500-H-FC-EP-PLOTS** The **ACT140DL** is a high performance, cost effective linear servo motor driven actuator that is faster and more accurate than a ballscrew or belt-drive without the costly, time consuming maintenance required. The ACT140DL is ideal for applications including assembly, pick and place machines, electronic assembly and qualification, packaging, vision inspection, dispensing, life sciences, image scanning and processing, and inject printing. The ACT140DL is configured as follows: **-0500:** 500mm travel linear actuator **-TTM:** Metric dimension mounting pattern and holes (standard) **-AS:** Linear optical encoder; 20 pm/Vpp output **-NCA:** Normally-closed end of travel limit switches with adjustable location. **-CMSxxxx-H:** Cable management system for [where xx = 50mm - 1500mm] single axis applications; Halls. **-FC:** Includes air cooling of linear motor forcer (20 psi compressed air supply required) **-EP:** End plates mounted on linear actuator base **-PLOTS:** Accuracy and repeatability plots http://www.aerotech.com/products/actuators/act.html B102149-00 WPI vertical actuator (1) (1).xls		$0

		Controls, Ampllfilers, and Cables		
3	1	**C1 9360-50** Motor power cable, 5.0 meters long -Motor/stage connector: 4 pin high power D -Amplifier connector: flying leads (with ferrite beads)	$135	$135
4	1	**C16501-50** Feedback cable, 5.0 meters long - Motor/stage connector: 25 pin D - Controller/drive rack end: 25 pin D	$135	$135
5	1	**SOLOIST-MC-MACHINE-MOTION DESIGNER-LABVIEW-MAINTENANCE-1-00-VERSION CURRENT** **SOLOIST:** Full installation of Soloist Controller and selected software components on a new system. Maintenance (software update) included in price for one year from date of purchase. **-MC:** MOTION COMPOSER STANDARD includes the Integrated Development Environment, Scope, System Diagnostics, and System Maintenance. **-MACHINE:** Provides the ability to: - Write, compile, execute, debug programs in Aerobasic - Full access to .NET 2.0 and C Library - Access full diagnostics, fault, and status information - Access and set I/O, registers, and variables - Collect, analyze and save data - View files from machine for analysis and record keeping - Connect PC to machine through Ethernet TCP/IP or USB - Upgrades can be installed (firmware or controller) using Loader **-MOTION DESIGNER:** The Motion Designer is an add-on software component that provides the ability to create, import, run, and evaluate motion profiles (trajectories). Iterative learning control. **-LABVIEW:** Includes LABVIEW 8.2 VI samples - **MAINTENANCE:** 1st year of maintenance is included with the initial purchase. Additional years can be purchased. http://www.aerotech.com/products/controllers/Soloist/index.cfm	$1,200	$1,200
6	1	**ENET-XOVER-45** 4.5m (14.7 ft) Ethernet cross over cable	$35	$35
7	1	**SOLOISTCP10-MXU** Soloist CP Series single axis PWM digital controller with USB and Ethernet interface. 5A continuous, 10A peak, 28-240 VAC supply input, and 85-240VAC control supply input for logic. Drives brushless, brush and stepper motor. Includes: - 4 digital outputs (sinking or sourcing), - 4 digital inputs (sinking or sourcing), - 2 high speed 5 VDC digital inputs (50 nsec delay), - one 16 bit analog differential input; +/-10 VDC - one 16 bit analog single ended output; +/-10 VDC , - one 24VDC, 1 amp brake relay - Single axis PSO capability - 2 quadrature encoder input channels (primary & auxiliary) - Estop sense input - Dedicated Home and Limit Inputs **-MXU:** Programmable encoder multiplier up to x1024 (x4096 after quadrature); No real time output. http://www.aerotech.com/products/controllers/Soloist/soloistcp.cfm	$1,985	$1,985

8	1	**INTEGRATION - TEST AS SYSTEM** Document, configure, and test components as a system. Intended for testing of components that are going to be used together in a complete and specific system configuration.	$215	$215
		SYSTEM TOTAL:		**$ 9,230**

CE REQUIREMENTS:

While the majority of Aerotech's electronic components are individually rated as "CE Compliant", the following options may be required in order to achieve a system level compliance to European CE standards. Contact your Aerotech Sales Engineer for more information.

9	0	**UFM-ST** AC Line Filter Module with screw terminals (required for A3200, Ensemble, Soloist amplifiers CE compliance). Includes MOV's for surge protection. 30A peak/10A RMS. 240VAC input voltage. http://www.aerotech.com/products/accessories/filter.html	$645	$0
10	0	**MFM1** Motor Filter Module, PWM drive output filter for reducing conducted switching noise up to 10dB. http://www.aerotech.com/products/accessories/mfm1.html	$520	$0

OPTIONAL SERVICES:

Aerotech's customer service department offers a wide-variety of products and services that complement your component/system purchase. From software training to on-site assistance, Aerotech's world-class customer service department is ready and willing to help. For detailed information or a quote on any of the items listed below, please contact Customer Service at 412-967-6440 or service@aerotech.com.

Optional products and Services offered by Aerotech's Customer Service Department:

A. AEROCARE $286

Extend the standard warranty for both components and systems for an additional 1 year. Also a variety of other options are available to fit your budget.

http://www.aerotech.com/warranty.html

B. TRAINING

Detailed system and software training available at Aerotech's facility in Pittsburgh, PA, at your site or online. Training can be customized to fit the needs of any user, from novice to expert.

http://www.aerotech.com/train.html

C. SYSTEM STARTUP ASSISTANCE

Setup and optimzation of your system the most efficient way. Have an expert onsite.

Also note that Aerotech also has an expansive user Knowledge Base (FAQs) that provides answers to the most common questions about Aerotech products. In addtion, the Customer Service website also includes a download section that give you instant access to hardware and software manuals, software, and online help files

Credit terms are established upon placement of order after credit review and approval. A minimum 25% deposit is due upon placement of the first order with new customers. A minimum 25% deposit is due upon placement for all orders which include nonstandard items. The warranty is in accordance with the terms stated in the Aerotech Warranty and Field Service Policy.

Shipping is FOB Aerotech's plant in Pittsburgh, PA, with freight charges prepaid and added to the invoice unless otherwise negotiated. All prices are in U.S. dollar.

Lead-Time: Estimated shipment is 6 weeks after approval of system drawings if applicable. For new Engineering Special (ES) systems, production does not begin until customer approval of system drawings has been received. A forecast delivery date will be provided on the order acknowledgement once the system has been scheduled.

Lead-Time Note: The estimated delivery dates listed above are based on Aerotech's existing business conditions at the time of quotation. Changing business conditions, component availability, and timing of order may impact the final delivery date. Please consult your Aerotech representative at time of order for confirmation of estimated lead times.

If you have any questions, please feel free to contact me. Best

regards,

✓

Jeremy Donatell
Area Manager
Aerotech, Inc.
Phone: 978.203.6082
Fax: 412.963.7459
Email: jdonatell@aerotech.com

CONDITIONS OF SALE

1. As used here in, the term "order" means the purchase order or other document placing an order for goods, to which the quotation or acknowledgment relates. The term "goods" means the products, materials, or services which are the subject hereof. The terms hereof are a part of the contract for the goods and shall prevail in the event of any conflict between these terms and the terms of the order.
2. All shipment are made FOB / Ex Works carrier at the point shown herein or in accompanying documents. Title and all risks of loss or damage to the goods will pass to the Purchaser upon delivery to carrier.
3. Credit terms are established upon placement of order after credit review. A minimum 25% deposit due on first order with new customers. The warranty is in accordance with the terms stated in the Aerotech Warranty and Field Service Policy. All orders are subject to the approval of Aerotech's credit department.
4. Unless otherwise agreed, we reserve the right to make deliveries of all or part of the goods in advance of the times specified. We agree to use our best efforts to meet the delivery schedule but we shall not be held liable in the event of delays in delivery or failure to deliver when due to conditions beyond our control. In such event our time for performance shall be extended for a period equivalent to the time consumed in eliminating such cause for delay.
5. Aerotech, Inc warrants its products to be free from harmful defects caused by faulty materials or poor workmanship for a minimum of one year from date of shipment from Aerotech. Aerotech's liability is limited to replacing, repairing or issuing credit, at its option, for any products, which are returned by the original purchaser during the warranty period. Aerotech makes no warranty that its products are fit for the use or purpose to which they may be put by the buyer, whether or not Aerotech's products are specifically designed and/or manufactured for buyer's use or purpose. Aerotech's liability on any claim for loss or damage arising out of the sale, resale or use of any of its products shall in no event exceed the selling price of the unit.

   THE EXPRESS WARRANTY SET FORTH HEREIN IS IN LIEU OF AND EXCLUDES ALL OTHER WARRANTIES, EXPRESSED OR IMPLIED, BY OPERATION OF LAW OR OTHERWISE. IN NO EVENT SHALL AEROTECH BE LIABLE FOR CONSEQUENTIAL OR SPECIAL DAMAGES.

   Aerotech's Warranty and Field Service Policy is incorporated herein by reference.
6. To the best of our knowledge and belief, the prices and other terms hereof conform to all applicable government regulations. We reserve the right to modify or withdraw any quotation if any term or provision thereof conflicts with or violates such regulations.
7. Except where otherwise expressly agreed, all patterns, tools, jigs and fixtures required in the performance of the order, notwithstanding any charges, therefore, shall be and remain our property and in our possession and control.
8. All materials or equipment owned or furnished by the Purchaser while in our possession will be carefully handled and stored by us, but we shall not be responsible for accidental loss thereof or damage thereto.
9. Cancellation in whole or in part of the order, or changes therein, can be made only with our consent and upon terms that will indemnify us against loss, and afford us an equitable profit.
10. The Purchaser agrees to pay, or to reimburse us for, any taxes (except Income Tax) levied by any taxing authority upon the goods, or in respect to the production, manufacture, transportation or sale thereof.
11. If the Purchaser becomes insolvent or is in default under the terms of this or any other agreement between the Purchaser and ourselves, we shall be entitled at our option to discontinue further performance of all or part of the order in addition to any and all other rights and remedies provided by law or equity and available to us in such event.
12. Unless otherwise specified all quotations are for immediate acceptance and are subject to prior sale of the goods and to withdrawal without notice. All orders are subject to acceptance by us in writing at our office at Pittsburgh, PA and no order shall be binding upon us unless so accepted.
13. We warrant that any goods comprising one of our regular line of products are delivered free from patent infringement when used for normal purposes. When otherwise used or when goods are manufactured by us to the Purchaser's designs or specifications, we assume no liability for actual or alleged patent infringement and the Purchaser in such event shall hold us harmless from any and all claims, suits, damages or expenses by reason thereof.
14. In the event that the order is a subcontract under a prime Department of Defense contract of the United States Government, the foregoing conditions are hereby modified to include such portions of the Armed Services Procurement Regulations (as amended at the time of acceptance of the order) as are applicable hereto.
15. The foregoing constitutes full statement of all terms and conditions of the order. No additions to our modifications of such terms and conditions shall be binding upon us unless approved in writing by an officer of this company. The acceptance by us of any order shall not constitute our acceptance of any terms of the order which conflict with these Conditions of Sale. The construction of any order or agreement relating hereto shall be governed by the laws of the Commonwealth of Pennsylvania.

0508

M. Alio Servo Motor Quote

Confidential Document for Worcester Polytechnic Institute Internal Use Only

6-D Nano Precision™

Budgetary Quotation

Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609-2280
Rep/Distrib: John Snow, Man in Motion
Attention: Blake Reeves
Telephone:
E-mail: breeves@wpi.edu

April 4, 2012
Quote – WPI BR 2012-04-04 r00 BUDGETARY
Delivery: ~ 10-12 Weeks ARO
Actual Delivery Confirmed at Time of Order
FOB: Colorado Factory
Terms: 50% Down ARO, 50% Net 30 Days
Quotation Valid for 30 Days

Item	Qty	Description	Unit Cost	Extended Cost
1	1	P/N: AI-LM-5000-tbd Description: Linear Stage - 50mm Travel, High Force DC Linear Motor, Precision Crossed Roller Bearings, Linear Optical Encoders with 1Vp-p Analog Output, Center Home Mark, End of Travel Limits and Anodized Aluminum Stage Structure. Motor Cable Length is ~3m, Encoder Cable Length is ~3m. Custom Stage with Side Mount Pneumatic Counter Balance.		
2	1	P/N: AI-LM-30000-tbd Description: Linear Stage - 300mm Travel, DC Linear Motor, Precision Crossed Roller Bearings, Linear Optical Encoders with 1Vp-p Analog Output, Center Home Mark, End of Travel Limits and Anodized Aluminum Stage Structure. Motor Cable Length is ~3m, Encoder Cable Length is ~3m. Custom Stage with Side Mount Pneumatic Counter Balance.		
3	1	P/N: AI-SAFETY-AIR Description: Safety - Air Pressure Monitor Switch. Integrated with the Controller.		
4	1	P/N: AI-PLT-300-CB Description: Plate - 300mm Air Counter Balance Mounting, Anodized Aluminum Stage Structure.		
5	2	P/N: AI-CAB-TC-01.5 Description: Cable - TONiC Encoder Interface to Controller, 1.5m Length		
6	1	P/N: AI-DT-GB-4-4-10/20 Description: 4-Channel PMAC Controller - 4-Axis Sin/Cos Interpolation, 4-Axis PWM Amplifiers 10A Continuous/20A Peak, Ethernet and USB Communication, Pro Suites Software.		
7	1	P/N: AI-SUPPLY-24-12-5 Description: Power Supply - 24V, +12V, -12V, 5V for the Controller		
8	1	P/N: AI-NRE Description: NRE - Custom System Design		
9	1	P/N: AI-LABOR-PROGRAM Description: Labor - Custom Controller Support and Documentation.		
			Total	**$45,390.00**

Prices are in US Dollars

The customer is responsible for 100% of all transportation costs including but not limited to: freight charge, crating, taxes, etc.
ALIO highly recommends the customer coordinates all shipping to make sure they are in control and are aware of all costs.

Quote Notes:

1. Final design and final maximum acceleration commitments to be defined upon future design review and collaboration. 4G acceleration may not be possible with presented concept.
2. Mounting structure if needed would be extra.
3. -
4. -
5. -

Thank you for this opportunity.
Dan Crews danc@alioindustries.com

TERMS AND CONDITIONS OF SALE

1. ACCEPTANCE. Quotation furnished by ALIO Industries ("AI") shall not be construed as an offer. Quotations furnished by AI are subject to, and shall not be binding upon AI until (i) actual receipt by AI of Buyers written purchase order based on the terms and conditions herein, without qualification, and (ii) AI's written acceptance of such purchase order at its main office in Wheat Ridge Colorado, U.S.A. The sole and exclusive terms of sale shall be those contained herein and in AI written acceptance of the purchase order. Any conflicting or additional terms contained in the purchase order or other documentation originating with Buyer shall be of no force or effect. AI reserves the right to make changes in design, manner of construction, use of materials or auxiliary equipment at any time without incurring any obligation toward Buyer or user of an apparatus previously sold.

2. PAYMENT: PRICE ADJUSTMENTS. Unless otherwise specified herein, (i) all prices are F.O.B. AI and (ii) terms of sale are Net 30 days. All amounts not paid by Buyer when due shall bear interest at the rate equal to the greater of (i) eighteen percent (18%) per annum or (ii) the maximum lawful rate. The price stated herein does not include any sales, use or other taxes unless so stated specifically. Such taxes will be added to invoice prices in those instances in which AI is required to collect them from Buyer; provided, however, if AI does not collect any such taxes and is later asked or required to pay such taxes by any taxing authority, Buyer shall make such payment to AI or, if requested by AI, directly to the taxing authority. If requested by AI, Buyer shall make reasonable progress payments. Changes in specifications or deliveries will be subject to change in price.

3. DELIVERY. Delivery dates specified herein are dependent upon the timely receipt from Buyer of all data and materials required for the design and / or construction of the equipment and of all materials required for testing it. AI shall not be liable for any delay or failure in delivery due, in whole or in part, to any cause or circumstance beyond its immediate control and without its fault, including, but not limited to, wars, acts of government authorities, embargoes, strikes or other labor and transportation difficulties, fires, floods, difficulties in obtaining raw materials or supplies, accidents and abnormal conditions. Buyer's acceptance of the product(s) upon its delivery shall constitute a waiver of all claims for loss or damage due to delay.

4. INSTALLATION. Unless AI agrees in writing to install the product(s), Buyer shall be responsible for installation of all product(s) and bear all expenses in connection therewith. If Buyer requests AI assistance with installation, additional charges will be added according to AI standard policy for such service that would include payment for labor, living and travel expense.

5. RISK OF LOSS. Regardless of the manner of shipment, title to the product(s) and the risk of loss or damage thereto shall pass to Buyer upon tender to the carrier at AI's plant.

6. ITEMS FURNISHED BY BUYER. All data, materials and equipment to be furnished by Buyer or procured by AI for Buyer for the construction, remodeling, or testing of products(s), or for any other purpose, shall be delivered at no cost to AI F.O.B. its plant and Buyer shall pay all costs of returning the same. Buyer shall pay all crating and delivery expenses for samples and parts delivered to it, and except as required for test purposes, the cost of producing parts or samples requested by Buyer.

7. LIMITED WARRANTY. AI warrants that, except as hereafter provided, the product(s) identified on the quotation (i) shall be free of any defects in workmanship, materials and construction for the period of one hundred eighty days from the date of shipment and (ii) shall comply with all written specifications furnished by Buyer and acknowledged by AI in writing. THIS LIMITED WARRANTY DOES NOT COVER, AND AI MAKES NO WARRANTY REGARDING, THE FOLLOWING: (i) PARTS THAT ARE NOT MANUFACTURED BY AI; (ii) DEFECTS OR FAILURES CAUSED BY ACCIDENT OR IMPROPER HANDLING OR INSTALLATION; (iii) DEFECTS OR FAILURES CAUSED BY THE FAILURE TO USE OR MAINTAIN THE PRODUCT(S) ACCORDING TO AI's RECOMMENDATIONS; (iv) PRODUCT(S)

MANUFACTURED PURSUANT TO PLANS, SPECIFICATIONS, DRAWINGS, OR DESIGNS SUBMITTED OR APPROVED BY BUYER; (v) DEFECTS OR FAILURES CAUSED BY UNSUITABLE ENVIRONMENTAL CONDITIONS OR ALTERATION, MODIFICATION, OR REPAIR OF THE PRODUCT(S) BY PERSONS OTHER THAN ALIO Industries; (vi) MATTERS RELATED TO SPEED OF PRODUCTION OR OUTPUT; AND (vii) SAFETY DEVICES OR FEATURES SHOWN IN APPLICABLE SPECIFICATIONS. THIS WARRANTY EXTENDS TO BUYER ONLY AND DOES NOT EXTEND TO ANY TRANSFEREE, ASSIGNEE OR SUCCESSOR OF BUYER.

8. REPAIR OR DEFECTS. In case of AI's material breach of the limited warranty set forth herein, AI shall have the time required of it to remedy the defect or failure. If AI is unable to remedy the defect or failure within such time, AI shall, at its election and in its discretion, either replace the product(s) or refund the purchase price.

9. EXCLUSIVE REMEDIES: NO CONSEQUENTIAL DAMAGES. THE REMEDIES SET FORTH IN PARAGRAPH 8 HEREOF SHALL BE BUYER'S SOLE AND EXCLUSIVE REMEDIES FOR AI's BREACH OF THE LIMITED WARRANTY SET FORTH HEREIN. UNDER NO CIRCUMSTANCES SHALL AI BE LIABLE TO BUYER OR ANY OTHER PARTY FOR ANY CONSEQUENTIAL, INCIDENTAL, ECONOMIC, DIRECT, INDIRECT, GENERAL OR SPECIAL DAMAGES, WHETHER ARISING OUT OF CONTRACT OR TORT, WHETHER ARISING OUT OF NEGLIGENCE OR STRICT LIABILITY, ARISING OUT OF, BASED UPON ON RELATING TO THE SALE, USE OR OPERATION OF THE PRODUCT(S).

10. CLAIMS. Buyer shall make no claim against AI for shortages unless Buyer provides written notice of such claim to AI within ten (10) days after delivery. Buyer shall make no other claims against AI unless Buyer provides written notice of such claims to AI within thirty (30) days after delivery or, in case of AI's alleged breach of the limited warranty set forth herein, within thirty (30) days after the date within the warranty period on which the defect or failure is or should have been discovered.

11. PATENTS. Where any product is manufactured from designs, drawings, plans, data or specifications not furnished by AI, Buyer agrees to indemnify, defend (with counsel acceptable to AI) and save harmless AI and its successors and assigns from against all suits at law or in equity and from all losses, damages, claims and demands arising out of actual or alleged infringement of any United States or foreign patent, trademark or copyright by reason of the use or sale of the product(s).

12. CONFIDENTIALITY AND PROPRIETARY INFORMATION. All plans, drawings, specifications, notes, instructions, engineering notices, data and technical information furnished by AI to Buyer shall at all times be property of AI, and Buyer shall not disclose such information to any party other than AI or a party duly authorized by AI. When its no longer reasonably necessary for Buyer to retain such information furnished in a tangible form, Buyer shall, at AI's request, return such information and all reproductions thereof.

13. FINANCIAL INSECURITY. If AI shall at any time in good faith doubt Buyer's financial responsibility, AI may decline to make shipment(s) hereunder except upon receipt of cash payment in advance
or security or other proof of responsibility satisfactory to AI. If Buyer fails in any way to fulfill its covenants and obligations hereunder, AI may defer completion and delivery until such breach is cured.

14. CANCELLATION. After acceptance by AI, Buyer may not cancel all or any part of the order except in the event (i) AI materially breaches any of the terms hereof or (ii) AI consents in writing to such cancellation and Buyer indemnifies AI against all direct, incidental, and consequential damages.

15. ASSIGNMENT. The rights and obligations under this agreement shall not be assigned or delegated by Buyer without prior written consent of AI.

16. REMEDIES. The warranties and remedies available to AI under the terms of this agreement shall be cumulative in addition to those implied or available at law. No waiver of any breach of this agreement shall be construed to constitute a waiver of any other breach or of any provisions hereof.

17. CONSENT TO JURISDICTION: APPOINTMENT OF PROCESS AGENT. Buyer hereby irrevocably submits to the jurisdiction of any Colorado or federal court sitting in Jefferson County, Colorado U.S.A., over any action or proceeding arising out of or relating to the product(s) and agree that all claims in respect of such action or proceeding may be heard and determined in any such court. Buyer further agrees that venue for any such action shall lie exclusively with courts sitting in Jefferson County, Colorado U.S.A., unless AI agrees to the contrary in writing. Buyer irrevocably waives, to the fullest extent it may effectively do so, the defense of an inconvenient forum to the maintenance of such action or proceeding. Buyer agrees that a final judgment in any such action or proceeding shall be conclusive and may be enforced in other jurisdictions by suit on the judgment or in any other manner provided by law.

18. EXPENSES AND ATTORNEYS FEES. Buyer agrees to pay any and all costs and expenses (including, without limitation, reasonable attorney's fees and litigation expenses) incurred by AI and arising
out of or relating to any breach of any covenant or agreement or the incorrectness or inaccuracy of any representation and warranty of Buyer contained in this agreement.

19. COMPLIANCE WITH LAWS. AI agrees that in the manufacture and sale of the product(s) to Buyer, AI shall comply with all applicable federal, state and local laws, ordinances and regulations, including, without limitation, the Fair Labor Standards Act, as amended, and the Federal Occupational Safety and Health Act of 1970, as amended. This Agreement incorporated by reference all the clauses required by the provisions of said laws, orders, and regulations.

20. ENTIRE AGREEMENT. There are no other representations, understandings or agreements previously made between the parties, except those that are expressly set forth herein. This agreement constitutes the entire agreement between the parties with respect to the subject matter hereof and cannot be changed, modified, discharged or terminated, except by a writing signed by both parties.

21. WAIVER. No waiver shall be deemed to have been made by any party of any of its rights hereunder unless the same shall be in writing and signed by the waivering party. Such waiver, if any, shall be a waiver only in respect to the specific instance involved and shall in no way impair the rights of the waiving party or the obligations of the other party in any other respect and at any other time.

22. GOVERNING LAW. This Agreement shall be governed by and construed and enforced in accordance with the laws of the state of Colorado, U.S.A. without giving effect to the principles of conflicts of law.

23. SEVERABILITY. In the event that any one or more terms or provisions hereof shall be held void or unenforceable by any court or arbitrator, all remaining terms and provisions hereof shall remain in force and effect.