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# **REXROTH BOSCH TWO AXIS SERVO TRAINER**

by

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Author's Declaration

We hereby declare that we are the sole authors of this report

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Peter Tarrant Project Manager	Dean Whaley Design Lead	Kevin Ilchuk Manufacturing Lead

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## Abstract

This document is a final report on the fourth-year mechanical engineering Capstone project: Two-Axis Servo Trainer/Bolt Tightener. This report covers the project background, current status, theory, activities, results, and conclusions. The project was sponsored by Rexroth Bosch who provided the opportunity to two BCIT fourth-year mechanical Capstone groups. The project was to create a physical servo motor trainer for learning employees and clients. The mechanism must be based on a commonly automated industry task, require position, velocity, and torque control, and 2-axis synchronization.

Our project was based on a bolt tightener. This type of automated machine is often seen in lumber mills for changing saw blades. The application also requires position control: where the socket head is, velocity control: how quickly its moving toward a bolt or tightening it, torque control: how tight the bolt is torqued, and two-axis synchronization: the socket must move forward at the same speed the bolt travels into the bore.

Most of the theory outlined in this report encompasses machine design and mechanics of materials. Calculations and the reasoning for each is explained with full solutions referred to in the appendices. The theory required in this project was mostly necessary for selecting components such as: gear boxes, motor mounting plates, and linear bearings. As well as mechanical theory, some electrical theory was applied in order to design and implement electrical circuits which control electric drives and motors.

The core of the report focuses on how we achieved the completion of a two-axis servo trainer – bolt tightening application. These sections explain the different phases of the project: Phase One – Controls Frame, and Phase Two – Bolt Tightening Mechanism, and the designing, manufacturing, and programming that was necessary to complete these phases both individually and collaboratively.

Currently, the project has been taken by Bosch Rexroth to their Port Coquitlam office where they will hire two co-op students to create a training program with our project.

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The project was completed on time and met the sponsor's objectives and deliverables. Every part was completed so that the system can be used in a training program, however we wished to program the bolt tightening in all three methods available from the drives and were unable to do so. The team successfully tightened and untightened bolts with the machine using easy commissioning software and digital I/O, but the function was not fully autonomous. Despite this, the sponsor was satisfied with the outcome of the project since it is intended to be a training device for programmers to learn how to use the three methods of control.

The team gained valuable industry experience over the course of this project and are gratified to have had the opportunity to work on an industry sponsored project. Bosch Rexroth's Greg Filek was a devoted, helpful, and enthusiastic sponsor who went out of his way to make sure we were equipped to handle any aspect of the project. Bosch Rexroth gained a functioning two-axis servo trainer and students who are familiar with their products, while the team gained invaluable real-world experience with a leading drives and controls company.

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## Acknowledgements

We'd like to take this opportunity to thank Greg Filek, Technical Sales Consultant at Rexroth Bosch, and our project sponsor. Throughout the entirety of the project Greg offered expert support and learning opportunities from industry. Without the help of Greg Filek and the resources provided by Rexroth Bosch this project could have never happened. In addition to Greg, Burk Schmidt (Application Engineer) provided feedback and suggestions on the original designs for phase two of the project.



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## 1. Introduction

The Two Axis Servo Trainer project was brought to our team by Greg Filek on behalf of Rexroth Bosch. The trainer is to be supplied to new employees of Rexroth Bosch, to new customers, or to new employees of current customers, to allow them to learn how to operate and use Rexroth Bosch's electric drives and software. Rexroth Bosch is one of the world's leading specialists in the field of drive and control technologies, and they provide numerous different types of drives to accomplish whatever your goal may be. This can make things confusing for someone trying to use their products as there have been numerous new innovations and advances in their technology over the years.

The desired outcome of our trainer will be comprised of designing and prototyping two pieces, the drive control frame, and a mechanical device to be operated with the drives, which are labelled phase one and phase two respectively. Phase one will be designed to be compact, easy to carry, and maintain the capability of holding up to four of any type of drive Rexroth Bosch offers. Phase two must be simple for anyone to understand how it works or what it is trying to accomplish, must only work with two axis', and must also be compact so that it can fit on an employee's desk. Our team chose to create a bolt tightening device for our phase two as it anybody can understand the premise of tightening a bolt. The device will be able to turn bolts up to a selected angular position or a specified torque. Additionally, it will be able to recognize if a bolt is defected by the terms of a stripped thread, stripped head, or some other sort of damage that affects the bolt torquing. This allows the user to input different variables into the program or the environment and observe how each interacts with one another.

The second purpose of this project is to evaluate and provide feedback on Rexroth Bosch's data sheets, reference material, and learning documents so that they can improve where necessary and clarify where needed. This will include the team learning to wire up the drives, use the drives with the provided commissioning software, and program the drives in graphical, text based, and ladder logic coding.

Hence, the objectives of this project are as follows:

- Design and assemble a fully functioning two axis desk trainer
- Correctly and safely wire and use Rexroth Bosch drives
- Learn to program the drives in graphical, text based, and ladder logic
- Create a trouble shooting report outlining the implications of Rexroth Bosch's data sheets and learning material

Further objectives of the project include proper implementation of the design process; as well as maximizing learning of Rexroth Bosch drives and software.

Deliverable materials for this project include:

- A functioning two axis servo trainer
- Progress reports to be completed weekly
- A comprehensive final report due at the conclusion of the project
- A proposal and final presentation for instructor presentation and review
- A comprehensive trouble shooting report for Greg Filek on behalf of Rexroth Bosch

### 1.1 Background

Rexroth Bosch, a drive and controls company based in Germany, is an original equipment manufacturer (OEM) of various engineering hardware such as: electric motors, and hydraulic components. In Canada their most profitable and established operations are in Ontario and Quebec. With the goal of expanding their presence in to British Columbia, they opened an office in Port Coquitlam, BC. So far, they have been successful in developing business relationships in the mining and forestry sectors. However, they have not had the same success in entering the automation and controls sector in the Lower Mainland of BC where food production and research and development are prominent.

Aiming to become more well-known in Vancouver's high-tech sector, Rexroth Bosch saw a mutually beneficial opportunity in providing BCIT students the chance work on a sponsored engineering design project. This project would allow BCIT students to

utilize and learn some of Rexroth Bosch's high-end equipment, while also familiarizing young engineers with their products.

The proposed project was to create a device that Rexroth Bosch and client trainees could operate, while learning how to program electric drives. This device would allow a beginner to physically see the results of their programming, and how the electric motors would respond. The mechanism should be based on a common automation task seen in industry. Rexroth Bosch selected the bolt tightening application as a suitable servo motor training device, as it is commonly seen in the forestry industry when saw blades need to be changed. Therefore, the project would be based on creating an automated bolt tightener for changing saw blades.

As outlined in the request for proposal (seen in Appendix APPENDIX C. Request for Proposal) Rexroth Bosch requested a bolt tightening servo trainer that must fit on an employee's desk, require position, velocity, and torque control, and two-axis synchronization. The system must be portable, and small enough to fit into a duffle bag for transportation. As well as this, the sponsor company is seeking feedback on the learning process of their hardware and software. As previously mentioned, a report will be submitted to Bosch Rexroth outlining the difficulties the team encountered during the project.



## 2. Detailed Description of the Current Status

Rexroth Bosch came forward to our team with two problems; Create a two-axis desk trainer that can be supplied to new employees and provide feedback on Rexroth Bosch documentation and data sheets. Feedback notes and areas where revision is required were documented as the project of creating the two-axis trainer was on-going.

### 2.1 The Two-Axis Trainer

The team's main problem was to create a two-axis trainer that was simple to understand and facilitated ease of use so that new employees could learn and familiarize themselves with Rexroth Bosch drives and software. The team chose a bolt tightening application which was supplied by Rexroth Bosch and was to simulate the automated changing of saw blades on large debarking machines used in the forest industry. Specifically, the team would focus on the tightening and loosening of bolts automatically, in small scale. To simulate the real world application, the prototype is required to be operable in conditions where lots of dust or airborne particulate and heavy vibration exists, able to withstand extreme temperatures ranging from  $-20^{\circ}\text{C}$  to  $75^{\circ}\text{C}$ , and must be able to change a bolt within 30 seconds with a torque tolerance of  $\pm 1$  lb-ft. Additionally, the program must be able to distinguish if a bolt has been damaged in any way or that it is not threading in properly.

### 2.2 Documentation

The secondary problem the team faced with this project is providing feedback and pointing out areas of Rexroth Bosch's documentation where revision and improvement is required. They want to clean up their documentation and data sheets and be confident that information is relayed to their customers clearly. The goal is for the customer to be able to understand, wire, and program the supplied drives with ease. Our team will be creating a trouble shooting report that will outline and address the issues our team faces in the creation of the two-axis trainer.

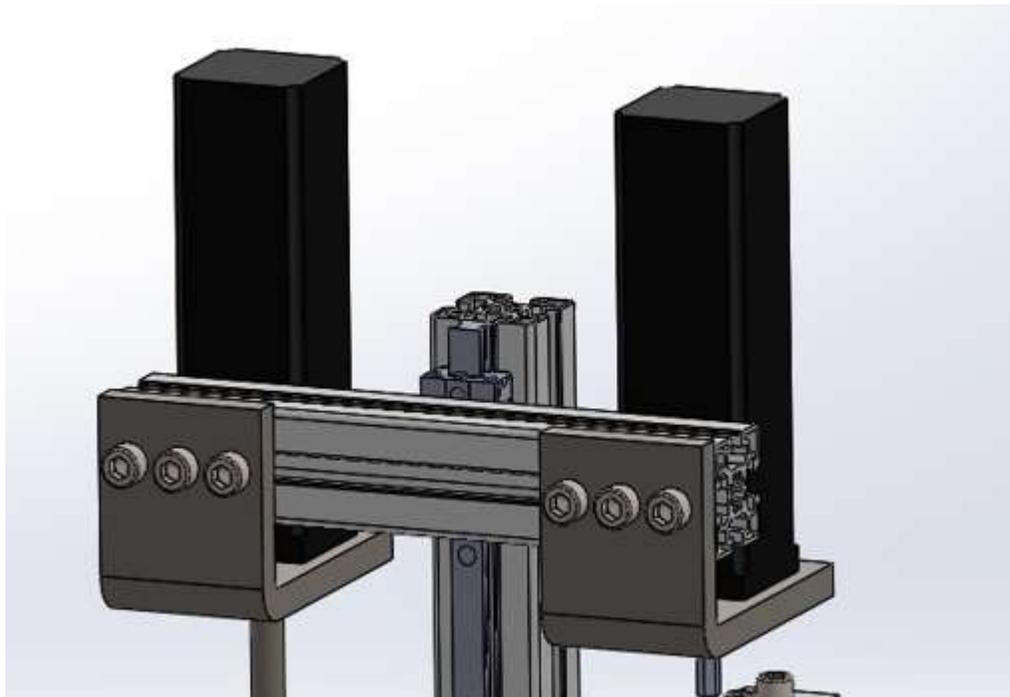


### 3. Theoretical Background

All solutions to technical problems that are being considered in a typical project, must have a sound theoretical base. Chapter 3 normally looks into the dominant theoretical fundamentals that are providing a basis for the project and explains them, while making appropriate connections with the methods used in the project analysis and solution. The content of this chapter normally relies heavily on reference literature.

#### 3.1 Loading on the System

In order to understand the dynamics of our system and select suitable components, calculating the loading of specific parts was required. Forces and moments in and about all three dimensional axes were considered. The location of interest in our system was where the main carriage assembly connects to the large linear slider, seen below in Figure 3.1.



*Figure 3.1 - Phase 2 Loading*

The full calculations can be seen in APPENDIX A. Calculations. The final calculated results are shown below in Table 3.1.

Table 3.1 - Axis Loading

Axis	Force (N)	Moment (N-m)
X	0	0.67
Y	0	7.6
Z	0	7.6
Source: Calculations in APPENDIX A		

These values were then compared to the values provided in the data sheets of the linear profile rail sliders that were available to us from Rexroth Bosch. This ensured the selected slider would not fail, and also provide a reasonable service life. Our system is intended to be used as a training device and not a high frequency operation bolt tightener. Therefore, the calculated dynamic load ratio must be greater than four, as stated by the data sheet, but does not need to be much greater than four since it will be in a low wear application. The datasheet for the selected slider can be seen in APPENDIX B. Datasheets.

### 3.2 Sizing Motors Mounts

The calculations in APPENDIX A. Calculations also show the loading on the motor mounts seen in Figure 3.1. Using the applied load, the stress in the mounts can be calculated. This stress was calculated in terms of thickness  $t$  of the cold rolled steel angle bar. Comparing this to the yield stress of steel, we were able to determine the adequate thickness of the angle bar, with a safety factor considered.

### 3.3 Motor Torque and Gear Boxes

This system requires two axes of motion: linear to move the socket head, and rotational to turn the socket head on a bolt. Since we were given two servo motors (MSK 030C-0900-NN-M1-UG0-NNNN) by the sponsor company, we needed to see if the provided motors would have the torques required for our application. If a motor did not supply the required torque, a gear box must be used, and the ratio calculated in order to the select the gear box. How the required torques, and the required gear box ratios were

calculated can be seen in APPENDIX A. Calculations. A summary of the findings can be seen below in Table 3.2.

*Table 3.2 - Gear Ratio*

<b>Application</b>	<b>Continuous Motor Torque (N-m)</b>	<b>Required Torque (N-m)</b>	<b>Gear Box Required?</b>	<b>Ratio</b>
Lead Screw	0.8	14	Yes	>18
Bolt Tightening	0.8	~50	Yes	~75
Source: Calculations in APPENDIX A				

From these calculations we were able to select the appropriate gear boxes. Our sponsor directed us to Apex Dynamics, Inc. to order the required gear boxes. The selected gear boxes were: AE090-060 (ratio: 60) and AE070-025 (ratio: 25). These are economy class gear boxes from the supplier. Our team placed an emphasis on saving costs for our sponsor company since lower costs would be desired in industry.



## 4. Description of the Project Activity and Equipment

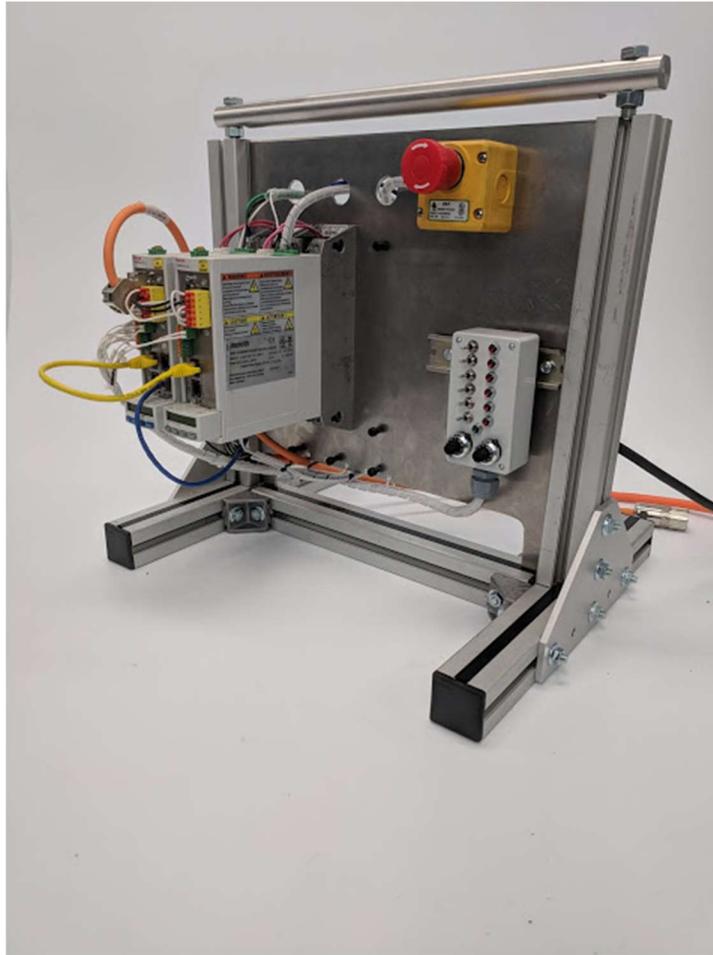
In order to complete this project, the team was required to design, prototype and assemble, and program the two-axis desk trainer. There were two phases to be designed and prototyped, and together they were programmed to operate.

### 4.1 Design

Design is broken up into two phases. The first phase contains both IndraDrives and serves as the brains of the project. Phase two is the mechanical application (bolt tightener) and is meant to demonstrate the program that is developed on phase one.

#### 4.1.1 Phase one

For phase one, the team was required to design the frame that would hold the electric drives and the electrical circuit. There were three different arrangements that the team was able to come up with, but it was ultimately narrowed down to the one presented in Figure 4.1. This option is sturdy, lightweight, compact, and holds the capability to holster four of any type of drive supplied by Rexroth Bosch. The rear side of the frame holsters any electrical splitting blocks, an AC to DC converter, and a Breaker. On the front of the frame the drives, an I/O box, and the emergency shut off can be found.



*Figure 4.1 - Phase 1 Design*

#### 4.1.2 Phase two – Design 1

The initial steps for phase two consisted of concept creation for the bolt tightening device. The team decided to utilize a ball screw and linear rail that was supplied by Rexroth Bosch to construct our design. Various vertical and horizontal concepts can be shown in Figure 4.2 - Phase 2 Concept Designs. In the end, the team decided to go with a vertical concept as it was simple, compact, organized, and utilized many of the provided parts and material and required less manufacturing and part ordering. The important things to note about this design were the torque required to lift the entire assembly which included the weight of two motors, the torque that we wanted to attain when tightening a bolt, and how we would accurately align the different bolts to be tightened.

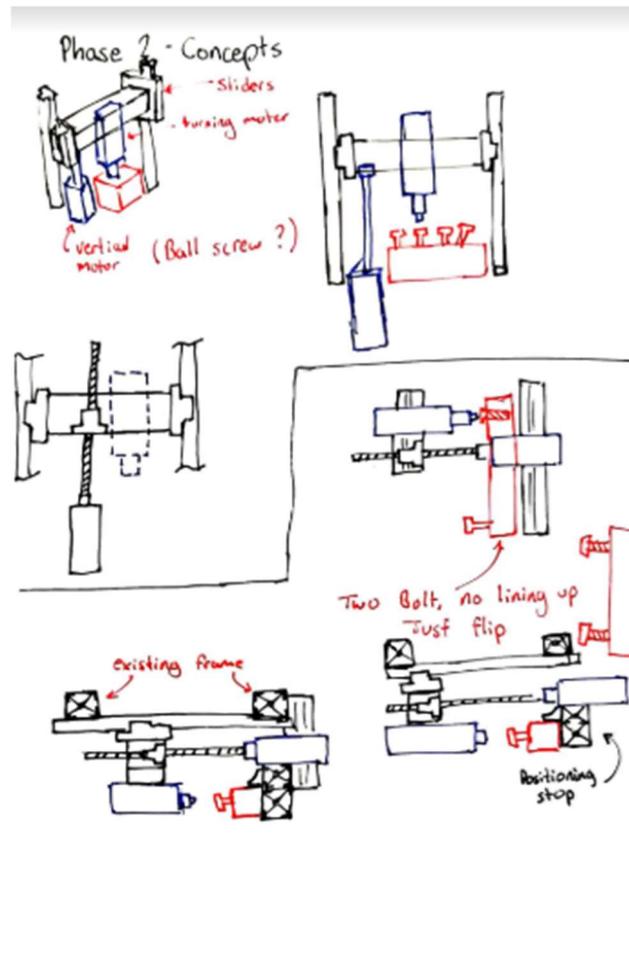
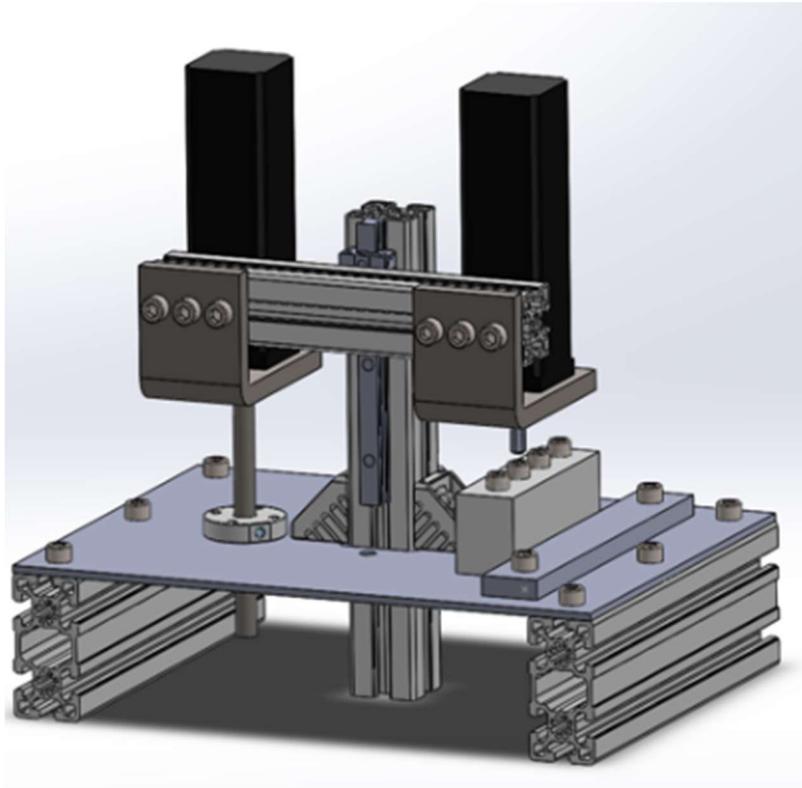


Figure 4.2 - Phase 2 Concept Designs

The team conducted various force, moment, and torque calculations to size gearboxes, the angle brackets, and the bearing force on the linear rail (APPENDIX A. Calculations). The motors supplied by Rexroth Bosch can supply a running torque of 0.8Nm, and a max torque of 4Nm. The team felt it was appropriate that a 12mm bolt be tightened to 50ft-lbs. this required a gearbox with a 60:1 ratio. Additionally, to lift the assembly holstering the two motors, it was found a gearbox of ratio 25:1 was required.

The final piece to be designed was the block containing three to four different bolts. The team ultimately chose to present 3 different bolts: A perfectly fine bolt and thread, a slightly stripped bolt head, and a bolt with tensioning screw. The block measures 4"x 2" x 1.625". To align the bolts, two holes were accurately drilled on the bottom and pins

were pressed in. The plate would then have holes to match these pins in which the block could be moved to align the different bolts. The proposed design can be seen in Figure 4.3 - Phase 2 Vertical Design.



*Figure 4.3 - Phase 2 Vertical Design*

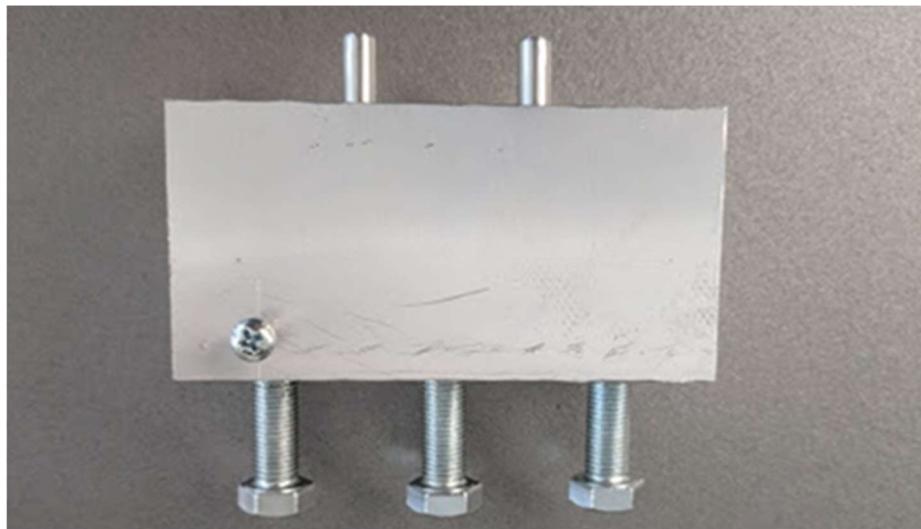
#### 4.1.3 Phase two – Design 2

The bolt tightening design the team previously came up with was well into production and all required parts had been ordered. When the gearboxes arrived, it turned out the one that we chose to lift the assembly was a lot larger and heavier than previously thought. This caused our team to construct a complete re-design of our bolt tightening device. After a few preliminary designs, we chose to perform the bolt tightening in a horizontal motion. This cancels out having to lift the weight of the gearbox, while also minimizing the size of the entire device. The design presented in \_\_\_\_\_, works in the same manner and utilizes the same parts from the previous design, with the

addition of another linear rail. To accomplish this design, a few more parts were required to be manufactured. This included the Rail Connecting Bracket, various mounting brackets, and a coupling to connect the motor shaft to the socket wrench shaft.

## 4.2 Manufacturing

To create both of our designs, minimal manufacturing was required as most of our parts were standard pieces or provided by our project sponsor. The parts to be manufactured were the Bolt Block, Rail Connecting Bracket, the Small Gearbox Mount, Motor Mount, and the Ball Screw Mount Block, and the Socket Coupling. The Bolt Block was required to be very accurate and precise so that the bolts would align correctly with the socket. The block (Figure 4.4 - Bolt Block) was manufactured completely on the vertical mill, attaining a tolerance of  $\pm 0.002$ ". The block holsters 3 different bolts as shown. One of these bolts is perfectly normal, one is slightly stripped on the threads, and the third has an adjustable friction screw. This allows the user to test the different bolts and observe the difference in the torque curves. This can then further be used to set alerts to detect defected bolts based on the differentiated torque curves.



*Figure 4.4 - Bolt Block*

The brackets that attach the gearbox and motor to the assembly were formed from 1/16" steel sheet metal. Holes were punched to allow attachment to both the frame or linear rail, and the gearbox or the motor. A challenge the team faced was accurately aligning holes and correctly measuring out the mounting frames to fit with the motor, gearbox, and linear rails. This is because we were not provided with CAD models of the given components, therefore the team was required to measure hole placement and sizing using methods of metrology.



*Figure 4.5 - Gearbox Mounting Bracket*

In order to attach the linear rails to the T-slot aluminum, the team created a plate which matched the width and length of the T-slot piece, and then drilled and tapped holes which lined up with the holes in the linear slider. Two additional clearance holes were added outside of the area of the linear slider to allow for attachment to the T-slot with T-nuts (Figure 4.6 - Linear Slider T-slot Mounting).



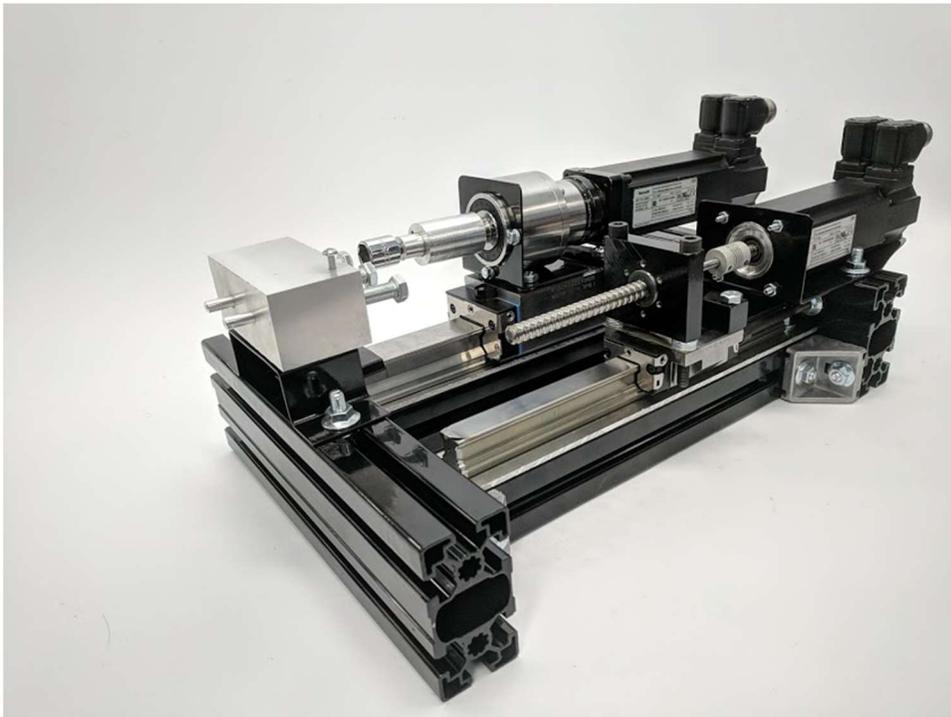
*Figure 4.6 - Linear Slider T-slot Mounting*

The Rail Connecting Bracket was designed to force the two sliders to move along together. It was required to be rigid to prevent any bending in the bracket. The linear sliders have 8mm threaded holes which allows for ease of attachment.

The final piece that was required to be created was the coupling which would securely connect the second motors gearbox to the shaft of the socket drive. This motor and gearbox combo would serve as our bolt tightening motor. The shaft of the gearbox had a key, so a hollow cylindrical piece of aluminum was created that had a hold the same diameter as the shaft of the gearbox. The team then broached a keyway into this piece to match the key on the gearbox. We then manufactured hollow solid cylindrical piece that would press fit into the keyed part. The inside diameter of the second piece

matched that of the shaft of the socket drive, so that it could be press fitted in. Because this is a high torque application, it required the press fit to have an interference of three to four thou.

Once all the pieces that needed to be manufactured were complete, the team powder coated the frame, and most of the bracket mounts black. The parts were then assembled and testing of the programming could begin.



*Figure 4.7 - Bolt Tightening Final Assembly*

### 4.3 Programming

The goal of this project was to provide a trainer for engineers to learn the IndraWorks platform on, as well as document the areas in which the old programming documentation needed to be revised. Because of this, the outcome of the programming section was not to deliver a fully autonomous bolt tightening device, but a list of areas in which the old documentation did not provide adequate guidance.

#### 4.3.1 Drive Layout

The IndraWorks platform is broken down into two main programs; IndraWorks DS and IndraWorks Engineering.

IndraWorks DS is a free version of IndraWorks Engineering and is typically used at the start of a project to verify single axis motion. The DS program is used on a per-drive basis to verify wiring, motor control, and drive integrity via the easy commissioning mode. The easy commissioning mode disables a few errors and safety features to allow each drive to be controlled individually. Any actual programming, or multi-axis motion needs to be done in IndraWorks Engineering.

The team had the opportunity to use the full version of the IndraWorks Engineering software, which is same software given to industrial clients of Rexroth Bosch. This was a great opportunity for the team to be able to learn an additional industrial software to those we regularly learn through BCIT.

The main two modes each drive can be in are parameter mode (PM) and operation mode (OM). These two modes denote the privileges the user has. In parameter mode the user can edit a long list of parameters the main consisting of a 16-bit word, and a parameter code or address. Depending on the use of that word, the individual bits can either be set directly, or through digital IO or other parameters. The two biggest assets for this section of the project were the in program help which listed what the individual bits corresponded to, and the third-year microcontrollers course (ELEX 7345) taught by David Romalo at BCIT. This course gave the necessary background information on bit manipulation and control words. When switching to operation mode, the controllers checked for conflicts in key control words and would only switch to operation mode if it was error free. However, the easy commissioning mode discussed earlier would suppress a few of the less critical checks in order to allow the user to test axis in what is assumed to be a controlled environment. In operation mode any bit that is not directly related to the control of the motor was locked and the drive would need to be returned to parametrization mode to be edited. Parameters such as E-Stop inputs, limit switches, and the control words remained open to allow for control of the motor.

For example; digital switches were mapped to specific bits of the control word to control the direction of motion.

#### 4.3.2 Networking

The area in which the team had the most trouble with regards to programming was networking. While the team had prior experience with programming, networking, and networking protocols were new. In addition, the documentation provided was aimed at personal with an application engineer background, and therefore did not go in-depth about standard networking protocols.

The cross communication of drives (CCD) utilized the SERCOS III communication protocol. Unlike SERCOS II, SERCOS III was designed to be used for slower speed applications and be communicated over Fiber or Ethernet. With a very limited networking background the team encountered various hurdles. The first of these was in the introduction of phases of communication. Phases -1 to 1 are used in the initializing to identify any communication problems. Phase 2 on the IndraDrive is the slave version of the parametrization mode. Phase 4 is the equivalent of the operation mode. In this mode motion is allowed, but most of the parameters are locked.

#### 4.3.3 Structured Text and CoDeSys

Actual programming of the IndraDrive in the IndraWorks Engineering is biased on the CoDeSys platform. CoDeSys (Controller Development System) is an industry standard when it comes to industrial controller. CoDeSys can be programmed using assembly language, structured text, ladder diagrams and function blocks. The team focused on structured text and was able to obtain an understanding on the basics.

While the syntax and interface of CoDeSys were foreign at first, they had many similarities to the C programming we encountered at BCIT. Figure 4.8 highlights many of the areas in which programming the IndraDrive was similar to the programming we did at BCIT. In red we see “DataType (STRUCT)”, this is the same process as typedef

struct {} in C programming, where custom structures of variables can be defined. In blue we see the global variable list, a familiar topic from engineering programming. Lastly, in yellow is the actual structured text program file which every line must be followed by a semi-colon this is the CoDeSys version of a .cpp file from C programming.

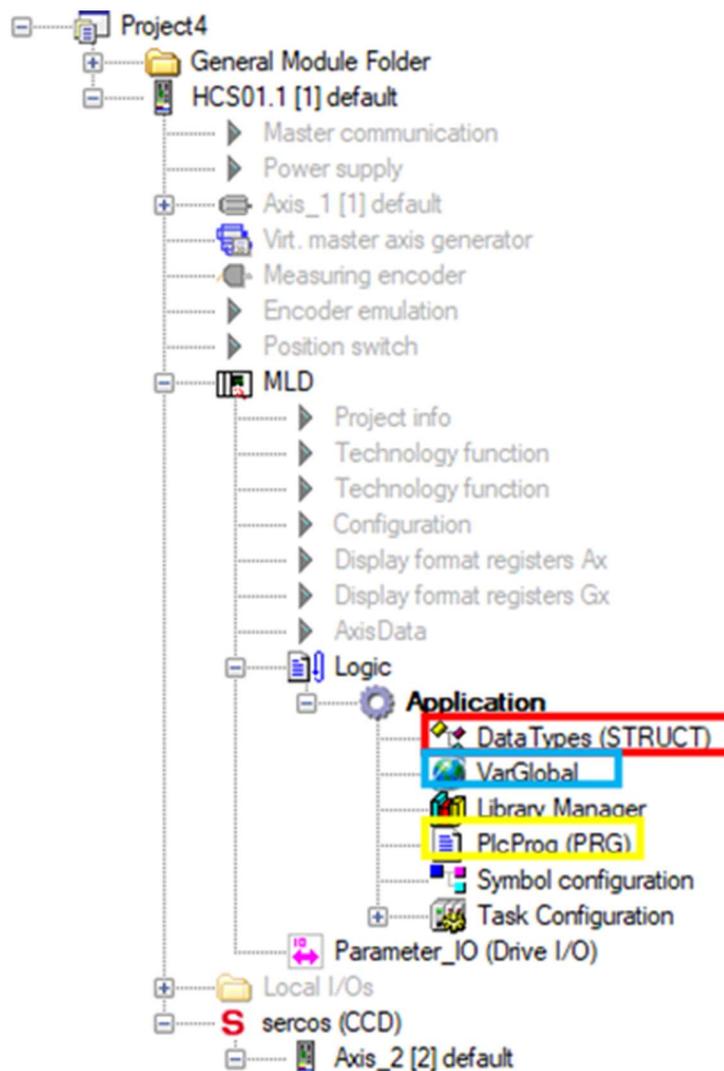


Figure 4.8 - IndraWorks Engineering



## 5. Discussion of Results

At the end of the project period, the team managed to fully prototype and assemble the two-axis bolt tightening trainer. In the sections below will be discussed the results of our two problems and the difficulties that were encountered over the course of the project.

### 5.1 The Two Axis Trainer

The first problem the team was required to solve was the creation of the two-axis trainer. The team was successful in creating the first prototype on time that met most of the requirements. The bolt tightening trainer has the capability of changing a bolt in less than 30 seconds, as well it is operable in conditions with lots of airborne materials or the outlined extreme temperature conditions. However, it is unknown if the torque tolerance is within 1 lb-ft. The team suspects that this condition is met as the motors have a high torque tolerance and the attached gearbox is accurate to within 0.1 arc minutes. To determine if this condition is met, a force sensor could be added to one side on the bolt block. An algorithm can then be created that will provide the user with the actual torque, which can then be compared with the given torque. The motors do have a torque sensor within them that relays information back to the drive, but with the size of the gearbox this information could be inaccurate.

Overall the two-axis prototype was successful, but the team encountered some difficulties along the way. The main difficulty was the lead time for the gear boxes the team ordered. The rest of the design was unable to be created without the gearboxes to work with. When the gearboxes did arrive, it turned out that they were a lot larger and heavier than expected, and the design would have to be revised. The team first looked at revising the vertical design by moving the motor and gearbox below the plate which cancelled out lifting the weight of the large gearbox, but this caused for the assembly being very tall which was undesirable. After several proposed revisions, the vertical design was thrown away completely and a new horizontal version was created. This caused for the team to restart the design and prototyping of the two-axis trainer.

The second problem the team ran into was the creation of the socket head attachment which would tighten and loosen bolts. It was desired that the socket head be spring loaded so that small misalignment could be negligible, and so that if the user were to make an error, there was something that had some give and the trainer would not be damaged. Additionally, the spring-loaded head would allow time for the socket to align with the bolt head. Unfortunately, with being short on time, the team was unable to come up with a design that was simple yet effective, and ended up resulting with a rigid coupling that attached the gearbox to the socket head. The rigid design allows solid transfer of torque and prevents slipping, however, if the user were to make an error then trainer could get damaged.

The last problem the team encountered in the design and manufacturing of the two-axis trainer was the lack of CAD files for the supplied components. Many of our components such as the motors, linear bearings, and the ball screw were supplied by Rexroth Bosch. However, we were unable to obtain exact CAD files of some of the supplied components which made it difficult to design for alignment of shafts and of holes on brackets for mounting. This caused the team to use a sufficient amount of time measuring the components and ensuring that pieces would fit. Additionally, some brackets were required to be shimmed or washers were added in order to align shafts. If the proper CAD files could be accessed, the parts could have been manufactured to properly align shafts and mounts.

## 5.2 Documentation

Throughout the course of the project, the team documented difficulties they encountered while creating the two-axis trainer. The majority of the issues came from the documentation related to programming the drives, but one issue that we ran into early on was the data sheet used to create a wiring diagram for the drive. The supplied data sheet for the drive was for an older version of the same drive and didn't contain information on the latest version. This caused the team to be confused with some ports on the drive, and inevitably unable to safely wire the drive confidently. The team was

able to look up online some information on the newer ports added to the drive, but the explanation of their workings was very vague and caused for more confusion. The team required a sufficient amount of help from our sponsor Greg Filek in order to complete the wiring diagram and safely wire the drives.



## 6. Conclusion

In conclusion, the two-axis servo trainer – bolt tightener was a success. The phase one system we produced uses two electric drives, which are safely wired and mounted on a control frame. The control frame also houses a digital I/O box with switches and lights for programmers to incorporate. The phase two system can be programmed to physically tighten a bolt right beside the learning programmer, so they can visually confirm their code. The bolt tightening system requires position, velocity, and torque control from the programmer, and also requires two-axis synchronization. A “trouble shooting” report has been created by the team for submission to Bosch Rexroth to help them understand our difficulties using their products so they can improve their documentation. In comparison to the request for proposal seen in APPENDIX X: RFP the delivered product is a working prototype that can tighten a bolt in less than 30 seconds, has the ability to detect stripped threads, misalignment, and other defects, and can tighten bolts within a torque tolerance. The project was completed within the specified timeline of Bosch Rexroth, and within the project scope.

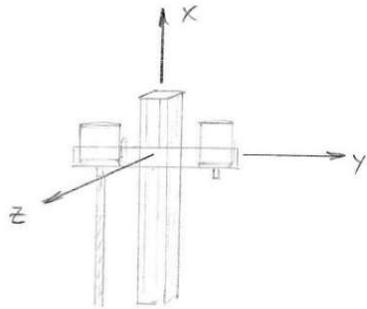
The team’s personal goal of mastering all three programming methods available in the electric drives fell short. Bolts were tightened using easy commissioning software and the control frame’s digital I/O. The sponsor was not dissatisfied by us not achieving this goal, since it doesn’t affect the end of them having a system that can be used to learn on for programmers. The team tried to learn all three methods of programming but faced many challenges in doing so. More time should have been assigned to learning the programming as it was more difficult than anticipated. The industry drives run on CoDeSys, an unfamiliar text-based programming language that was very complicated. Because of this we were unable to master all the methods of programming the drives.

In the future, this project could be improved by adding a spring-loaded socket head, instead of a rigid that is currently used. This would ensure that when the socket head collides with the bolt head before it has latched on, the temporary load is transferred into a spring and not the frame of the system. Another area of improvement would be to add a load cell to the bolt block to calculate the torque directly at the bolt tightening

stage. This torque could be compared to the calculated torque in the program which would come from the motor torque sensor and calculated using the gear box ratio and inertia, in order to validate its accuracy.

## APPENDIX A. Calculations

## Loading



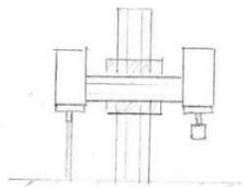
$$M_{\text{motor}} = 2.5 \text{ kg}$$

$$M_{\text{angle}} \approx 2 \text{ kg}$$

$$M_{\text{T-slot}} \approx 0.75 \text{ kg}$$

$$M_{\text{slider}} \approx 1.0 \text{ kg}$$

Z - axis

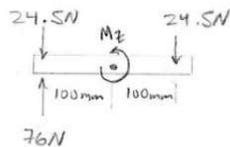


Force Ball Screw to lift:  $\sum F_x = 0$

$$F_{\text{BS}} = (2.5 \text{ kg} + 2.5 \text{ kg} + 2 \text{ kg} + 0.75 \text{ kg})(9.81 \text{ m/s}^2)$$

$$F_{\text{BS}} = 76.0 \text{ N}$$

Calculate  $M_z$ :  $\sum M_z = 0$

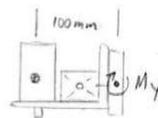
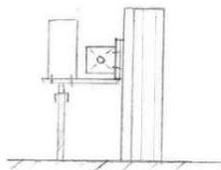


$$M_z = (76 - 24.5 \text{ N})(0.1 \text{ m}) + (24.5 \text{ N})(0.1 \text{ m})$$

$$M_z = 7.6 \text{ N}\cdot\text{m}$$

$$F_z = 0 \text{ N}$$

Y - axis:



Assume center of mass at motor.

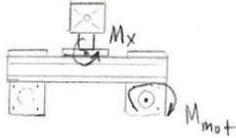
$$\sum M_y = 0$$

$$M_y = (76 \text{ N})(0.1 \text{ m}) = 7.6 \text{ N}\cdot\text{m}$$

$$M_y = 7.6 \text{ N}\cdot\text{m}$$

$$M_y = 0 \text{ N}$$

X-axis:



$$\sum M_x = 0$$

$$M_{mot} = \frac{M_{bolt}}{GB}$$

Assume 50 N·m to  
tighten 1/2" Bolt

$$M_{bolt} \approx 50 \text{ N}\cdot\text{m}$$

$$M_{mot\ max} = 0.8 \text{ N}\cdot\text{m}$$

$$GB \approx 75$$

$$M_{mot} = \frac{50}{75} = 0.67 \text{ N}\cdot\text{m}$$

$$M_x = 0.67 \text{ N}\cdot\text{m}$$

$$F_x = 0 \text{ N}$$

## Sizing Bolt Tightening Gear Box

$$\sum M_x = 0$$

$$M_{\text{mot}} = \frac{M_{\text{Bolt}}}{GB}$$

Assume  $50 \text{ N}\cdot\text{m}$  to  
tighten  $\frac{1}{2}$ " Bolt

$$M_{\text{Bolt}} \approx 50 \text{ N}\cdot\text{m}$$

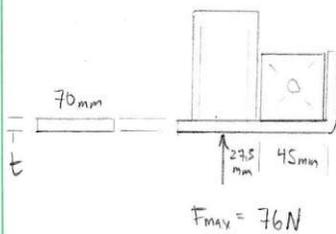
$$M_{\text{mot max}} = 0.8 \text{ N}\cdot\text{m}$$

$$GB_{\text{Bolt}} \approx 75$$

$$M_{\text{mot}} = \frac{50}{75} = 0.67 \text{ N}\cdot\text{m}$$

## Sizing Angle Bar

Sizing Angle Bar:



$$M_{\text{max}} = (76 \text{ N})(0.0725 \text{ m}) = 5.5 \text{ N}\cdot\text{m}$$

$$\sigma_y = \frac{Mc}{I} = \frac{(5.5) \left(\frac{t}{2}\right)}{\frac{0.07 t^3}{12}} = \frac{471.429}{t^2}$$

$$\sigma_{y\text{st}} = 250 \cdot 10^6 \text{ Pa} = \frac{471.429}{t^2}$$

$$t_{\text{st}} = 1.37 \text{ mm}$$

Steel Angle Bar from Metal Supermarket:  $4 \times 4 \times 0.188 \text{ in}$

$$0.188 \text{ in} = 4.7 \text{ mm} \gg 1.37 \text{ mm}$$

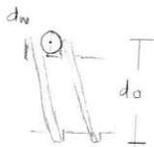
## Sizing Lead Screw Gear Box

Lead Screw Torque:

$$T' = W \left( \frac{D_m}{2} \right) \left[ \frac{f \pi D_m + L \cos(\alpha)}{\pi D_m \cos(\alpha) - f L} \right]$$

Our ball screw: 1532 - 4 - 6013

$d_o = 12$   $P = 5$   $L = 1/5$   $d_w = 2.5 =$  ball diameter



$$d_m = \frac{d_o + (d_o - d_w)}{2} = 10.75 \text{ mm}$$

$\alpha = 30^\circ$  Backlash = 0.02 mm  $f = 0.12$

$$T' = (76) \left( \frac{0.01075}{2} \right) \left[ \frac{0.12 \pi (0.01075) + \frac{1}{5} \cos(30^\circ)}{\pi (0.01075) \cos(30^\circ) - 0.12 (\frac{1}{5})} \right] = 13.8 \text{ N}\cdot\text{m}$$

$T'' = 0$  Ball or roller

$$\underline{T_{BS} = 13.8 \text{ N}\cdot\text{m}}$$

$$T_{\text{motor max}} = 0.8 \text{ N}\cdot\text{m}$$

$$\boxed{GB_{BS} > 18}$$

## Service Life

Profile Rail Slider Load Capacities:

$C = 12800 \text{ N}$   $C_o = 18400 \text{ N}$   $V_{\text{max}} = 5 \text{ m/s}$   $a_{\text{max}} = 500 \text{ m/s}^2$

$$M_{x \text{ max}} = 120 \text{ N}\cdot\text{m} > 0.67 \text{ N}\cdot\text{m} \checkmark$$

$$M_{y \text{ max}} = 120 \text{ N}\cdot\text{m} > 7.6 \text{ N}\cdot\text{m} \checkmark$$

$$M_{z \text{ max}} = 180 \text{ N}\cdot\text{m} > 7.6 \text{ N}\cdot\text{m} \checkmark$$

$$F_{\text{comb}} = |F_y| + |F_z| + c \frac{|M_x|}{M_{K \text{ max}}} + c \frac{|M_y|}{M_{y \text{ max}}} + c \frac{|M_z|}{M_{z \text{ max}}} = 1422.5 \text{ N}$$

$$\text{Dynamic Load Ratio} = \frac{C}{F_{\text{comb}}} = 9 > 4 \checkmark$$

## APPENDIX B. Datasheets

## General technical data and calculations

**Load on bearing for calculating the service life****Note**

In general, the minimum value of 4.0 should not be fallen short of for both the static and dynamic load ratios. In the case of applications that place high demands on rigidity and/or the service life, a higher load ratio is necessary. With tensile loads, check the screw stability. See the chapter entitled "Installation Information".

Dynamic load ratio

$$\frac{C}{F_{m' \max}}$$

Static load ratio

$$\frac{C_0}{F_{\text{eff}' \max}}$$

**Combined equivalent load**

In the case of a combined vertical and horizontal external load, calculate the dynamic equivalent load  $F_{\text{comb}}$  according to formula (5).

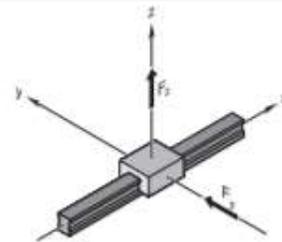
**Note**

The structure of the ball rail system permits this simplified calculation.

**Note**

Reduce an external load that affects the ball runner block at any angle with the correct sign to  $F_y$  and  $F_z$  and insert the amounts into formula (5) or (6).

$$(5) \quad F_{\text{comb}} = |F_y| + |F_z|$$

**Combined equivalent load in conjunction with moments**

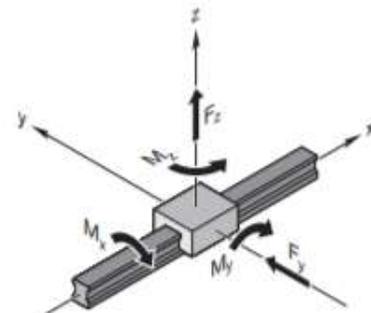
Using formula (6), you can combine all the partial loads that occur in a load case into one single comparison load, i.e. the combined equivalent load.

**Notes**

Including moments as stated in formula (6) only applies to an individual ball guide rail with just one ball runner block. The formula is simpler for other combinations.

The forces and moments plotted in the coordinate system can also have an effect in the opposite direction. Reduce an external load that affects the ball runner block at any angle to  $F_y$  and  $F_z$  and insert the amounts into formula (6). The structural design of the ball runner blocks allows this simplified calculation.

$$(6) \quad F_{\text{comb}} = |F_y| + |F_z| + C \cdot \frac{|M_x|}{M_t} + C \cdot \frac{|M_y|}{M_L} + C \cdot \frac{|M_z|}{M_L}$$



## Motor Specs

<b>Rexroth</b>	3-PHASE SYNCHRONOUS PM-MOTOR		<b>7260</b>
	TYP: MSK030C-0900-NN-M1-UG0-NNNN		
MNR: R911308683	FD: 15W31	Made in Germany	m 2,5 kg
Natural convection Md0 60k 0,8 Nm Id0 60k(eff) 1,5 A		SN: 7260404839893 A11	<b>SI</b> <b>UL</b> <b>US</b> <b>CE</b> Inverter Duty VPWM
	n max. 9000 min-1	Km 0,58 Nm/A	T.CL. 155
	KE(eff) 35,6 V/1000 min-1	U(max) AC 600 V	I.Sy. ECM1
			IP65
Bosch Rexroth AG, DE-97816 Lohr			

## Linear Profile Rail Slider

### General technical data and calculations

#### Load on bearing for calculating the service life

##### Note

In general, the minimum value of 4.0 should not be fallen short of for both the static and dynamic load ratios. In the case of applications that place high demands on rigidity and/or the service life, a higher load ratio is necessary. With tensile loads, check the screw stability. See the chapter entitled "Installation Information".

Dynamic load ratio

$$\frac{C}{F_{m^* \max}}$$

Static load ratio

$$\frac{C_0}{F_{\text{eff}^* \max}}$$

#### Combined equivalent load

In the case of a combined vertical and horizontal external load, calculate the dynamic equivalent load  $F_{\text{comb}}$  according to formula (5).

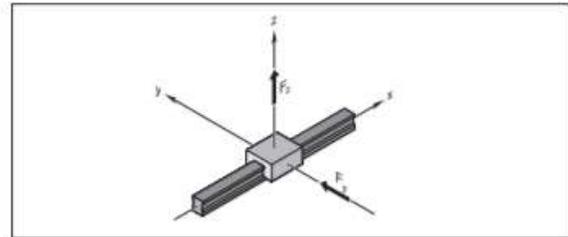
##### Note

The structure of the ball rail system permits this simplified calculation.

##### Note

Reduce an external load that affects the ball runner block at any angle with the correct sign to  $F_y$  and  $F_z$  and insert the amounts into formula (5) or (6).

$$(5) \quad F_{\text{comb}} = |F_y| + |F_z|$$



#### Combined equivalent load in conjunction with moments

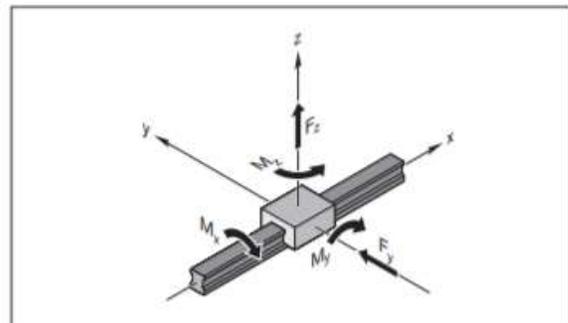
Using formula (6), you can combine all the partial loads that occur in a load case into one single comparison load, i.e. the combined equivalent load.

##### Notes

Including moments as stated in formula (6) only applies to an individual ball guide rail with just one ball runner block. The formula is simpler for other combinations.

The forces and moments plotted in the coordinate system can also have an effect in the opposite direction. Reduce an external load that affects the ball runner block at any angle to  $F_y$  and  $F_z$  and insert the amounts into formula (6). The structural design of the ball runner blocks allows this simplified calculation.

$$(6) \quad F_{\text{comb}} = |F_y| + |F_z| + C \cdot \frac{|M_x|}{M_t} + C \cdot \frac{|M_y|}{M_L} + C \cdot \frac{|M_z|}{M_L}$$



### 4.3 MSK030C Technical Data

Description	Symbol	Unit	MSK030C-0900-NN
Continuous torque at standstill, 60K	$M_{0,60}$	Nm	0,8
Continuous current at standstill, 60K	$I_{0,60(\text{eff})}$	A	1,5
Continuous torque at standstill, 100K	$M_{0,100}$	Nm	0,9
Continuous current at standstill, 100K	$I_{0,100(\text{eff})}$	A	1,7
Maximum torque	$M_{\text{max}}$	Nm	4,0
Maximum current	$I_{\text{max}(\text{eff})}$	A	6,8
Torque constant at 20°C	$K_{M,N}$	Nm/A	0,58
Constant voltage at 20°C	$K_{EMK,1000}$	V/min <sup>-1</sup>	35,6
Winding resistance at 20°C	$R_{12}$	Ohm	9,80
Winding inductivity	$L_{12}$	mH	14,100
Leakage capacitance of the component	$C_{\text{ab}}$	nF	1,3
Number of pole pairs	$p$	-	3
Moment of inertia of rotor without brake <sup>1)</sup>	$J_{\text{rot}}$	kg*m <sup>2</sup>	0,00003
Thermal time constant	$T_{\text{th}}$	min	15,0
Maximum speed	$n_{\text{max}}$	min <sup>-1</sup>	9000
Sound pressure level	$L_p$	dB[A]	<75
Ambient temperature during operation	$T_{\text{um}}$	°C	0 ... 40
Degree of protection	-	-	IP65
Insulation class EN 60034-1	-	-	F

1) Specified without brake. If necessary, add the moment of inertia brake.  
 Fig.4-8: Technical data

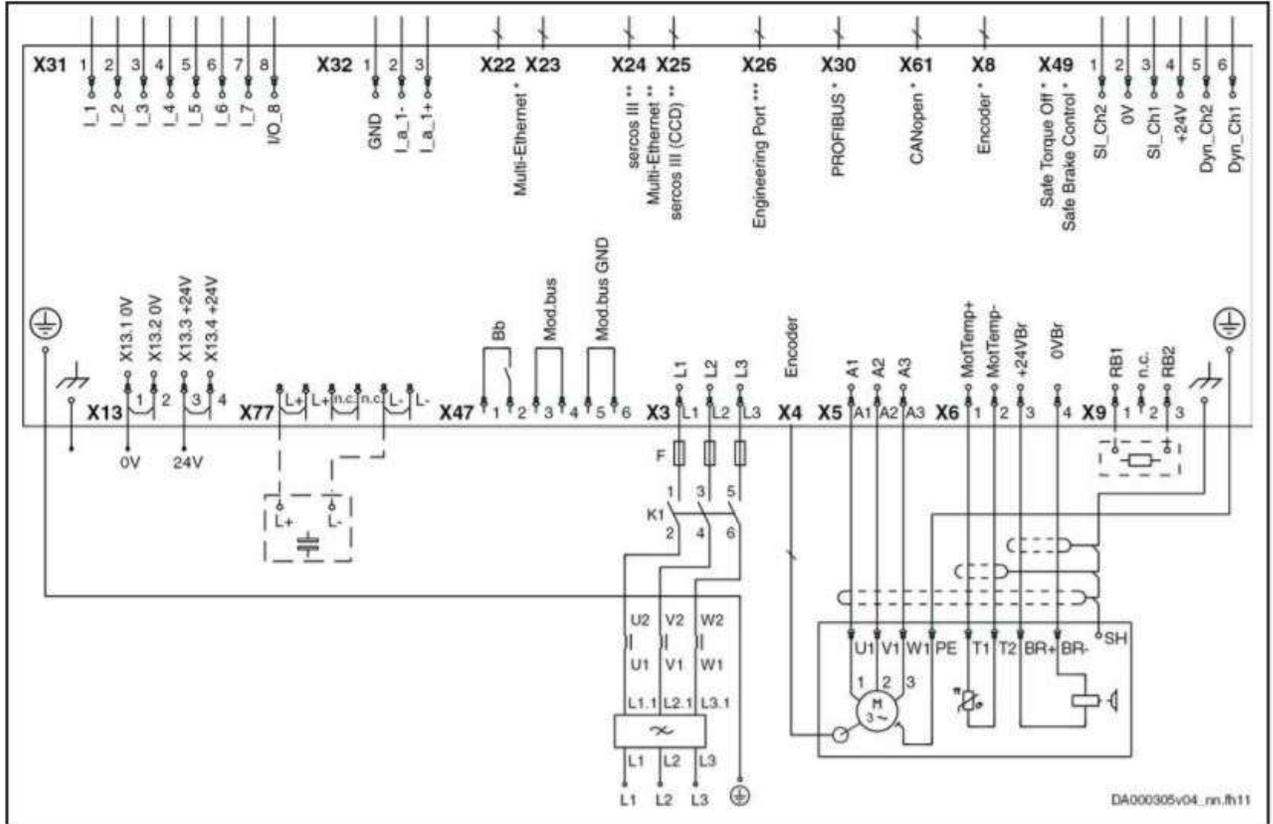
Description	Symbol	Unit	BREMSE-231389
Holding torque	$M_4$	Nm	1,0
Rated voltage ±10%	$U_N$	V	24
Rated current	$I_N$	A	0,40
Connection time	$t_1$	ms	3
Disconnection time	$t_2$	ms	4
Moment of inertia brake	$J_{\text{rot}}$	kg*m <sup>2</sup>	0,000007
Mass brake	$M_{\text{Br}}$	kg	0,2

Fig.4-9: MSK030: Holding brake - Technical data (optional)

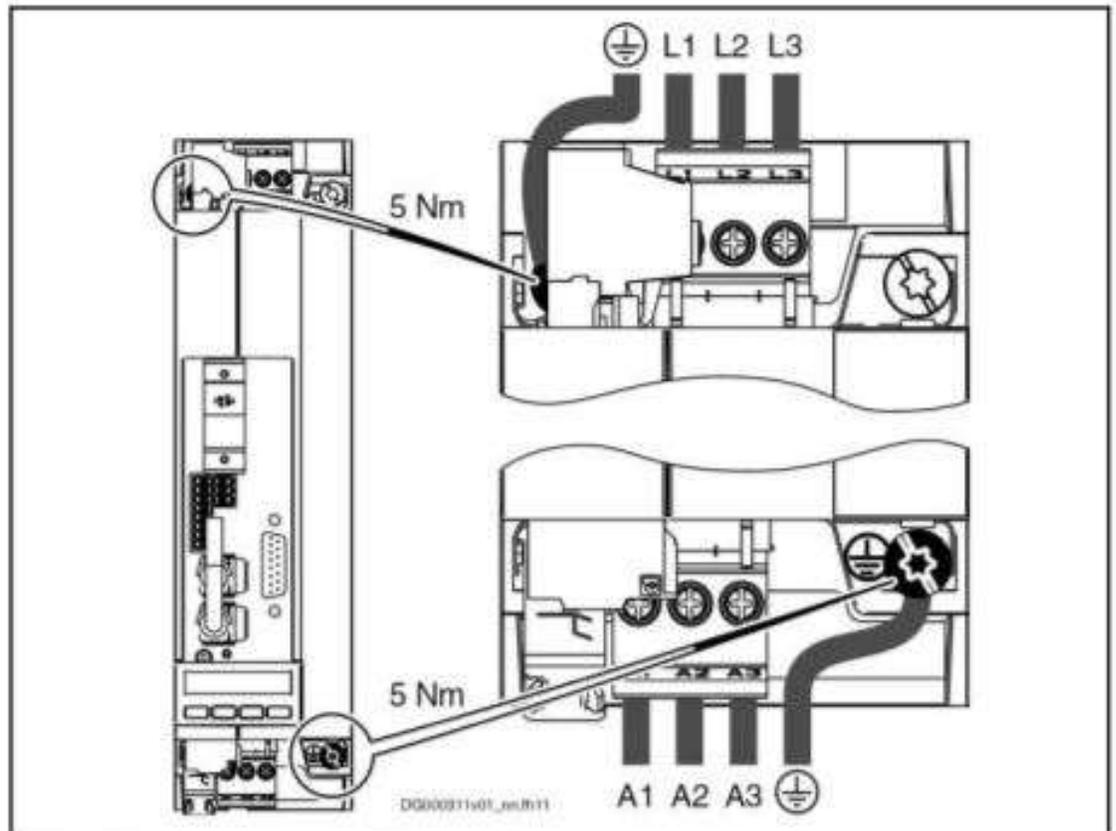
Electrical Connection of IndraDrive Cs

## 6.2 Electrical Connection

### 6.2.1 Overall Connection Diagram



**Installation** Connect the equipment grounding conductor of the mains or motor cable via thread **M5** to the housing of the device (identification mark  $\oplus$ ; tightening torque: **5 Nm**). The screws **M5×12** required for this purpose are part of the supplied accessory HAS09.



L1, L2, L3  
A1, A2, A3

Mains connection  
Motor connection

Fig.6-5:

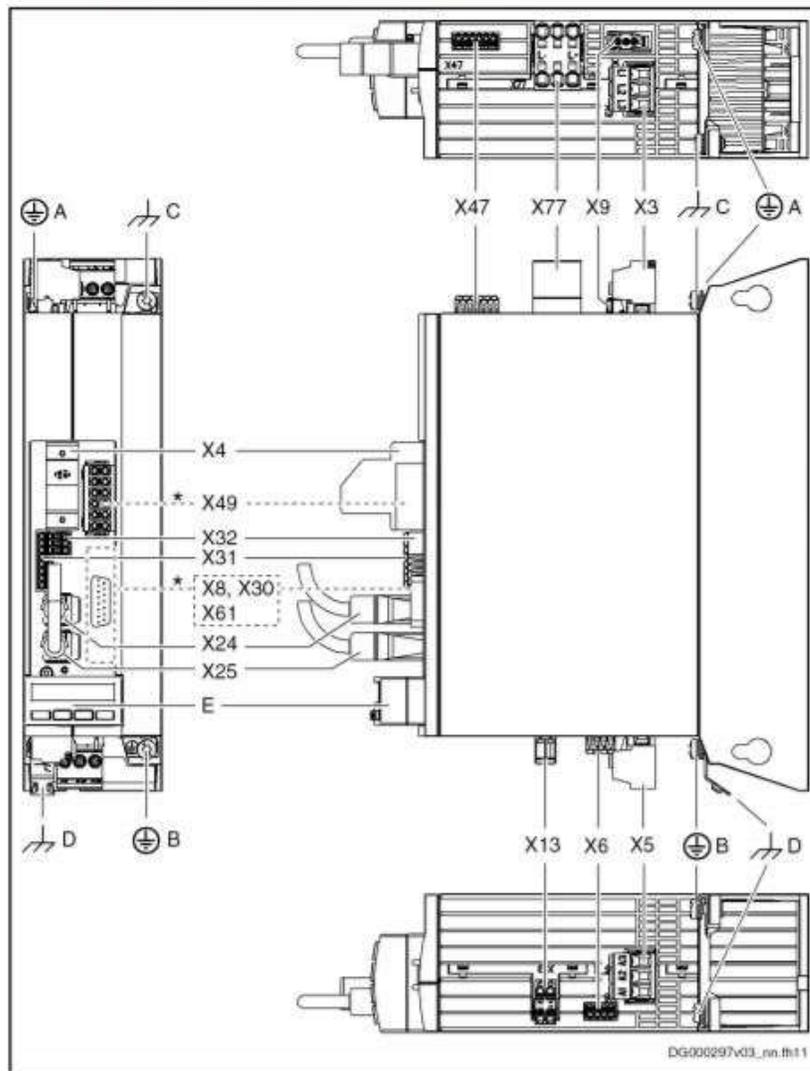
Connection Point of Equipment Grounding Conductor

## Connection Points of IndraDrive Cs

## 6.2.2 Connection Points

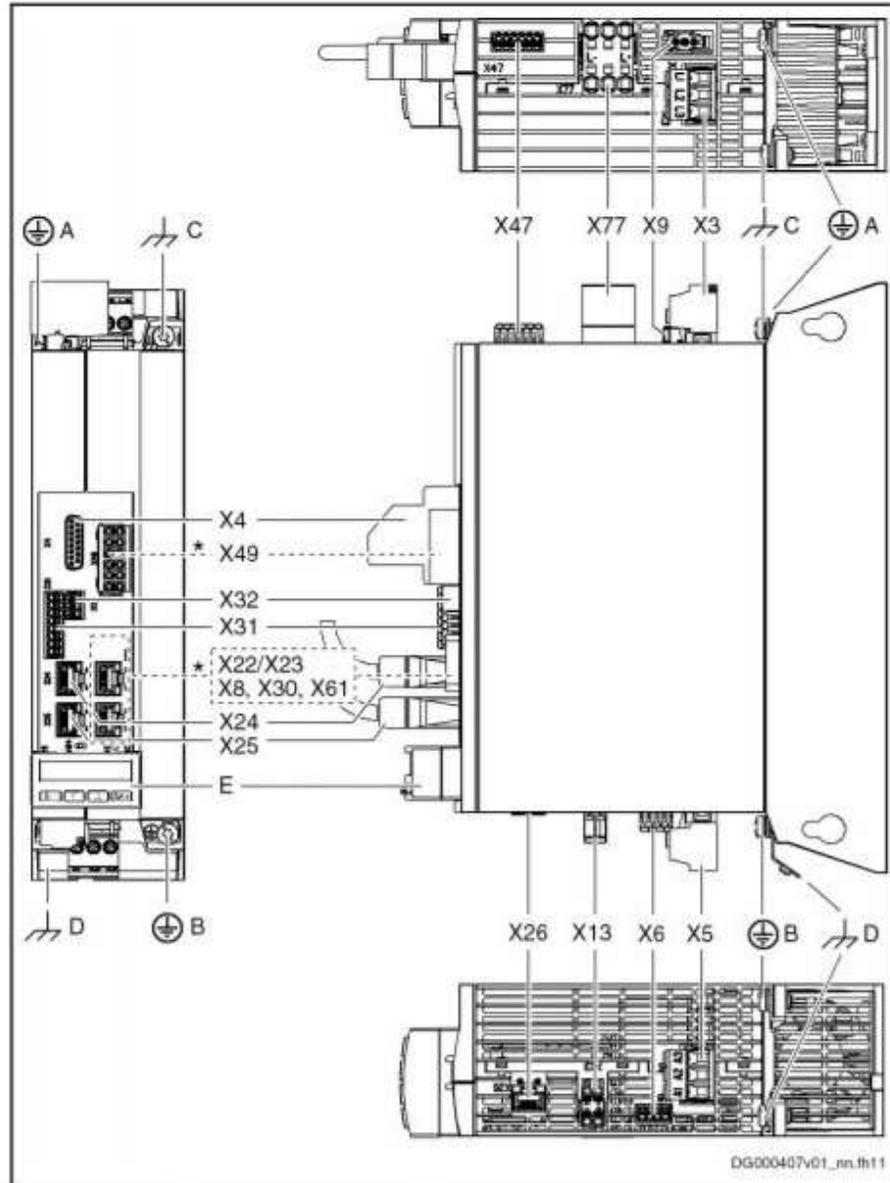
## Arrangement of the Connection Points HCS01

Connection Points HCS01 (ECONOMY, BASIC)



*	Optional connection point
A	Connection point of equipment grounding conductor, mains
B	Connection point of equipment grounding conductor, motor
C	Shield connection control lines
D	Shield connection motor cable
E	Control panel
X3	Mains connection
X4	Motor encoder
X5	Motor connection
X6	Motor temperature monitoring, motor holding brake
X8	Optional encoder evaluation (EC); optional encoder emulation (EM)
X9	Integrated/external braking resistor
X13	24V supply (control voltage)

## Connection Points HCS01 (ADVANCED)



- \* Optional connection point
- A Connection point of equipment grounding conductor, mains
- B Connection point of equipment grounding conductor, motor
- C Shield connection control lines
- D Shield connection motor cable
- E Control panel
- X3 Mains connection
- X4 Motor encoder
- X5 Motor connection
- X6 Motor temperature monitoring, motor holding brake
- X8 Optional encoder evaluation (EC); optional encoder emulation (EM)
- X9 Integrated/external braking resistor
- X13 24V supply (control voltage)
- X22 / X23 Optional communication Multi-Ethernet (ET)
- X24 / X25 sercos III master
- X26 Engineering interface
- X30 Optional communication PROFIBUS (PB)

## APPENDIX C. Request for Proposal

### **Request for Proposal: Mechanical Engineering Services for 2 Axis Trainer**

*Bosch Rexroth Canada*

October 2017

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#### **Introduction:**

Bosch Rexroth is a premier cross technology solutions company that supports mechanical and plant engineering around the world. We are seeking a suitable company to design and manufacture a system to automate bolt tightening to change the blades on a log roundup machine. We are currently accepting proposals in response to this RFP in order to find a qualified source to provide a working prototype of an automated bolt tightening machine.

#### **Project Description:**

This project includes designing and manufacturing a working prototype for an automated bolt tightening machine used within a large log debarking machine. This machine will be automated using products provided by Bosch Rexroth. The goal is to tighten a bolt within 30 seconds, while also automatically inspecting it for defects such as stripped threads, bends in the shaft or a stripped head.

#### **Scope:**

The chosen firm will be required to design and manufacture a working prototype of the described project. This project is limited to a prototype and is not required to be full scale or mass produced.

#### **Evaluation Criteria:**

- Working prototype
- Tightens bolt
- Checks for stripping, alignment, and other defects
- Tightens within torque tolerance

#### **Technical Requirements:**

- Torque tolerance of +/- 1 lb-ft
- Withstand dust and temperature of -20– 75 °C
- Time to change 1 bolt: less than 30 seconds
- Ability to operate in environments with heavy vibrations

#### **Timeline:**

This project is expected to be completed by May 2018. The chosen firm must present a timeline with proposed milestones and dates in their proposal. Proposal due date is November 7 2017.

#### **Budget:**

\$45,000 - \$60,000

All required motors and drivers will be supplied.

**Submission Guidelines and Requirements:**

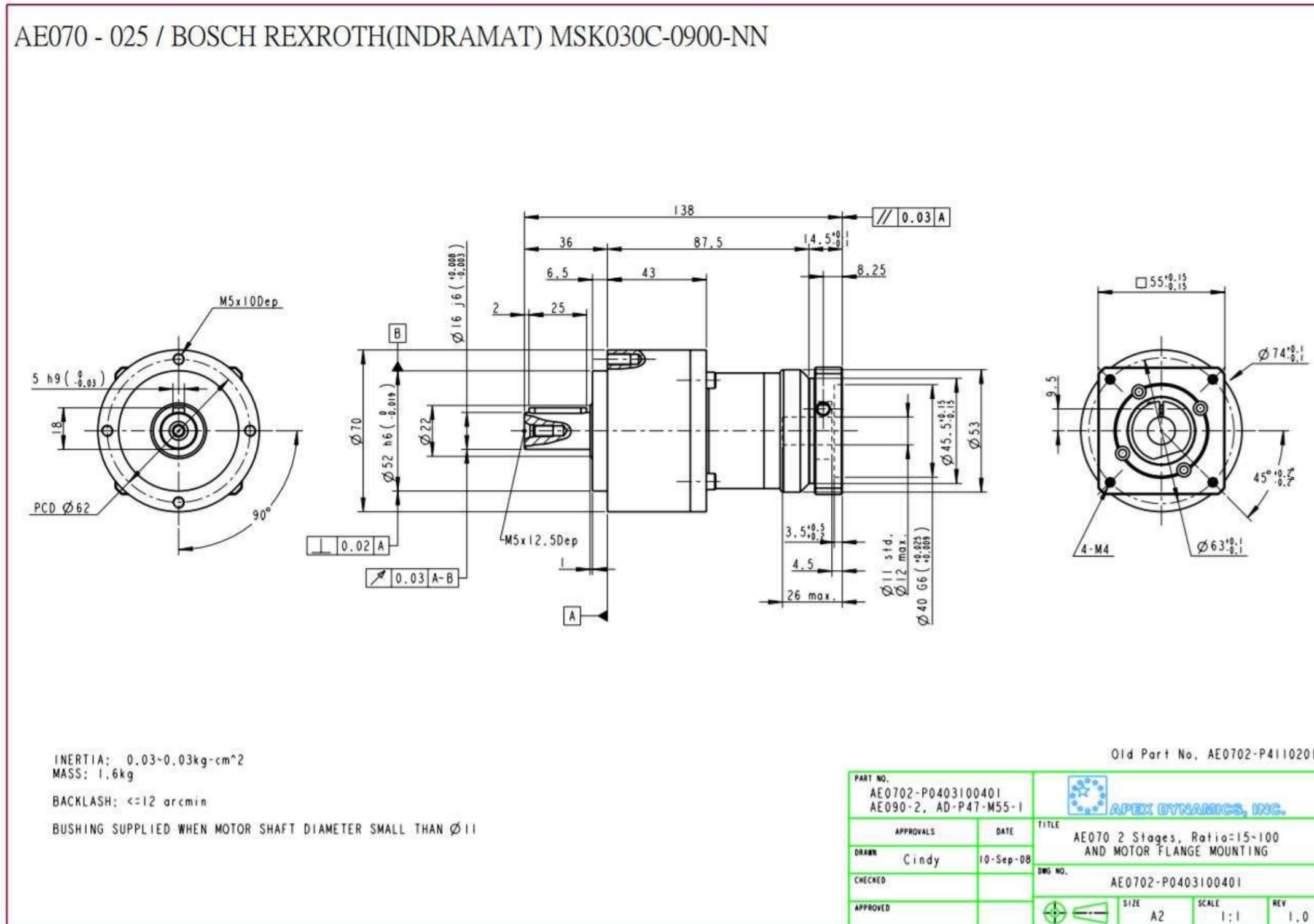
1. Only qualified firms with prior experience on projects such as this should submit proposals in response to this RFP.
2. A technical proposal must be submitted and not exceed 20 pages. The proposal must include a proposed solution as well as rough conceptual sketches as to how the team will attempt to tackle the problem.
3. A timeline with proposed milestones must be submitted as applicable.
4. Bidders must provide a cost breakdown which includes labour and materials.
5. A portfolio of previous completed projects, with descriptions and outcomes to demonstrate the capability and experience of the group.
6. Bidders are required to include their company's capabilities or facilities which relate to the project.
7. A short description of your company's background.

**Evaluation Factors:**

1. Relevant past performance and experience
2. Responsiveness of proposal to the requests put forward through this RFP
3. Proposed cost
4. Competency

APPENDIX D. Engineering Drawings

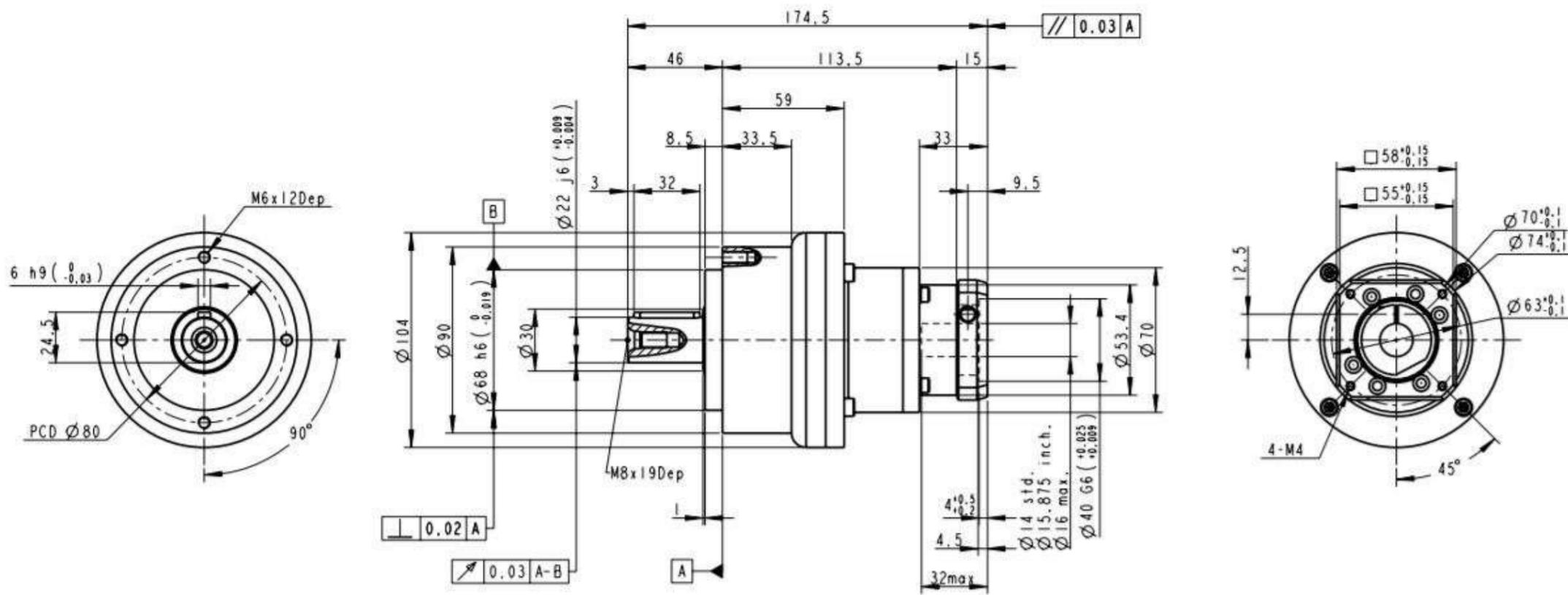
AE070-25 Gear Box





AE090-60 Gear Box

AE090 - 060 / BOSCH REXROTH(INDRAMAT) MSK030B-0900-NN



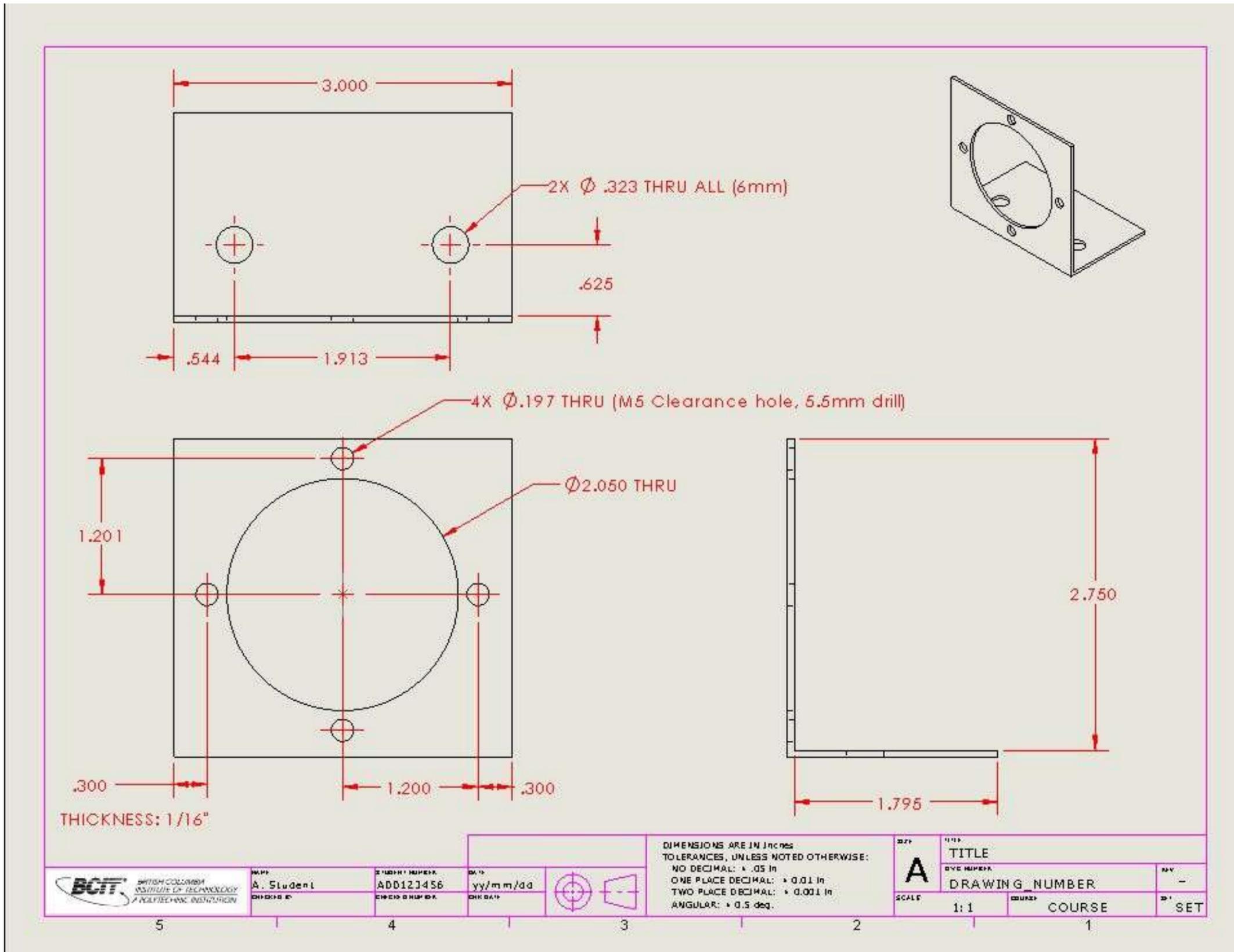
INERTIA: 0.13-0.13kg-cm<sup>2</sup>  
 MASS: 4.7kg  
 BACKLASH: <=12 arcmin  
 BUSHING SUPPLIED WHEN MOTOR SHAFT DIAMETER SMALL THAN Ø14

Old Part No. AE0902-P4120204

PART NO. AE0902-P0403200304 AE090-2, AD-P64-M55-4			
APPROVALS	DATE	TITLE AE090 2 Stages, Ratio=15-100 AND MOTOR FLANGE MOUNTING	
DRAWN Cindy	10-Sep-08	DWG NO. AE0902-P0403200304	
CHECKED			SIZE A1    SCALE 1:1    REV 1.0
APPROVED			

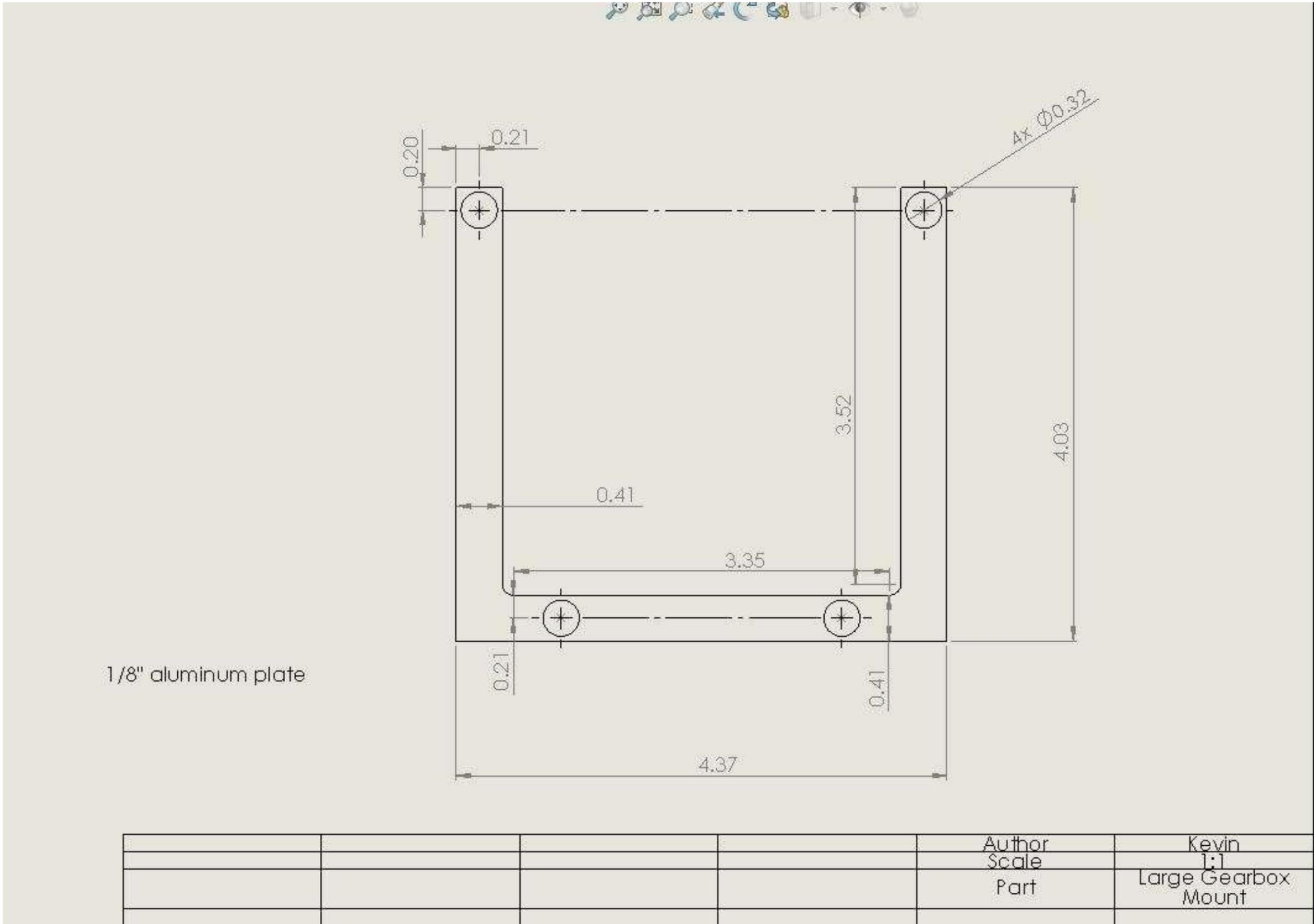


AE070-25 Gear Box Mounting Bracket



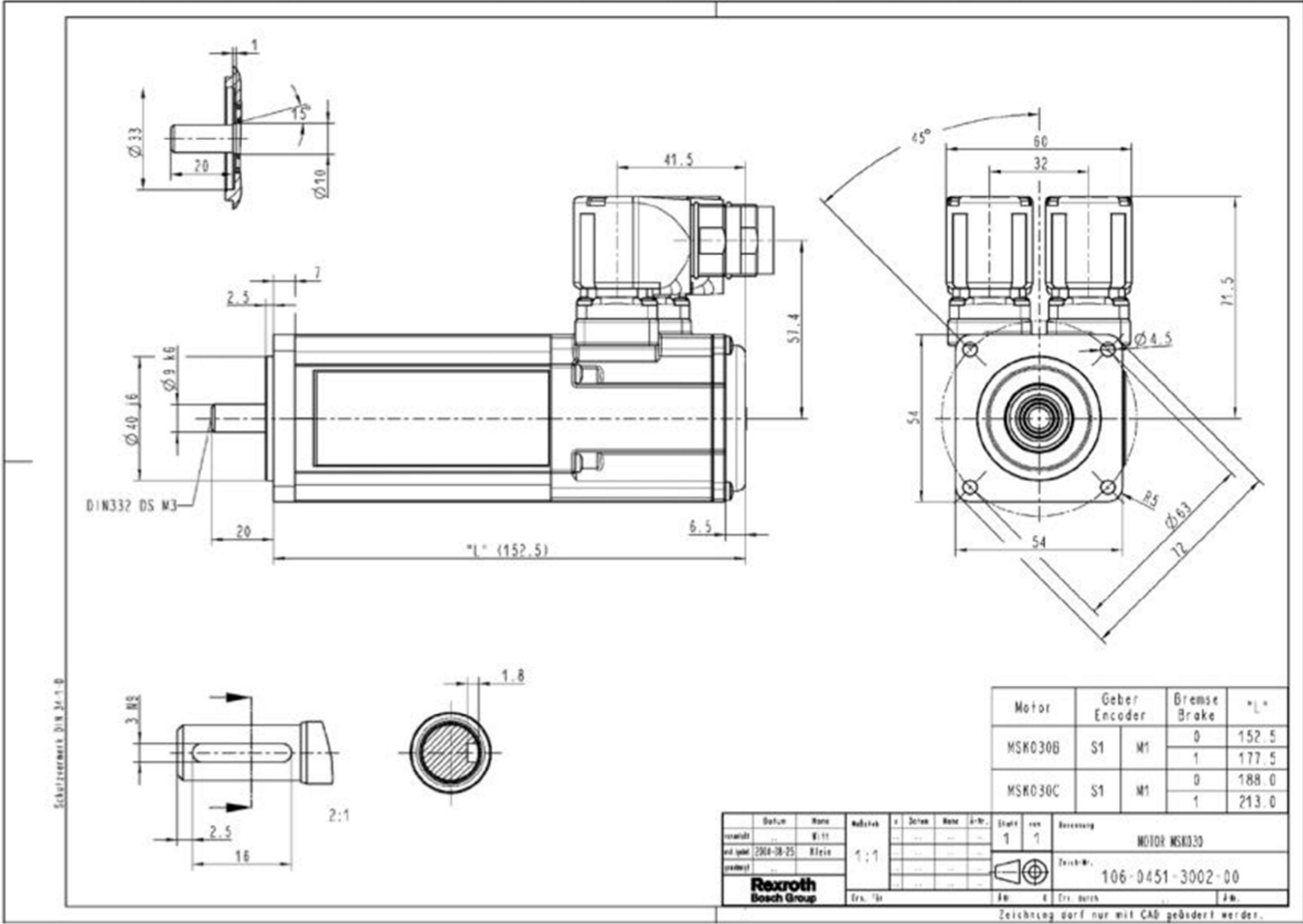


AE090-60 Gear Box Mounting Bracket



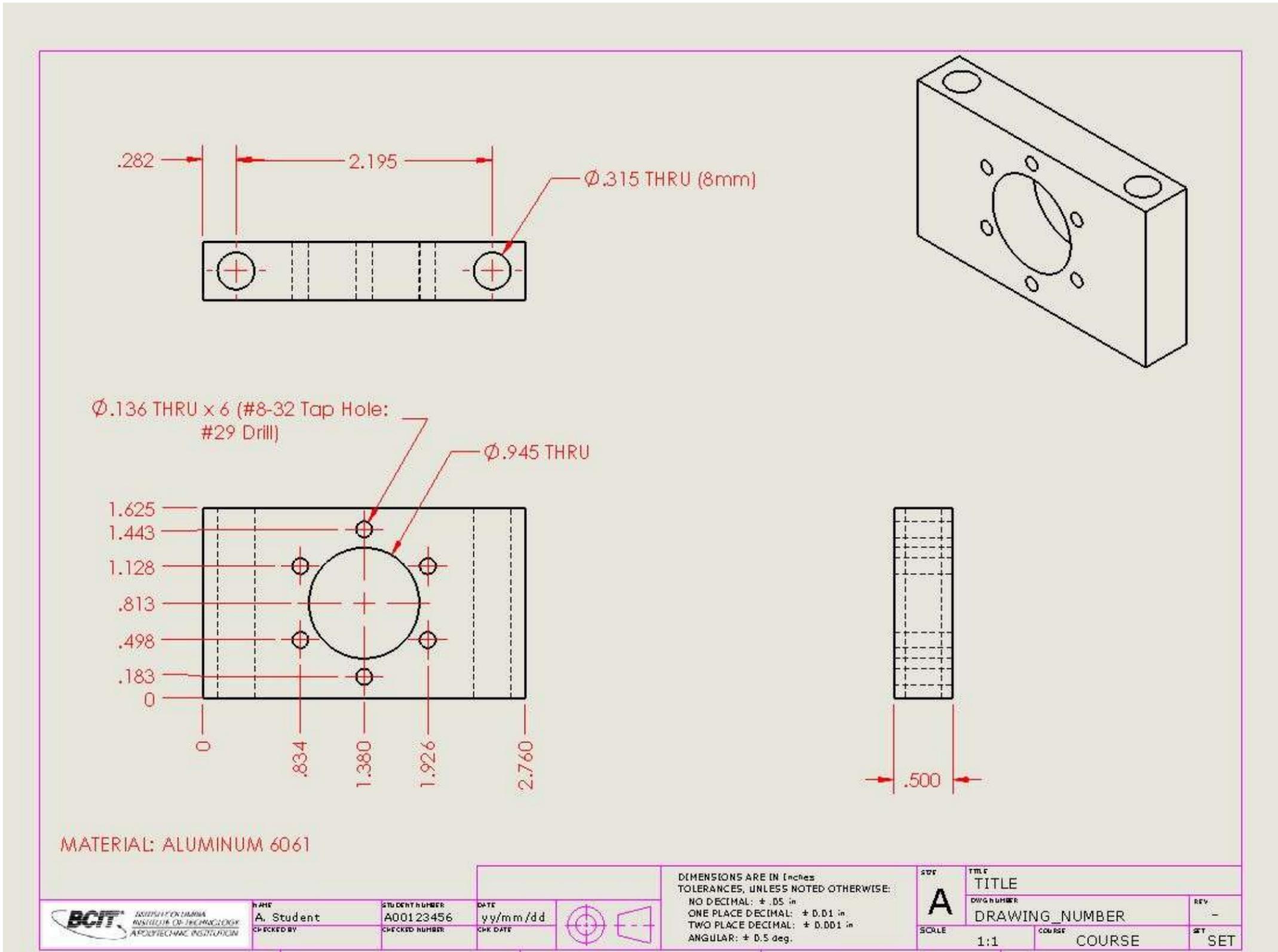


MSK030C Servo Motor



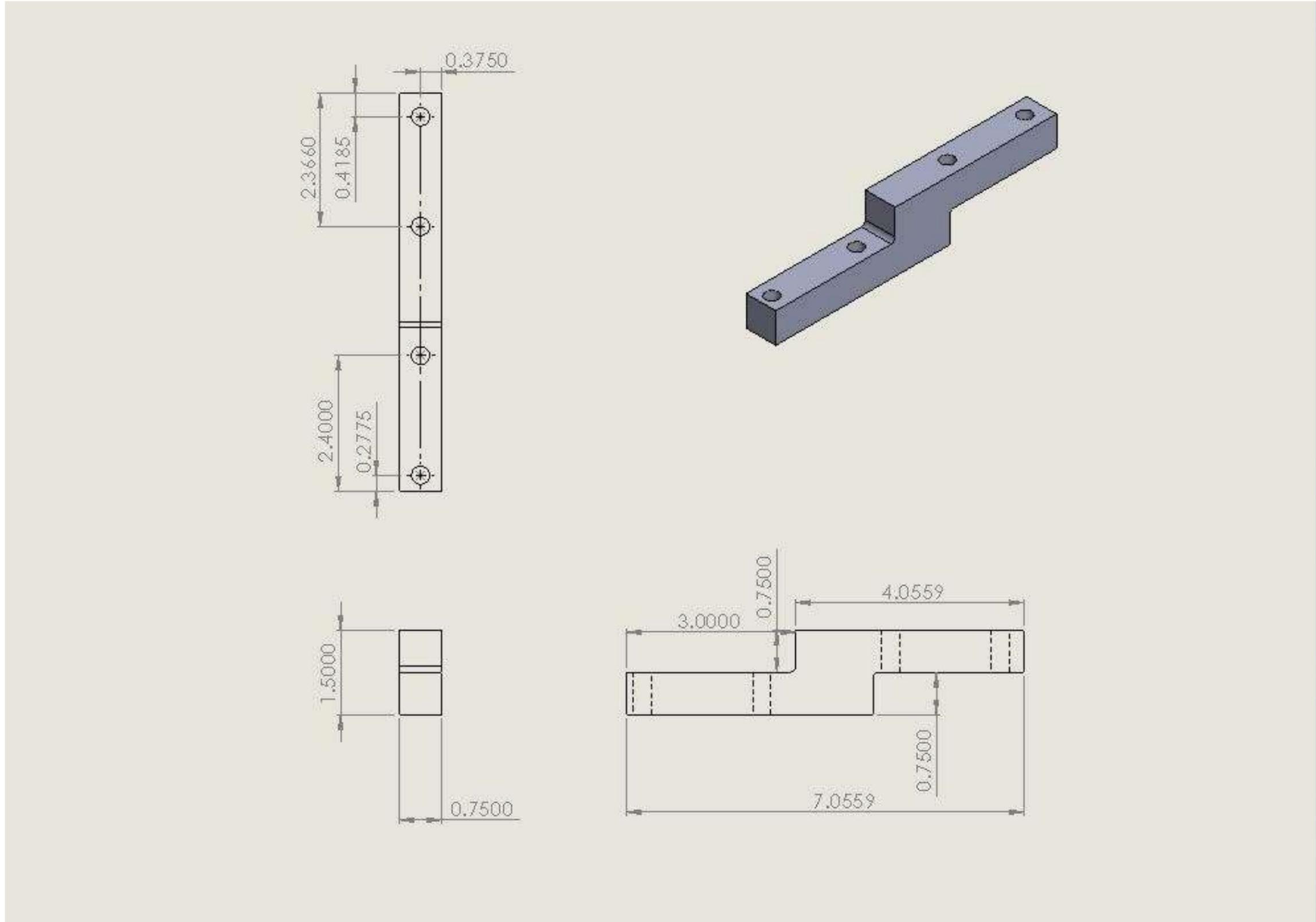


Lead Nut Attachment Block





Connecting Bracket





Bolt Block

