# DESIGN AND DEVELOPMENT OF A RECONFIGURABLE TESTING SYSTEM FOR BIOMECHANICAL AND ORTHOPEDIC EXPERIMENTAL RESEARCH

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2018

Major Subject: Mechanical Engineering

# ABSTRACT

The goal of this work was to develop a versatile mechanical testing load frame and control system that incorporates hardware and software components that can be readily reconfigured to meet the unique needs of a wide variety of orthopedic testing applications. The technical requirements of the system included a maximum axial loading capacity of at least 2000lbf and a maximum torsional loading capacity of at least 250 in-lbf. The system was physically designed using Solidworks, including the load frame and selected actuators, before being fabricated and assembled. Custom software for the system was developed using LabVIEW, and consists of three primary sections: the control system loop, data recording, and the user interface. The control system loop is structured as a finite state machine (FSM) to allow for easier troubleshooting as well as expansion of control types. The data recording consist of two separate loops, one of which operates deterministically to store data in a clustered real time first in first out (RTFIFO) variable while the second records this collected data to a text file on the cRIO system. The user interface allows the operator to change the system control type such as position or load, create a file for data recording, and displays information about the system during operation. The user interface also includes various safety checks to prevent the user from damaging the system. The system's final cost came out to approximately $47,023 including a safety screen, custom fixturing for upcoming Biomechanical Environments Laboratories (BMEL) projects, and an estimation for work hours. The system is being prepared for used in an Food and Drug Administration (FDA) Good Laboratory Practice

(GLP) regulated study and will be validated as required for the study. A user’s manual was created for the system including information concerning assembly for a linear and torsional loading scenario, operation of the current software version, and steps for adding and changing sensors in the system.

# ACKNOWLEDGEMENTS

To my family for always supporting and encouraging me. To my mother, who always pushed me to do more than the bare minimum, taught me to be detailed in my work, and made me finish what I started. To my father, you taught me to be able to take things in stride, always seek a deeper understanding than what was given at face value, and to work hard with my own two hand. To my Sister, who was and still is a sweeter sibling than I deserve.

To my advisor Dr. Michael Moreno, for giving me the opportunity to develop a system of my own and trusting in my capability.

To everyone in the lab, your support will always be remembered. I could not have made it through without you all.

Finally, to Gary Dean Sorensen who inspired me to pursue engineering and Stella Michelle Ray for being an example of perseverance.

# CONTRIBUTORS AND FUNDING SOURCES

## Contributors

This work was supervised by a thesis committee consisting of Professor Michael Moreno of the Mechanical Engineering Department, Professor Harry Hogan of the Mechanical Engineering Department, and Professor Brian Saunders of the Department of Veterinary Medicine and Biomedical Sciences.

## Funding Sources

There are no outside funding contributions to acknowledge related to the research and compilation of this document.

# NOMENCLATURE

National Instruments (NI)

Biomechanical Environments Laboratory (BMEL)

Reconfigurable Testing System (RTS)

Ethernet for Control Automation Technology (EitherCAT)

Compact Reconfigurable Input/Output (cRIO)

Real Time First in First Out (RTFIFO)

Finite State Machine (FSM)

Joint Motion Simulator (JMS)

Food and Drug Administration (FDA)

Good Laboratory Practice (GLP)

Quality Assurance (QA)

National Institute of Standards and Technology (NIST)

American Society for Testing and Materials (ASTM)

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# CHAPTER I

# INTRODUCTION

## 1.1 Background and Motivation

### *1.1.1 Testing Systems*

Mechanical testing has been used for decades to evaluate and characterize materials. The characterization of a uniform, elastic material is commonly performed using a tensile test on a uniaxial load frame. The process of evaluating a material expands in complexity when it must apply to a specific component of a design, such as stainless steel used for scissors or titanium used in bone plates for fracture fixation. To properly evaluate materials for a design, the mechanical testing procedure must be adapted to relate to the design's intended use, as material properties alone do not determine design efficacy. A relatable mechanical test is referring to a loading setup/scenario which is representative of the loading conditions that the material and design will be exposed to in its intended application. When unrelatable mechanical tests are performed to determine the efficacy of a design, or material, the results may only describe a part of the performance or none at all. This need for a relatable mechanical test is especially important when pertaining to biomechanical applications, such as the in vivo loading conditions experienced by orthopedic devices or joints. An example of a custom setup for joint simulation is shown in Figure 1.

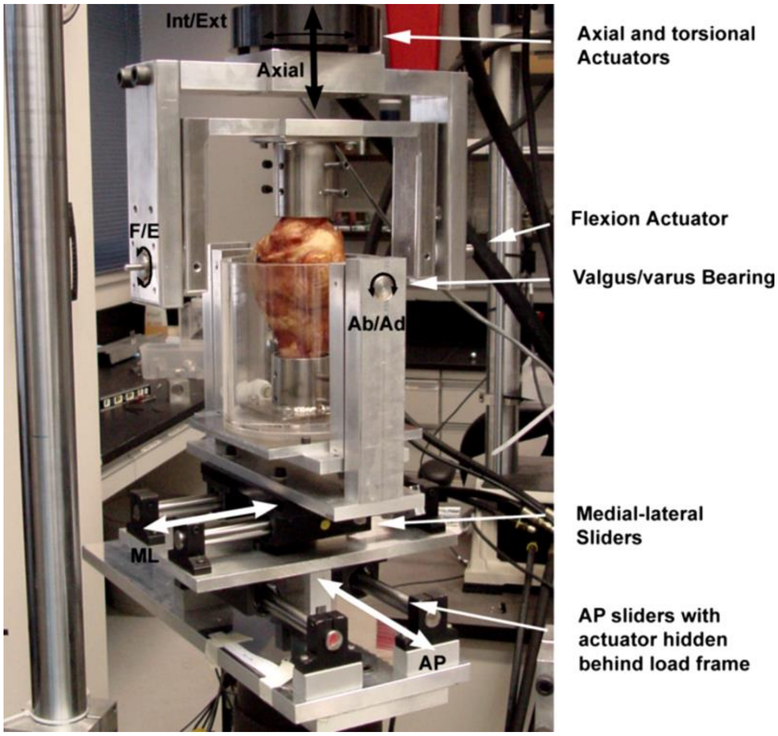


**Figure 1 – Custom knee simulator for wear testing of standard knee implant by Sutton et al. [1]. Reprinted with permission from Elsevier Publications.**

With the extensive variation in loading conditions throughout the body and the complex geometric configurations of bones and joints, creating a relatable mechanical test can be difficult, time consuming, and expensive. All of these factors are compounded upon when designing an experiment on a common uniaxial testing system as these systems generally come with a lack of configurability beyond the functions intended by the company. Some companies will work to expand the functionality of the system, but this can be a costly and time consuming process which may not be viable for a given project's budget or deadline. There is a need for a reconfigurable test system to reduce both the time and cost, of developing relatable mechanical tests for biomechanical scenarios and evaluating orthopedic hardware.

### *1.1.2 Common Testing System and Challenges*

A common testing system, in the context of this document, refers to a vertically adjustable linear actuating system with or without a torsional component capable of control by an operator and data collection, such as the system shown in Figure 2. These systems are sold by companies such as TestResources, Instron, and MTS with operation performed using company specific software. The initial cost of these systems can easily be upwards of $50,000, with additional costs for fixturing, sensory hardware, and operational software.

These common testing systems have a single centered mounting location on the bottom platform with a similar mounting location on the linear actuator shaft. Such test systems exist in a variety of sizes, functional complexity, and cost. Test systems from companies such as MTS and Instron have had decades to improve their systems' hardware and software [2]–[4], leading to refined testing systems ready to operate upon purchase and installation.

**Figure 2 – Test Resources 830AT testing system in Texas A&M University's Biomedical Engineering department**

These common testing systems have wide and expanding functionality. A limitation of these systems is the inability to configure the layout of the system elements nor integrate 3rd party components. Typically there is only the flexibility to allow for adjustment of the vertical location of the linear actuator and the exchange of company specified load cells, which must properly integrate with the company's software. Due to a reoccurring need for off-axis loading in biomechanical based investigations [1], [5]–[9], this limited configurability leads to required expansive design of custom fixturing to adapt the system for desired loading scenarios such as the one shown in Figure 3.

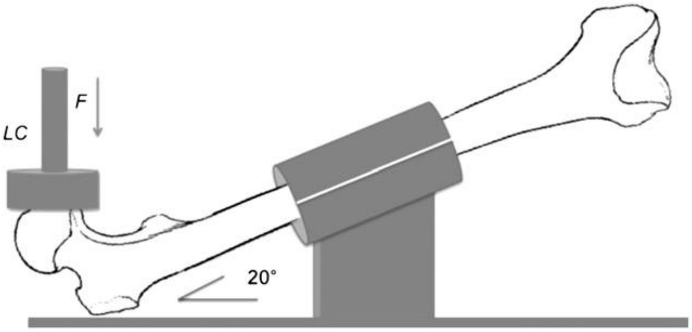


**Figure 3 – Simulated fall configuration of femur by Steenhoven et al. [8]. Reprinted with permission from Elsevier Publications .**

Inclusion of auxiliary hardware such as safety screens or an environmental chamber, in addition to expanding the system’s sensory devices (thermocouples, load cells, LVDT’s, etc.), can be difficult if not impossible to properly integrate into the system. One of the primary reasons this can be impossible is the system’s controller hardware and the company-specific software. To incorporate additional sensory devices, the system would have to be designed with additional input/output channels for integrating digital and analog signals. Then the system’s software would need to be able to integrate the sensory devices into the operational feedback loop of the system to properly synchronize the data collection and any potential output signals.

In a recent study done in the BMEL, two different types of orthopedic hardware for the fracture fixation of fifth metatarsal Jones fractures were evaluated on cadaveric specimens [10]. It was determined that cantilever bending in the medial-lateral direction would best simulate the fracture pattern seen in clinical studies. At the time the only available load frame was a TestResources 830 Series Axial Torsion test machine, which falls within the description previously stated of a common test system. This experimental setup, shown in Figure 4, required the design of extensive custom fixturing in order to apply simple cantilever loading to the desired test specimen, taking approximately four months and over $4,000 for setup design.

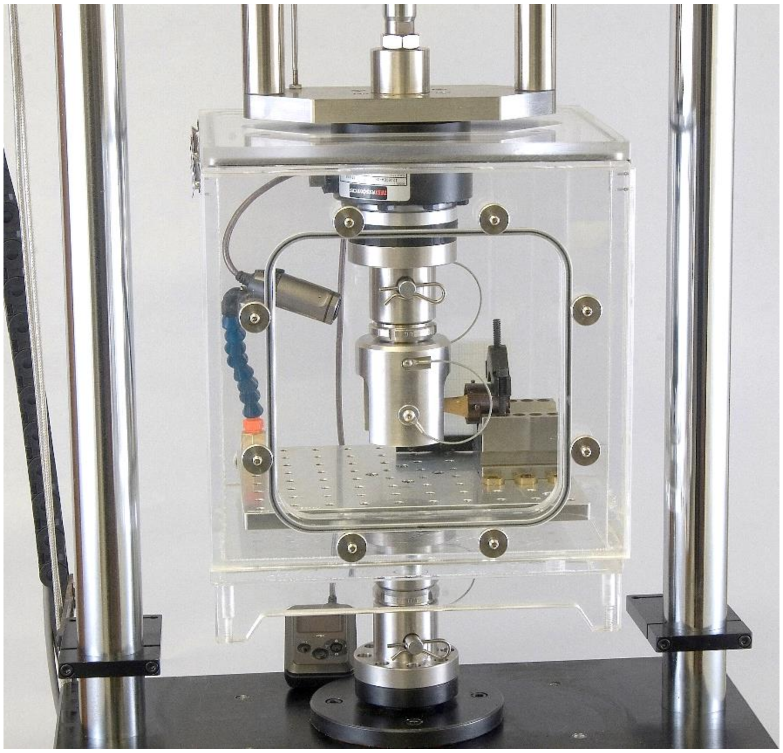


**Figure 4 – Custom setup for cantilever loading of cadaveric 5th metatarsal specimens for the evaluation of fracture fixation hardware by Duplantier et al. [10]. Reprinted with permission from SAGE Publications.**

In addition to an increased time and cost, it was desired to implement other sensors into the system to synchronize data collection with the testing. This was impossible without a company service engineer coming on site to evaluate the setup and sensory hardware, which was not a feasible option given the project’s timeline. To account for this inability to expand the system, external optical measurements were used which added significant time to the post experiment evaluation of the collected data.

For complex loading scenarios, an alternative to a common testing system is a highly specialized testing system. An example of such a system is Endolab's knee wear testing system displayed in Figure 5. While these systems are able to recreate complex physiological loading, the cost of such a system can be upwards of $100,000, and the system will be limited to a singular function.

**Figure 5 – Endolab Knee Wear Test ISO 14243-1, reprinted from Endolab [11]**

Being able to expand a test system's physical functionality and operate the system with a more modular software will allow for less time consuming modification at a lower cost to the end user. A custom reconfigurable test system (RTS) is desired to reduce the initial cost, the time to design custom fixturing, and to allow for simpler expansion of the system on a project-to-project basis.

## 1.2 Specific Aims

### *1.2.1 Specific Aim 1*

Design and build a RTS that is capable of axial and torsional loading. This process will include (1) the selection of linear and torsional actuators, (2) the detailed design of the system using Solidworks, (3) the fabrication of the designed system, and (4) the integration of a biobath.

### *1.2.2 Specific Aim 2*

Develop LabVIEW based control system for the RTS, including a custom user interface for linear and torsional loading. This involves (1) the selection of the necessary control system hardware to manage communication and information collection from a variety of sources, (2) development and implementation of a control VI.

### *1.2.3 Specific Aim 3*

Create an operators manual with procedures for system setup, operational protocol, and calibration.

# CHAPTER II

# SYSTEM DESIGN

## 2.1 Introduction

Solidworks, National Instruments (NI) hardware, and LabVIEW are commonly used throughout industry as well as academia in engineering fields. The goal of this design is to allow for reconfiguration and system expansion for multiple ongoing and future projects in the BMEL. The physical components were designed in Solidworks and compiled into a functional assembly. By creating a detailed assembly of the system in Solidworks, future users will be able to design various configurations and fixtures while the system is actively used for other projects and may not be directly accessible. The control system hardware was purchased from NI with the software of the system programmed using LabVIEW. Using NI hardware and the LabVIEW programming language, future users can begin preliminary programing for various new configurations in parallel with physical system expansion and design.

## 2.2 Design Considerations

The design considerations for the system were determined based on the expected experimental needs of the BMEL, as well as consideration of loads found amongst similar biomechanics and orthopedic experiments in available literature. The final design goals chosen were a maximum axial loading of 2000 lbf and a maximum torsional loading of at least 250 in-lbf. In addition, a maximum sampling rate of 1 kHz was desired as a sufficient data acquisition speed to implement PID based control and to collect sufficient data to represent most orthopedic experiments.

### *2.2.1 Past Projects*

A previous project completed in the BMEL, was the evaluation of orthopedic hardware for the fracture fixation of 5th metatarsal Jones fractures. This project was performed on a TestResources 830 axial torsional testing system and required axial loading up to 75 lbf. Another previous project was evaluating fracture repair plates in an equine model. This ended up requiring over 2000 lbf of axial loading, however equine evaluations are expected to have extremely high loads due to the animal's size. It was determined that the designed system would not need to evaluate these high load equine models.

### *2.2.2 Ongoing Projects*

At the time of initial system design, two projects in the BMEL needed to be performed on the then, theoretical RTS. The first project is the evaluation of a novel "bone cuff" device which is intended to be used to facilitate the repair of commutative fractures. The expected loads based on previous lab evaluations was approximately 1000 lbf of single axis, linear loading. A custom system was needed for this project as the experimentation must be done under GLP protocol. A requirement of an experiment under GLP protocol, is the complete control of access to testing systems. Testing systems available at Texas A&M University, while capable of performing the necessary loading, could not reasonably be access regulated for the expected duration of the project due to the systems being a departmental resource and necessary for classes.

The next project under consideration was a cadaveric study relating to femoral dislocation from the acetabulum, with a focus on the femoral capsule integrity. Experiments were found in the literature performed on cadaveric specimens, with the intended result of causing dislocation, resulting in a maximum documented axial force of approximately 160 lbf [12].

### *2.2.3 Future Projects*

In order to prepare for future projects, various experimentations were reviewed throughout the available literature focusing primarily on human specimens. The primary concern with preparing the system for future experiments is to have hardware with loading capabilities that can reach the maximum desired loadings of the experiments. An assumption was made that under compressive axial loading the human femur would require the highest amount of loading. From available experimental data it was found that the estimated human cadaveric femur's maximum compressional loading was approximately 900 lbf [13]. Under 3-point bending the maximum load with orthopedic hardware was approximately 1,169 lbf [14].

## 2.3 Software and Hardware Selection

### *2.3.1 Product Family*

The goal of the testing system design is not only that the system be physically reconfigurable, but that the expansion of system hardware and sensors be relatively simple. For this reason, National Instruments' LabVIEW software was chosen as the primary coding language to be used for control and data acquisition. LabVIEW software was chosen due to previous experience with the software through academic career, extensive support through university available training modules, and flexible nature when paired with NI hardware. The multitude of input/output modules and general component modularity of NI hardware allows for system expansions without being an expert in data acquisition systems. In addition LabVIEW and NI products are commonly used in both academic research as well as industry. The company is also well established throughout the engineering field so it is expected that there will be continued support for the hardware.

Kollmorgen was chosen for the acquisition of actuation systems to satisfy the needs of the system. Kollmorgen was chosen due to the company being well established company, existing for over 100 year. Kollmorgen also has a wide variety of different motors and actuation systems capable of addressing the design considerations. In addition NI partnered with the Kollmorgen company in 2013 to allow direct incorporation of the companies sophisticated servo motor drivers directly into the LabVIEW SoftMotion control software using the driver's Ethernet for Control Automation Technology (EitherCAT) protocol.

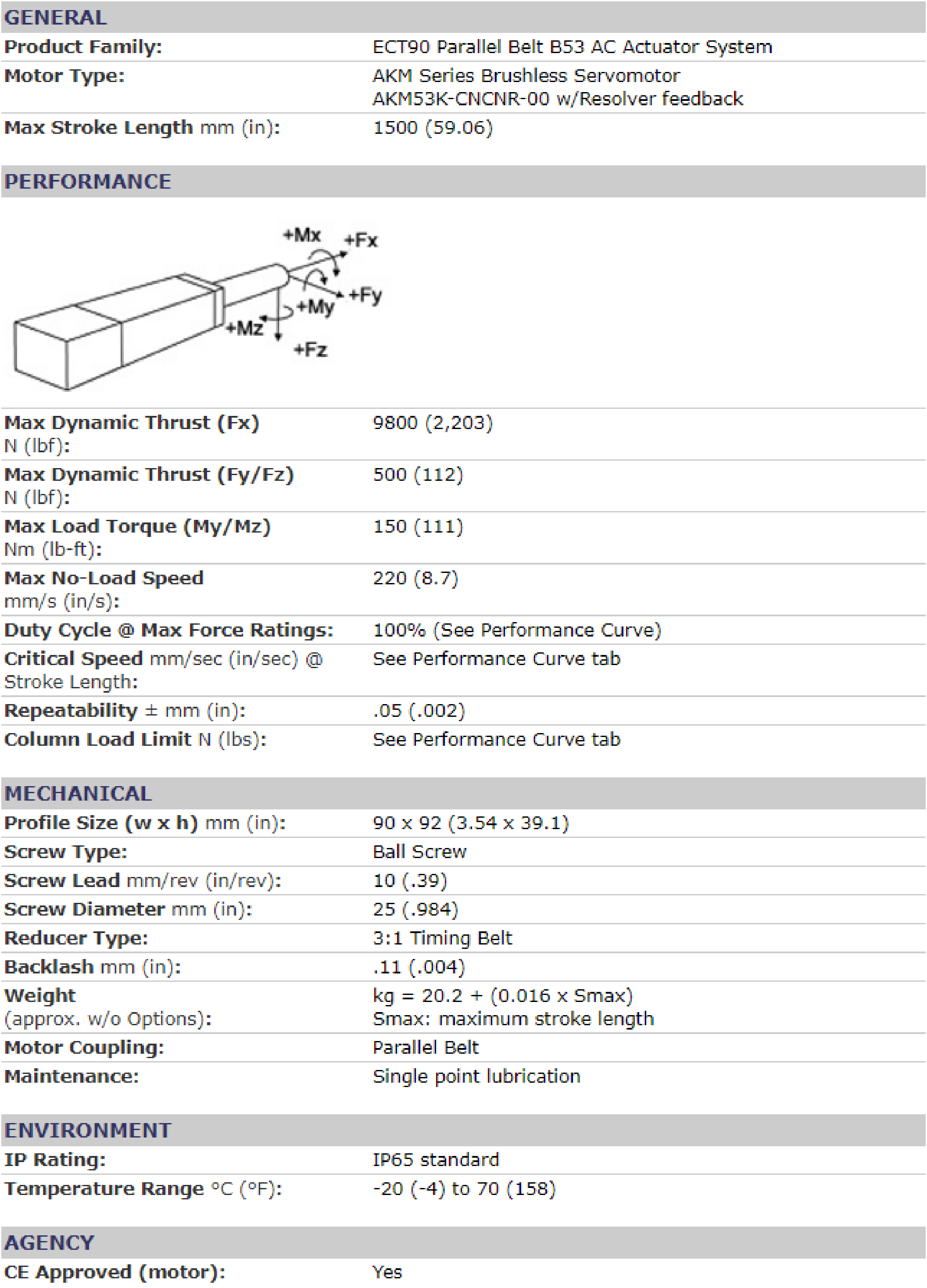
### *2.3.2 National Instruments Hardware*

The primary controller of the system is the Compact Reconfigurable Input/Output (cRIO)-9064. The system has a 667 MHz Dual-Core CPU, 512 MB DRAM, 1 GB Storage, Zynq-7020 FPGA, and a 4-slot chassis for C series modules, shown in Figure 6. The cRIO controller acts as the primary communication hub between the host PC and the Kollmorgen servo motor driver. The deterministic functionality of the system will allow for the necessary control system response for various safety measures as well as data acquisition. Currently the only C series module purchased for the system was the NI-9205 which has ±10 V, 16-bit analog to digital resolution with 32 single input (16 differentia) input channels with a capability of sampling at 250 kS/s. This will allow for sampling of various sensors such as load cells, LVDT’s, extensometers, and any other sensors that output an analog signal. With the three additional open chassis slots, expansion for digital I/O modules and analog output modules are simple to integrate. This ease of interchangeable control system hardware allows for system adjustment on a per project basis.

**Figure 6 – cRIO 9064 with four slot chassis, reprinted from National Instruments [15]**

### *2.3.3 Kollmorgen Hardware*

For the linear actuator of the testing system, the ECT09-B53S03PB-2510 servo driven electric cylinder was selected with detailed specifications shown in Figure 7. This actuator is capable of the desired 2000 lbf axial loading capacity and can operate with a 100% duty cycle, allowing for long term fatigue studies.



**GENERAL**

| | |
|---|---|
| **Product Family:** | ECT90 Parallel Belt B53 AC Actuator System |
| **Motor Type:** | AKM Series Brushless Servomotor<br>AKM53K-CNCNR-00 w/Resolver feedback |
| **Max Stroke Length** mm (in): | 1500 (59.06) |

**PERFORMANCE**

| | |
|---|---|
| **Max Dynamic Thrust (Fx)** N (lbf): | 9800 (2,203) |
| **Max Dynamic Thrust (Fy/Fz)** N (lbf): | 500 (112) |
| **Max Load Torque (My/Mz)** Nm (lb-ft): | 150 (111) |
| **Max No-Load Speed** mm/s (in/s): | 220 (8.7) |
| **Duty Cycle @ Max Force Ratings:** | 100% (See Performance Curve) |
| **Critical Speed** mm/sec (in/sec) @ Stroke Length: | See Performance Curve tab |
| **Repeatability** ± mm (in): | .05 (.002) |
| **Column Load Limit** N (lbs): | See Performance Curve tab |

**MECHANICAL**

| | |
|---|---|
| **Profile Size (w x h)** mm (in): | 90 x 92 (3.54 x 39.1) |
| **Screw Type:** | Ball Screw |
| **Screw Lead** mm/rev (in/rev): | 10 (.39) |
| **Screw Diameter** mm (in): | 25 (.984) |
| **Reducer Type:** | 3:1 Timing Belt |
| **Backlash** mm (in): | .11 (.004) |
| **Weight** (approx. w/o Options): | kg = 20.2 + (0.016 x Smax)<br>Smax: maximum stroke length |
| **Motor Coupling:** | Parallel Belt |
| **Maintenance:** | Single point lubrication |

**ENVIRONMENT**

| | |
|---|---|
| **IP Rating:** | IP65 standard |
| **Temperature Range** °C (°F): | -20 (-4) to 70 (158) |

**AGENCY**

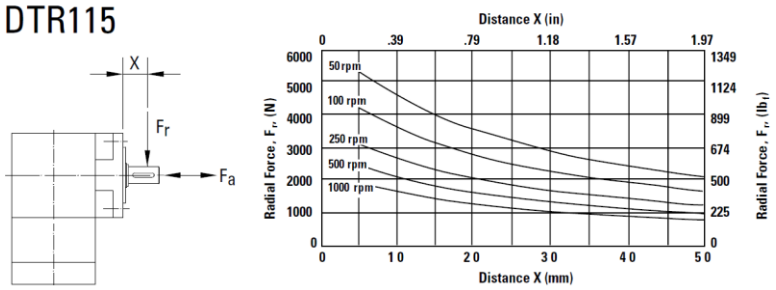
| | |
|---|---|
| **CE Approved (motor):** | Yes |

**Figure 7 – ECT90 technical specifications from Kollmorgen product advisor, reprinted from Kollmorgen [16]**

The actuator functions with an AKM53K servo motor which requires the AKD-P01206-NBEC-0000 driver based on maximum operational current of the motor, shown in Figure 8. A driver which operates on single phase power was chosen over 3 phase due to limitations on available power in the building.

**Figure 8 – Solidworks rendering of Kollmorgen AKD-PO1206-NBEC-0000 servo motor driver**

For torsional actuation the DTR115-010-GIF00432211- RM115-40 gearhead was selected which was a custom variation of the DTR115 series. The DTR115 series was one of the few gearheads capable of handling both tension and compression based axial loadings. This was taken into account for potential combined axial-torsion loadings in future projects and system configurations.



| Speed<br>rpm | Axial Load, $F_a$<br>N [$lb_f$] |
|---|---|
| 50 | 8196 [1844] |
| 100 | 6505 [1464] |
| 250 | 4793 [1078] |
| 500 | 3804 [856] |
| 1000 | 3019 [679] |

**Figure 9 – DTR115 torsional gear head technical information concerning external loading, reprinted from Thompson Linear [17]**

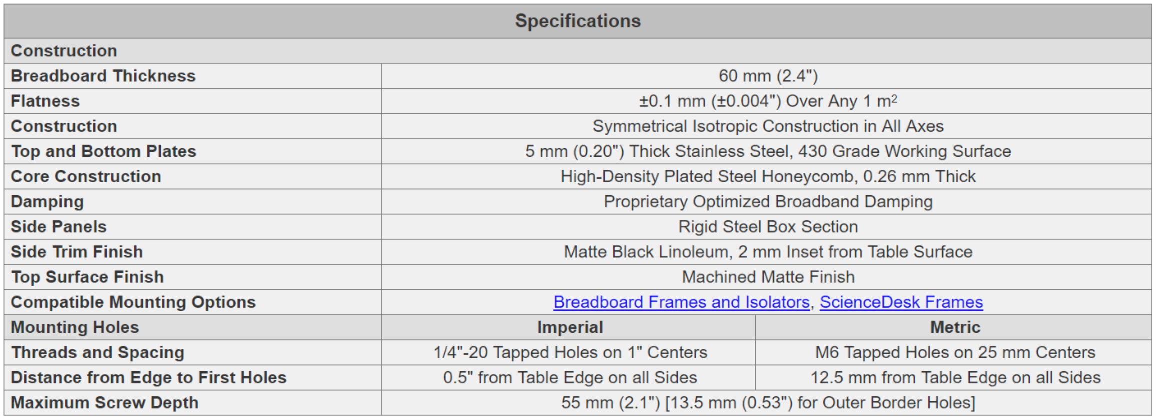
### *2.3.4 LVDT and Load Cells*

A TransTek Series 210-220 15 inch stroke LVDT was chosen based on the 12 inch stroke of the actuator to avoid reaching the ends of the LVDT. This was paired with a TransTek Series 1000 0scillator/demodulator to convert the LVDT multi-channel output to an analog signal to read using the NI-9205 analog input module.

## 2.4 Load Frame Design and System Configurations

### *2.4.1 Load Frame and System Base*

Keeping in mind the desire for configurability of the system on a physical scale, it was desired to use existing and easily purchasable components to construct the load frame. The load frame of a testing system is the structural components, which carry the primary load during a given test/action. 80/20 Inc.'s aluminum extruded profiles were chosen due to the components being readily available, multiple attachment points through the t-slots, and companies' large set of hardware available for mounting. This gives the system a large amount of flexibility for total frame configurations, but also mounting options for various sensors and additional actuators/motors. The profiles chosen to make up the primary components of the load frame were the #3060 profiles from 80/20 Inc. ThorLab's breadboards were chosen as the systems base to allow for a large amount of flexibility in the mounting locations for fixtures, additional hardware, and sensors. The Nexus breadboard B2436F was chosen based on available space for the bed of the testing system with specifications shown in Figure 10.



| Specifications | | |
|---|---|---|
| **Construction** | | |
| **Breadboard Thickness** | 60 mm (2.4") | |
| **Flatness** | ±0.1 mm (±0.004") Over Any 1 m$^2$ | |
| **Construction** | Symmetrical Isotropic Construction in All Axes | |
| **Top and Bottom Plates** | 5 mm (0.20") Thick Stainless Steel, 430 Grade Working Surface | |
| **Core Construction** | High-Density Plated Steel Honeycomb, 0.26 mm Thick | |
| **Damping** | Proprietary Optimized Broadband Damping | |
| **Side Panels** | Rigid Steel Box Section | |
| **Side Trim Finish** | Matte Black Linoleum, 2 mm Inset from Table Surface | |
| **Top Surface Finish** | Machined Matte Finish | |
| **Compatible Mounting Options** | Breadboard Frames and Isolators, ScienceDesk Frames | |
| **Mounting Holes** | **Imperial** | **Metric** |
| **Threads and Spacing** | 1/4"-20 Tapped Holes on 1" Centers | M6 Tapped Holes on 25 mm Centers |
| **Distance from Edge to First Holes** | 0.5" from Table Edge on all Sides | 12.5 mm from Table Edge on all Sides |
| **Maximum Screw Depth** | 55 mm (2.1") [13.5 mm (0.53") for Outer Border Holes] | |

**Figure 10 – ThorLabs B2436F breadboard specifications, reprinted from ThorLabs [18]**

The #3060 profiles were assembled and mounted to the ThorLabs breadboard with custom adaption plates made from 304 stainless steel. An additional adaption plate was created to mount the chosen linear actuator which secures to the aluminum profiles. A Solidworks assembly of the frame can be seen in Figure 11 with fabrication drawings and assembly details in Appendix B.

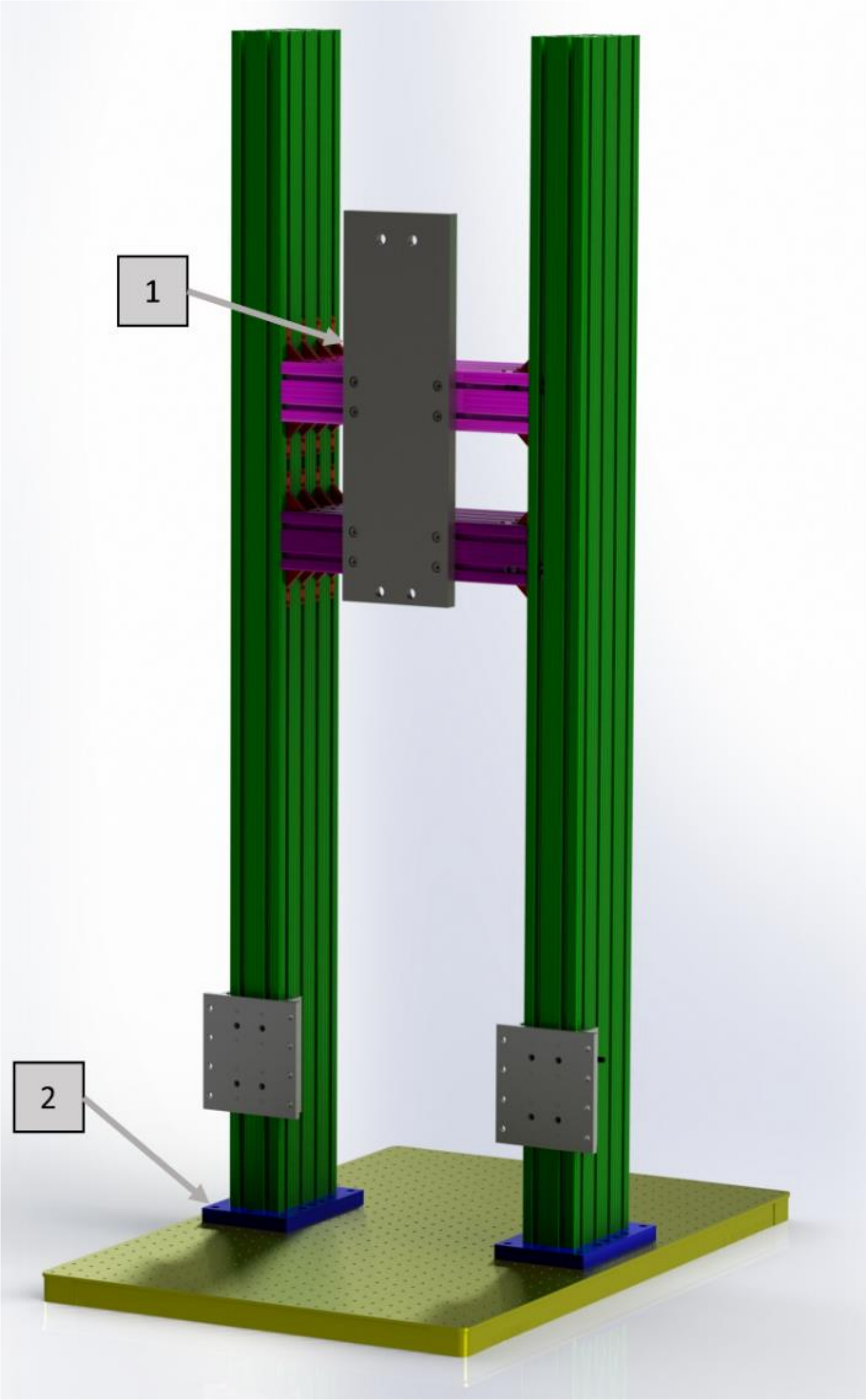


**Figure 11 – Isometric Solidworks view of the RTS frame with Thorlabs breadboard and 1) custom mounting plate for linear actuator, 2) custom mounting plates for 80/20 profile to breadboard**

### *2.4.2 Uniaxial Configuration*

The electric servo linear actuator mounts to the adaption plate with four M12 socket head cap screws. In addition to the linear actuator, and LVDT is mounted to the aluminum profiles of the frame and are shown in Figure 12.

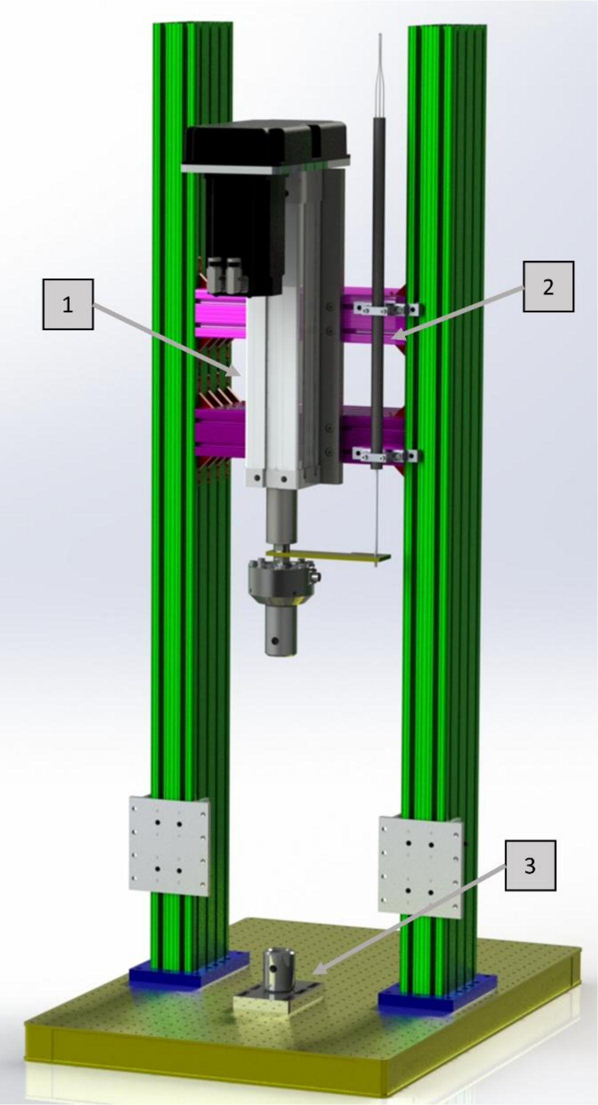


**Figure 12 – Uniaxial configuration of the RTS. 1) Electromechanical servo driven actuator, 2) Trans Tek LVDT with mounts, 3) custom fixture for mounting to the ThorLabs breadboard**

The components attached to the end of the linear actuator are shown in Figure 13. The construct ends with a female mounting fixture which allows for a standard attachment method between testing systems in the BMEL. In addition, this standard attachment method allows for quicker fixturing design and fabrication due to machinist and engineer's familiarity.

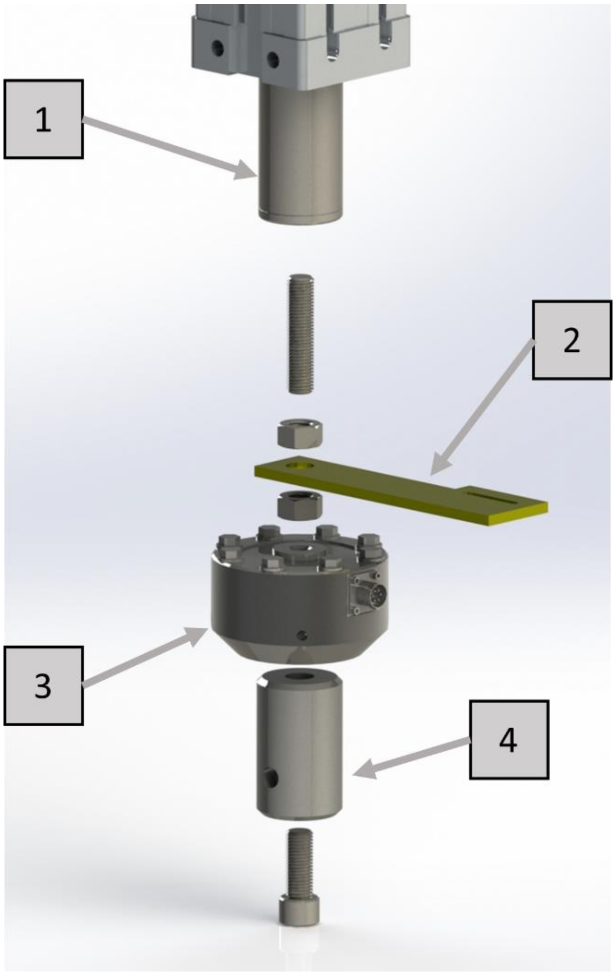


**Figure 13 – Exploded view of components attached to the end of the linear actuator. 1) Linear actuator shaft, 2) LVDT attachment to the actuator, 3) LCF 456 series load cell, 4) BMEL standardized female attachment method for experimental fixturing**

### *2.4.3 Torsional Actuation Configuration*

The current torsional configuration uses the same load frame layout. The linear bearings on the load frame are used for the manual positioning of the load cell and female mounting fixture. The custom mounting fixture on the Thorlabs breadboards is removed and replaced with the torsional actuator shown in Figure 14.

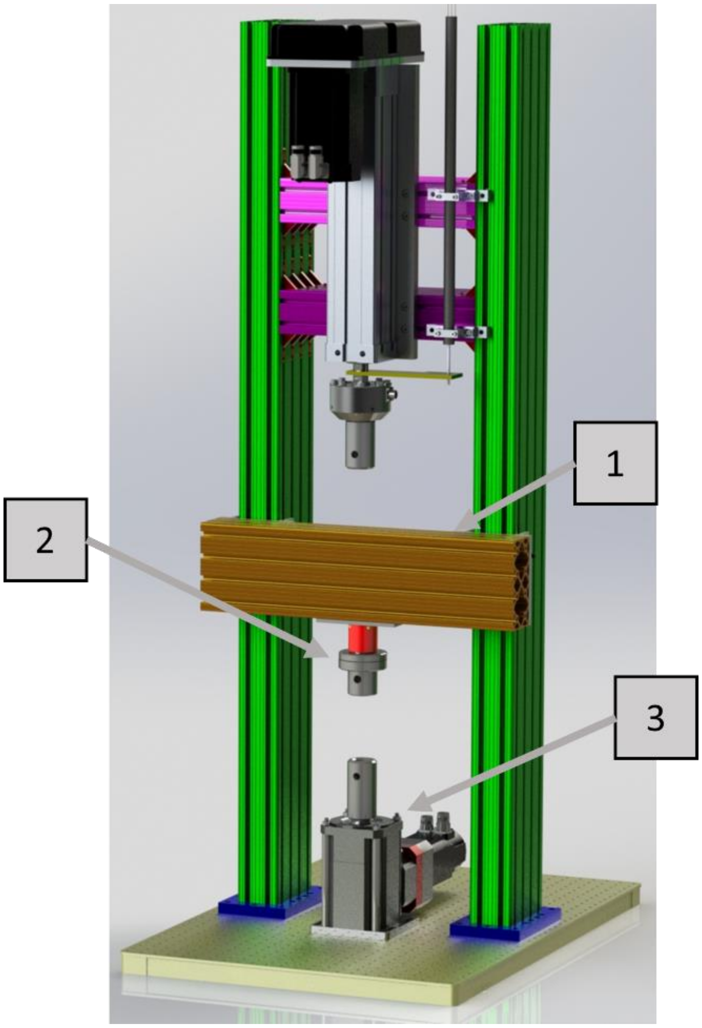


**Figure 14 – Torsional actuation configuration with 1) the loading member added to the linear bearings, 2) Torsional load cell and associated fixtures, 3) Torsional actuator with associated mounting fixtures**

The load cell is attached to a horizontal aluminum profile and ends with the same standard female mounting fixture used in the BMEL and is shown in Figure 14.

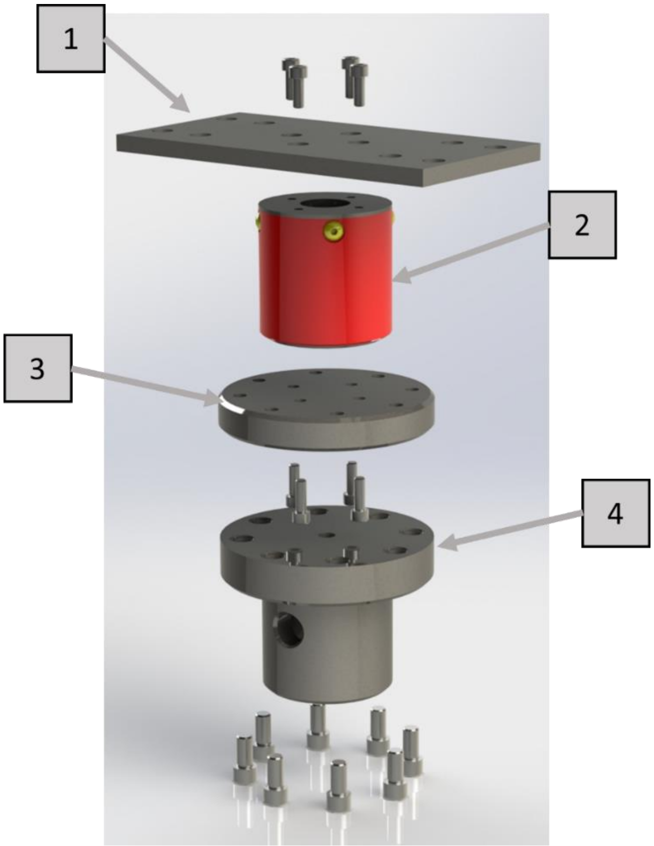


**Figure 15 – Solidworks exploded view of mounting method for the torsional load cell. 1) Adaption plate for load cell to 80/20 profile, 2) Futek TFF400 series load cell, 3) Adaption plate for load cell to BMEL female mounting fixture 4) Pre-existing BMEL female mounting fixture**

The torsional actuator is servo driven and connects to the control system hardware that has previously operated the linear actuator. The actuator is mounted to the Thorlabs breadboard using custom fixturing shown in Figure 16.

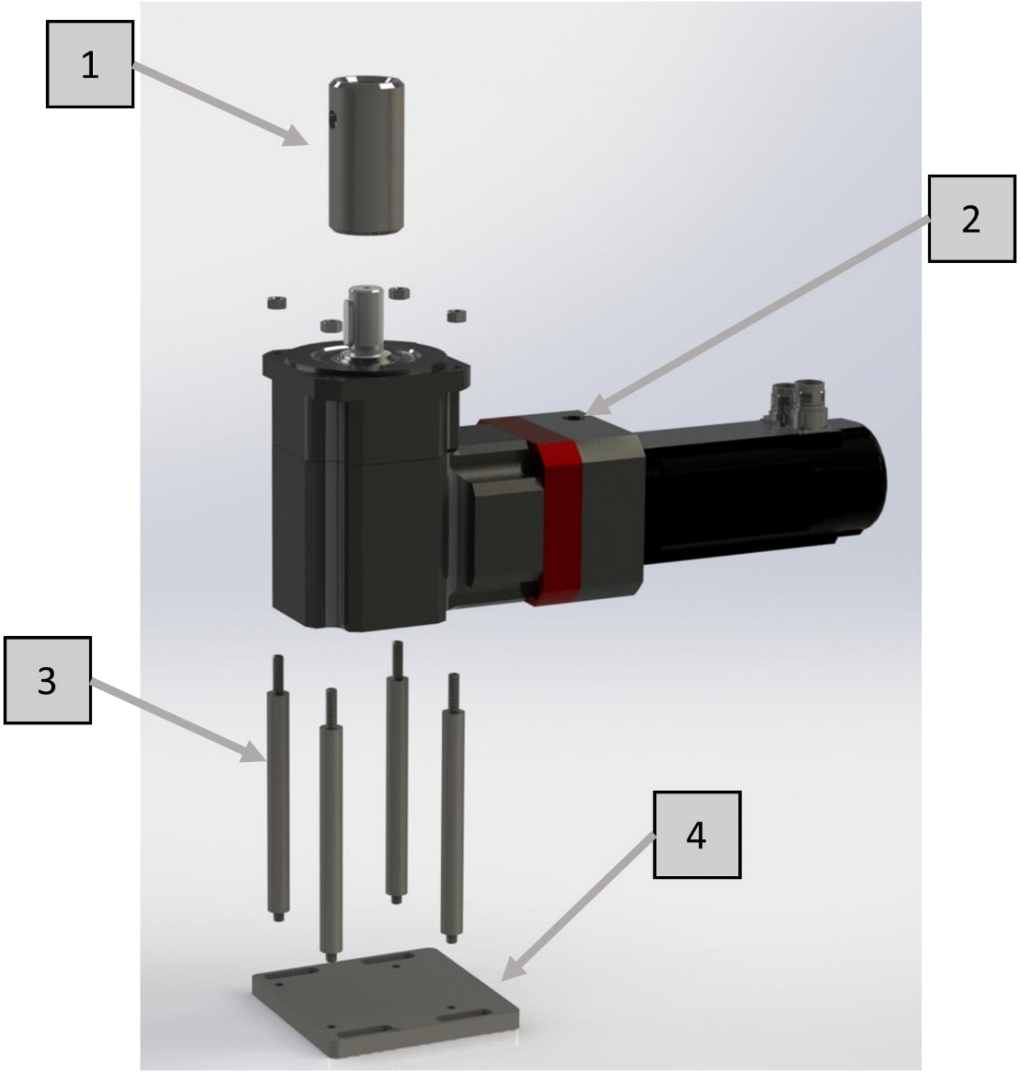


**Figure 16 – Torsional actuator and associated mounting fixtures. 1) BMEL female mount, 2) Torsional actuator and associated servo motor, 3) Load bearing rods for mounting, 4) Adaption plate to Thorlabs breadboard**

### *2.4.4 Additional Features and Configurations*

A common need in biomechanical experimentation, particularly the evaluation of soft tissues, is the integration of a biobath. With the use of the lab standardized female mounting fixtures, the integration of an existing bio bath is possible with no additional fixturing and is shown in Figure 17.

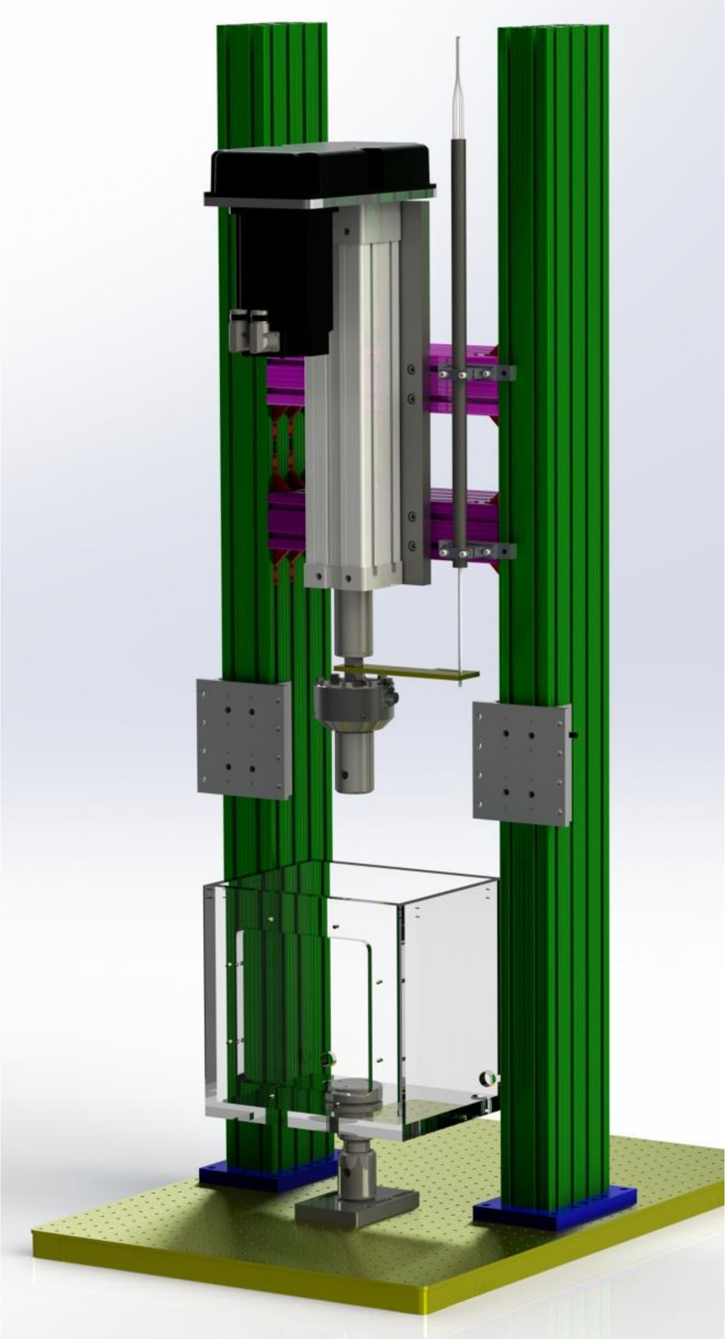


**Figure 17 – Integration of a biobath with the uniaxial configuration of the RTS**

Shown in Figure 18 is a potential configuration including a simplified frame and a high precision linear actuator, with a cost estimate shown in Table 1. In this configuration, the frame could be simplified to a single column under a smaller maximum load of approximately 120 lbf.

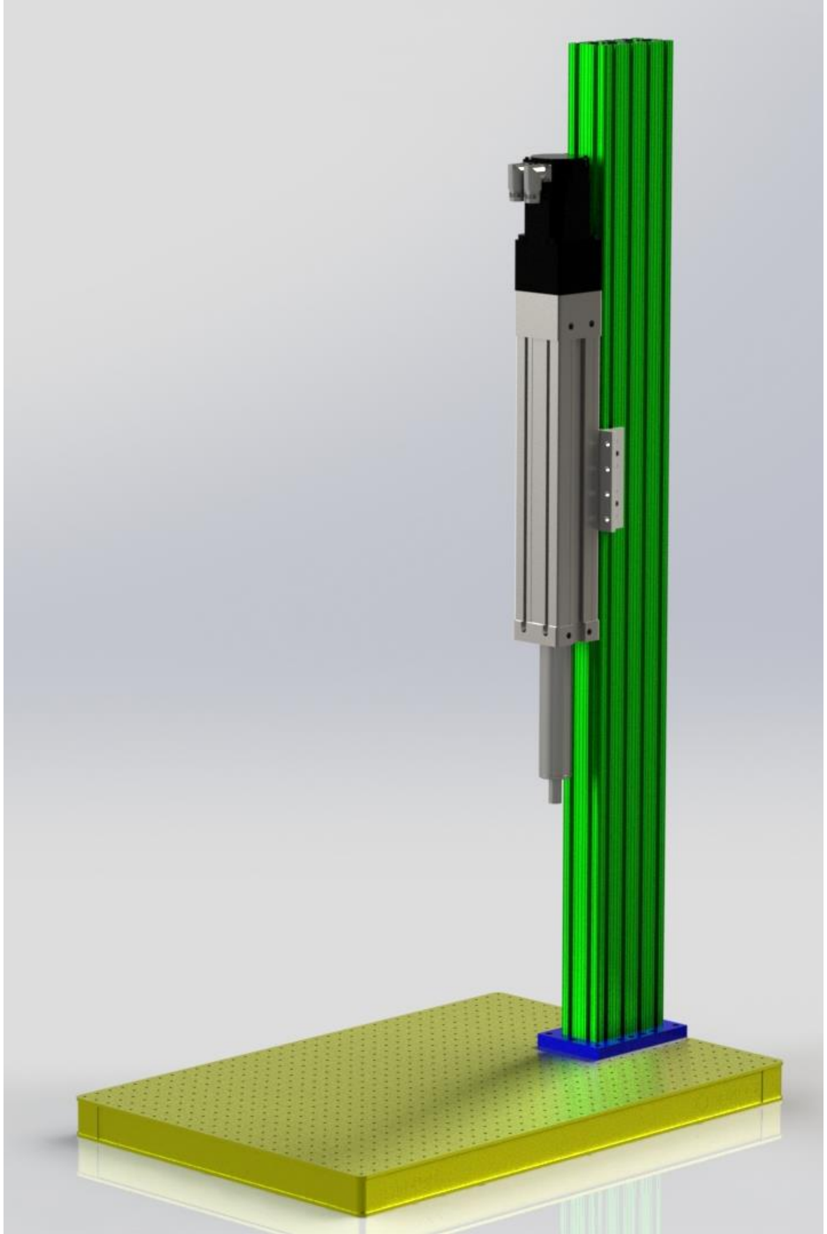


**Figure 18 – Potential configuration of RTS with a Thompson Linear T90-B32 precision linear actuator and simplified frame configuration.**

**Table 1 – Estimate cost of additional components to integrate the Thompson Linear T90-B32 actuator into the RTS**

| Item | Cost |
|---|---:|
| Thompson Linear T90-B32 | $1,200 |
| Custom adaption components | $150 |
| AKM4x Servo Motor | $950 |
| **Total** | $2,300 |

Another example of a potential system configuration is the inclusion of a rodless actuator shown in Figure 19 with a cost estimate shown in Table 2. As with the configuration in Figure 18, both actuator types can be controlled using the existing AKD with minor configuration to match the specific AKM associated to the actuator. The communication methods and overall functionality of the software and control system hardware, discussed in the following chapter, do not significantly change with configuration of the AKD.

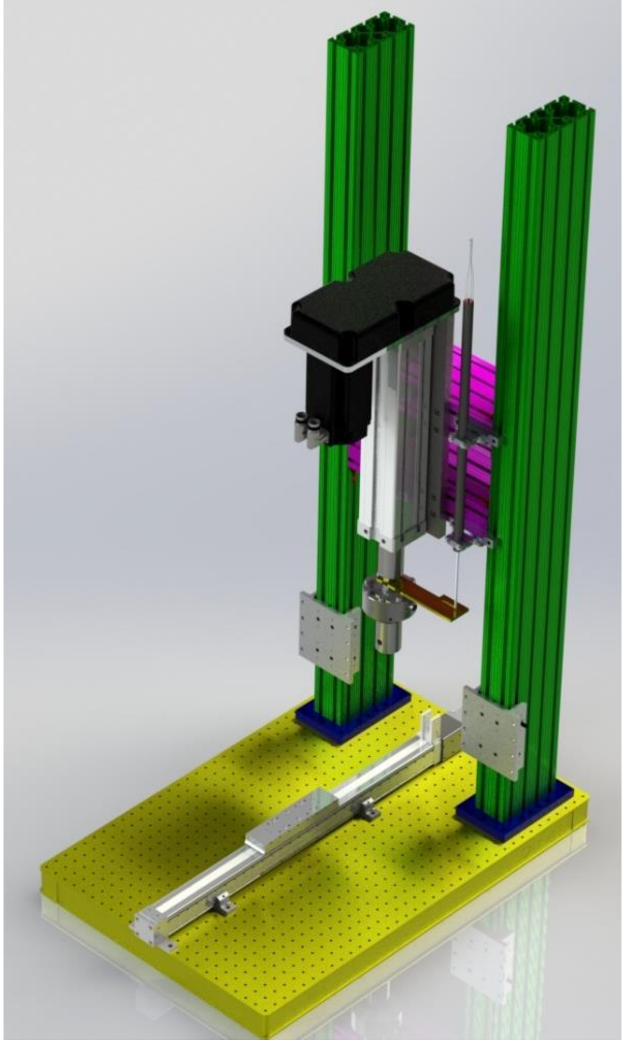


**Figure 19 – Potential configuration of the RTS with the Thompson Linear R3 rodless actuator with an AKM3x series servo motor**

**Table 2 – Estimate cost of additional components to integrate the Thompson Linear R3 actuator excluding labor into existing RTS**

| Item | Cost |
|---|---:|
| Thompson Linear R3 Actuator | $1,500 |
| AKM3x Servo Motor | $800 |
| AKD-P00306 | $870 |
| **Total** | $3,170 |

# CHAPTER III

# SYSTEM SOFTWARE

## 3.1 Introduction

LabVIEW software was used to program the control system for the reconfigurable testing system. The goal of the software design was to create a system with safety checks, data recording, and a user friendly interface. In addition, it was desired to create the code in such a way as to ease the expansion of the system hardware for future use. This was done by creating a custom user interface (UI) within LabVIEW that operates on the PC system with the time critical deterministic functionality operating on the cRIO. During operation, the cRIO has three main loops which run continuously; these loops are the Control System, Data Logging, and Data Recording/Publishing. The Control System loop handles the communication between the code and the hardware of the system, including safety cutoffs and PI control. The Data Logging loop collects data from the various sensory hardware, such as load cells and LVDTs, and records the values at a given time to an internal variable. The Data Recording/Publishing loop takes the data from the Data Logging loop and records the information to a specified file while also publishing data to the PC for display on the UI.

## 3.2 LabVIEW Modules

This next section describes the various LabVIEW modules that were used throughout the RTS's software. Each module is an addition to the base LabVIEW software package available from National Instruments.

### *3.2.1 SoftMotion*

SoftMotion is a commonly used module in LabVIEW for the control of stepper and servo motors. LabVIEW's SoftMotion module allows for the implementation of various operation such as trajectory generation, spline interpolation, and definition of control system axes [19]. Specifically concerning advanced servo motor drivers, such as the Kollmorgen AKDs, SoftMotion has built in operations allowing for fast development and ease of communication and control using Ethernet for Control Automation Technology (EitherCAT) protocol [20].

### *3.2.2 Real-Time*

Real-Time is a common and necessary module in LabVIEW for development of deterministic applications. Real-Time allows for the control of deterministic target systems, the setting of loop execution priority, automatic or manual assignment of individual CPU cores, and system resource monitoring during software execution [21].

## 3.3 Software Design

### *3.3.1 Overview*

The LabVIEW project created to operate the RTS can be broken down into four primary LabVIEW VI's or loops.

1. Control System
2. Data Logging
3. Data Recording/Publishing
4. User Interface

The first three VI's operate on the cRIO as each have time critical tasks which require deterministic functionality. The User Interface operates on the PC allowing the tasks of displaying information to be offloaded from the cRIO system. The systems runs through an initialization sequence, then begins the simultaneous and continuous execution of the primary VI's mentioned. When operation is terminated, a shutdown sequence is initiated to safely power down all hardware before cutting communication. A diagram outlining the structure of the LabVIEW Project and critical VI's is shown in Figure 20.

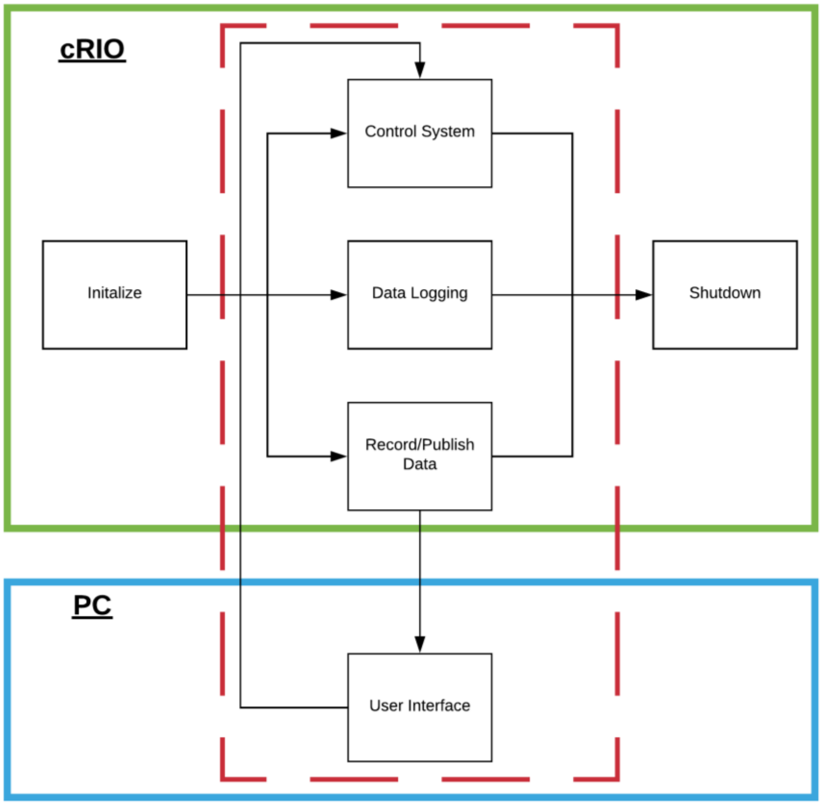


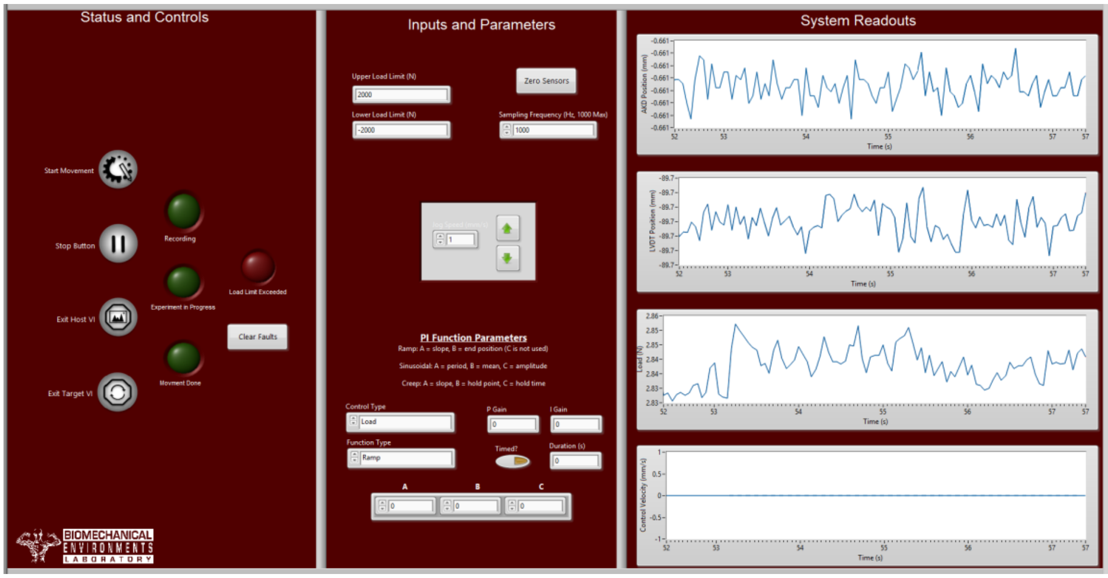
**Figure 20 – Layout of primary LabVIEW project VI's between the cRIO and PC systems. The red dashed box indicates a continuous execution during RTS operation while the black arrows indicate communication between loops.**

The LabVIEW code operates on the cRIO device using scan mode. This mode of functionality allows for quick development without an understanding of Field Programmable Gate Array (FPGA) programming and system compiling [22].

### *3.3.2 User Interface*

**Overview**

The user interface consists of three sections. The status and Controls section contains the buttons which initiate a state change in the control loop as well as indicator lights to assist the operator. The next section are the inputs and parameters section, this is where the values are defined by the operator for the various movement types the system is capable of performing. The last section are the system readouts, which contain various graphs for the operator to monitor the system in real time.



Upper Load Limit (N)
2000

Lower Load Limit (N)
-2000

Sampling Frequency (Hz, 1000 Max)
1000

Jog Speed (mm/s)
1

**PI Function Parameters**

Ramp: A = slope, B = end position (C is not used)

Sinusoidal: A = period, B = mean, C = amplitude

Creep: A = slope, B = hold point, C = hold time

Control Type
Load

P Gain
0

I Gain
0

Function Type
Ramp

Timed?

Duration (s)
0

A
0

B
0

C
0

**Figure 21 – View of the user interface seen while operating the RTS immediately after initialization sequence and all parameters at default values**

## Status and Controls

The status and controls section of the user interface serves two primary purposes; to allow the operator to initiate commands to the software's primary control loop and to indicate the current condition of the system. The status and controls section of the user interface is shown in Figure 22.

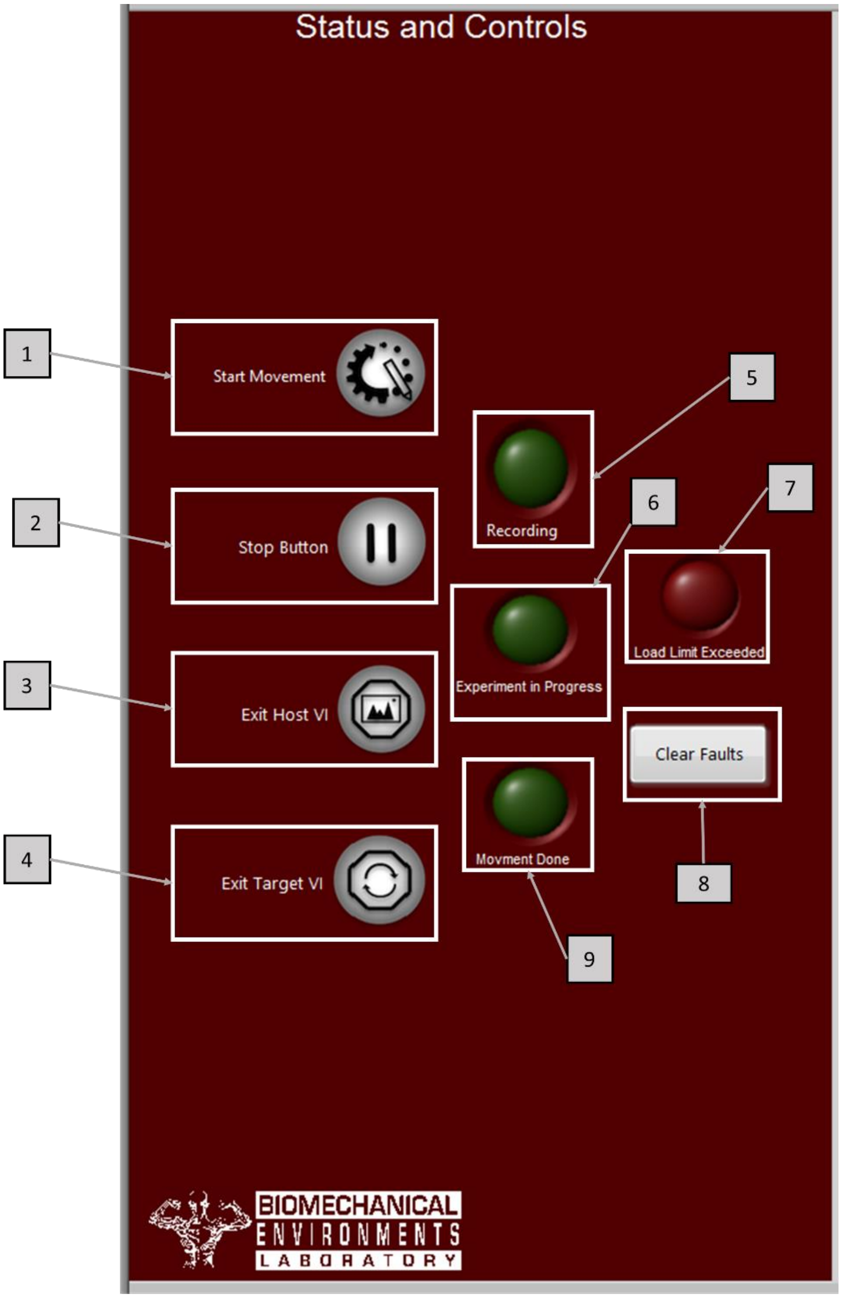
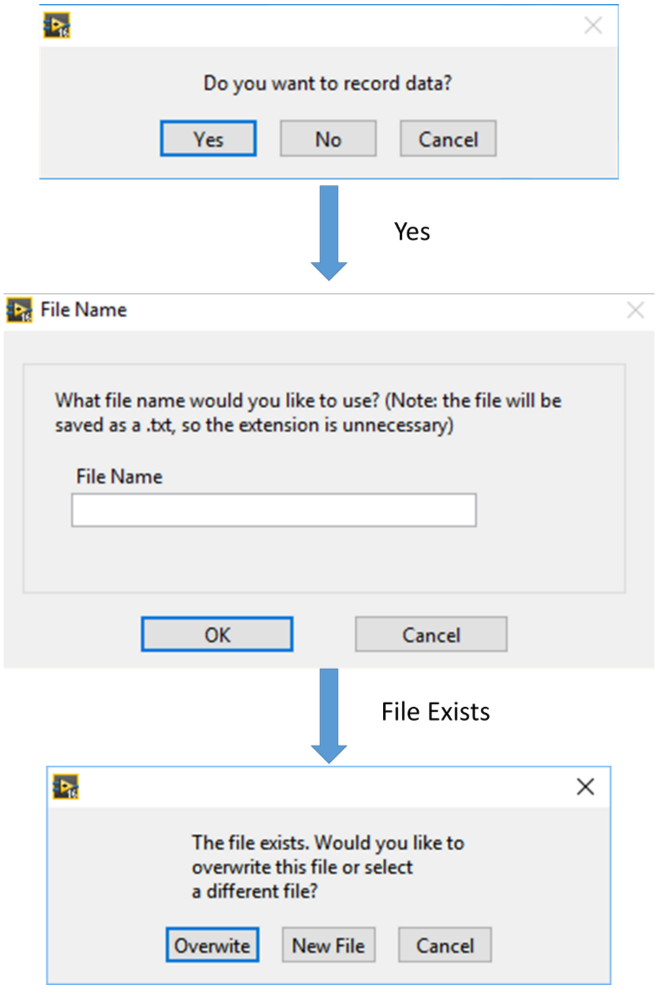


**Figure 22 – An isolated view of the status and controls section of the user interface: 1) Initiates a PI controlled movement defined by the operator 2) Stops all current movement in the system and disables the AKD, 3) Exits the user interface VI which leaves the cRIO in communication with the system, 4) Exits the cRIO out of the various control loops and sends the system into a shutdown sequence, 5) Indicator showing if data is being collected, 6) Indicator showing experiment in process, 7) Indicator for exceeding user defined load, 8) Clears faults on the AKD, 9) Indicator showing when a movement is completed**

When the start movement button is pressed a series of popups follow, shown in Figure 23, for file creation and data recording if desired by the operator. This series of popups performs several checks prior to allowing the system to begin a movement:

1. Check to see if the cRIO can be accessed
2. Check to see if a file with the same name has been created
3. Removes any user input extension as the default is a .txt file
4. Creates a file header with experimental information
5. Cross checks that the file indicated by the user was created and is accessible on the cRIO's non-volatile memory


Do you want to record data?

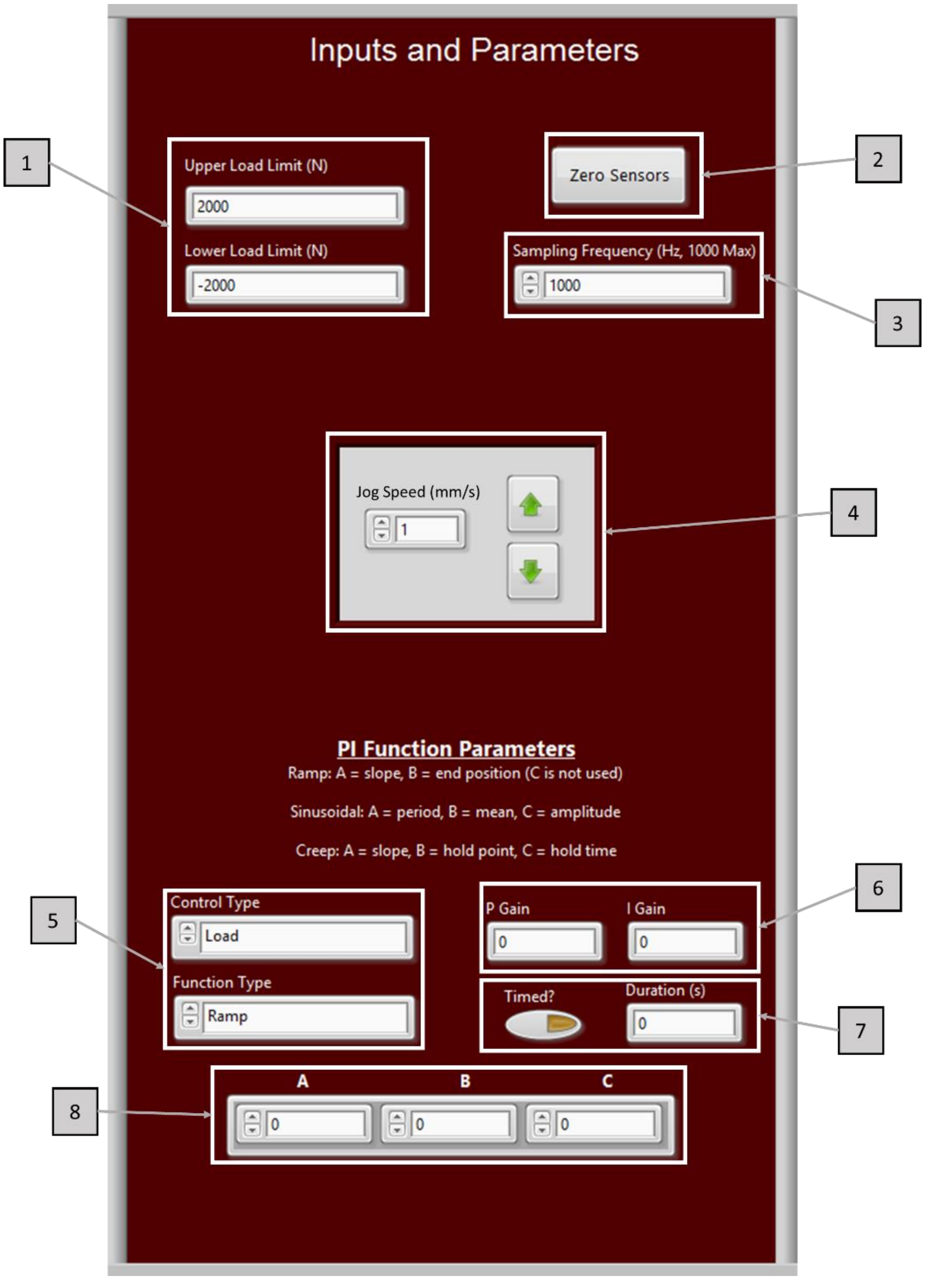
What file name would you like to use? (Note: the file will be saved as a .txt, so the extension is unnecessary)

The file exists. Would you like to overwrite this file or select a different file?

**Figure 23 – Data recording and file creation popup sequence when start movement is initiated on the user interface**

### Inputs and Parameters

The inputs and parameters section of the user interface allow the operator to set numeric values associated with the various movement types the system is capable of. This section of the user interface can easily be expanded as the functionality of the system expands through the addition of input fields. The inputs and parameters section of the user interface is displayed in Figure 24.



Inputs and Parameters

Upper Load Limit (N): 2000

Lower Load Limit (N): -2000

Sampling Frequency (Hz, 1000 Max): 1000

Jog Speed (mm/s): 1

PI Function Parameters

Ramp: A = slope, B = end position (C is not used)

Sinusoidal: A = period, B = mean, C = amplitude

Creep: A = slope, B = hold point, C = hold time

Control Type: Load

Function Type: Ramp

P Gain: 0

I Gain: 0

Timed?

Duration (s): 0

A: 0

B: 0

C: 0

**Figure 24 – An isolated view of the inputs and parameters section of the user interface: 1) Sets the value at which the load limit will trip and stop movement, 2) Pulls the current value from the load or position as an offset towards zero, 3) Sets the sampling frequency at which data is recorded, 4) Controls and speed input for the jog function, 5) The control (position or load) and function type (linear, sinusoidal, creep) for the PI control loop, 6) The proportional and integral values for the PI control loop, 7) Button to toggle a timed cutoff and input to set duration, 8) Parameters associated with PI controller function type set by the operator**

### System Readouts

The system readouts section contains real time displays of information pertaining to the systems operation. This information allows for the operator to monitor parameters so the system can be stopped if necessary. The system readouts section of the user interface is displayed in Figure 25.

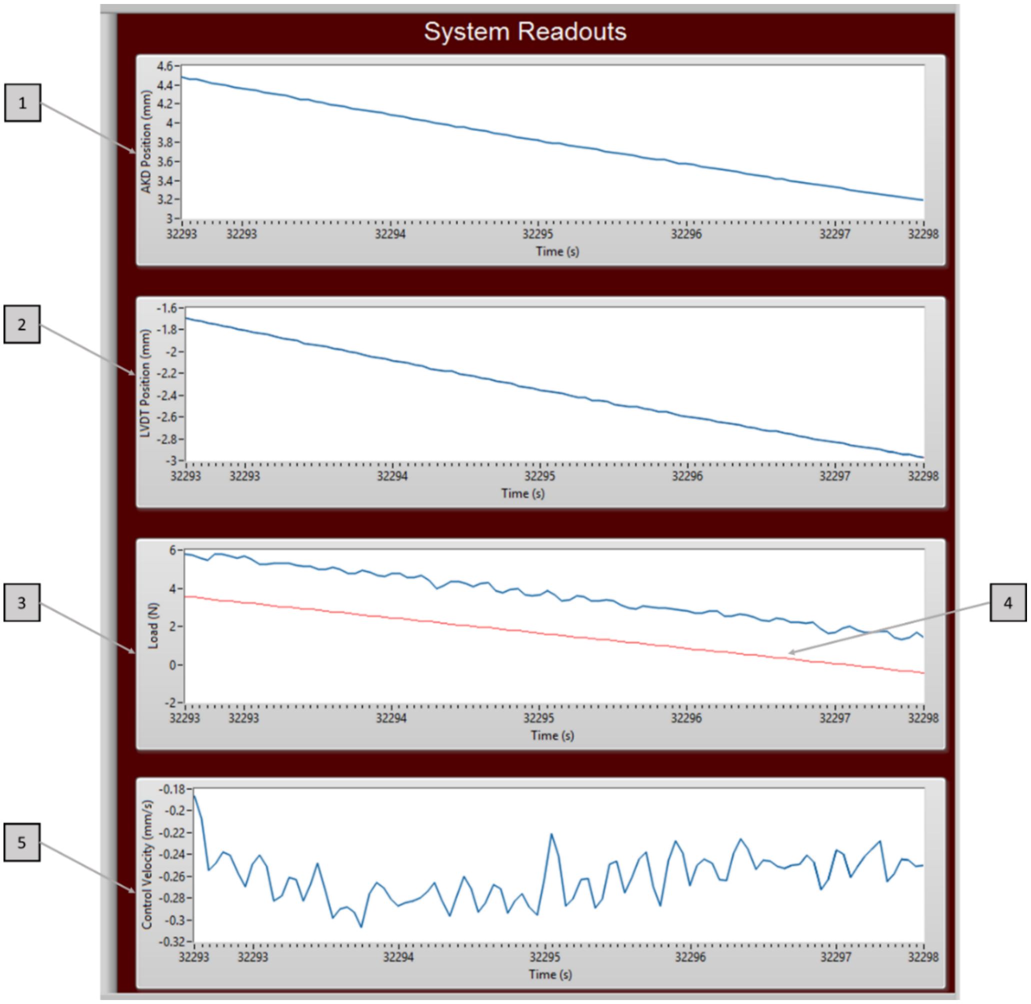


**Figure 25 – Isolated view of the system readouts section of the user interface showing a load control movement with arbitrary PI control parameters: 1) Position output from the AKD based on the servo motor encoder, 2) LVDT output, 3) Load cell output, 4) The red line indicates the target value created by the function generator for the PI control, 5) The velocity output from the PI controller via EitherCAT to the AKD**

### *3.3.3 Control Loop*

**Overview**

The control loop is the section of the LabVIEW project which handles the communication with the Kollmorgen AKD. The control loop sends commands to the AKD based on the internal sub VI's. The structure of the Control Loop is what is known as a Finite State Machine (FSM). A FSM is a coding architecture in which the system or machine under control is always in a single finite state. These states allows for easier expansion of the system as well as debugging. The control system VI has four states; wait, quick move, experiment, and stop. A diagram depicting the highest level of operation of the control loop is shown in Figure 26.

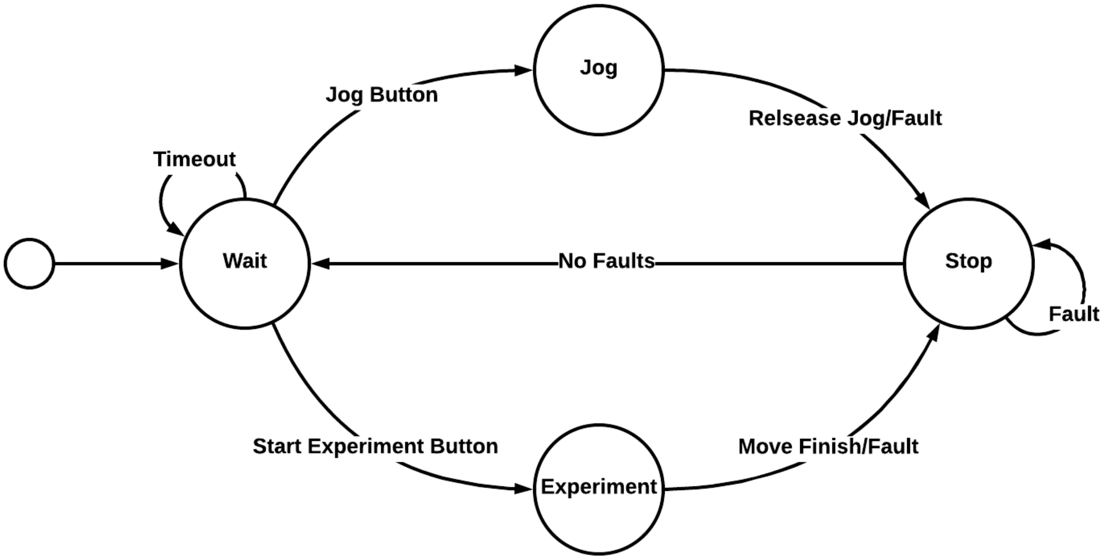


**Figure 26 – Finite state machine diagram of the control loop of the RTS**

Nested inside the various states are several safety checks, some of which are set by the operator and others that are built into the code such as:

- **Load limit** – a user defined limit set in the user interface. If the load cell measures a value higher that the user defined value a stop sequence is immediately initiated
- **Maximum user defined velocity** – a user defined value for the jog state. If an excessively large value is input a dialog window will pop up requesting a value within the safe limits of the system be selected
- **Error passing and handling** – if an error is triggered throughout any sub VI's the error will be passed through the loop triggering either custom fault handling or an immediate stop and shutdown sequence of the system
- **Experimental time out** – a user defined parameter for the experiment move state. If the duration of the move, regardless of function, exceeds the defined value a stop sequence is triggered
- **PI control velocity limits** – an internally defined value for the experiment move state. This prevents the PI control algorithm from sending velocity values to the AKD controller which could potentially cause damage to the system. This is used for both normal operation of the system and especially for the trial of new functions within the PI control

### Wait State

While the control loop is in the wait state it is checking for a state change, from the user interface, of both the quick move and experiment buttons. At this point the AKD driver is completely disabled and power is not provided to the motor components.

### Jog State

When a state change is initiated from the jog buttons on the user interface, a LabVIEW invoke node send a command to the AKD with the operator defined velocity via EitherCAT protocol. The jog state operates solely on velocity based control. During the jog state, data is not recorded as this function is intended for positioning of the actuator for experimental setup.

### Experiment State

When the control loop shifts to the experiment state, a PI control algorithm sends velocity based control information to the AKD with data recorded to the operator defined file on the cRIO system. The PI algorithm parameters such as the desired function, gains, and control type are defined by the operator on the user interface prior to starting the movement. The functions, shown in Figure 27, and control types currently implemented into the system are:

- Functions
    - **Linear/Ramp -** This follows a linear function defined by the slope and the starting point
    - **Sinusoidal** – This follows a sinusoidal function defined by the mean, period, and amplitude
    - **Creep** – This follows a linear ramp to a desired value which is held, then returns to the initial starting point defined by slope, end point, and hold time

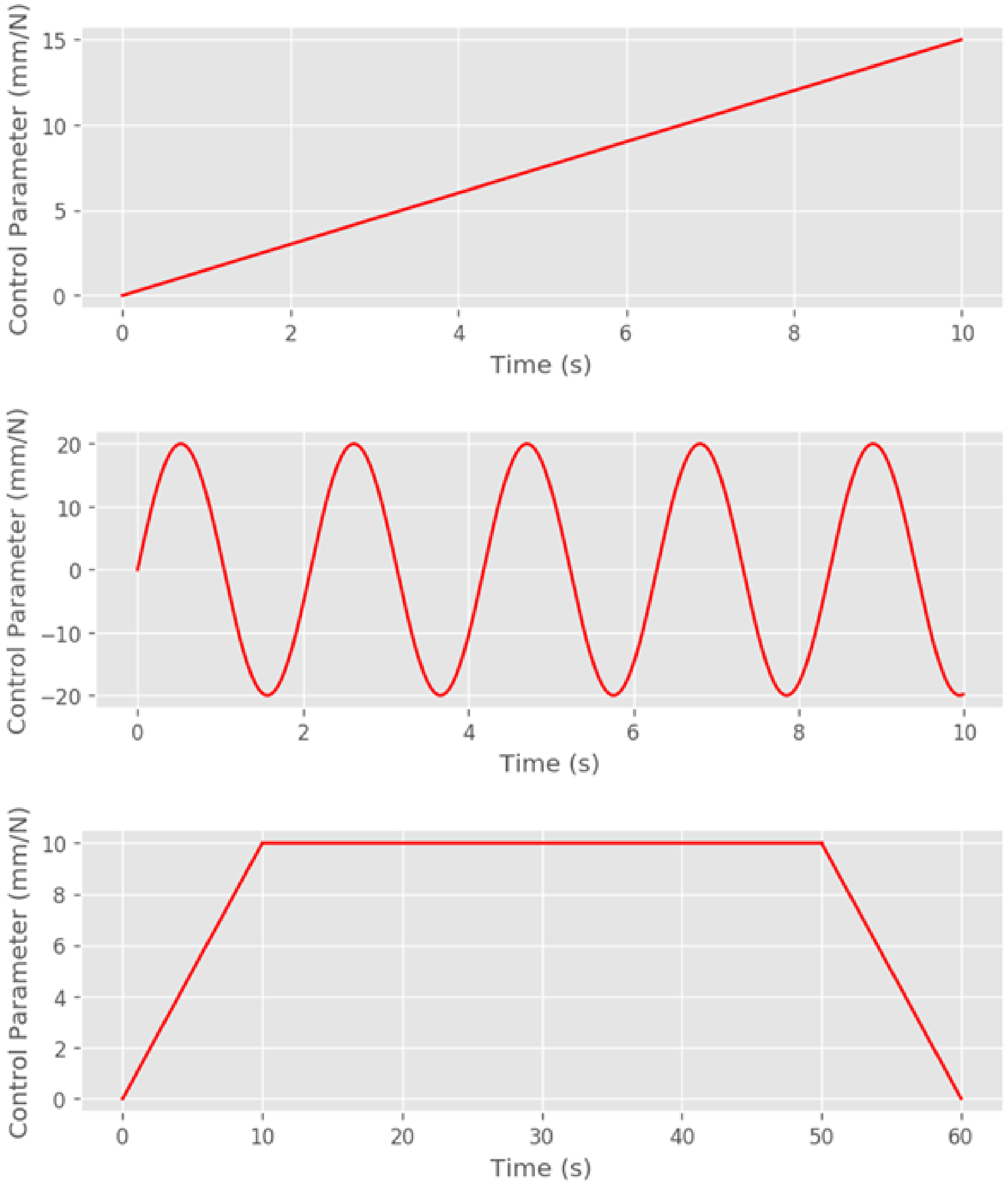


**Figure 27 – Arbitrary examples of the function types currently implemented into the RTS PI controller**

- Control Type
    - **Position** – This uses the LVDT digitally filtered feedback
    - **Load** – This uses the load cell digitally filtered feedback

A diagram of the PI controller is displayed in Figure 28.

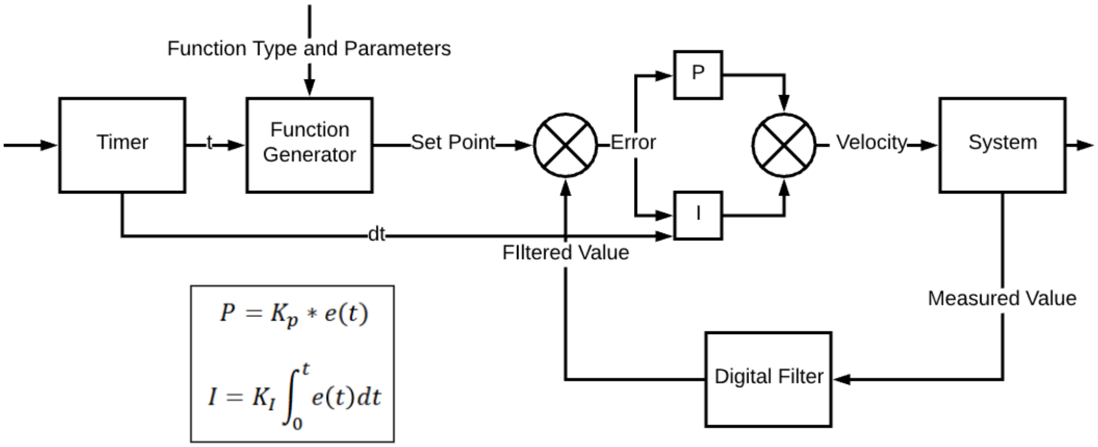


**Figure 28 – Flow diagram of the RTS PI controller**

### Stop State

The stop state is triggered when a movement is finished, a fault is tripped, or the stop button is pressed on the user interface. The stop sequence digitally disables the ADK which cuts power from the servo motor while stopping data from writing to the designated file. Disabling the drive as oppose to other stopping methods available in LabVIEW ensures that regardless of driver state or commands sent power will immediately be cut from the servo motor.

### *3.3.4 Data Logging Loop*

The data logging loop is the most time critical operation as this loop handles the collection of data from the analog input signals and the time stamping of the collected data. The data is filtered and stored in a real time first in first out (RTFIFO) cluster variable at a sampling rate of 1 kHz. This RTFIFO cluster has a defined capacity of 150 data points, with data read and recorded every 48ms this is sufficient overflow to allow the data to be properly recorded in the data recording/publishing loop. The process of the data logging loop is shown in Figure 29.

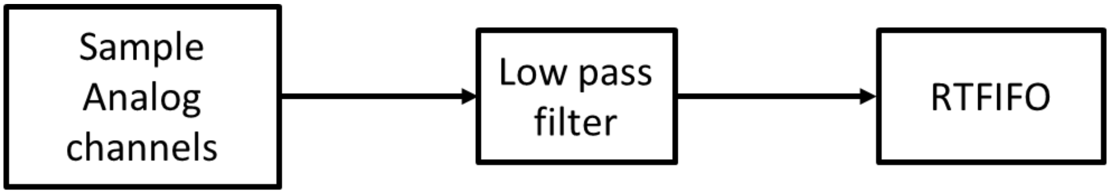


**Figure 29 – Breakdown of the data flow in the data logging loop VI**

It was necessary to isolate the data logging functionality from the control loop due to the communication methods between the cRIO and the AKD. The EitherCAT communication method causes an approximately 8ms jitter in the control loop when using the lowest level of command functions available in LabVIEW. While this is not detrimental to the control loop, as this is lower than the loop's specified period, it does interfere with the data collection at a 1 kHz sampling rate.

### *3.3.5 Data Recording/Publishing*

The data recording/publishing loop is the only non-deterministic loop operating on the cRIO. The function of the loop is the creation of a file for data recording, communicating variable information with the user interface vi on the PC system, and writing data to the created file. During data recording and communicating information with the PC system, the loop checks the RTFIFO clustered data so that only new values are recorded to the file and sent to the user interface, shown in Figure 30.

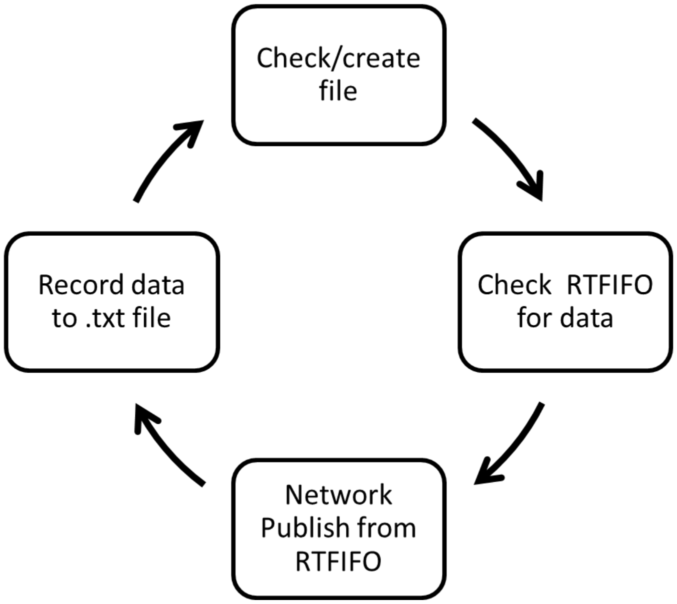


**Figure 30 – Breakdown of the data flow of the data recording/publishing VI**

### File Creation

The file module is a custom sub VI inside of the data recording/publishing VI. This sub VI is responsible for the creation of the file on the cRIO, writing a header with experimental information, writing the active experimental data, and closing out the file. The creation of this sub VI was necessary in order to write information to a file location without opening and closing the file after each data point, which occurs with most LabVIEW express write to file VI's. This file creation sub VI has three cases: create file, write to file, and close file.

The create file case pulls a string designated by the operator in the user interface and creates a .txt file on the cRIO using the string as the file name. Immediately after creating the file, the experimental information defined by the operator in the user interface is written in a header format to the file. This contains information such as the date, sensor offset and sensitivity values, and all of the PI control information. The write case of the file module sub VI takes the clustered RTFIFO values and converts them to a string before writing to the file. The close case closes the .txt file and terminates the reference path.

### Network Published Variables

Network published variables are a variable type in LabVIEW for non-deterministic communication across loops [23]. Because the RTFIFO variables must maintain determinism for proper data collection the values are written to a network published variable cluster, which then communicates the data to the user interface through the EitherCAT protocol.

# CHAPTER IV

# SYSTEM SUMMARY AND CONCLUSIONS

## 4.1 System Cost and Comparison

The total cost of the RTS comes out to approximately $47,023 with the system shown in Figure 31.

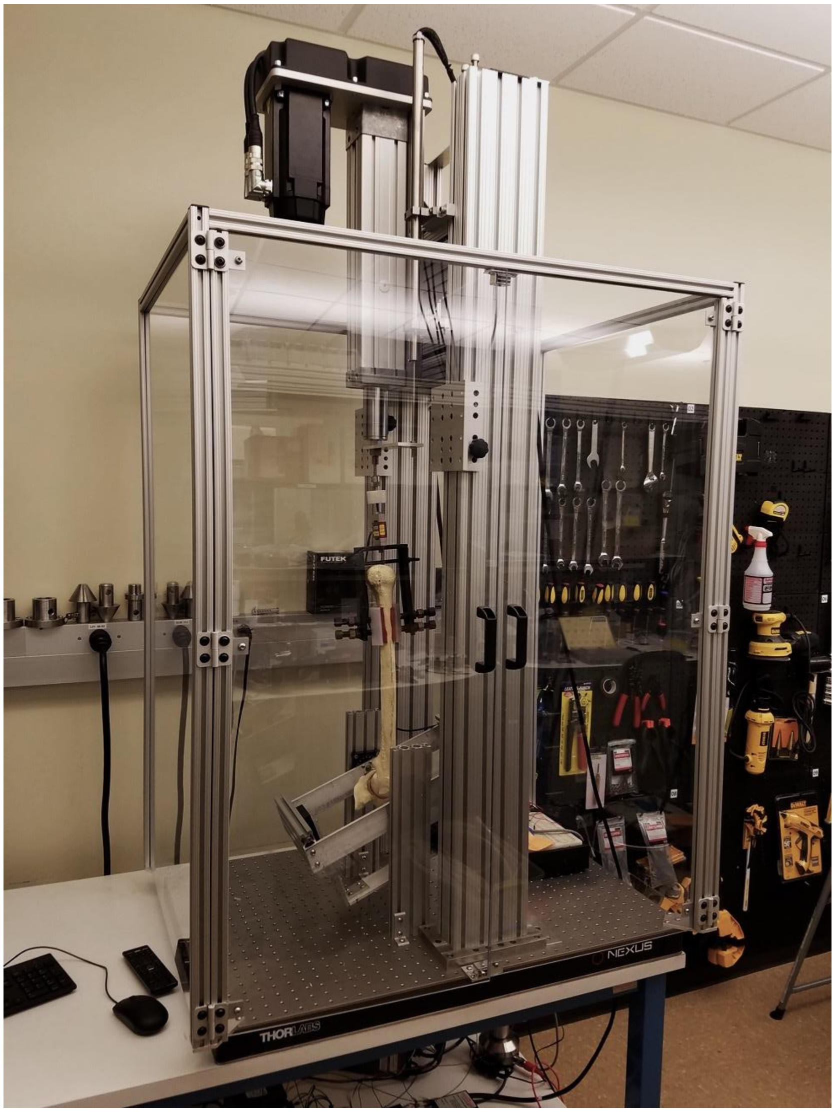


**Figure 31 – The constructed RTS in a uniaxial configuration with safety screen and fixturing with a Sawbone model for an ongoing study in the BMEL to evaluate acetabular capsule repairs**

This cost includes the fixturing involved with the system as well as fixturing for upcoming projects, additional sensors with NIST calibration, and an estimate for worker hours. A simplified cost breakdown can be seen in Table 3 with a detailed bill of materials located in Appendix B.

**Table 3 – Categorized cost breakdown for the RTS including additional fixturing for studies and an estimated cost for worker hours**

| Categories | Sum of Cost |
|---|---:|
| Actuators | $10,277.00 |
| Connectors | $476.56 |
| Electronics | $11,426.54 |
| Fabrication | $2,360.00 |
| Frame | $1,485.30 |
| Material | $1,170.25 |
| Software | $2,471.85 |
| Workstation | $799.37 |
| Safety Screen | $549.01 |
| Worker Hours | $16,008.00 |
| **Grand Total** | **$47,023.88** |

The Instron 5966 uniaxial test system was chosen to compare to the RTS. The Instron 5966 model has a linear capacity of 2,200 lbf, a single 2,200 lbf load cell, and Instron's Bluehill Universal testing software. In order to have a more direct comparison, features of the RTS were removed from the cost breakdown such as the safety screen, specific testing fixtures, the torsional actuator, and additional sensors. The total price for the Instron 5966 was $54,641 with the RTS totaling approximately $33,302. The comparison of the two systems cannot be simplified to only the system cost. Other things to consider with the Instron system are the support from the company, on site installation, and system validation. The drawbacks however include the restrictions of the systems software, inability to integrate third party sensors, and inability to expand the systems operational axis as discussed previously in section 1.1.

## 4.2 System Calibration and GLP Validation

An upcoming study in the BMEL, is the evaluation of a novel biodegradable device for the repair and fixation of communicated fractures in long bones. This device has been developed in a collaborative research endeavor with the Houston Methodist Research Hospital and is intended for use in humans as a medical device. Due to the device’s novel design, and desire to move to clinical studies in humans, it is necessary for the collaborative study to operate under the United States Food and Drug Administration (FDA) Good Laboratory Practice (GLP) regulations [24]. GLP is the requirement that a FDA approved Quality Assurance (QA) system be in place at the facility in which the intended nonclinical study is occurring. The QA systems is to ensure correct documentation occurs concerning the study evaluations performed to make sure the results are reliable and reproducible.

For the RTS, this QA system requires written records of calibrations be saved as well as fabrication drawings on all fixturing designed for the system. In order to address the QA system, all of the current load cells and LVDT are calibrated in accordance with the National Institute of Standards and Technology (NIST) by third parties.  This NIST calibration includes traceable documentation of calibration to a metrological standard, satisfying the GLP requirements concerning system component calibration.

In addition to the calibration of individual sensors, system level GLP validation for the RTS will be performed. This process will consist of:

- **System Alignment** – The quantitative measurement of the alignment of the top and bottom fixturing of the system. This will be performed with a custom test protocol and NIST calibrated equipment.
- **System Displacement Validation** – The evaluation that the displacement recorded in the system by the software, matches the displacement of the physical actuator. This protocol will be based on the American Society of Testing and Materials (ASTM) E2309 document [25].
- **System Speed Validation –** The evaluation that the speed of the actuator matches the system readouts and inputs. This protocol will be based on the ASTM E2658 document [26]. One item necessary for this process is a NIST calibrated function generator which will be used as a calibrated, traceable timestamp.
- **System Deflection –** The evaluation of the deflection of the system in a specific experimental configuration. This information will be collected using the BMEL's Vicon motion capture system.

## 4.3 System Limitations

One of the major limitations of the RTS is that complete reconfiguration of the system can be physically demanding on the user. The linear actuator for example, weighs approximately forty-seven pounds, which to safely remove from or attach to the system, requires at least two individuals.

The LabVIEW software currently operates using the cRIO's scan engine configuration. While this is also a benefit because it allows for quick development and modification of the code, it requires a large amount of CPU resources when collecting data from multiple cRIO modules. In addition it limits the loop rates to a maximum of 1 kHz [22]. The current default functions, discussed in section 3.3.3, that the system can follow are ramp, sinusoidal, and creep. This library of available functions needs to be expanded upon. In addition, the functionality to execute a series of movements is needed in the system to allow for easier preconditioning of tissues.

## 4.4 Future System Developments

### *4.4.1 Physical Developments*

**Linear Actuator Adjustment**

Currently adjusting the height of the linear actuator in the uniaxial configuration, discussed in section 2.4.3, is a time consuming and manual process. The process involves using the actuator to move itself, using a support and the jog functionality. This process can be seen in Appendix A section " Concepts have been developed for the implementation of a hand crank system using a lead screw. This lead screw design would be mounted to the RTS's vertical columns using the available t-slots. Another concept under consideration is the implementation of a pulley system with a hand operated wench which can be connected and disconnected as needed.

### Axial-Torsion Configuration

The RTS currently is unable to operate combined axial and torsional loading. In order to expand the system for this functionality, a physical configuration will need to be developed to prevent torsional loading from being applied directly to the linear actuator's cylinder. The linear actuator has an internal lead screw and an anti-rotation mechanism which cannot have external torsional loading. An additional AKD will need to be purchased to operate the servo motor on the torsional actuator. Expansion of the code for axial-torsional loading would involve duplicating the current PI controller sub VI and adding a torsional feedback channel.

## *4.4.2 Software Developments*

### Custom Movement/Loading Profiles

In the BMEL it is often necessary to recreate physiological loadings for the evaluation of hardware and cadaveric specimens.  To recreate this physiological loading, it is often necessary to follow a loading or position profile that is made up of experimentally collected data. This experimental data can be turned into a motion profile using LabVIEW's built in spline interpolation functions. The ability to upload a custom profile from external data will allow for implementation of any custom motion in both positional and load controlled movements.

### Multi-Step Experimental Paradigms

A reoccurring need when testing biological tissues is preconditioning. Currently the operator has to define the preconditioning test parameters, then manually define the experimental test after the preconditioning ends. This process forces the user to monitor the test and constantly be ready to define and start the experimental test. This necessary human interaction can cause inconsistency between tests as well as the process being an inefficient use of the operator's time. The ability for the user to define the preconditioning loading and experimental loading initially, then having the system automatically continue would greatly expedite the experimental process.

### Dynamic Load Cell Selection

The BMEL has a steadily growing inventory of load cells. On the RTS, the load cells are frequently exchanged to meet different experimental needs and to maximize the resolution of the data collected. It has been observed that changing the values in the program to account for varying load cell sensitivity is commonly forgotten until the load readout is checked on the user interface. A desire has been expressed to have the option to select the load cell, based on the items serial number, from a library in the LabVIEW. This selection would automatically adjust the parameters specific to the load cell based on the calibration data. This library could be created manually in the LabVIEW code and be updated as load cells are added to the BMEL inventory or after recalibration.

### 4.5 Conclusion

The BMEL performs a variety of mechanical tests to evaluate biological materials and orthopedic devices. These tests range from characterization of materials to ex vivo contralateral comparisons under physiologically relevant loadings. Due to this experimental variety, there is a large amount of work in developing experimental setups on a project by project basis, often with the time requirement increasing with an increased desire for physiological relevance. Developing these experimental setups on a common testing system can bring about many problems including limits on physical space, the inability to integrate third party sensors, and the inflexibility of the systems' software. This thesis work set out to address the need of the BMEL for a test system that could be used in a BSL-2 space under GLP regulations, was an affordable alternative to commercially available systems, and could be reconfigured for current and future projects with potential to expand the system's overall functionality at any time. This was done by designing a test system with readily available modular physical components, expandable control system hardware, and LabVIEW based control software. Currently in the BMEL, the RTS is being utilized by other researchers for additional projects beyond those mentioned in this document.

The RTS will allow future researchers in the BMEL to continually develop and expand the systems functionality. This thesis provides a detailed explanation of the RTS's physical design and selected actuation components, as well as the LabVIEW software. In addition, this thesis provides documentation for future researchers in the BMEL to operate the system from a user standpoint and also to continue the development of the software with an understanding of the current architecture. These resources will allow the next researcher to begin development with an organized foundation, leading to faster and more advanced developments in the system's functionality.

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APPENDIX A

## RTS User's Manual

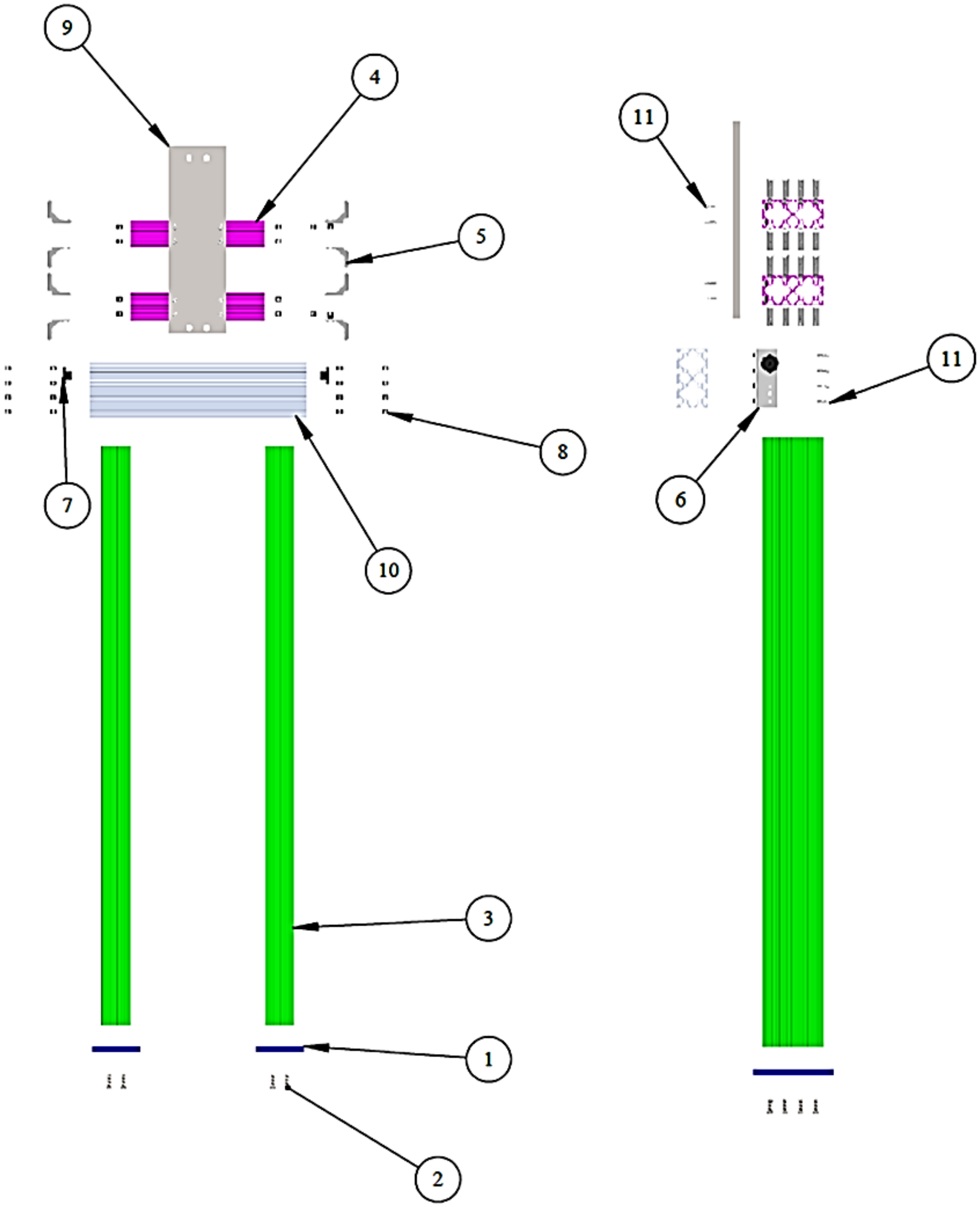
# Reconfigurable Testing System User and Developer Manual

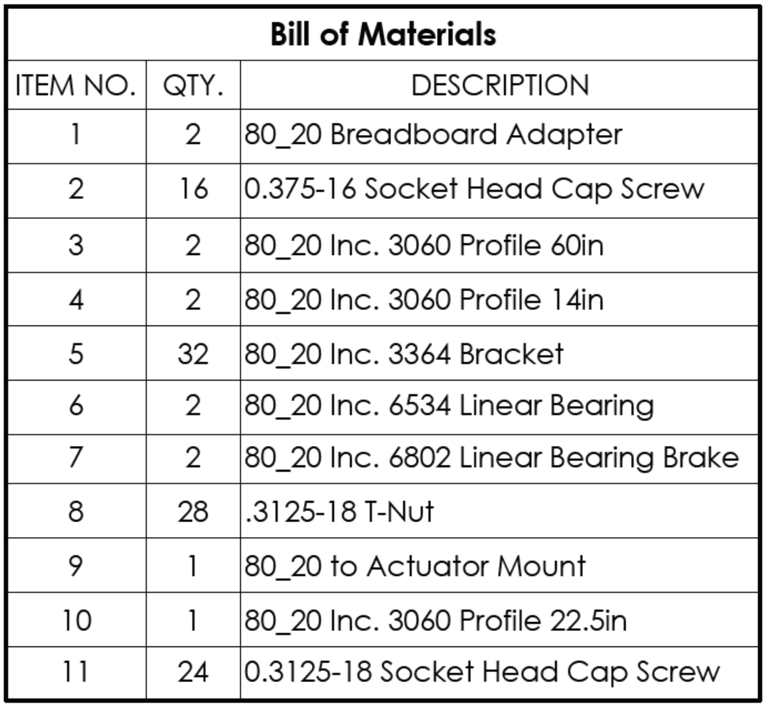
By Aaron Stone

Revision Date: February, 25th 2018

## System Assembly

### *Frame Assembly*

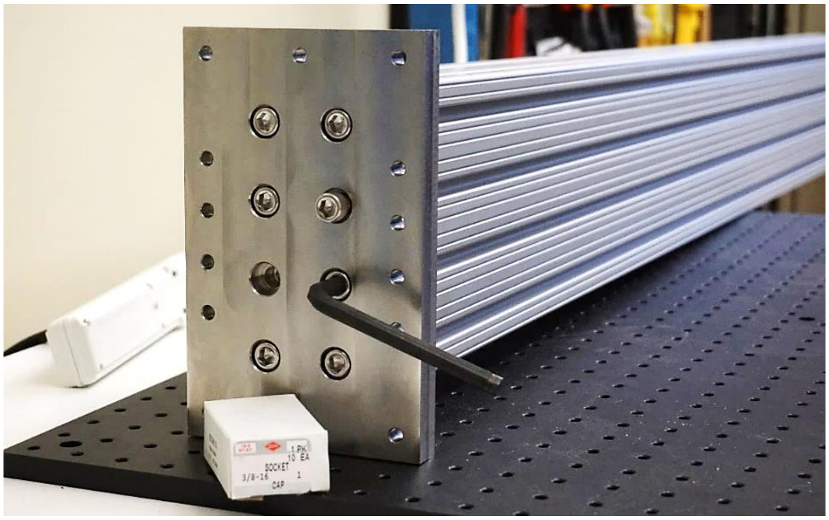




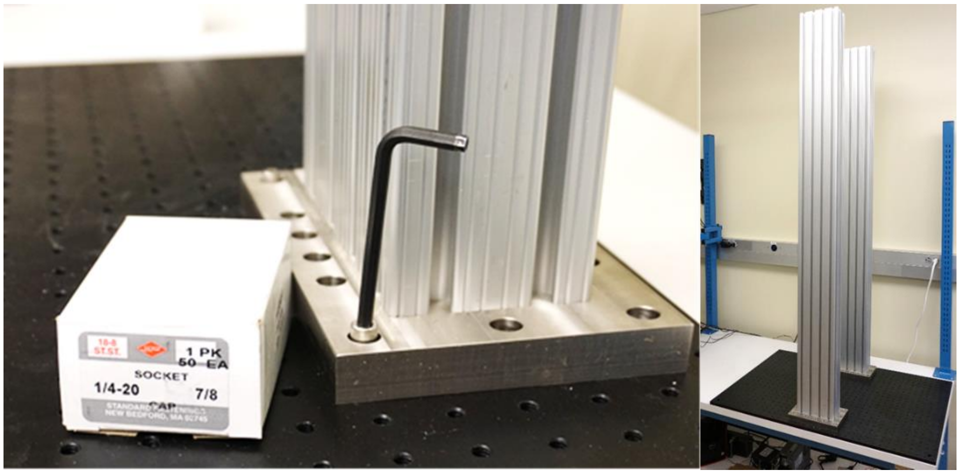
**Bill of Materials**

| ITEM NO. | QTY. | DESCRIPTION |
|---|---|---|
| 1 | 2 | 80_20 Breadboard Adapter |
| 2 | 16 | 0.375-16 Socket Head Cap Screw |
| 3 | 2 | 80_20 Inc. 3060 Profile 60in |
| 4 | 2 | 80_20 Inc. 3060 Profile 14in |
| 5 | 32 | 80_20 Inc. 3364 Bracket |
| 6 | 2 | 80_20 Inc. 6534 Linear Bearing |
| 7 | 2 | 80_20 Inc. 6802 Linear Bearing Brake |
| 8 | 28 | .3125-18 T-Nut |
| 9 | 1 | 80_20 to Actuator Mount |
| 10 | 1 | 80_20 Inc. 3060 Profile 22.5in |
| 11 | 24 | 0.3125-18 Socket Head Cap Screw |

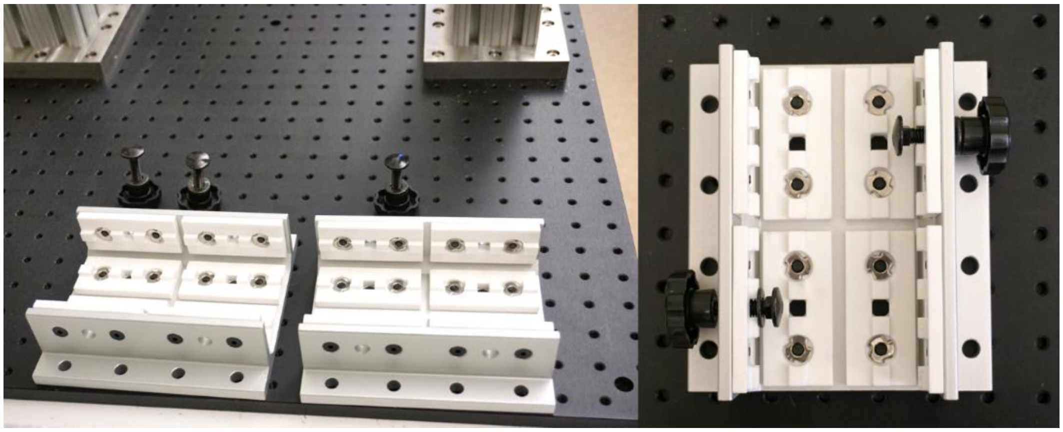
1. Attach the 80_20 Breadboard Adaptor (Item 1) to the 60in length 80_20 Inc. 3060 aluminum profiles using (16) 0.375-16 Socket Head Cap Screws. These will be the vertical columns of the load frame.



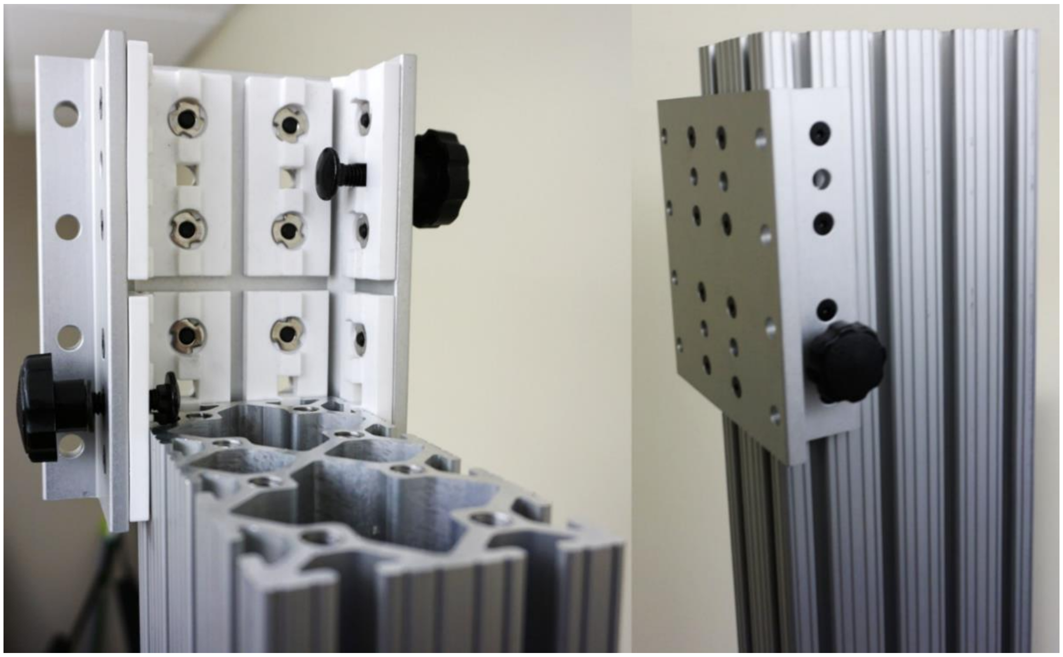
2. Mount the assembled components form Step 1 to the ThorLabs breadboard using (28) ¼-20 Socket Head Cap Screws.



3. Assemble linear bearing brakes (Item 7) to the 80_20 linear bearings (Item 6). There are only 3 linear bearing brakes currently.

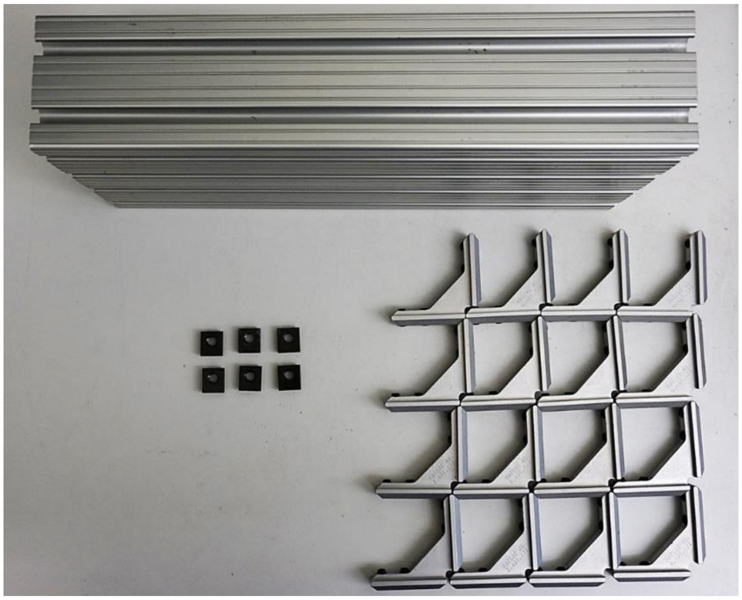


4. Slide linear bearings on top of vertical columns



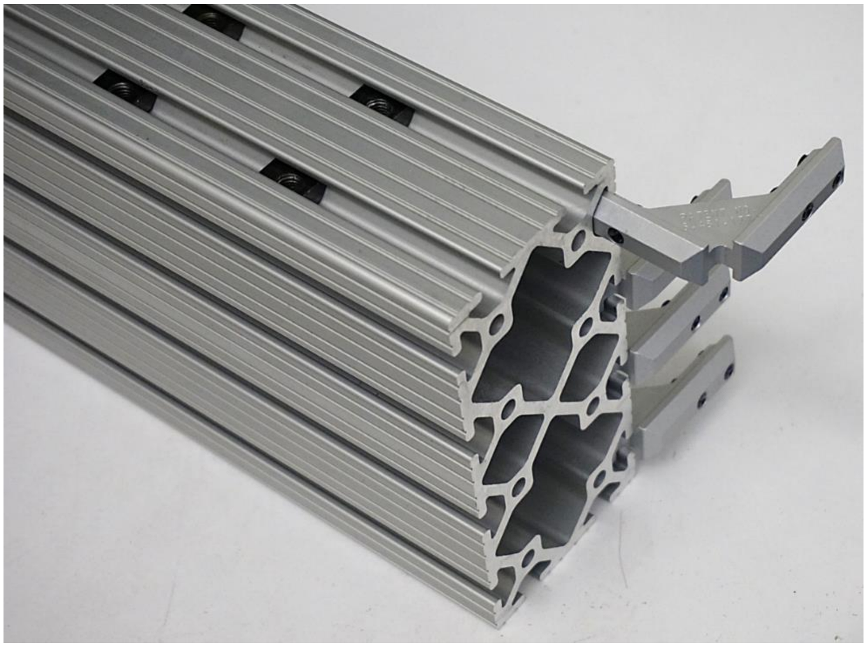
5. Move linear bearings to the bottom of vertical columns

6. Gather the horizontal aluminum profiles (Item 10), t-slots (Item 8), and aluminum brackets (Item 5)



7. Slide 6 t-slots (Item 8) into the top and bottom tracks, 3 per slot, on the narrow side of the horizontal aluminum profile (Item 10)

8. Insert aluminum brackets (Item 5) onto the ends along the long side of the horizontal aluminum profile (Item 10)

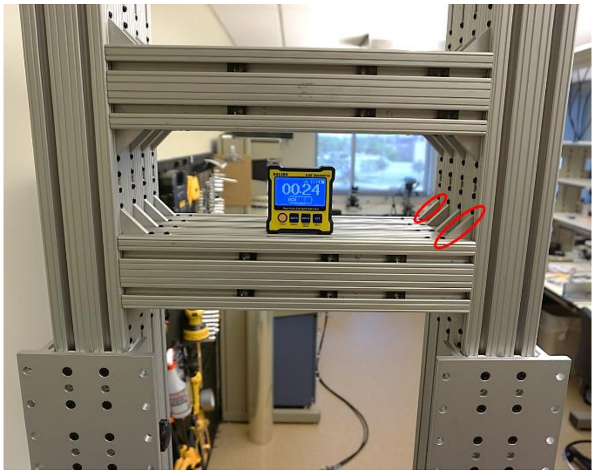


9. Steps 6-8 should be done for both of the horizontal aluminum profiles. None of the aluminum braces should be tightened at this point.

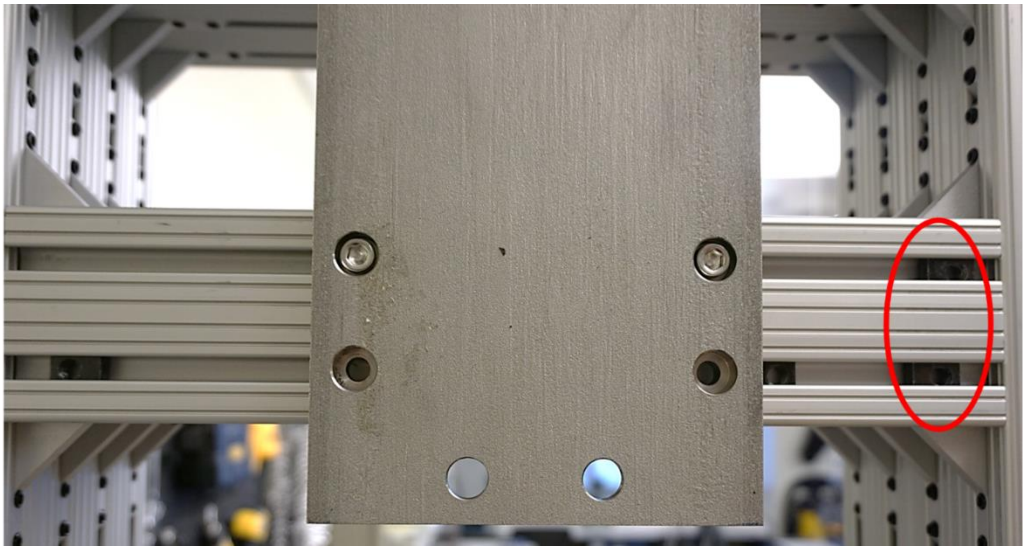
    a. As of 12-14-17: Only 2 aluminum brackets need to be added to each area (for a total of 8 brackets per horizontal aluminum profile). For sufficient stability at maximum loading conditions.

10. Slide horizontal aluminum profile between vertical columns, aligning all aluminum braces appropriately. This typically requires a lot of shifting of components but will slide with little resistance when everything is aligned. If the horizontal member resist movement ensure it is level and DO NOT force the member.

11. Lock the bottom horizontal aluminum profile by tightening the aluminum braces, ensure the profile is level. (Note: before final positioning it is only necessary to tighten the outer most aluminum braces on the top and bottom circled in red). At this point do not lock the top profile as it will need to be positioned further. DO NOT OVER TIGHTEN, this will damage the aluminum over the life of the system. If the desired height of profiles is known, position accordingly on frame at this step.



12. Take the 80/20 Actuator Mount (Item 9) and mount to the t-slots as shown below using four 5/16-18 socket head cap screws. Make sure two of the t-slots are positioned to the far right side for mounting the LVDT later.



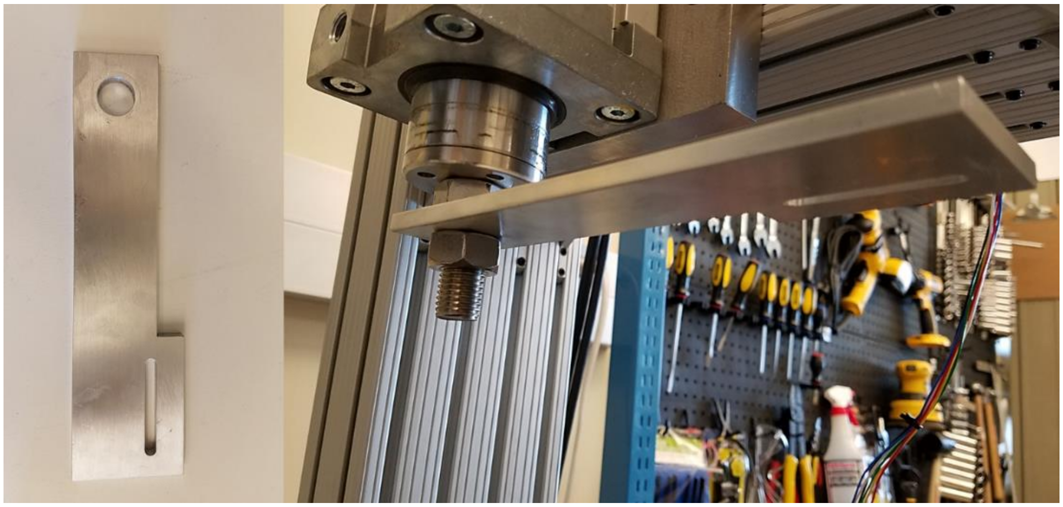
13. Position top horizontal aluminum profile to where the t-slots align with the holes in the 80/20 Actuator Mount (Item 9) and secure with 5/16-18 socket head cap screws

### *Linear Actuator and Base Fixture Mounting*

1. With AT LEAST 2 PEOPLE, lift the actuator to the 80/20 actuator mounting plate and secure with 4 M12 socket head cap screws in the orientation shown below. The actuator cannot be mounted with the servo motor towards the back as the brake will come into contact with the top horizontal aluminum profile.

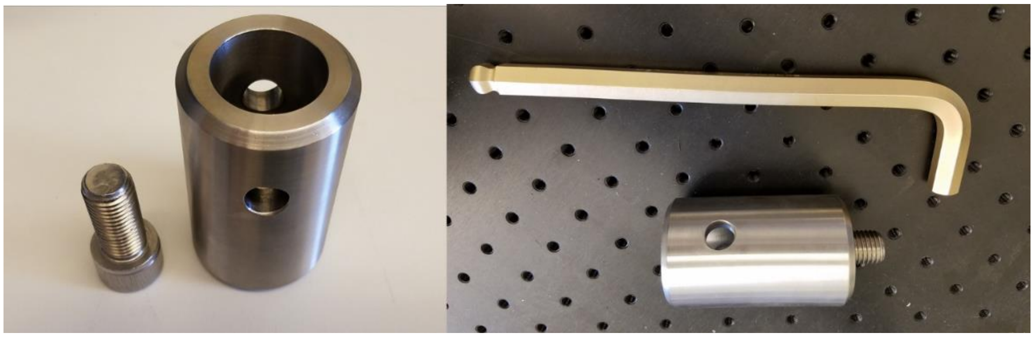
2. On the actuator shaft, by hand, screw in an M16 x 2 70mm long stainless steel threaded rod until the threaded rod bottoms out. Secure the threaded rod by tightening on an M16 nut using a 10” crescent wrench.

3. Take the LVDT to actuator mount (left) and secure using an M16 nut in orientation shown (right). When securing the LVDT to actuator mount, tighten until there is resistance to rotation but where the mount can be rotated by tapping gently with a hammer. The slot will be used for securing the extension rod from the LVDT and will be positioned at a later step.

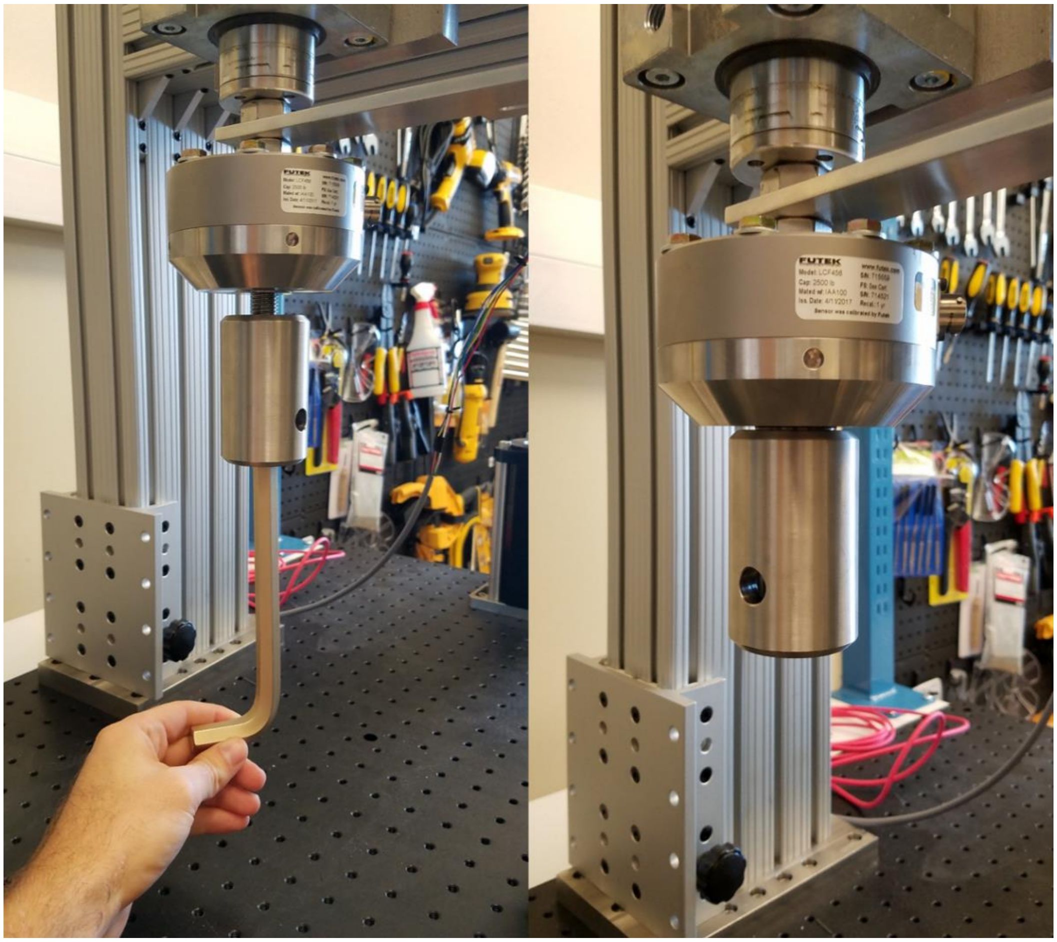


4. Mount desired load cell (Futek LCF 456 shown). Hand tighten only.

5. The is mounted to the load cell using an M16 x 2mm 35mm long socket head cap screw.



6. Align Actuator to Female MTS adaptor to where the holes are facing forward and tighten socket head cap screw.



7. Mount the LVDT mounts (left) to the load frame using the t-slot nuts that were shifted over in step 12 of “Frame Assembly”. Ensure mounts are level before tightening.

8. Mount LVDT as shown (left), do not over tighten LVDT mounts. Loosely secure (hand tighten only) the end of the LVDT extension rod with two nuts and washers (right).

### *Linear Actuator Height Adjustment*

The adjustment of the actuator height is currently a slow and manual process in which the actuator is used to lift itself. The following steps will walk through how the actuator has previously been adjusted.

1. Mount a pancake style load cell to the system capable of handling >2,000lbf.
    a. See section **Error! Reference source not found.** if needed

    Note: The force required to move the actuator is ~150lbf however it is best to use a load cell that is safe from damage from an incorrect movement input to the actuator.
2. Initialize system according to section **Error! Reference source not found.**
3. Find a construct capable of handling 2,000lbf of loading. This will vary depending on the current height of the actuator and final desired height.
    a. Due to the stroke of the actuator being 12in, movement from the very bottom possible position to the top will require movement in two steps
    b. Below is a setup previously used to adjust the actuator height. The actuator female MTS fixture will push directly on the steel plates to lift or lower the actuator.

4. Set the lower load limit in the User Interface to 75lbf (333N)
5. Jog the actuator within 1mm of contact with the construct at any rate desired being careful not to ram the actuator into the construct
6. Set the jog speed to 0.1 mm/s or less
7. Jog the actuator until the load limit trips
    a. This is to preload the actuator before loosening the brackets which hold the system in place. This is to keep the actuator from dropping suddenly.
8. Loosen the LVDT mounts
    a. It is usually only necessary to loosen the side that connects to the vertical column (protractor from old picture)

9. Begin loosening the angled brackets. You must loosen all of the bolts in the brackets

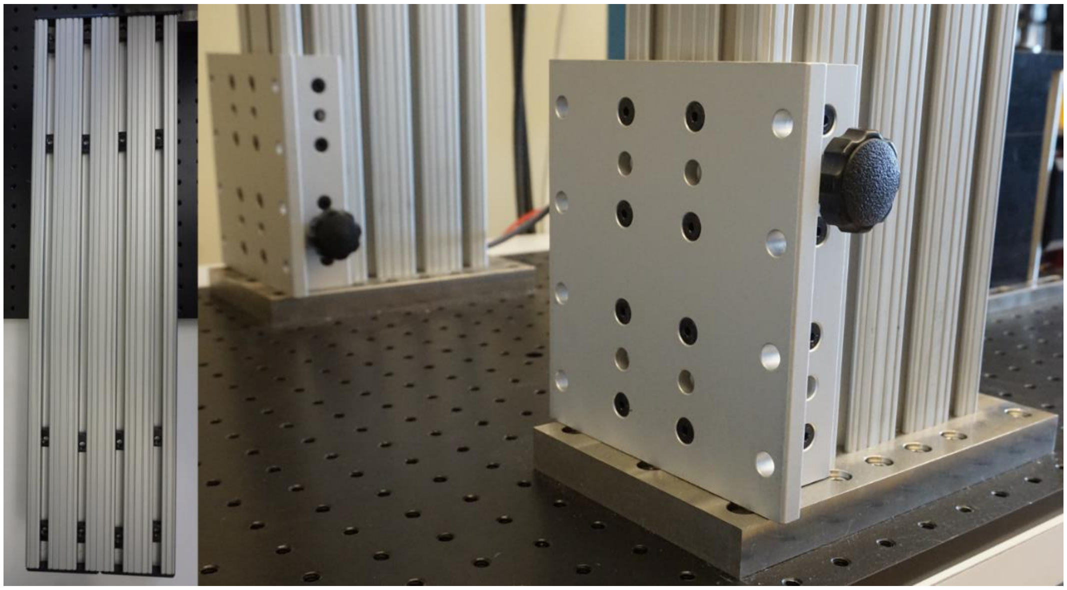
    a. When loosened properly the angled bracket should shift a little when shaken by hand

10. The load readout on the system should be at approximately 150lbf (667N)
11. Set the upper load limit to 200lbf (-800N) and the lower load limit to 75lbf (-333N)
    a. The majority of the weight should always be supported by the actuator

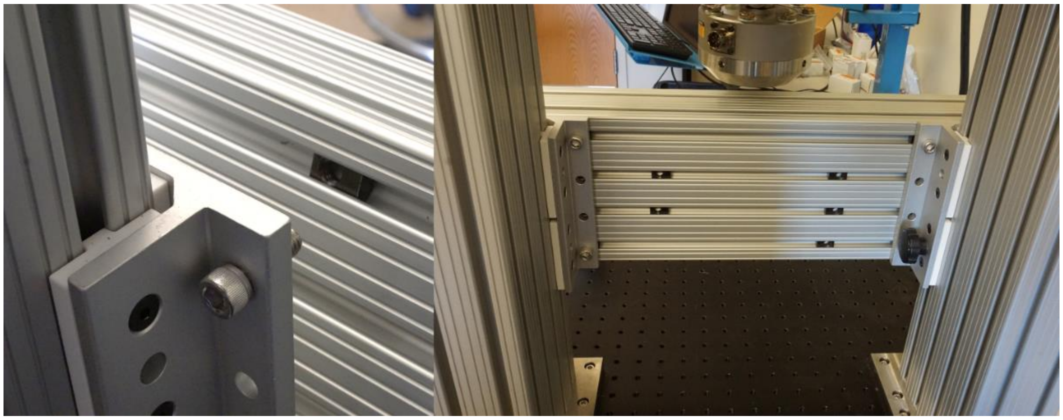
12. Set the jog rate to 0.5 mm/s
13. Begin jogging the system in the appropriate direction. The load readout should increase or decrease depending on the direction the actuator is being moved but should stabilize during movement.
    a. It may be required occasionally to tap and shake the angled brackets as they can bind up in the system.
    b. If the load limit trips and the actuator does not move check that the angled brackets and LVDT mounts are loosened
    c. Adjust the load limits only if **absolutely necessary** to acquire movement.
    d. The actuator **only has 12in of stroke**, check the actuator periodically during adjustment to make sure you do not attempt to overextend/retract the actuator.
    e. Do not completely retract the actuator into the housing (rectangular body) or you will not be able to remove the constructs after.
14. When the actuator is in the final position desired (or do to stroke limitations) secure all of the angled brackets and LVDT mounts.
    a. If further movement is desired but limited by stroke. **Only tighten the bottom 4 angled brackets and the LVDT mounts.** This is sufficient to hold the actuators weight while a new construct is selected.
15. Retract actuator away from construct and remove construct

### *Torsional Actuator Mounting*

1. <u>After completing section 1.1</u> Frame Assembly, if torsional testing is desired, position horizontal components high enough to where there is sufficient room for the linear bearings for the experiment. Take the 22.5" aluminum extrusion and place 16 t-slot nuts (left).

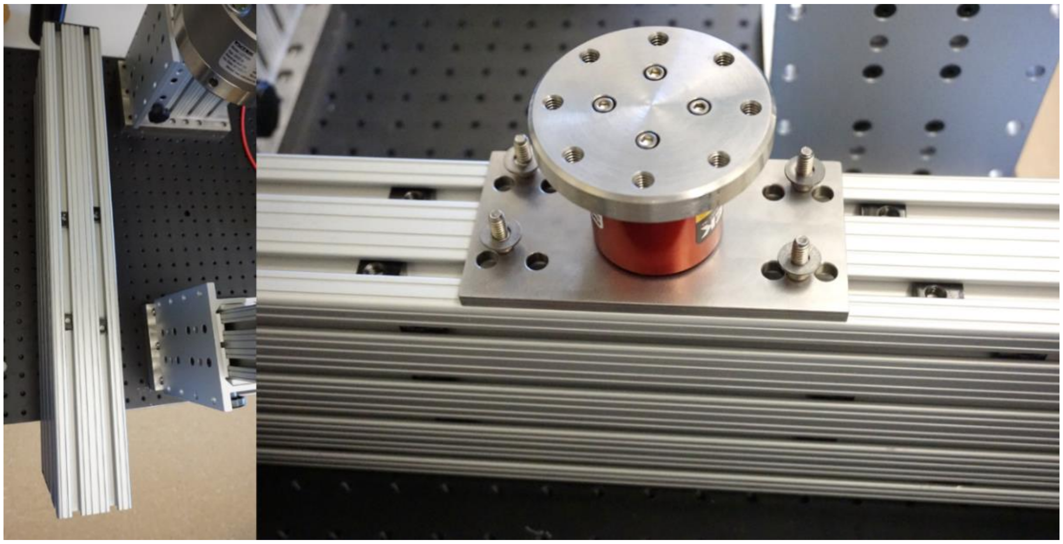


2. Mount 22.5" aluminum extrusion to the linear bearings using 5/16-18 x 0.75" socket head cap screws. Be sure to position the t-slot nuts for accessibility (right).

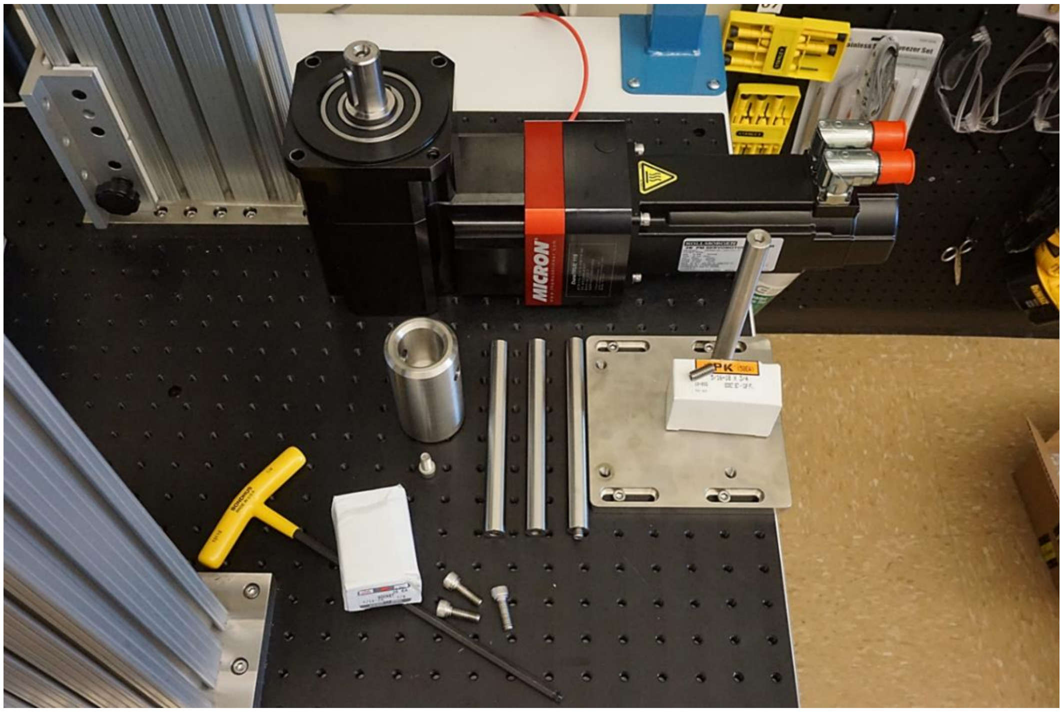


3. Assemble desired load cell and adaption plates (picture below is Futek TFF400 style with custom adaptors.

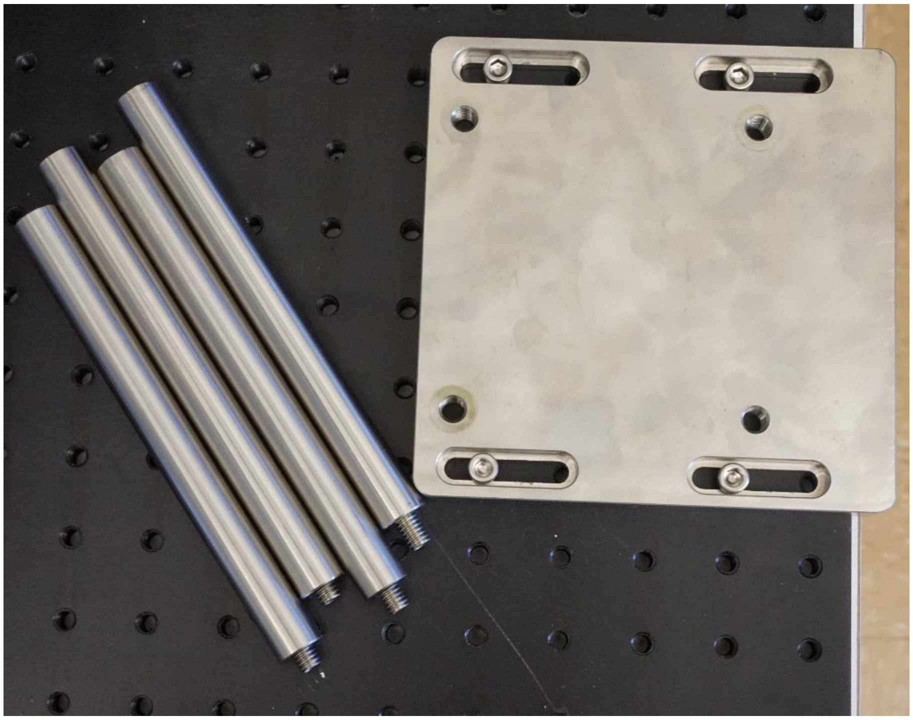
4. Mount the load cell to the horizontal extrusion using t-slot nuts (left). This can be done before or after mounting the horizontal extrusion but care must be taken to not damage the load cell.



5. Gather hardware and torsional actuator for setup.



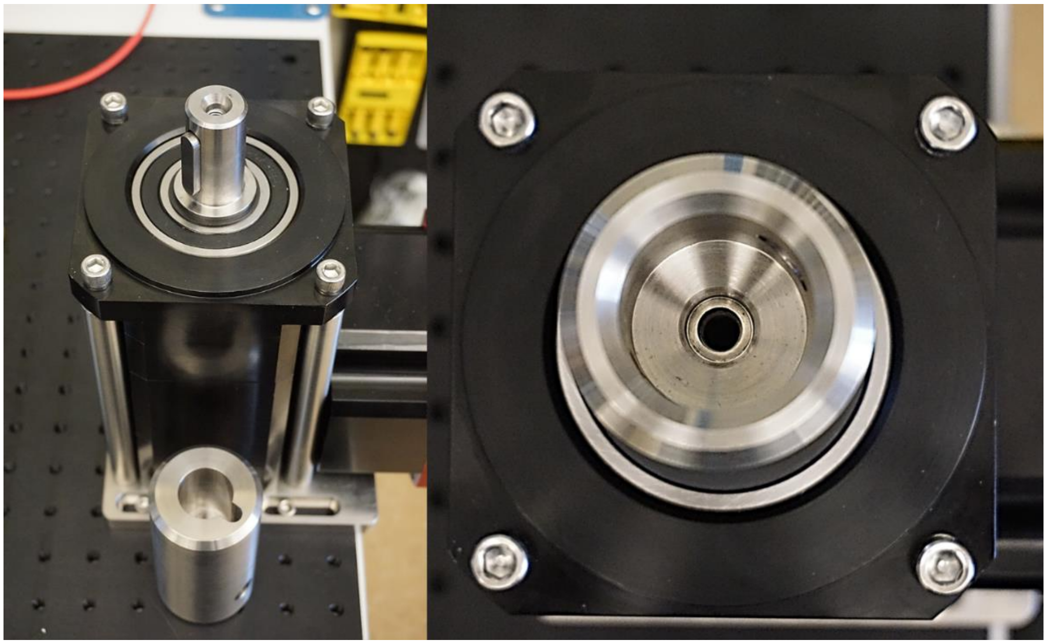
6. Attach base plate to breadboard using 4 ¼ - 20 x 7/8” socket head cap screws. Tighten 5/16-18 x 3/4" socket set cup screws into one end of the cylindrical supports.



7. Insert cylindrical supports in to base plate, tightening by is hand sufficient.

8. Slide torsional actuator on the top of the cylindrical supports

9. Using four 5/16-18 x 7/8” Socket head cap screws, secure the torsional actuator to the cylindrical supports. Then place the torsional female MTS adaptor and secure with one M8 x 1.25 mm thread 16mm long.



## Control System Hardware Setup

Steps in this section assume that all the necessary hardware has been installed on the Host computer. This necessary software includes:

- LabVIEW 2016 or newer
- LabVIEW RealTime Module
- LabVIEW SoftMotion
- NI Device Monitor
- NI Industrial Communications for EitherCAT 16.1 or newer
- cRIO Drivers (see National Instruments website for current drivers)
- Kollmorgen Workbench Software

### *AKD Configuration*

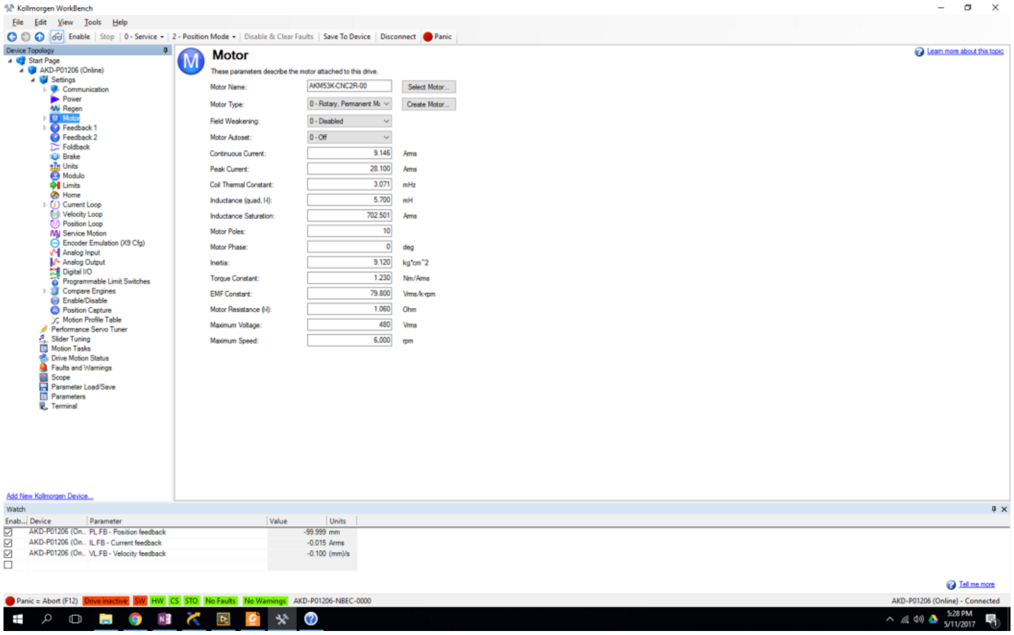
The AKD must be configured if the motor is changed. For example, if the system has been operated using the linear actuator and it is then desired to use the torsional actuator. The torsional actuator must be connected and the configuration of the driver must be done in the Kollmorgen Workbench Software.

**WARNING:** If the driver is not properly configured the motor can easily be damaged during operation as the current will not be properly limited from the driver.

1. For wiring and connections read the “AKD Quick Start Guide”. This is located in the lab’s Google Drive as well as Kollmorgen’s website.
2. Read sections 6 through 14 of the “Kollmorgen AKD User Guide” completely prior to performing the driver configuration.

**Note:** The **linear actuator motor** when connected to the AKD **will not auto-set** to the correct parameters due to the feedback type. The torsional actuator however can be configured using the auto-set feature described in the “Kollmorgen AKD User Guide”.

The following parameters are for the linear actuator with the **AKM53K-CNC2R-00** servo motor attached.



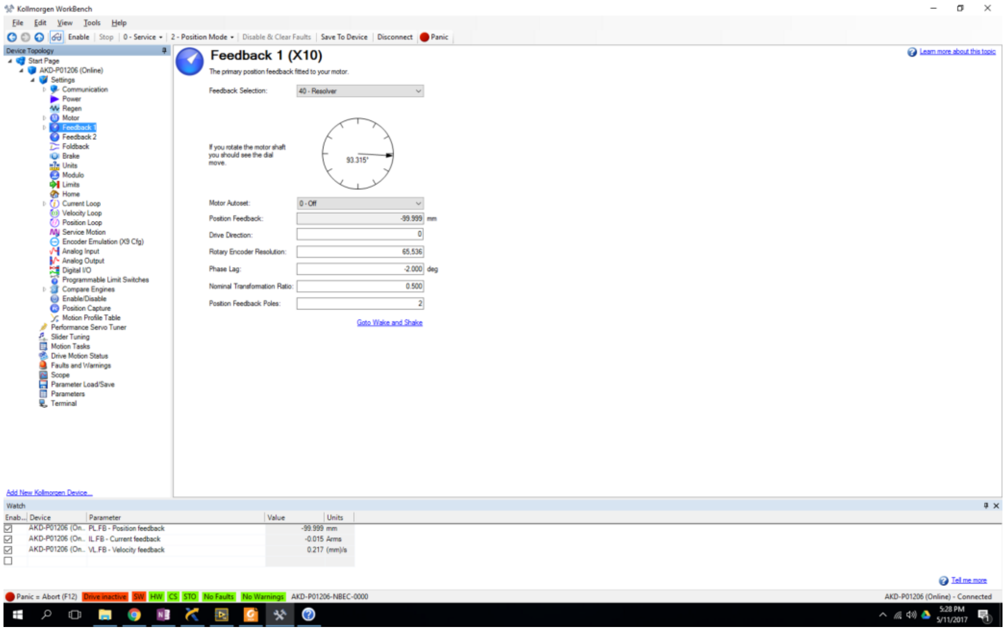
**Motor**

These parameters describe the motor attached to this drive.

| | | |
|---|---|---|
| Motor Name: | AKM53K-CNC2R-00 | |
| Motor Type: | 0 - Rotary, Permanent Ma | |
| Field Weakening: | 0 - Disabled | |
| Motor Autoset: | 0 - Off | |
| Continuous Current: | 9.146 | Arms |
| Peak Current: | 28.100 | Arms |
| Coil Thermal Constant: | 3.071 | mHz |
| Inductance (quad, l-l): | 5.700 | mH |
| Inductance Saturation: | 702.501 | Arms |
| Motor Poles: | 10 | |
| Motor Phase: | 0 | deg |
| Inertia: | 9.120 | kg*cm^2 |
| Torque Constant: | 1.230 | Nm/Arms |
| EMF Constant: | 79.800 | Vrms/k-rpm |
| Motor Resistance (l-l): | 1.060 | Ohm |
| Maximum Voltage: | 480 | Vrms |
| Maximum Speed: | 6,000 | rpm |

Watch

| Enab... | Device | Parameter | Value | Units |
|---|---|---|---|---|
| ☑ | AKD-P01206 (On... | PL.FB - Position feedback | -99.999 | mm |
| ☑ | AKD-P01206 (On... | IL.FB - Current feedback | -0.015 | Arms |
| ☑ | AKD-P01206 (On... | VL.FB - Velocity feedback | -0.100 | (mm)/s |
| ☐ | | | | |



**Feedback 1 (X10)**

The primary position feedback fitted to your motor.

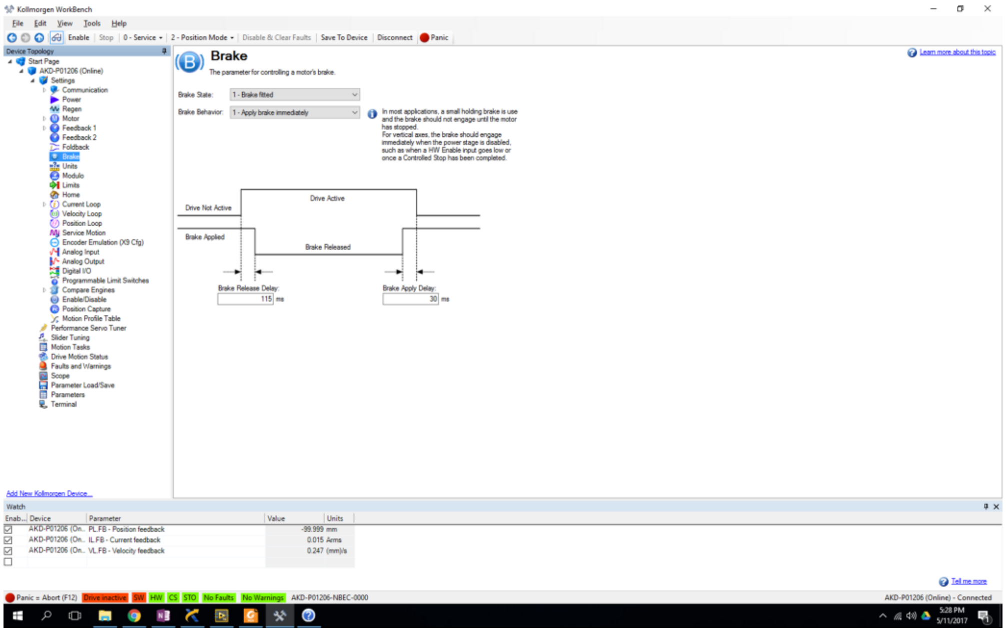
Feedback Selection: 40 - Resolver

If you rotate the motor shaft you should see the dial move.

| | | |
|---|---|---|
| Motor Autoset: | 0 - Off | |
| Position Feedback: | -99.999 | mm |
| Drive Direction: | 0 | |
| Rotary Encoder Resolution: | 65,536 | |
| Phase Lag: | -2.000 | deg |
| Nominal Transformation Ratio: | 0.500 | |
| Position Feedback Poles: | 2 | |

Watch

| Enab... | Device | Parameter | Value | Units |
|---|---|---|---|---|
| ☑ | AKD-P01206 (On... | PL.FB - Position feedback | -99.999 | mm |
| ☑ | AKD-P01206 (On... | IL.FB - Current feedback | -0.015 | Arms |
| ☑ | AKD-P01206 (On... | VL.FB - Velocity feedback | 0.217 | (mm)/s |
| ☐ | | | | |



**Brake**

The parameter for controlling a motor's brake.

Brake State: 1 - Brake fitted

Brake Behavior: 1 - Apply brake immediately

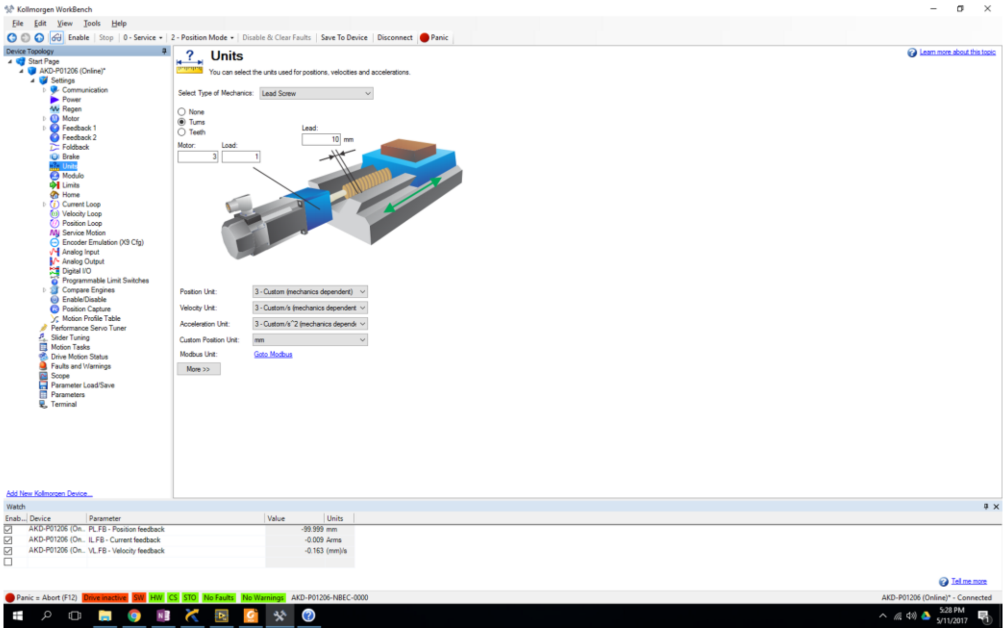
In most applications, a small holding brake is use and the brake should not engage until the motor has stopped.
For vertical axes, the brake should engage immediately when the power stage is disabled, such as when a HW Enable input goes low or once a Controlled Stop has been completed.

Brake Release Delay: 115 ms

Brake Apply Delay: 30 ms

Watch

| Enab... | Device | Parameter | Value | Units |
|---|---|---|---|---|
| ☑ | AKD-P01206 (On... | PL.FB - Position feedback | -99.999 | mm |
| ☑ | AKD-P01206 (On... | IL.FB - Current feedback | 0.015 | Arms |
| ☑ | AKD-P01206 (On... | VL.FB - Velocity feedback | 0.247 | (mm)/s |
| ☐ | | | | |



**Units**

You can select the units used for positions, velocities and accelerations.

Select Type of Mechanics: Lead Screw

○ None
● Turns
○ Teeth

Motor: 3

Load: 1

Lead: 10 mm

Position Unit: 3 - Custom (mechanics dependent)

Velocity Unit: 3 - Custom/s (mechanics dependent

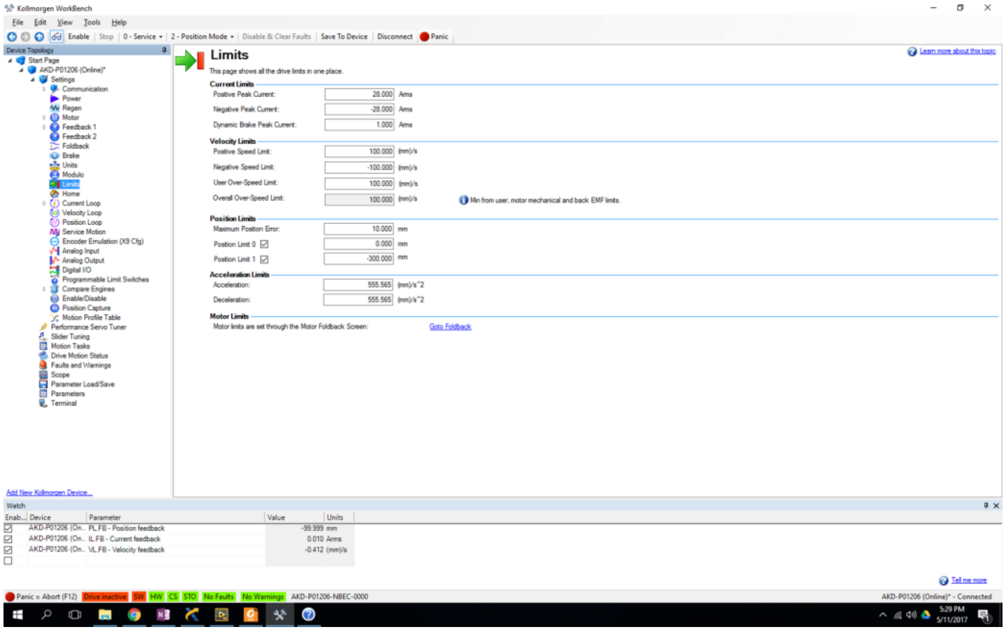
Acceleration Unit: 3 - Custom/s^2 (mechanics depende

Custom Position Unit: mm

Modbus Unit: Goto Modbus

Watch

| Enab... | Device | Parameter | Value | Units |
|---|---|---|---|---|
| ☑ | AKD-P01206 (On... | PL.FB - Position feedback | -99.999 | mm |
| ☑ | AKD-P01206 (On... | IL.FB - Current feedback | -0.009 | Arms |
| ☑ | AKD-P01206 (On... | VL.FB - Velocity feedback | -0.163 | (mm)/s |
| ☐ | | | | |



## Limits

This page shows all the drive limits in one place.

**Current Limits**

Positive Peak Current: 28.000 Arms
Negative Peak Current: -28.000 Arms
Dynamic Brake Peak Current: 1.000 Arms

**Velocity Limits**

Positive Speed Limit: 100.000 (mm)/s
Negative Speed Limit: -100.000 (mm)/s
User Over-Speed Limit: 100.000 (mm)/s
Overall Over-Speed Limit: 100.000 (mm)/s
Min from user, motor mechanical and back EMF limits.

**Position Limits**

Maximum Position Error: 10.000 mm
Position Limit 0 ☑ 0.000 mm
Position Limit 1 ☑ -300.000 mm

**Acceleration Limits**

Acceleration: 555.565 (mm)/s^2
Deceleration: 555.565 (mm)/s^2

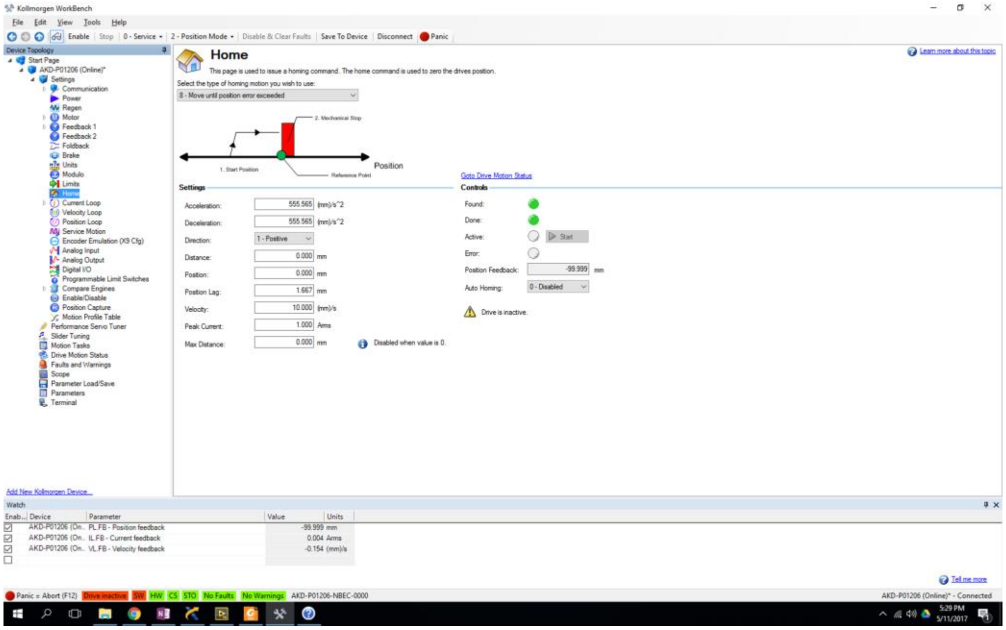
**Motor Limits**

Motor limits are set through the Motor Foldback Screen: Goto Foldback

Watch

| Enab... | Device | Parameter | Value | Units |
|---|---|---|---|---|
| ☑ | AKD-P01206 (On... | PL.FB - Position feedback | -99.999 | mm |
| ☑ | AKD-P01206 (On... | IL.FB - Current feedback | 0.010 | Arms |
| ☑ | AKD-P01206 (On... | VL.FB - Velocity feedback | -0.412 | (mm)/s |
| ☐ | | | | |

Panic = Abort (F12) Drive inactive SW HW CS STO No Faults No Warnings AKD-P01206-NBEC-0000 AKD-P01206 (Online)* - Connected



## Home

This page is used to issue a homing command. The home command is used to zero the drives position.

Select the type of homing motion you wish to use: 8 - Move until position error exceeded

Goto Drive Motion Status

**Settings**

Acceleration: 555.565 (mm)/s^2
Deceleration: 555.565 (mm)/s^2
Direction: 1 - Positive
Distance: 0.000 mm
Position: 0.000 mm
Position Lag: 1.667 mm
Velocity: 10.000 (mm)/s
Peak Current: 1.000 Arms
Max Distance: 0.000 mm
Disabled when value is 0.

**Controls**

Found: ●
Done: ●
Active: ○ Start
Error: ○
Position Feedback: -99.999 mm
Auto Homing: 0 - Disabled
Drive is inactive.

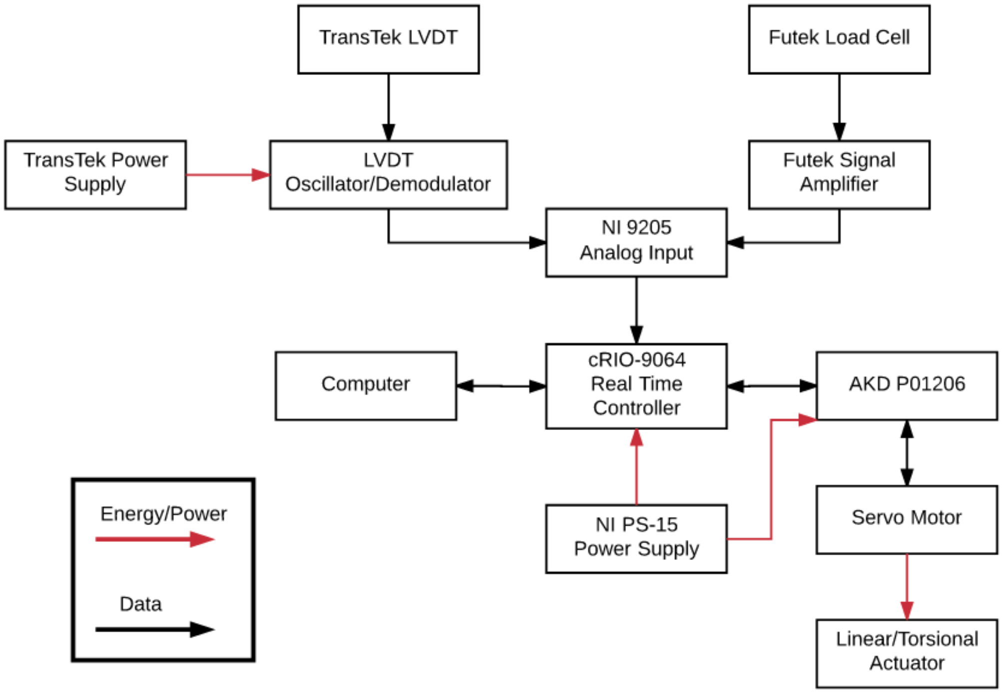
Watch

| Enab... | Device | Parameter | Value | Units |
|---|---|---|---|---|
| ☑ | AKD-P01206 (On... | PL.FB - Position feedback | -99.999 | mm |
| ☑ | AKD-P01206 (On... | IL.FB - Current feedback | 0.004 | Arms |
| ☑ | AKD-P01206 (On... | VL.FB - Velocity feedback | -0.154 | (mm)/s |
| ☐ | | | | |

Panic = Abort (F12) Drive inactive SW HW CS STO No Faults No Warnings AKD-P01206-NBEC-0000 AKD-P01206 (Online)* - Connected

## *System Connections*

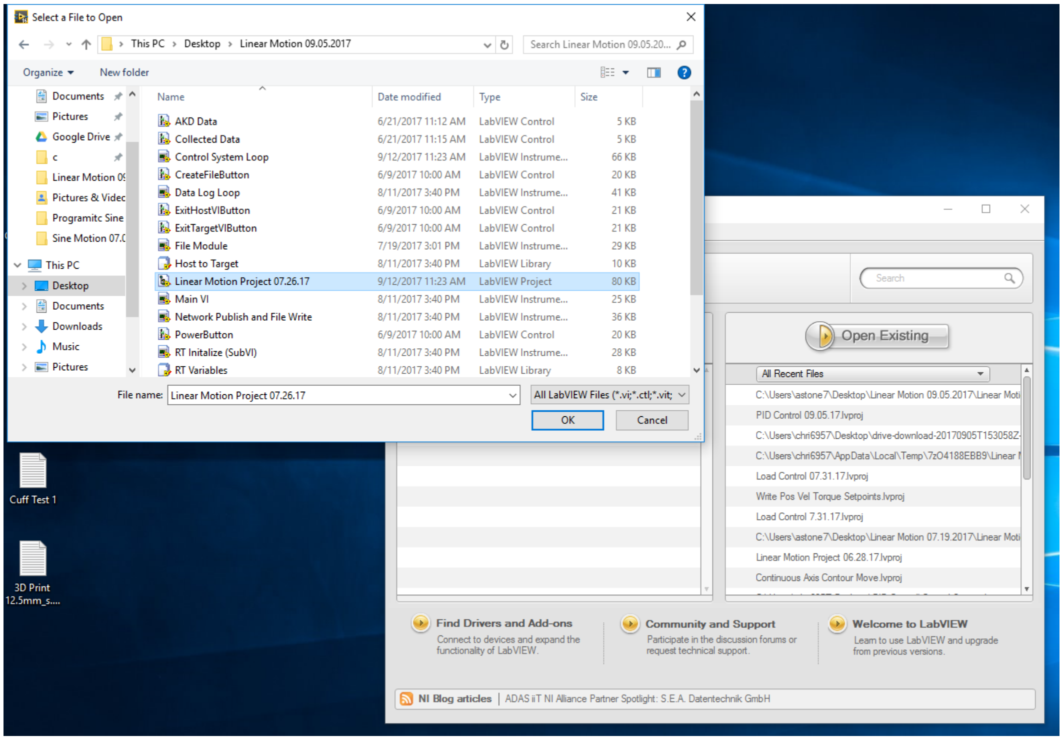
General connection diagram for control system hardware and sensory components for linear actuator assembly described in Section 1.2.



# Software

## *Initializing Connections*

1. Turn on power strip. The AKD, cRIO, and Futek signal amplifier should light up and a fan activate on the AKD.
2. Log into desktop and open LabVIEW
3. Navigate to folder with desired control option and open the file with .proj extension. Always download the most updated version from the BMEL team drive.



| Name | Date modified | Type | Size |
|---|---|---|---|
| AKD Data | 6/21/2017 11:12 AM | LabVIEW Control | 5 KB |
| Collected Data | 6/21/2017 11:15 AM | LabVIEW Control | 5 KB |
| Control System Loop | 9/12/2017 11:23 AM | LabVIEW Instrume... | 66 KB |
| CreateFileButton | 6/9/2017 10:00 AM | LabVIEW Control | 20 KB |
| Data Log Loop | 8/11/2017 3:40 PM | LabVIEW Instrume... | 41 KB |
| ExitHostVIButton | 6/9/2017 10:00 AM | LabVIEW Control | 21 KB |
| ExitTargetVIButton | 6/9/2017 10:00 AM | LabVIEW Control | 21 KB |
| File Module | 7/19/2017 3:01 PM | LabVIEW Instrume... | 29 KB |
| Host to Target | 8/11/2017 3:40 PM | LabVIEW Library | 10 KB |
| Linear Motion Project 07.26.17 | 9/12/2017 11:23 AM | LabVIEW Project | 80 KB |
| Main VI | 8/11/2017 3:40 PM | LabVIEW Instrume... | 25 KB |
| Network Publish and File Write | 8/11/2017 3:40 PM | LabVIEW Instrume... | 36 KB |
| PowerButton | 6/9/2017 10:00 AM | LabVIEW Control | 20 KB |
| RT Initalize (SubVI) | 8/11/2017 3:40 PM | LabVIEW Instrume... | 28 KB |
| RT Variables | 8/11/2017 3:40 PM | LabVIEW Library | 8 KB |

File name: Linear Motion Project 07.26.17

All LabVIEW Files (*.vi;*.ctl;*.vit;

C:\Users\astone7\Desktop\Linear Motion 09.05.2017\Linear Moti
PID Control 09.05.17.lvproj
C:\Users\chri6957\Desktop\drive-download-20170905T153058Z-
C:\Users\chri6957\AppData\Local\Temp\7zO4188EBB9\Linear
Load Control 07.31.17.lvproj
Write Pos Vel Torque Setpoints.lvproj
Load Control 7.31.17.lvproj
C:\Users\astone7\Desktop\Linear Motion 07.19.2017\Linear Moti
Linear Motion Project 06.28.17.lvproj
Continuous Axis Contour Move.lvproj

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Connect to devices and expand the functionality of LabVIEW.

**Community and Support**
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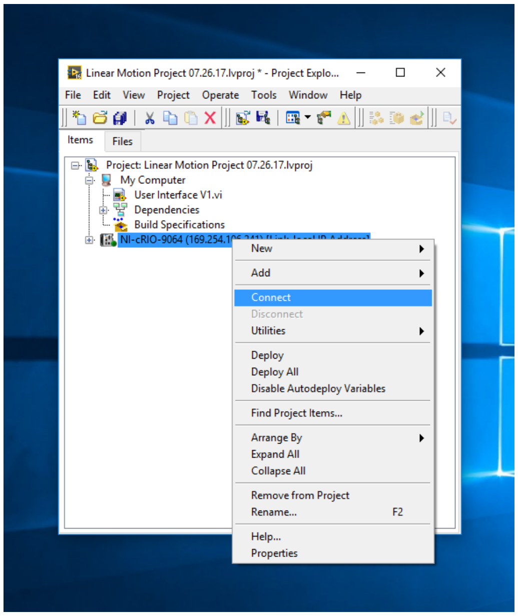
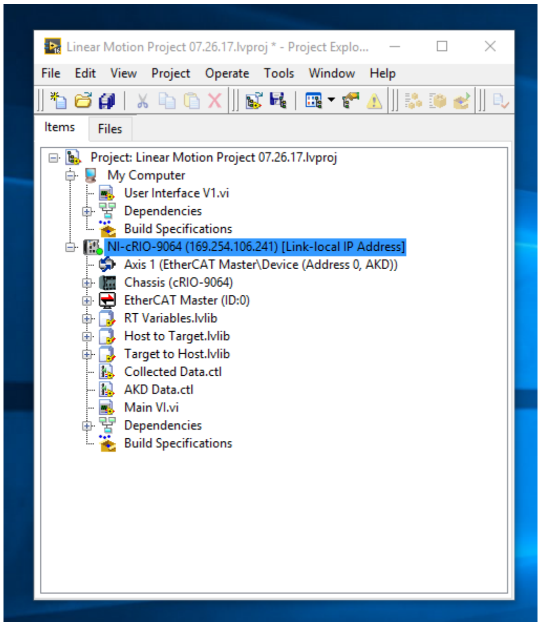
**Welcome to LabVIEW**
Learn to use LabVIEW and upgrade from previous versions.

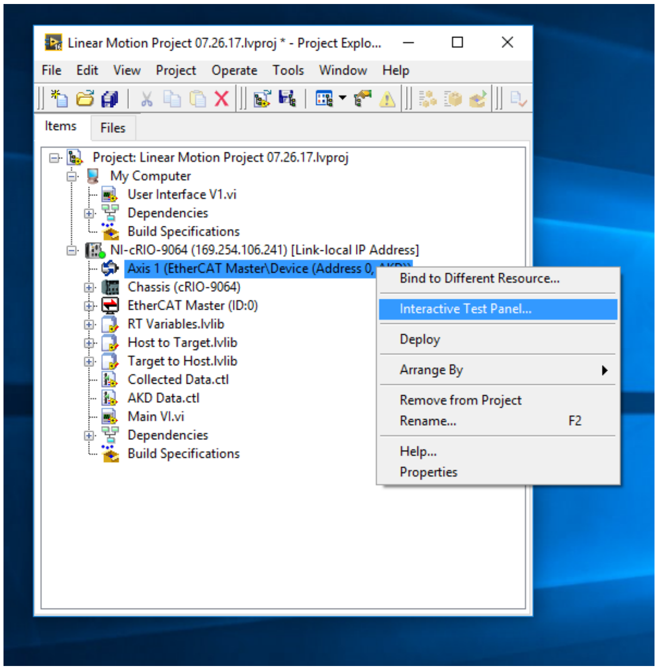
ADAS iiT NI Alliance Partner Spotlight: S.E.A. Datentechnik GmbH

4. Right click on the cRIO controller in the LabVIEW project tree and click connect. The light should turn green when the Host (PC) connects properly with the Target (cRIO).

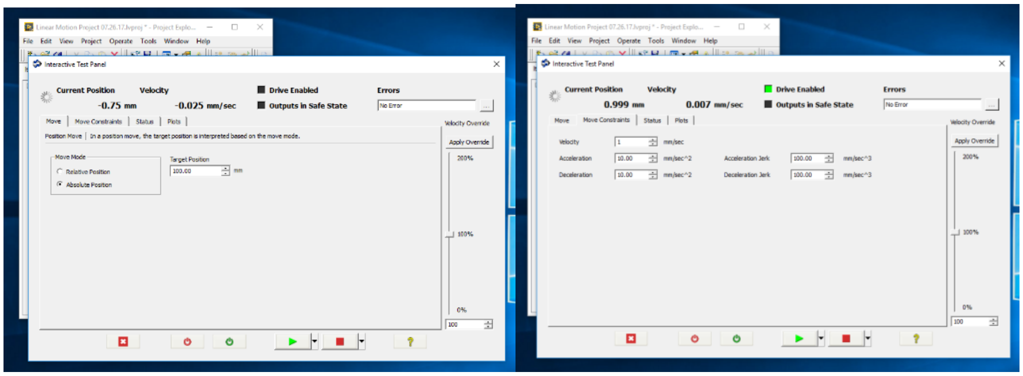




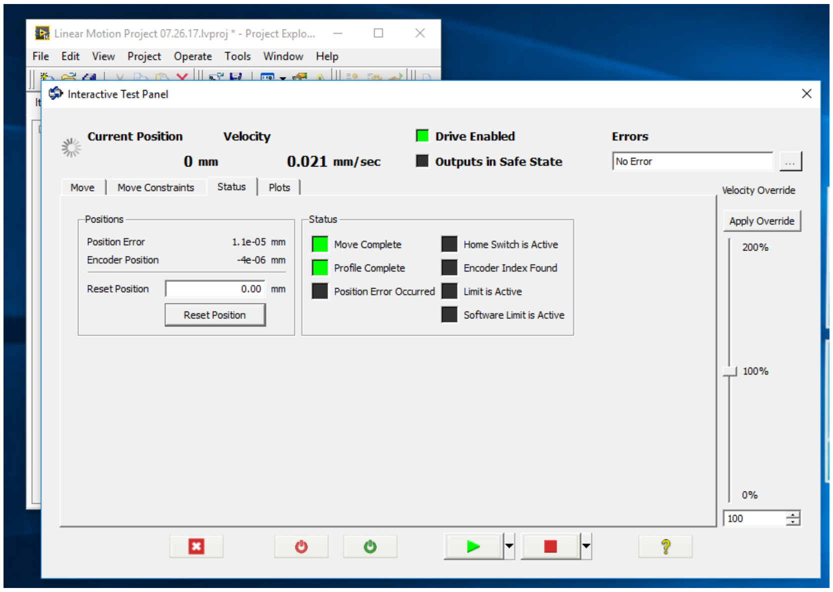
5. If this is the first time running a system it is important to check that communication is working correctly for the servo motor. This can be done using the interactive test panel, which is accessed by right clicking on the axis designated for the motor. **If the system has been operated previously in its current configuration, you can skip to Section 3.4.**



6. The following panel should appear. Press the green power button to enable the drive. Make sure values for acceleration and velocity are low for initial testing.



7. Navigate to status tab to reset actuator position if needed.



Current Position: 0 mm

Velocity: 0.021 mm/sec

🟩 Drive Enabled

■ Outputs in Safe State

Errors: No Error

Positions

Position Error: 1.1e-05 mm

Encoder Position: -4e-06 mm

Reset Position: 0.00 mm

Status

🟩 Move Complete

🟩 Profile Complete

■ Position Error Occurred

■ Home Switch is Active

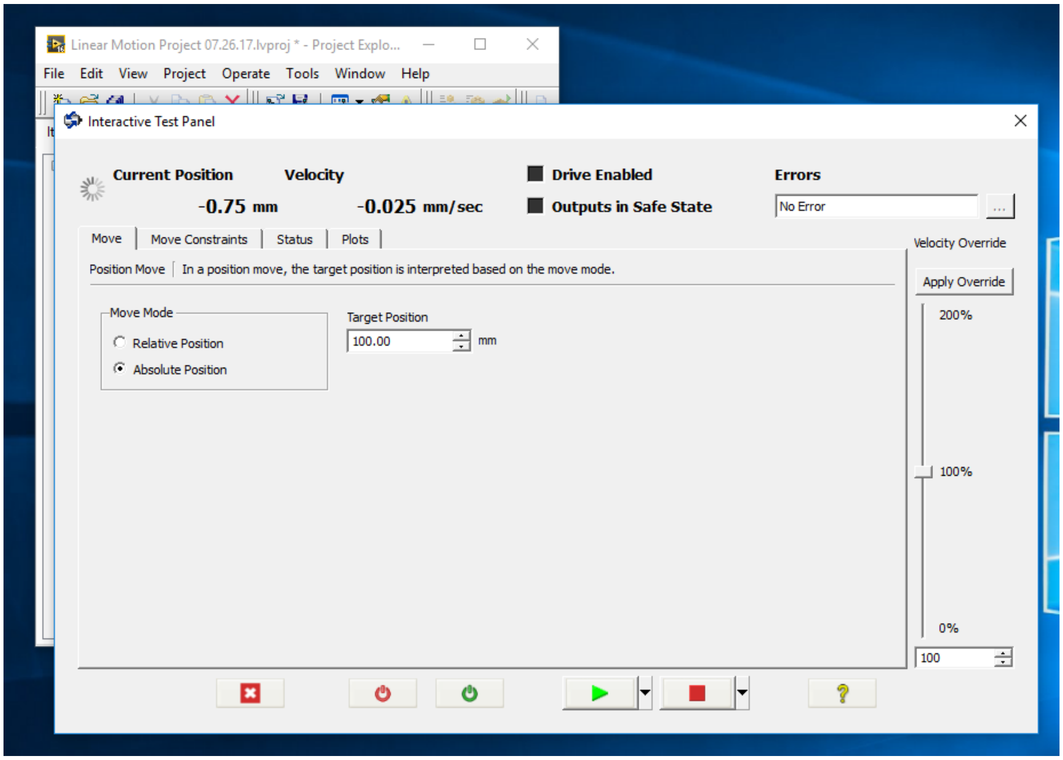
■ Encoder Index Found

■ Limit is Active

■ Software Limit is Active

Velocity Override: 100

8. Ensure final move position is the correct direction. **<u>A positive value will move the actuator into the rectangular housing while a negative value will extend the actuator outwards.</u>**



Current Position: -0.75 mm

Velocity: -0.025 mm/sec

■ Drive Enabled

■ Outputs in Safe State

Errors: No Error

Position Move | In a position move, the target position is interpreted based on the move mode.

Move Mode

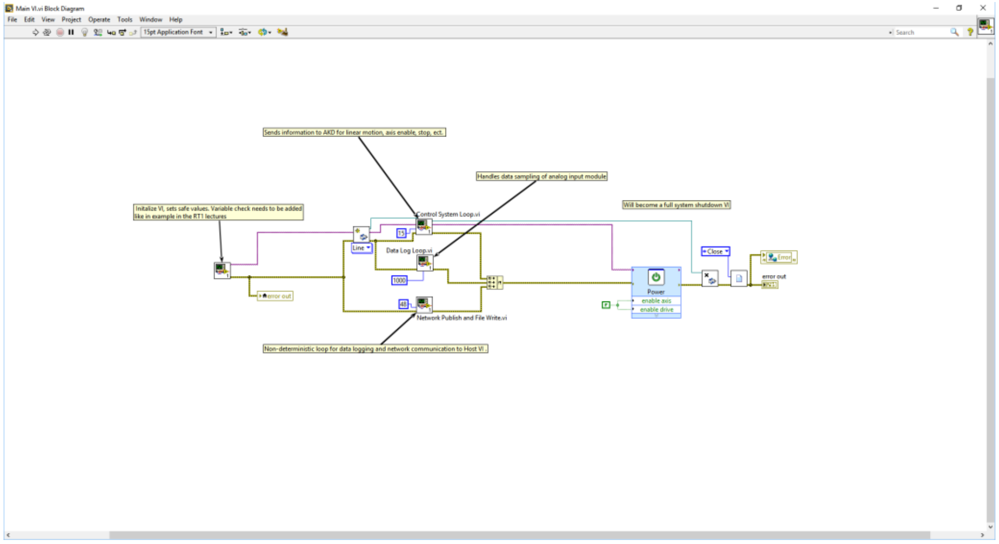
○ Relative Position

● Absolute Position

Target Position: 100.00 mm

Velocity Override: 100

9. In the LabVIEW project tree open (double click) the “Main.VI”. This is the software which will be deployed on the Target and is the primary control code for the load frame.



Sends information to AKD for linear motion, axis enable, stop, ect.

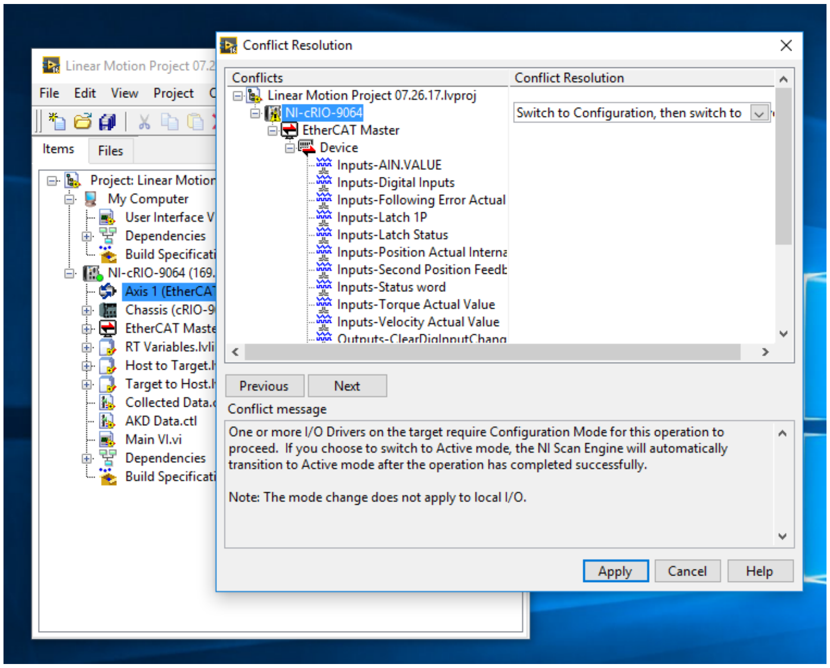
Handles data sampling of analog input module

Initalize VI, sets safe values. Variable check needs to be added like in example in the RT1 lectures

Will become a full system shutdown VI

Non-deterministic loop for data logging and network communication to Host VI .

10. In the “Main.VI” press Run then minimize
    a. If the conflict resolution screen shows click apply. This will pop up the first time a VI is run on the cRIO system as it needs to configure the scan engine settings.



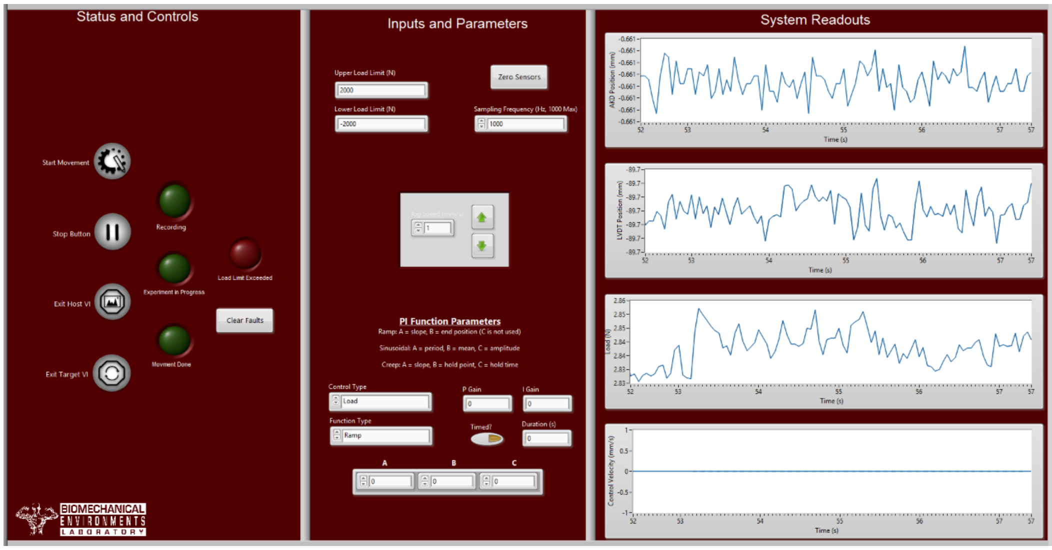
Conflict Resolution: Switch to Configuration, then switch to

Conflict message

One or more I/O Drivers on the target require Configuration Mode for this operation to proceed. If you choose to switch to Active mode, the NI Scan Engine will automatically transition to Active mode after the operation has completed successfully.

Note: The mode change does not apply to local I/O.

11. In the LabVIEW project tree open (double click) the "User Interface.VI". This is the software which is deployed on the Host and is how the user sends commands to the Target. Press Run when opened. When the program initializes correctly the graphs should all show fluctuating data (except current velocity) as shown below. From here the system is ready to operate.



Upper Load Limit (N): 2000

Lower Load Limit (N): -2000

Sampling Frequency (Hz, 1000 Max): 1000

Jog Speed (mm/s): 1

**PI Function Parameters**

Ramp: A = slope, B = end position (C is not used)

Sinusoidal: A = period, B = mean, C = amplitude

Creep: A = slope, B = hold point, C = hold time

Control Type: Load

Function Type: Ramp

P Gain: 0

I Gain: 0

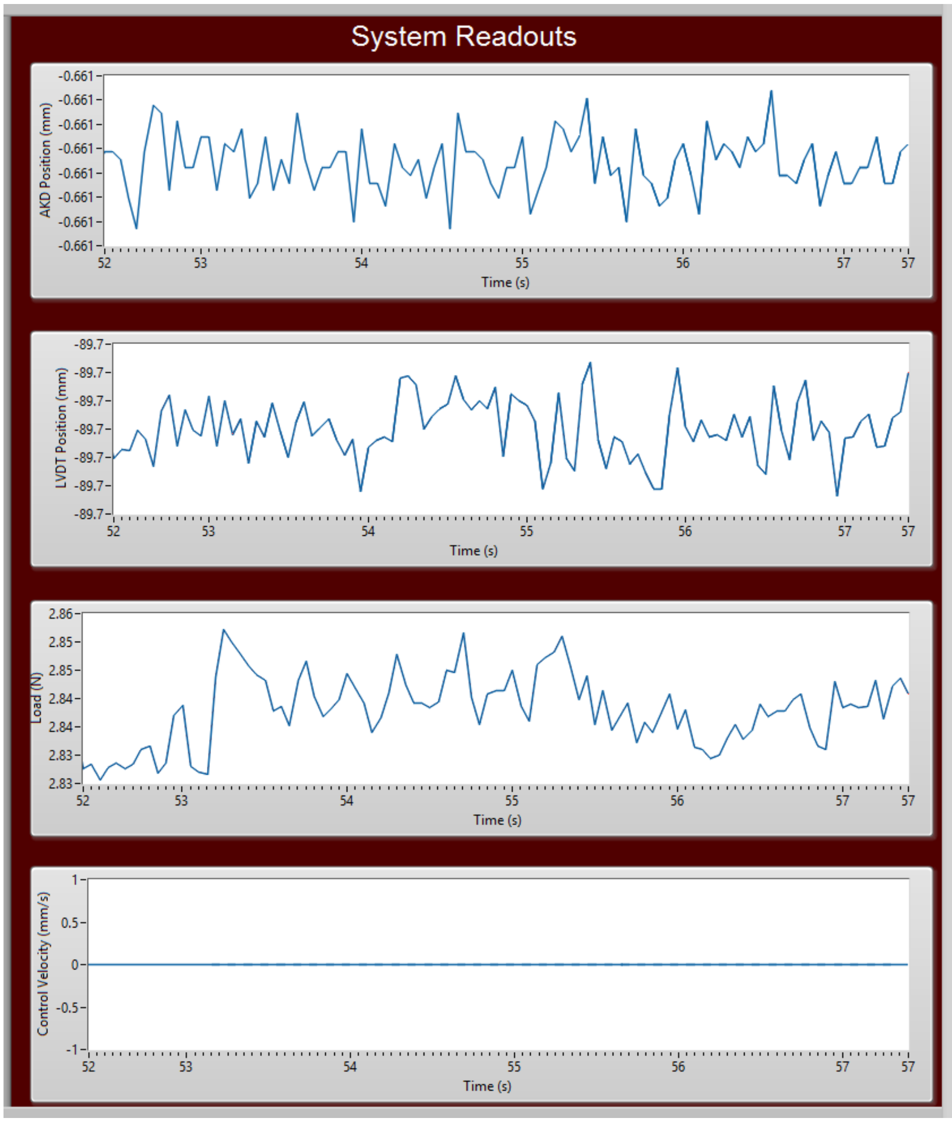
Duration (s): 0

A: 0

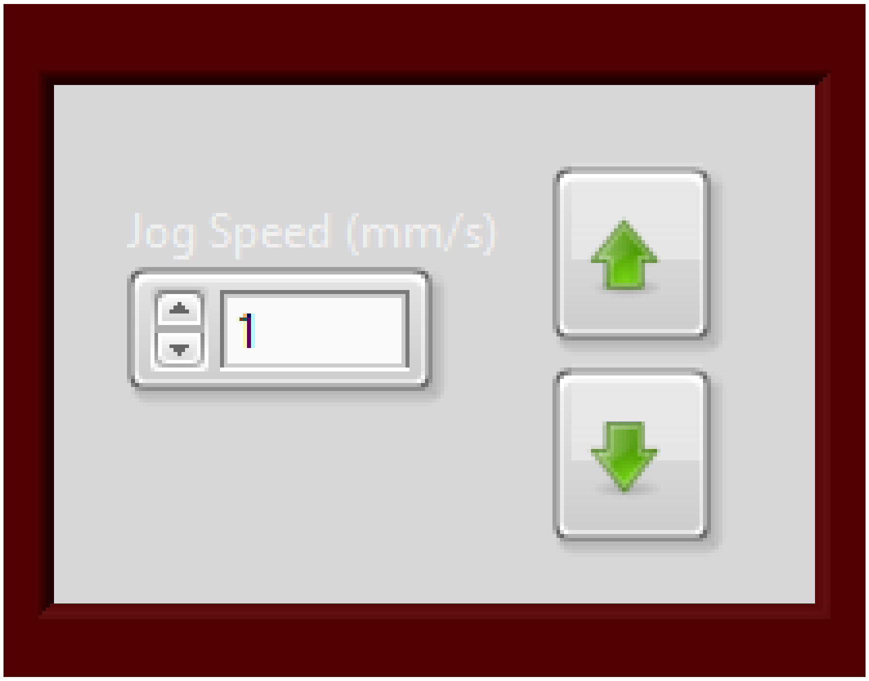
B: 0

C: 0

a. If the top three graphs show a perfectly straight line (after the graphs auto scale), the Main.vi did not execute properly. The flat lines indicate that data is not being sent from the cRIO to the PC. Abort both VI’s and repeat steps 9-11.
b. If the problem persists disconnect from the cRIO in the project window, and power cycle the system.



1. The system readouts display network published information from the cRIO via the Ethernet connection. (data shown is idle noise)
   a. AKD Position - indicates the actuator displacement determined from the encoder inside the servo motor.
   b. LVDT Position – indicates the direct value from the TransTek LVDT
   c. Load (N) – readout from the designated load cell
   d. Control Velocity – this is the velocity that is written to the AKD when the system is under operation of the PI control loop.



Jog Speed (mm/s): 1

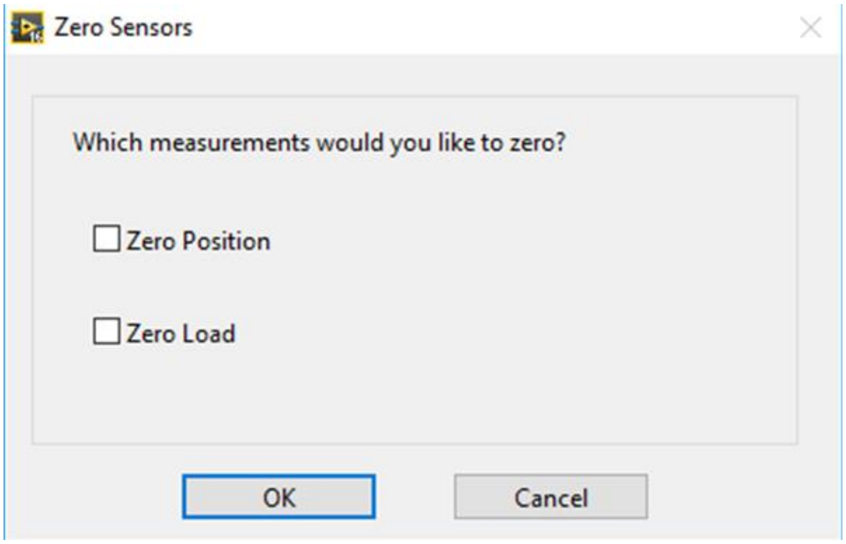
2. Use the jog buttons to position the actuator. The maximum speed for the linear actuator is 10mm/s. The top arrow moves the actuator cylinder into the rectangular housing, while the bottom will extend from the housing

Upper Load Limit (N): 2000

Lower Load Limit (N): -2000

Sampling Frequency (Hz, 1000 Max): 1000

3. Set the upper and lower load limits.
    a. If the lower load limit is higher than the upper a dialog box will appear requesting a new value.
4. Set the sampling frequency (will affect the data recording only)

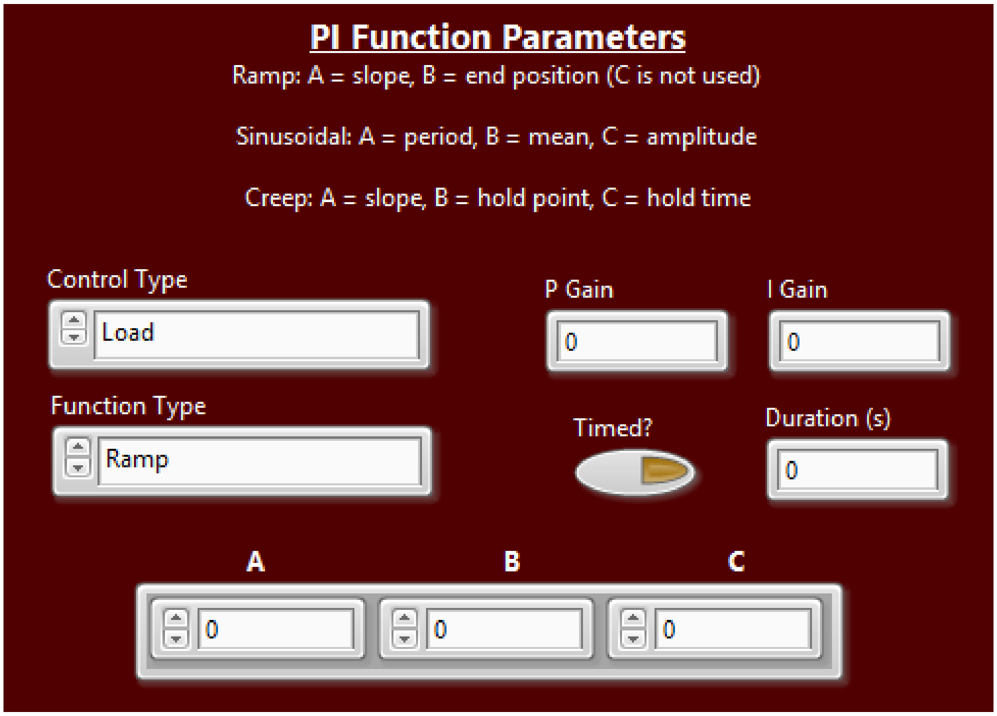


Which measurements would you like to zero?

☐ Zero Position

☐ Zero Load

5. Zero sensors if needed. These will add an offset to the load value or the LVDT. When pressed the (above) dialog box will appear allowing the items to be zeroed by checking the indicator boxes.



**PI Function Parameters**

Ramp: A = slope, B = end position (C is not used)

Sinusoidal: A = period, B = mean, C = amplitude

Creep: A = slope, B = hold point, C = hold time

Control Type: Load

P Gain: 0

I Gain: 0

Function Type: Ramp

Timed?

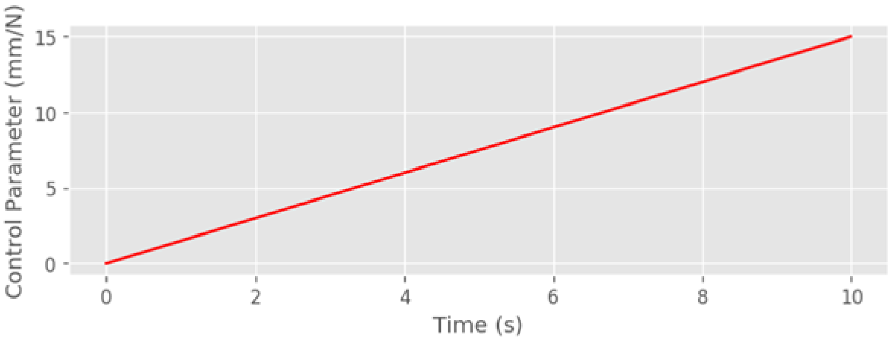
Duration (s): 0

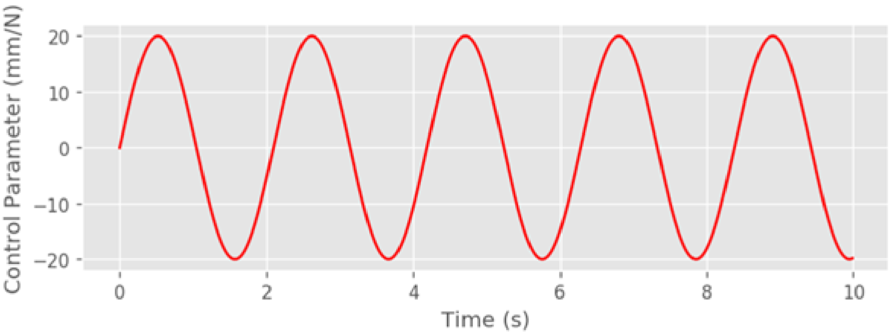
A: 0

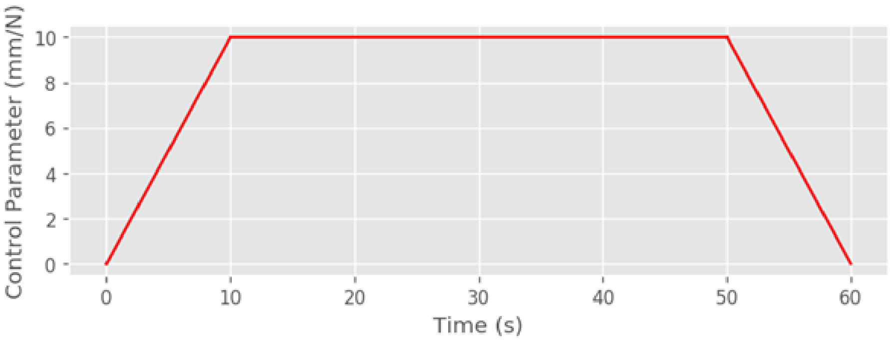
B: 0

C: 0

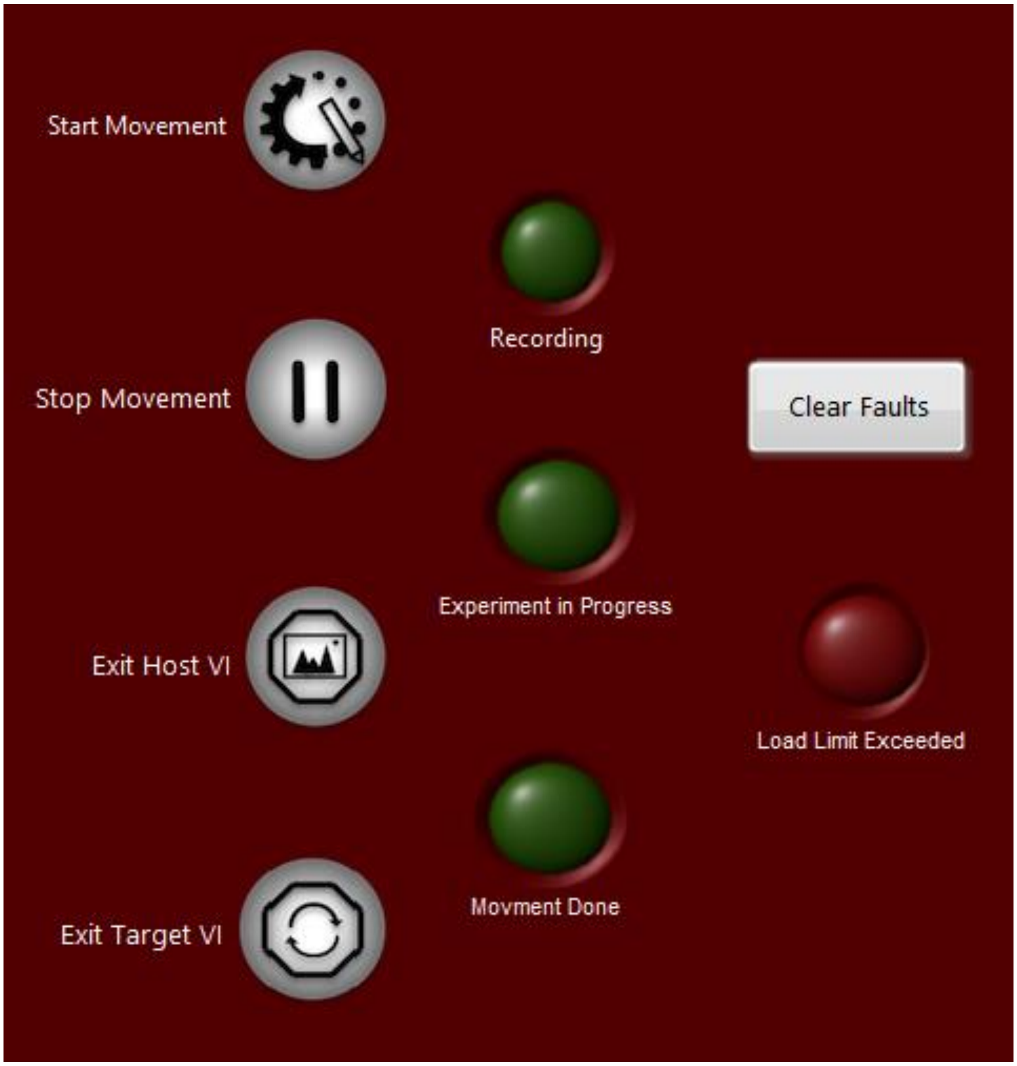
6. Set the PI function parameters for the desired experimental run
   a. **Control Type** – This refers to the sensor the PI function will refer to when determining the error. This can be Load or Position. Load will be the attached load cell or the LVDT







b. **Function Type** – This is the function path the system will follow, arbitrary examples are shown above, and this can be Ramp, Sinusoidal, or Creep.
c. **P Gain** – This is the proportional gain value for the PI controller
d. **I Gain** – This is the Integral gain value for the PI controller
e. **Timed? and Duration** – This will specify a set time for the experiment to run once started. The "Timed?" boolean must be lit if a timed run is desired. This time immediately starts when the experiment starts and will stop regardless if the function has reached the desired end point.
f. **A, B, C –** These parameters are defined differently for each function type (see image). The units are all Newton, millimeters, and seconds



7. Press Start Movement and follow the prompts for file creation
    a. When naming a file do not include any extension
8. Press Stop Movement button on the UI or the physical Emergency Stop if it is desired to stop a movement

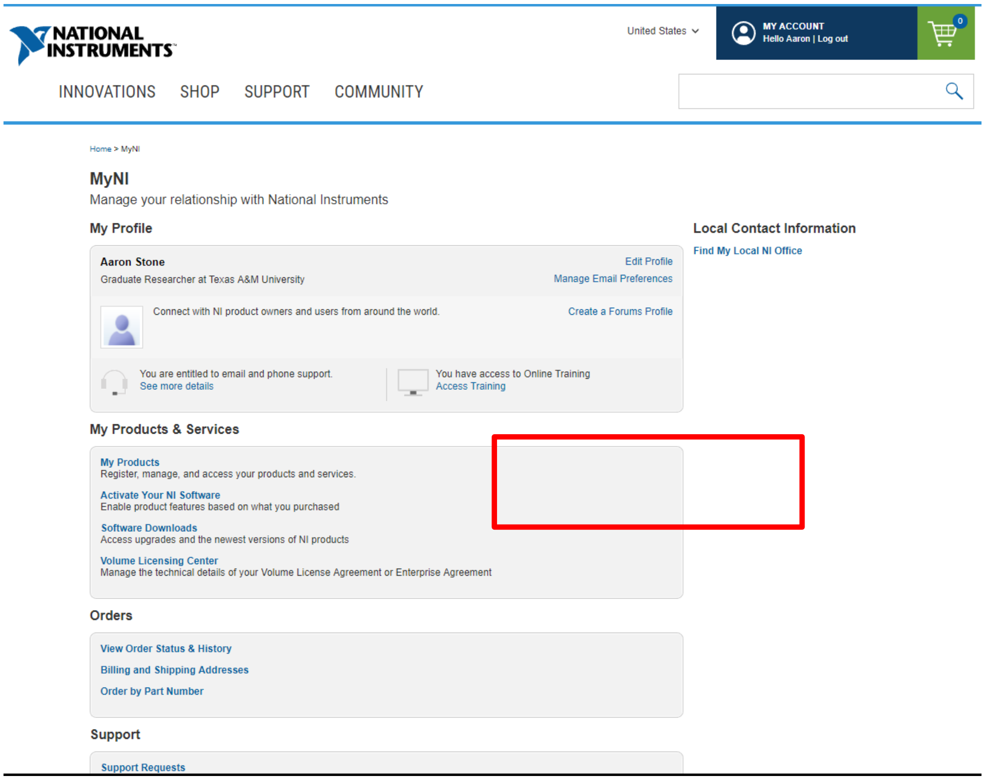
### Learning Resources for Development

National Instruments has a plethora of learning resources for the LabVIEW program. If you need to develop on the system the following resources are available:

## *LabVIEW Core Training Modules*

These are classes available for free for TAMU students that are normally for obtaining the LabVIEW certifications.

1. Create an NI account using you *@tamu.edu email address.
2. Navigate to My Account and select Access Training



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Volume Licensing Center
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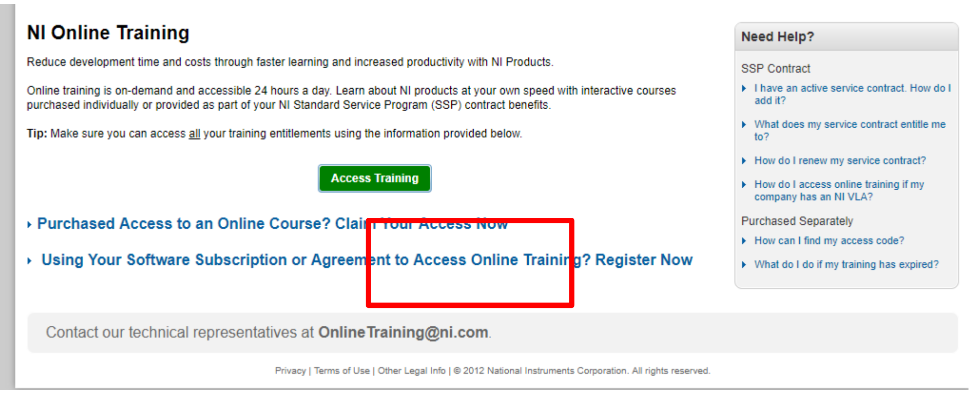
Billing and Shipping Addresses

Order by Part Number

Support

Support Requests

3. Select Access Training



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- How can I find my access code?
- What do I do if my training has expired?

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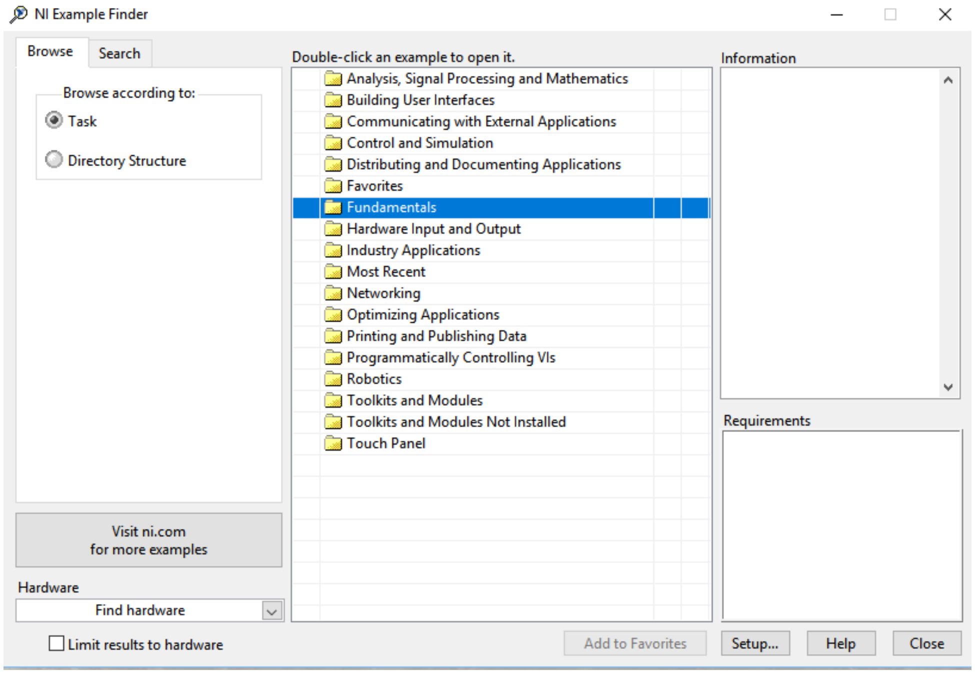
4. Scroll through the page and take the following courses as needed, in order. These are just the basic useful courses.
   a. LabVIEW Core 1
   b. LabVIEW Core 2
   c. LabVIEW Real-Time 1

*LabVIEW Examples*

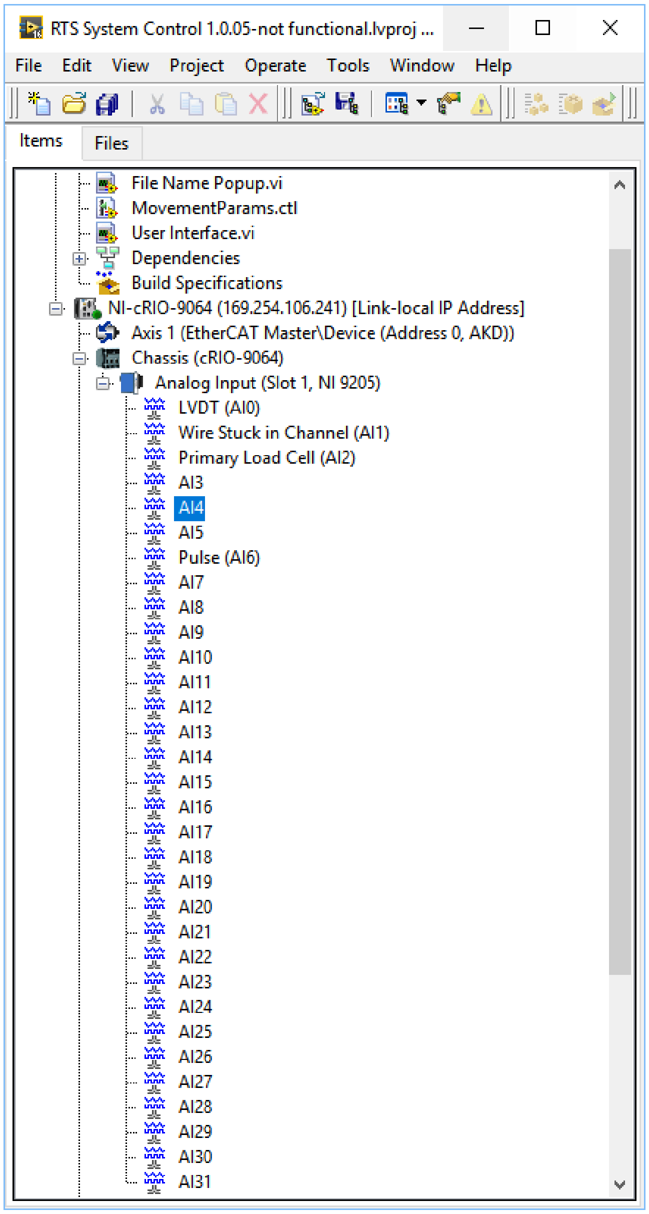
LabVIEW examples consist of VI’s available in the LabVIEW software (NI Example Finder). These can be found under the Help menu once an existing or new VI is opened.



## Code Development and System Reconfiguration

### *Changing the primary Load Cell*

1. Connect the load cell through the necessary signal conditioners
2. Navigate to the LabVIEW project tree
3. Expand the Chassis to where the cRIO modules are displayed and expand the analog input module



File Name Popup.vi
MovementParams.ctl
User Interface.vi
Dependencies
Build Specifications
NI-cRIO-9064 (169.254.106.241) [Link-local IP Address]
Axis 1 (EtherCAT Master\Device (Address 0, AKD))
Chassis (cRIO-9064)
Analog Input (Slot 1, NI 9205)
LVDT (AI0)
Wire Stuck in Channel (AI1)
Primary Load Cell (AI2)
AI3
AI4
AI5
Pulse (AI6)
AI7
AI8
AI9
AI10
AI11
AI12
AI13
AI14
AI15
AI16
AI17
AI18
AI19
AI20
AI21
AI22
AI23
AI24
AI25
AI26
AI27
AI28
AI29
AI30
AI31

4. Connect the load cell to the channel labeled “Primary Load Cell”

    a. For a Futek Load cell this should be the wires from the IAA100 signal conditioner

5. Navigate to the UI Initalize.vi
6. Change the constant value for the Load Cell Sensitivity variable
    a. This constant is the **Newton/Volt** information pertaining to the specific load cell
    b. **Warning:** The units for the constant must be N/V or the load limits and PI controller will not function correctly and can damage the system or the load cell

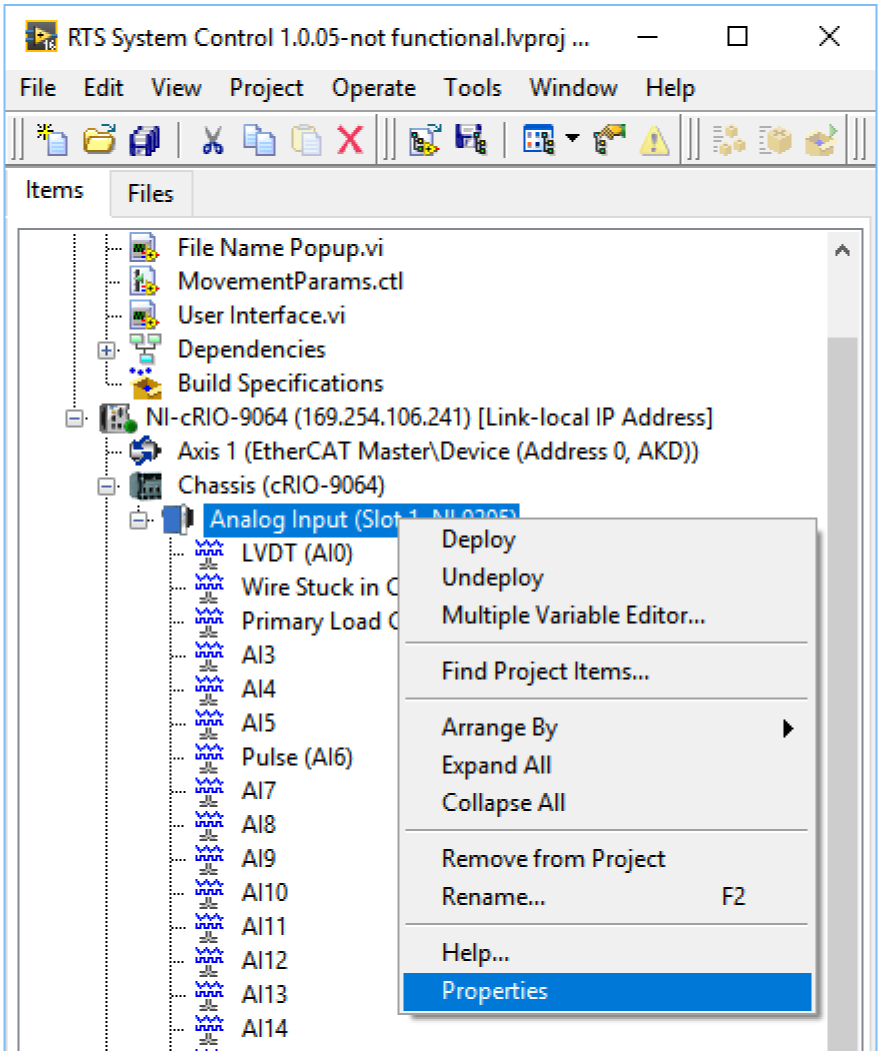
7. Save the VI's and hang free weights from the load cell to ensure the readouts have the correct values

### *Adding an Additional Sensor*

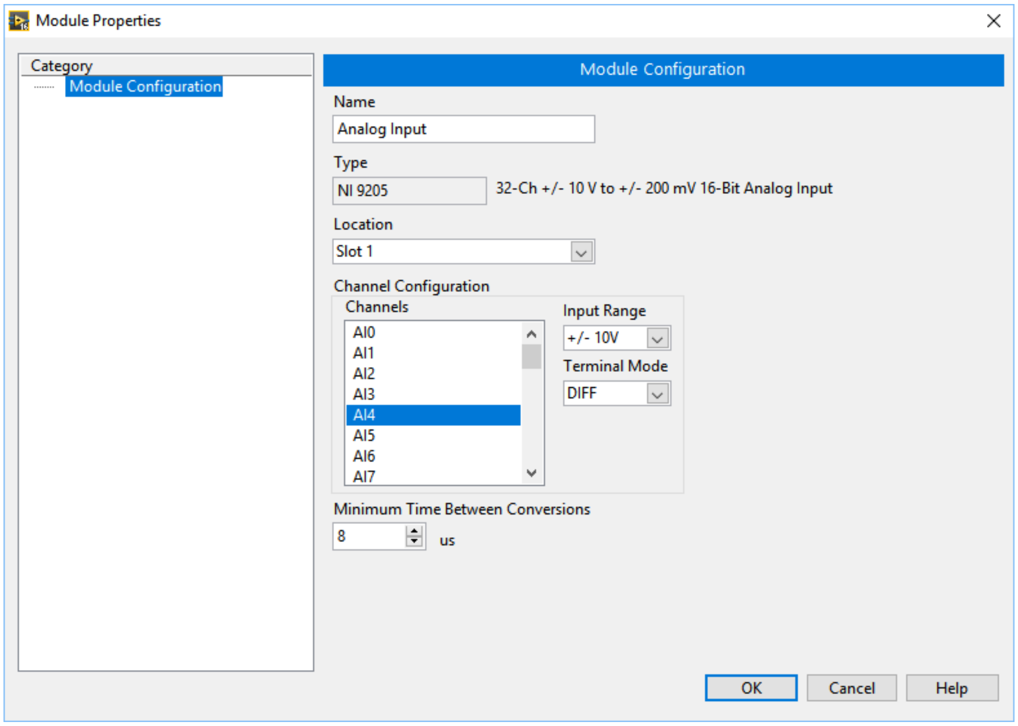
The following steps are specifically for the NI-9205 Analog Input module, however the procedure is similar for other modules. This includes adding sensors only for data collection and display on the User Interface.

If it is necessary for the sensors to communicate with the PI controller (in addition to the Primary LVDT and Primary Load Cell, further development is needed.

1. Navigate to the LabVIEW project tree
2. Expand the Chassis to where the cRIO modules are displayed and expand the desired input module
3. Right Click the input module in the project tree and select properties



4. Select the desired available channel and configure as needed.
    a. For the NI-9204 most channels will be use in the Differential (DIFF) at a 10V range as shown



Module Configuration

Name: Analog Input

Type: NI 9205 32-Ch +/- 10 V to +/- 200 mV 16-Bit Analog Input

Location: Slot 1

Channel Configuration

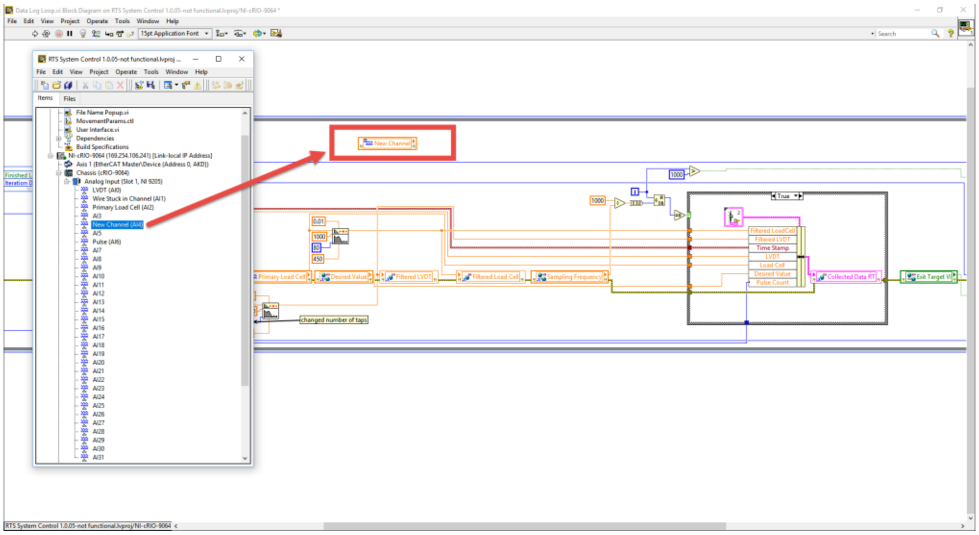
Channels: AI0, AI1, AI2, AI3, AI4, AI5, AI6, AI7

Input Range: +/- 10V

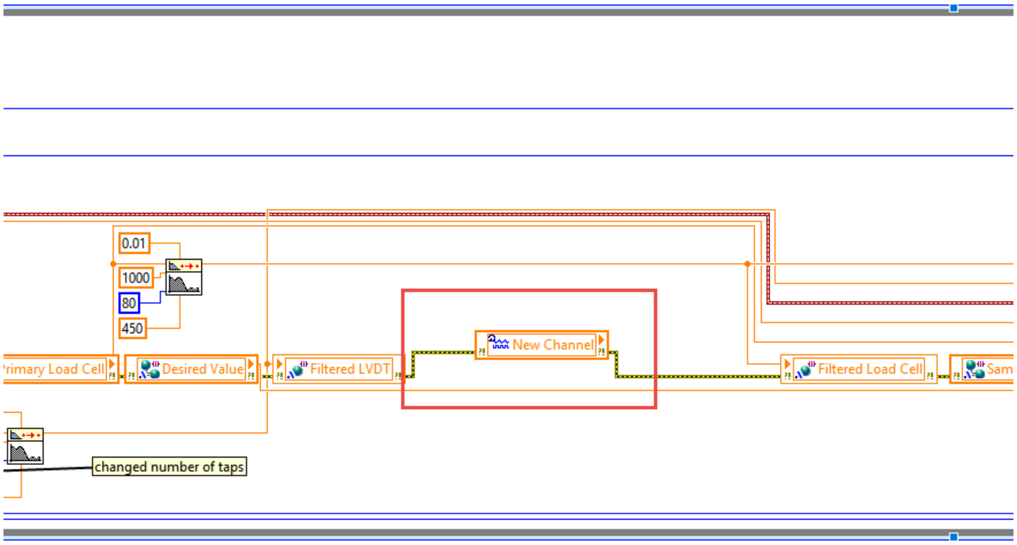
Terminal Mode: DIFF

Minimum Time Between Conversions: 8 us

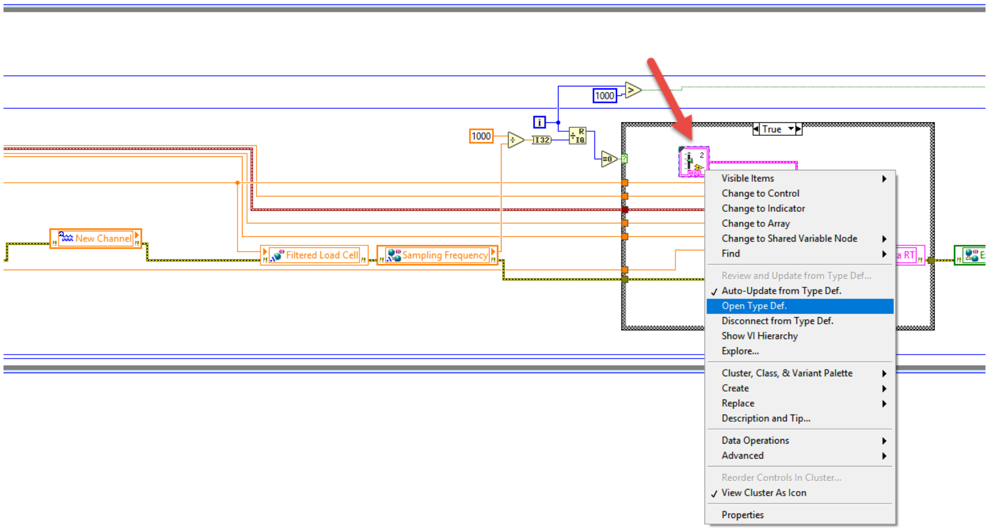
5. Once the channel is configured navigate to the Data Log Loop.vi
6. Drag the channel from the project view tree to the Data Log Loop.vi block diagram



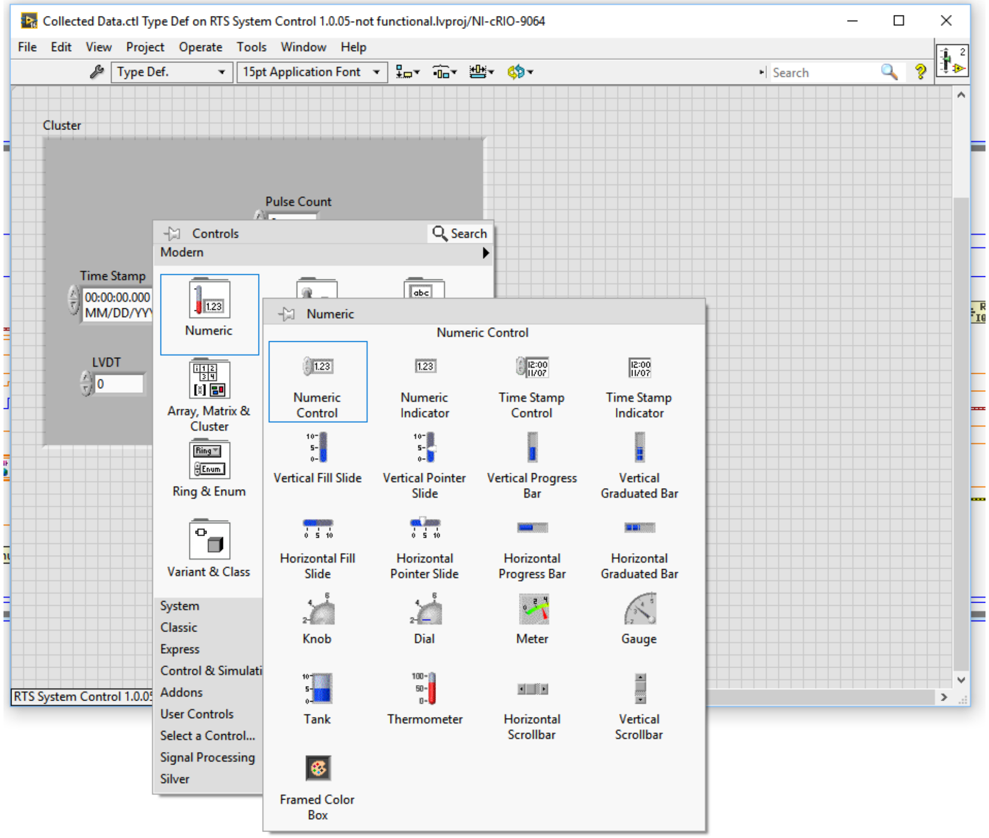
7. Run the error line through the new channel



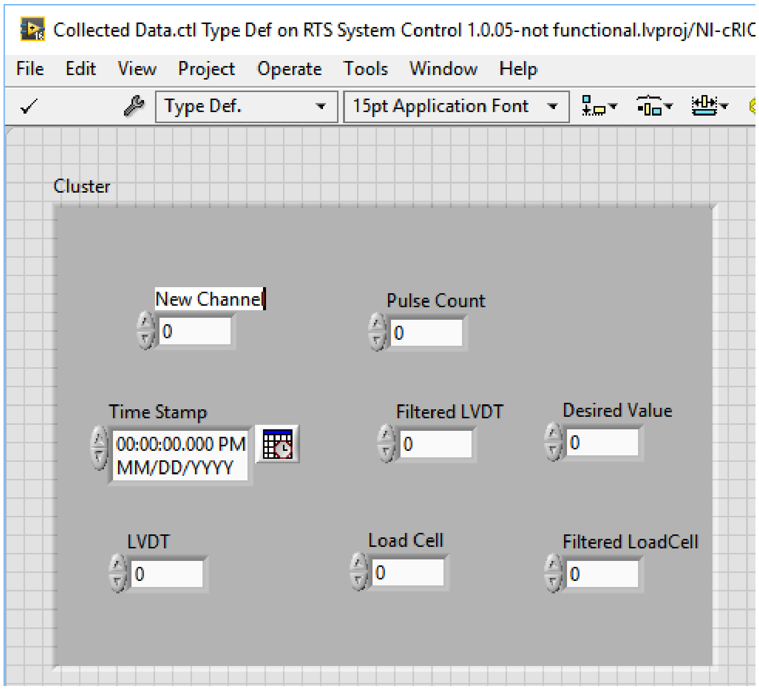
8. Right click the cluster icon shown and select Open Type Def.
    a. More information on Clusters and Type Def. can be found on NI white pages



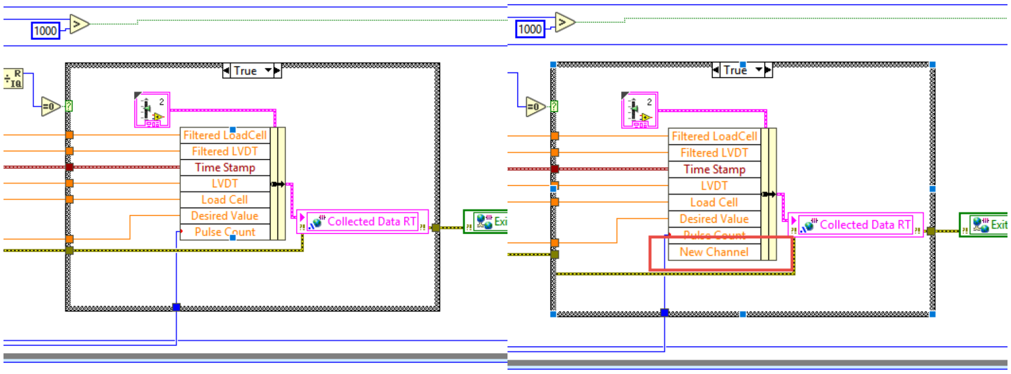
9. Right click inside the Cluster (named Collected Data.ctl) and add the necessary element for the data type. Be sure to name the new element appropriately then save and close the Collected Data.ctl.



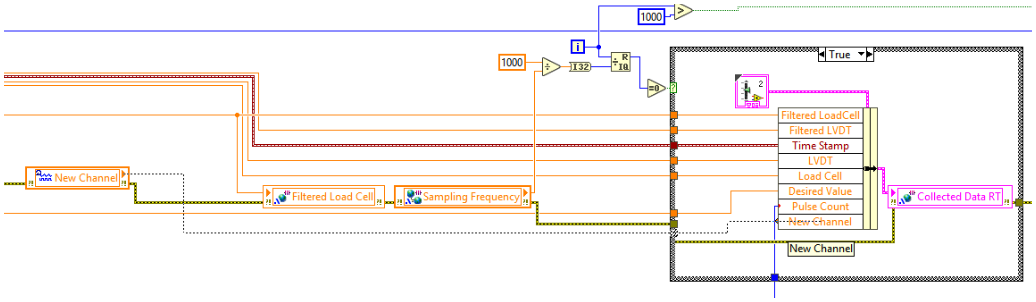
10. Name the new element appropriately then save and close the Collected Data.ctl.



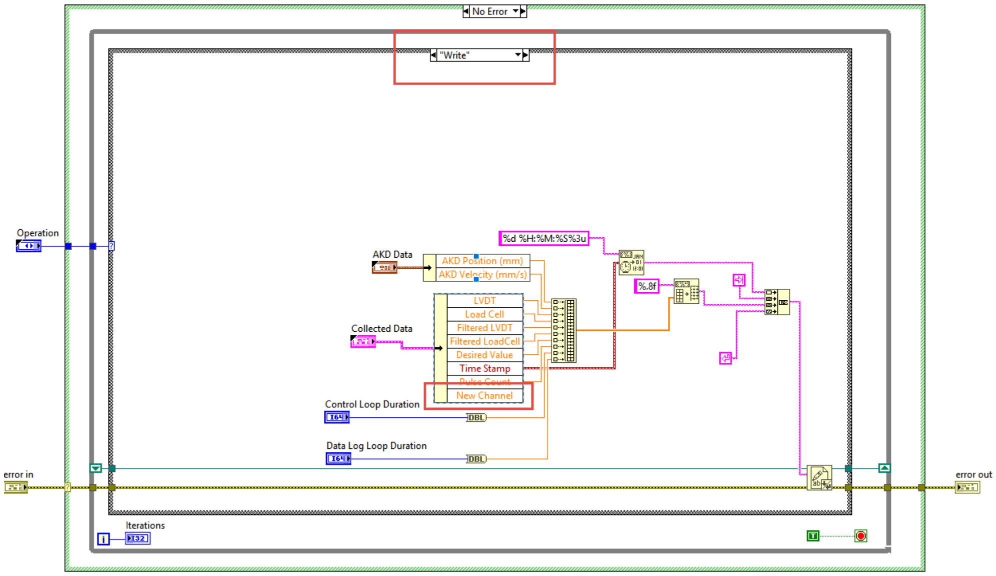
11. Return to the Data Log Loop.vi block diagram and expand the bundle by name element until the new channel is displayed.



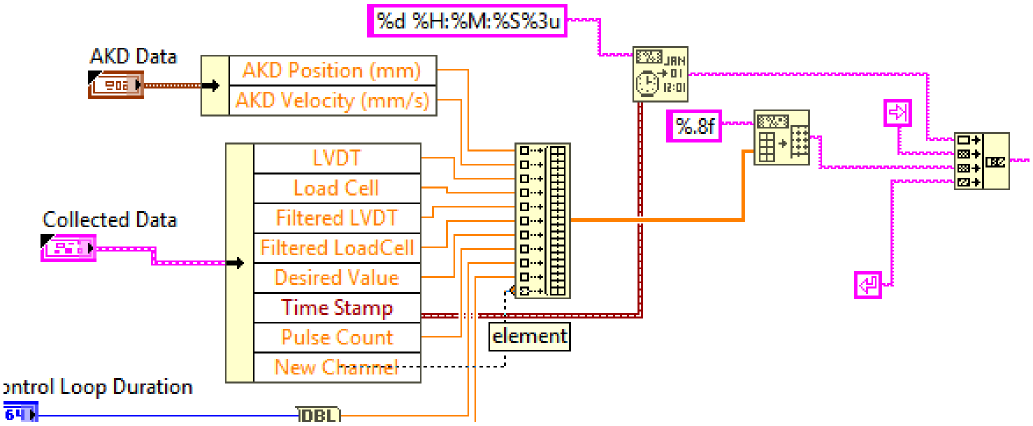
12. Wire the new variable to the bundle by element channel



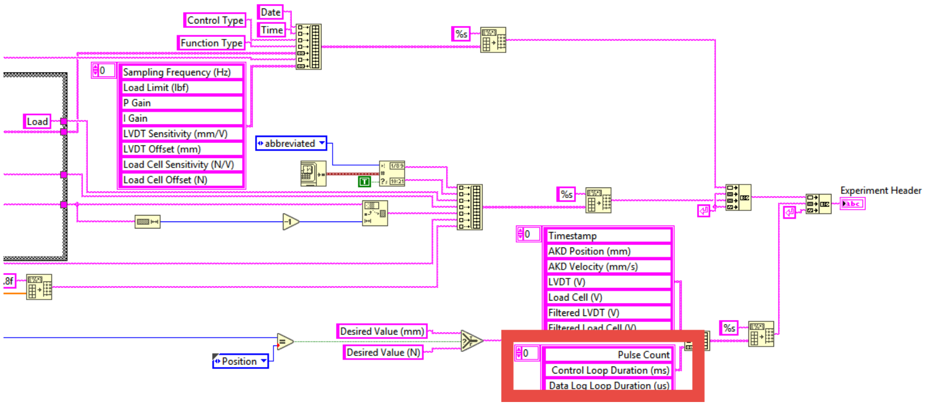
13. Save the Data Log Loop.vi and navigate to the File Module.vi
14. Navigate to the “Write” case in the File Module.vi
15. Expand the Unbundle by Name element until the new channel is displayed



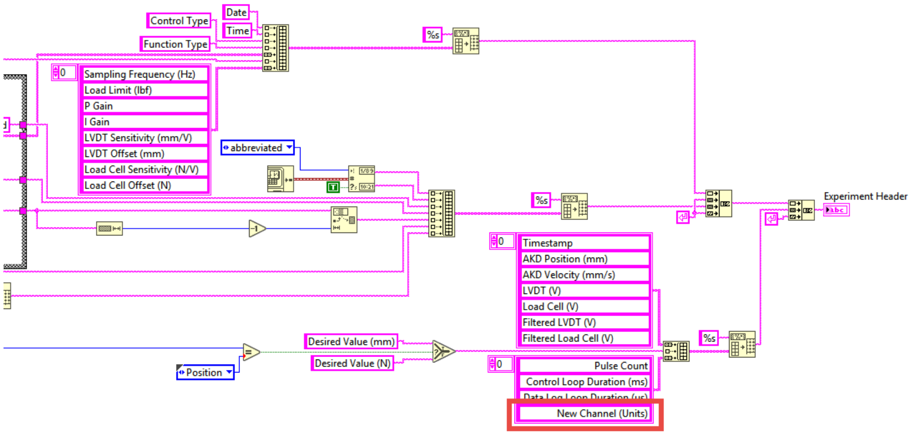
16. Expand the Build Array element and wire the New Channel. Always add the new channel to the bottom of the build array element. This will make adjusting the file header simpler.



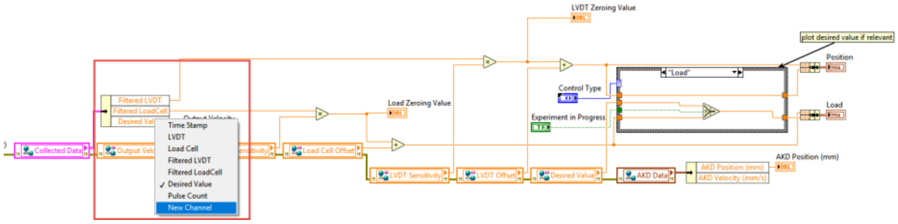
17. Navigate to the GetExperimentHeader.vi block diagram
18. Locate the shown array of string elements and expand the array by the number of new channels



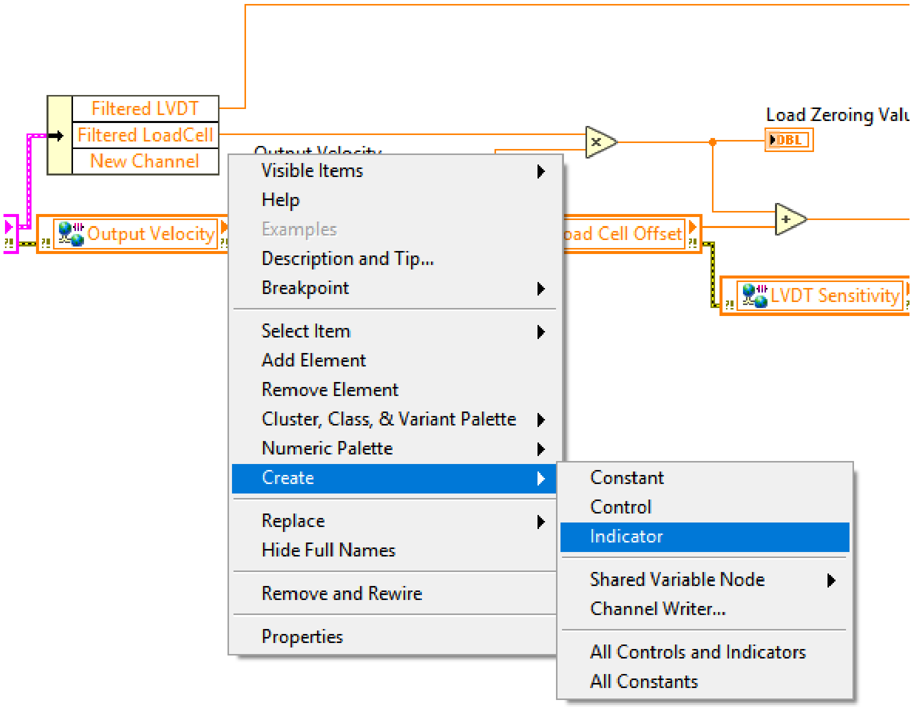
19. Add the name identifier for the new channel in the string array



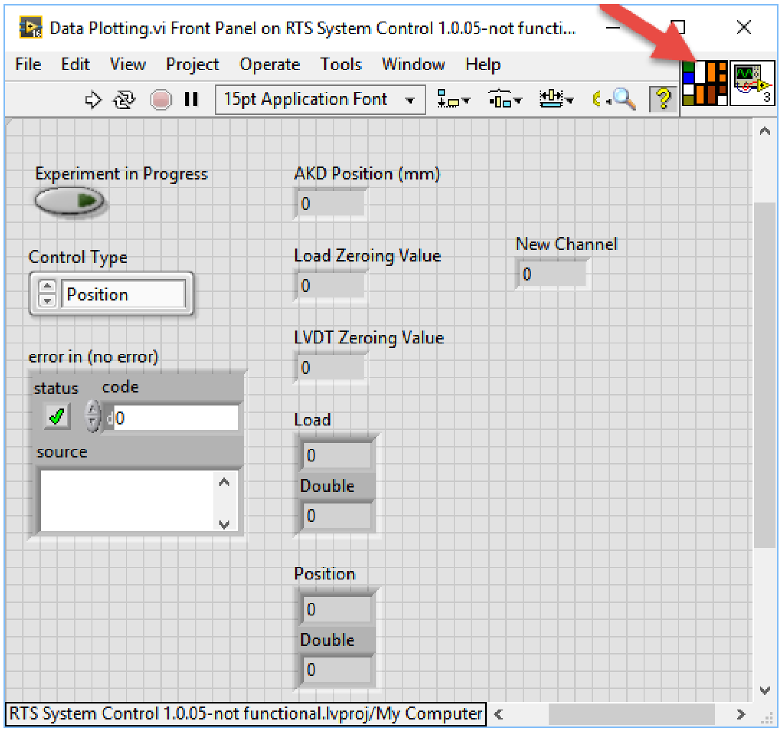
20. If you want to display the new channel on the User Interface continue through the following steps. If **not**, run a test to make sure the header and new channel lineup correctly in the output file. The easiest way to do this is run an experiment while recording data with all experimental parameters set to zero then open the .txt file in Google Chrome.
21. Navigate to the User Interface.vi block diagram then to the Data Plotting.vi (you will need both open)
22. In the Data Plotting.vi expand the Unbundle by Name element by the number of new channels, selecting the new channel(s) by left clicking the name

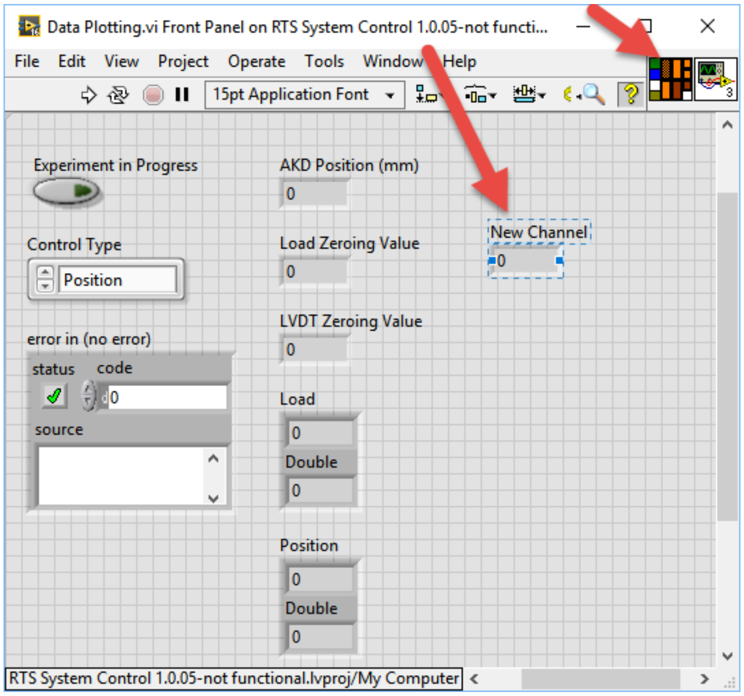


23. Right click the wire location of the new channel and create and indicator



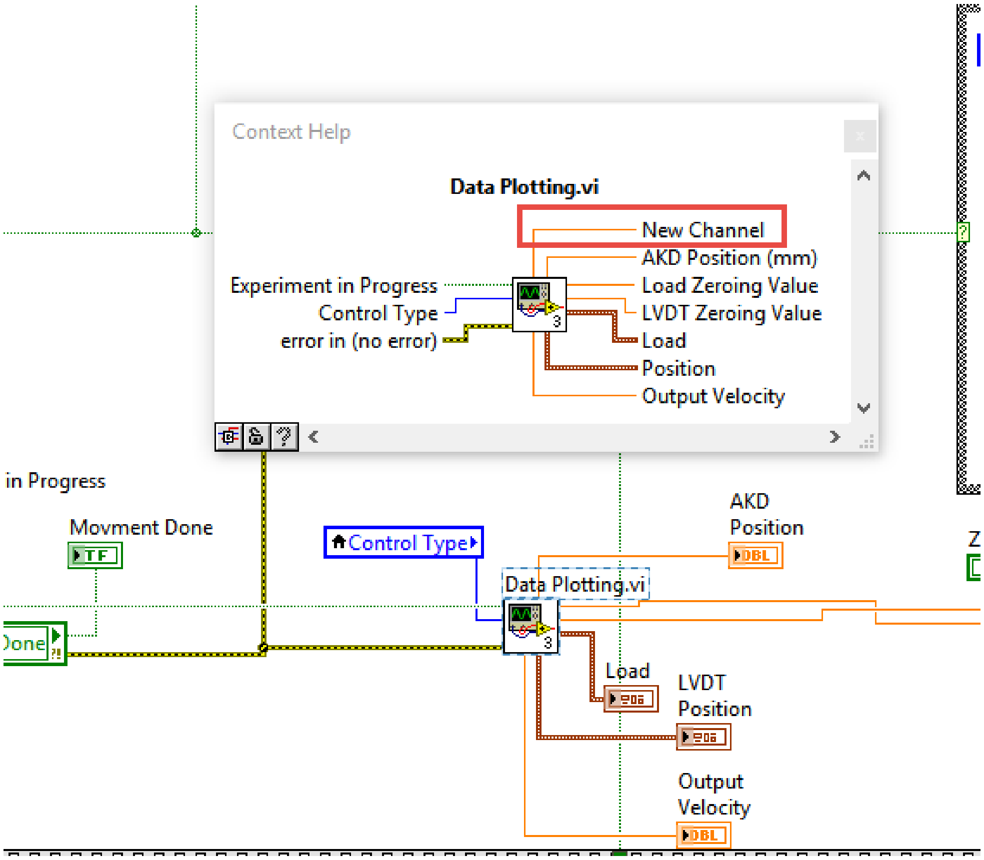
24. Navigate to the Data Plotting.vi front panel
25. In the upper right corner of the window left click one of the empty white squares (this is to create a terminal on the sub VI for wiring to a display in the main UI) then left click the new channel indicator.



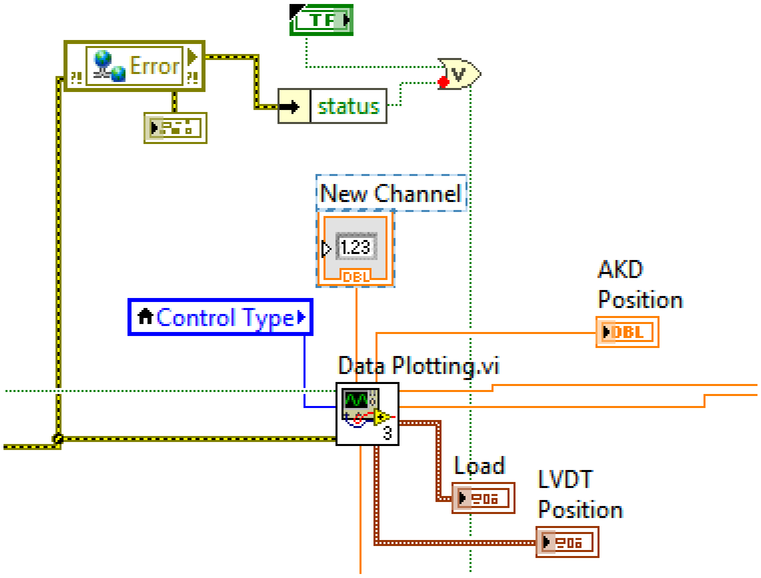


26. Save the Data Plotting.vi and return to the User Interface.vi block diagram

27. Press Ctr+H to bring up the context help and hover the mouse over the Data Plotting.vi. This will display the sub vi's terminals, which should now include the new terminal created in step 25.
    a. If you do not see the new channel's terminal in the context help check back in the Data Plotting.vi and wire the terminal again



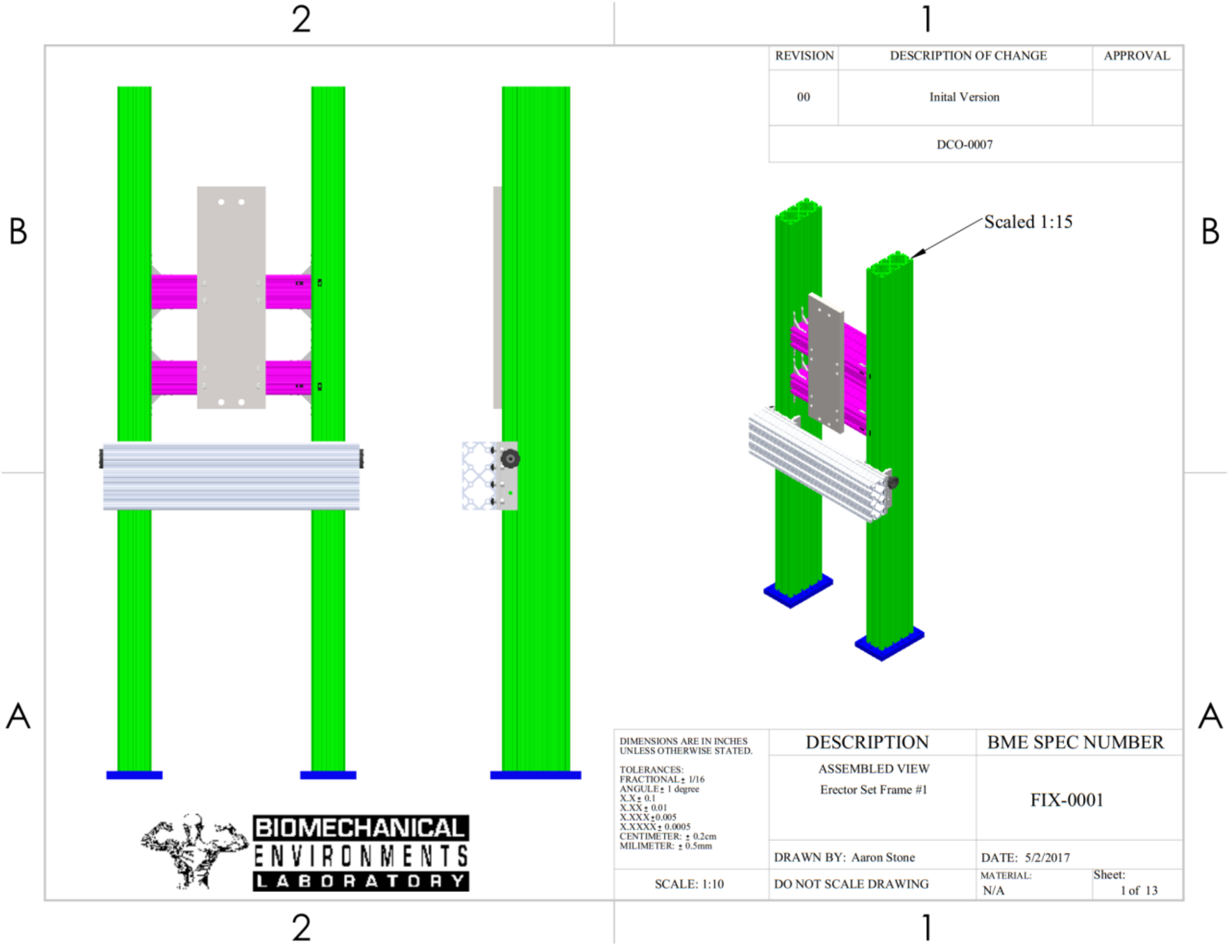
28. Right click the terminal on the Data Plotting.vi and create the desired indicator



29. Position the new channel indicator in the desired position on the User Interface front panel
30. Run a mock movement to make sure the header and new channel lineup correctly on the output file and that the UI displays correctly. One way to do this is to run an experiment while recording data with all PI parameters set to zero then check the .txt file in Google Chrome.

# APPENDIX B

## Frame Assembly and Fabrication Drawings



| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| | DCO-0007 | |

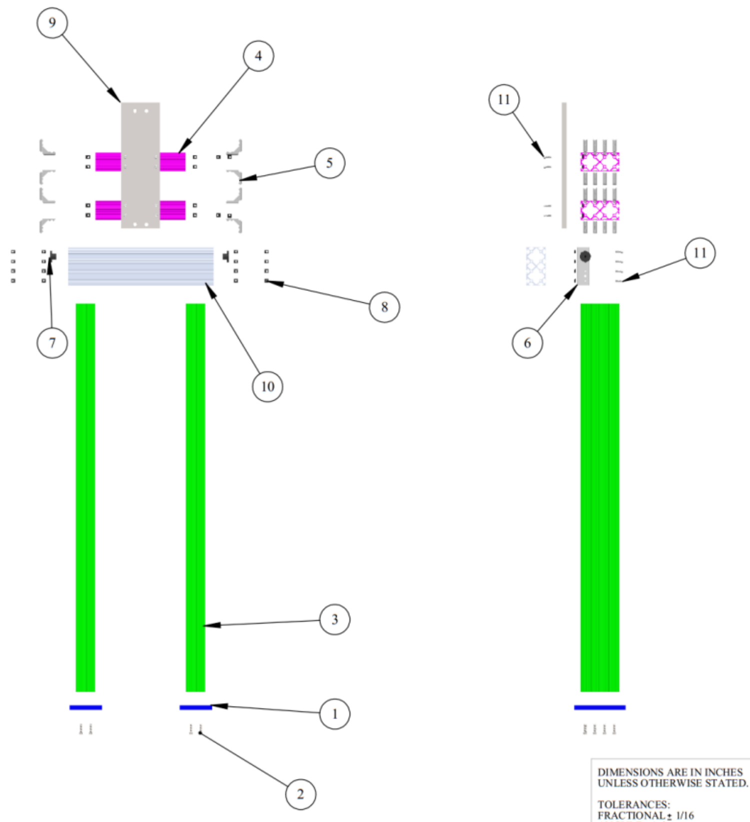
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE STATED.

TOLERANCES:
FRACTIONAL ± 1/16
ANGULE ± 1 degree
X.X ± 0.1
X.XX ± 0.01
X.XXX ±0.005
X.XXXX ± 0.0005
CENTIMETER: ± 0.2cm
MILIMETER: ± 0.5mm

| DESCRIPTION | BME SPEC NUMBER |
|---|---|
| ASSEMBLED VIEW<br>Erector Set Frame #1 | FIX-0001 |
| DRAWN BY: Aaron Stone | DATE: 5/2/2017 |

SCALE: 1:10
DO NOT SCALE DRAWING
MATERIAL: N/A
Sheet: 1 of 13

| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| | DCO-0007 | |



**Bill of Materials**

| ITEM NO. | QTY. | DESCRIPTION |
|---|---|---|
| 1 | 2 | 80_20 Breadboard Adapter |
| 2 | 16 | 0.375-16 Socket Head Cap Screw |
| 3 | 2 | 80_20 Inc. 3060 Profile 60in |
| 4 | 2 | 80_20 Inc. 3060 Profile 14in |
| 5 | 32 | 80_20 Inc. 3364 Bracket |
| 6 | 2 | 80_20 Inc. 6534 Linear Bearing |
| 7 | 2 | 80_20 Inc. 6802 Linear Bearing Brake |
| 8 | 28 | .3125-18 T-Nut |
| 9 | 1 | 80_20 to Actuator Mount |
| 10 | 1 | 80_20 Inc. 3060 Profile 22.5in |
| 11 | 24 | 0.3125-18 Socket Head Cap Screw |

BIOMECHANICAL
ENVIRONMENTS
LABORATORY

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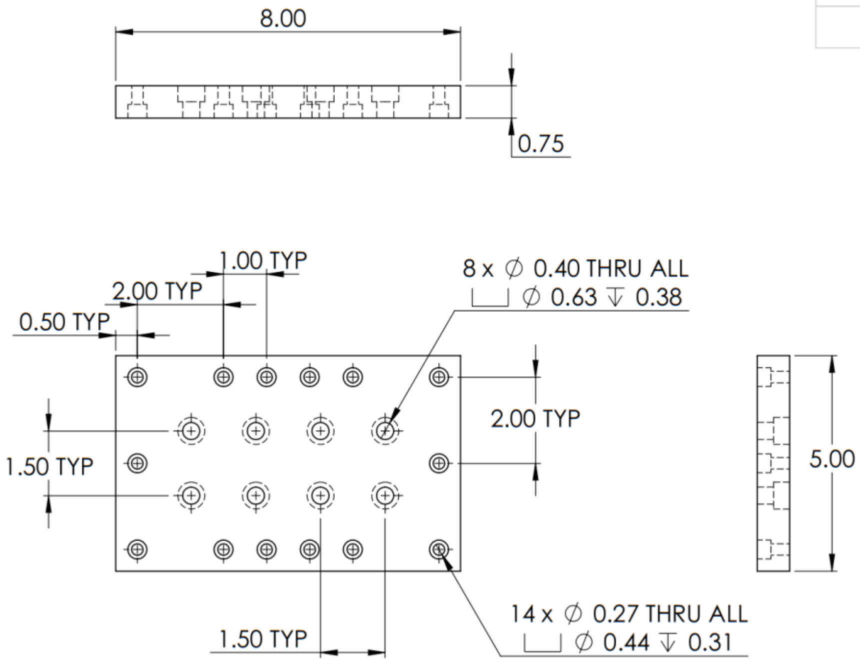
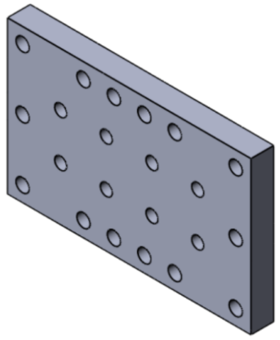
|---|---|---|---|
| DIMENSIONS ARE IN INCHES UNLESS OTHERWISE STATED.<br>TOLERANCES:<br>FRACTIONAL ± 1/16<br>ANGULE ± 1 degree<br>X.X ± 0.1<br>X.XX ± 0.01<br>X.XXX ±0.005<br>X.XXXX ± 0.0005<br>CENTIMETER: ± 0.2cm<br>MILIMETER: ± 0.5mm | DESCRIPTION<br>EXPLODED VIEW<br>Erector Set Frame #1 | BME SPEC NUMBER<br>FIX-0001 | |
| | DRAWN BY: Aaron Stone | DATE: 5/2/2017 | |
| SCALE: 1:20 | DO NOT SCALE DRAWING | MATERIAL:<br>N/A | Sheet:<br>2 of 13 |

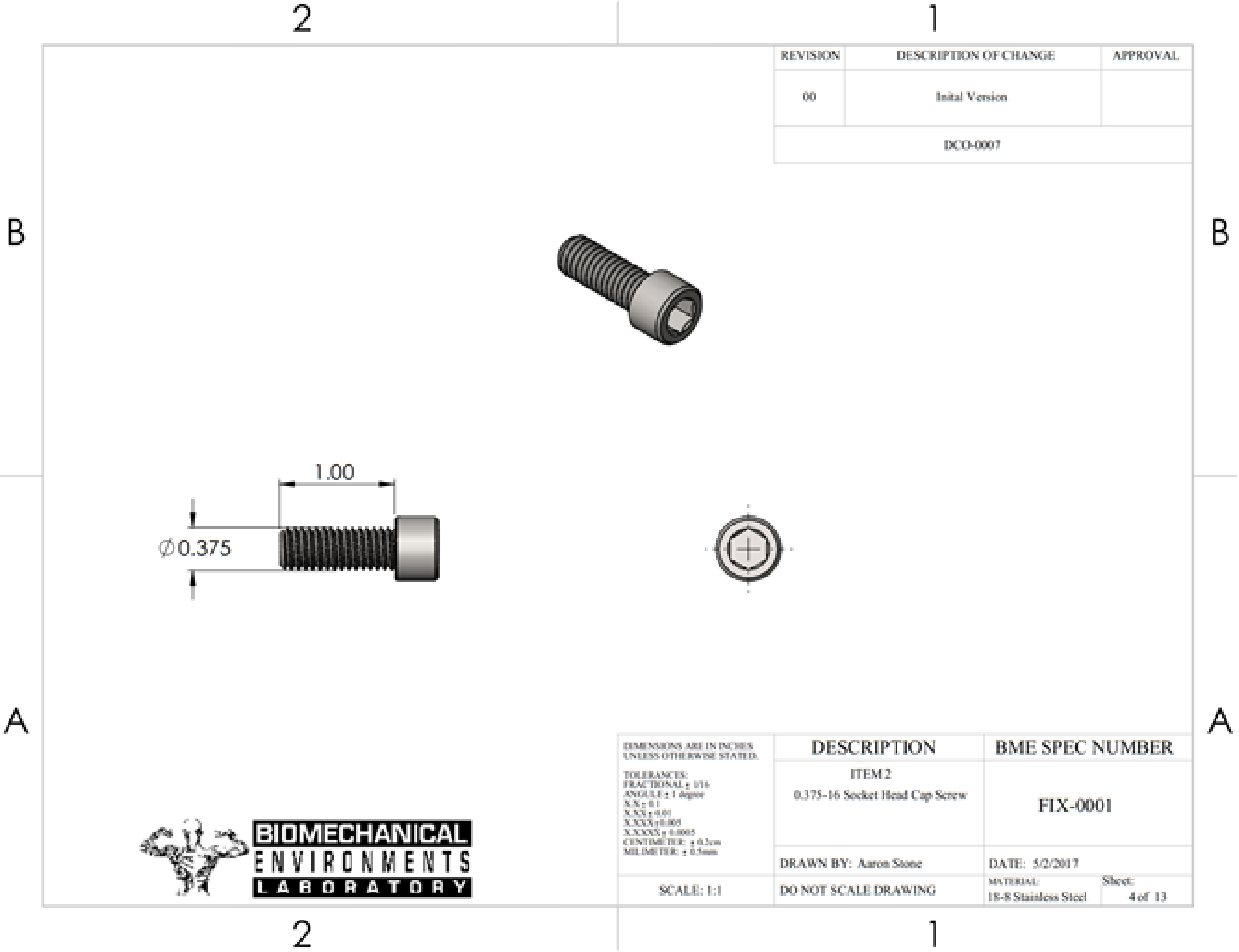
| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| | DCO-0007 | |





BIOMECHANICAL ENVIRONMENTS LABORATORY

| | | | |
|---|---|---|---|
| DIMENSIONS ARE IN INCHES UNLESS OTHERWISE STATED.<br>TOLERANCES:<br>FRACTIONAL ± 1/16<br>ANGULE ± 1 degree<br>X.X ± 0.1<br>X.XX ± 0.01<br>X.XXX ±0.005<br>X.XXXX ± 0.0005<br>CENTIMETER: ± 0.2cm<br>MILIMETER: ± 0.5mm | DESCRIPTION | BME SPEC NUMBER | |
| | ITEM 1<br>80_20 Breadboard Adapter | FIX-0001 | |
| | DRAWN BY: Aaron Stone | DATE: 5/2/2017 | |
| SCALE: 1:3 | DO NOT SCALE DRAWING | MATERIAL:<br>304 Stainless Steel | Sheet:<br>3 of 13 |



| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| DCO-0007 | | |

BIOMECHANICAL ENVIRONMENTS LABORATORY

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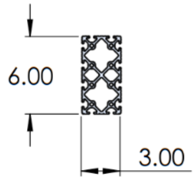
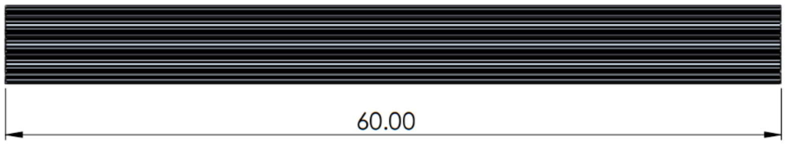
|---|---|---|
| DIMENSIONS ARE IN INCHES UNLESS OTHERWISE STATED.<br>TOLERANCES:<br>FRACTIONAL ± 1/16<br>ANGULE ± 1 degree<br>X.X ± 0.1<br>X.XX ± 0.01<br>X.XXX ±0.005<br>X.XXXX ± 0.0005<br>CENTIMETER: ± 0.2cm<br>MILIMETER: ± 0.5mm | DESCRIPTION<br>ITEM 2<br>0.375-16 Socket Head Cap Screw | BME SPEC NUMBER<br>FIX-0001 |
| | DRAWN BY: Aaron Stone | DATE: 5/2/2017 |
| SCALE: 1:1 | DO NOT SCALE DRAWING | MATERIAL:<br>18-8 Stainless Steel<br>Sheet:<br>4 of 13 |

| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| DCO-0007 | | |

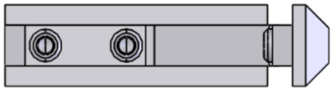


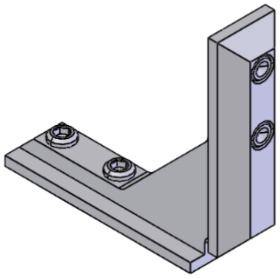


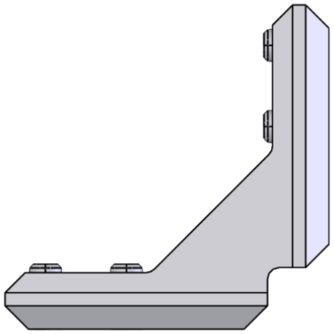
| | | | |
|---|---|---|---|
| DIMENSIONS ARE IN INCHES UNLESS OTHERWISE STATED.<br>TOLERANCES:<br>FRACTIONAL ± 1/16<br>ANGULE ± 1 degree<br>X.X ± 0.1<br>X.XX ± 0.01<br>X.XXX ±0.005<br>X.XXXX ± 0.0005<br>CENTIMETER: ± 0.2cm<br>MILIMETER: ± 0.5mm | DESCRIPTION | BME SPEC NUMBER | |
| | ITEM 3<br>80_20 Inc. 3060 Profile 60in | FIX-0001 | |
| | DRAWN BY: Aaron Stone | DATE: 5/2/2017 | |
| SCALE: 1:10 | DO NOT SCALE DRAWING | MATERIAL:<br>6105-T5 Aluminum | Sheet:<br>5 of 13 |

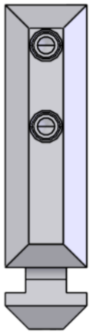
BIOMECHANICAL
ENVIRONMENTS
LABORATORY

| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| DCO-0007 | | |









BIOMECHANICAL ENVIRONMENTS LABORATORY

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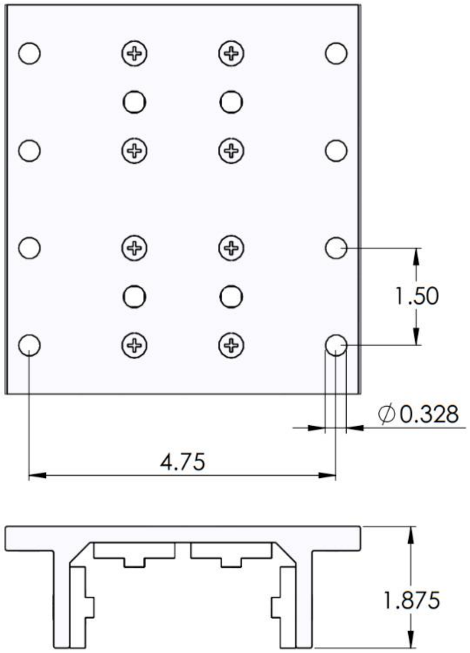
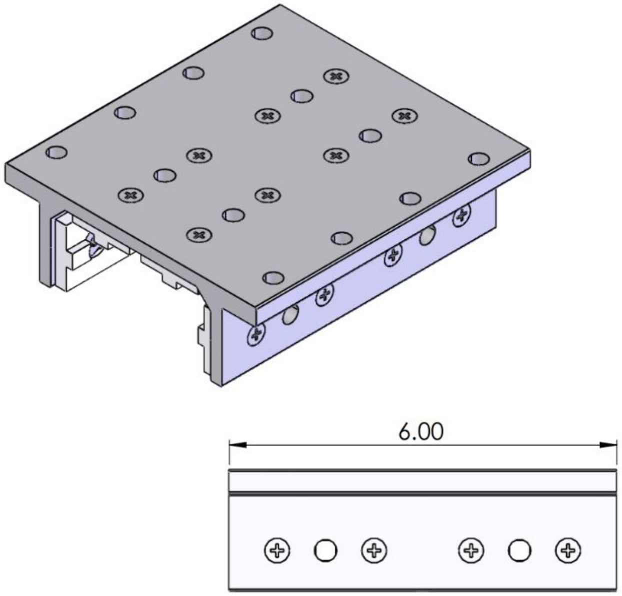
|---|---|---|
| DIMENSIONS ARE IN INCHES UNLESS OTHERWISE STATED.<br>TOLERANCES:<br>FRACTIONAL ± 1/16<br>ANGULE ± 1 degree<br>X.X ± 0.1<br>X.XX ± 0.01<br>X.XXX ±0.005<br>X.XXXX ± 0.0005<br>CENTIMETER: ± 0.2cm<br>MILIMETER: ± 0.5mm | DESCRIPTION<br>ITEM 5<br>80_20 Inc. 3364 Bracket | BME SPEC NUMBER<br>FIX-0001 |
| | DRAWN BY: Aaron Stone | DATE: 5/2/2017 |
| SCALE: 1:1 | DO NOT SCALE DRAWING | MATERIAL:<br>6105-T5 Aluminum<br>Sheet:<br>7 of 13 |

| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| DCO-0007 | | |

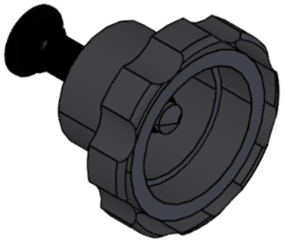


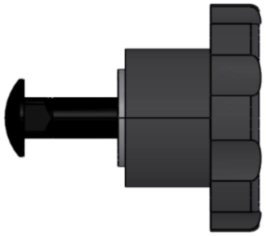


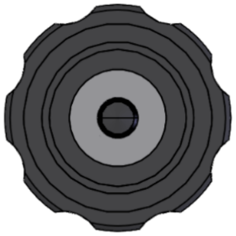
| DIMENSIONS ARE IN INCHES UNLESS OTHERWISE STATED. | DESCRIPTION | BME SPEC NUMBER |
|---|---|---|
| TOLERANCES:<br>FRACTIONAL ± 1/16<br>ANGULE ± 1 degree<br>X.X ± 0.1<br>X.XX ± 0.01<br>X.XXX ± 0.005<br>X.XXXX ± 0.0005<br>CENTIMETER: ± 0.2cm<br>MILIMETER: ± 0.5mm | ITEM 6<br>80_20 Inc. 6534 Linear Bearing | FIX-0001 |
| | DRAWN BY: Aaron Stone | DATE: 5/2/2017 |
| SCALE: 1:2 | DO NOT SCALE DRAWING | MATERIAL: 6105-T5 Aluminum<br>Sheet: 8 of 13 |

BIOMECHANICAL
ENVIRONMENTS
LABORATORY

| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| DCO-0007 | | |







BIOMECHANICAL
ENVIRONMENTS
LABORATORY

DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE STATED.

TOLERANCES:
FRACTIONAL ± 1/16
ANGULE ± 1 degree
X.X ± 0.1
X.XX ± 0.01
X.XXX ±0.005
X.XXXX ± 0.0005
CENTIMETER: ± 0.2cm
MILIMETER: ± 0.5mm

| DESCRIPTION | BME SPEC NUMBER |
|---|---|
| ITEM 7<br>80_20 Inc. 6802 Linear Bearing Brake | FIX-0001 |

DRAWN BY: Aaron Stone

DATE: 5/2/2017

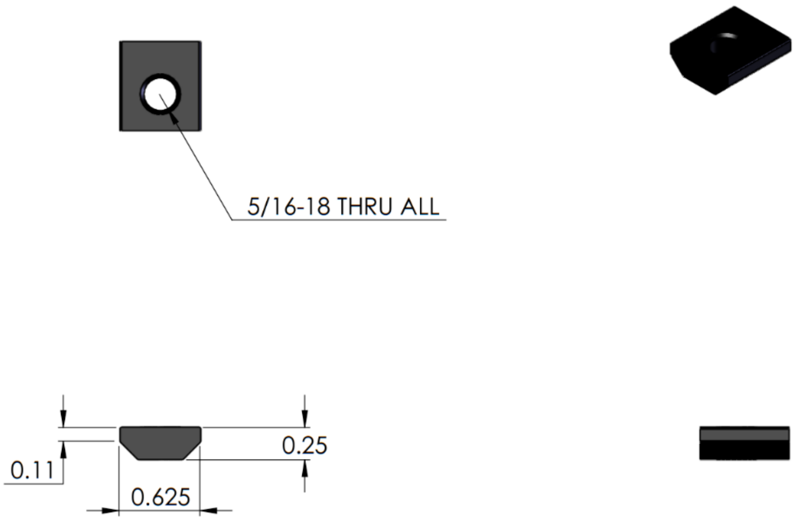
SCALE: 1:1

DO NOT SCALE DRAWING

MATERIAL:
N/A

Sheet:
9 of 13

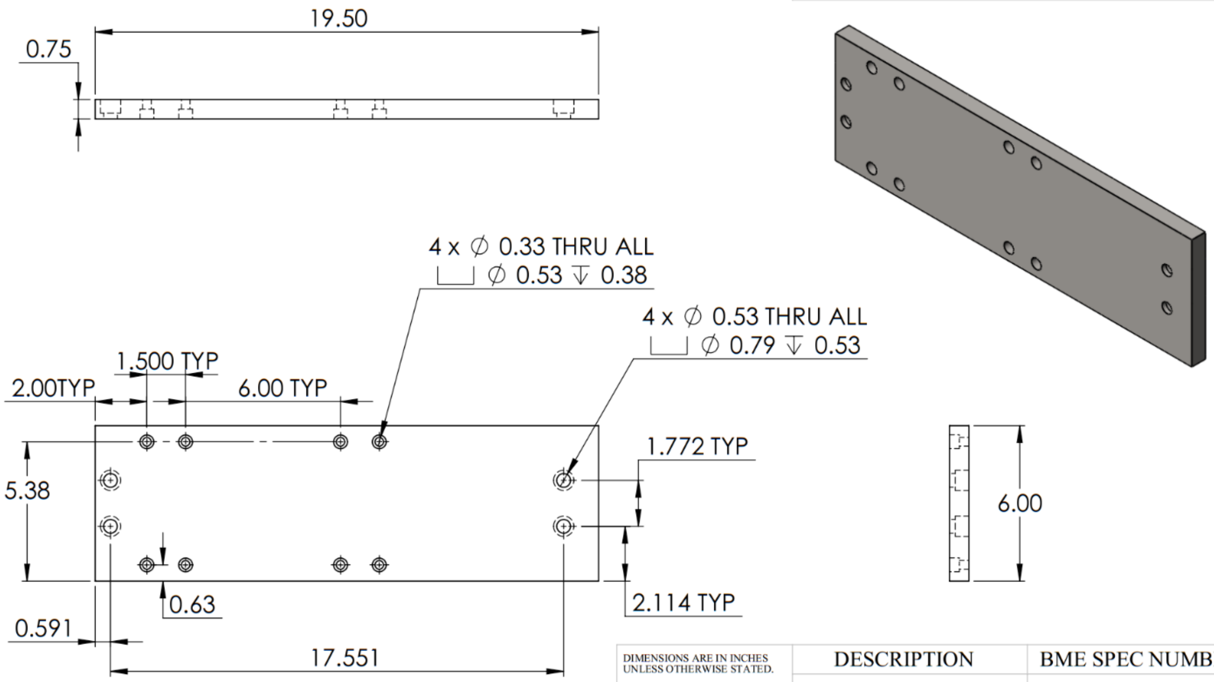
| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| | DCO-0007 | |



|  |  |  |  |
|---|---|---|---|
| DIMENSIONS ARE IN INCHES UNLESS OTHERWISE STATED.<br>TOLERANCES:<br>FRACTIONAL ± 1/16<br>ANGULE ± 1 degree<br>X.X ± 0.1<br>X.XX ± 0.01<br>X.XXX ± 0.005<br>X.XXXX ± 0.0005<br>CENTIMETER: ± 0.2cm<br>MILIMETER: ± 0.5mm | DESCRIPTION<br>ITEM 8<br>.3125-18 T-Nut | BME SPEC NUMBER<br>FIX-0001 | |
| | DRAWN BY: Aaron Stone | DATE: 5/2/2017 | |
| SCALE: 1:1 | DO NOT SCALE DRAWING | MATERIAL:<br>Carbon Steel | Sheet:<br>10 of 13 |

BIOMECHANICAL
ENVIRONMENTS
LABORATORY

| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| DCO-0007 | | |



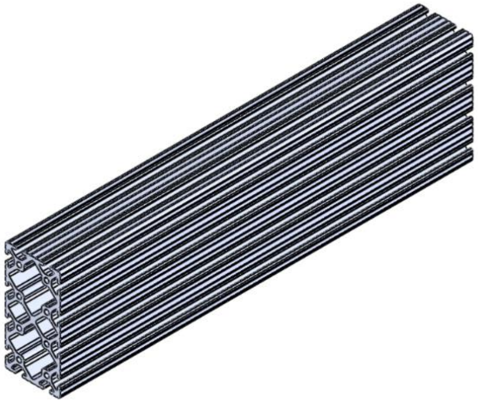
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE STATED.

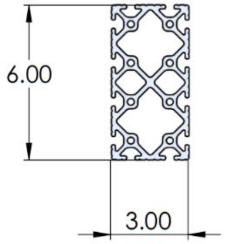
TOLERANCES:
FRACTIONAL ± 1/16
ANGULE ± 1 degree
X.X ± 0.1
X.XX ± 0.01
X.XXX ±0.005
X.XXXX ± 0.0005
CENTIMETER: ± 0.2cm
MILIMETER: ± 0.5mm

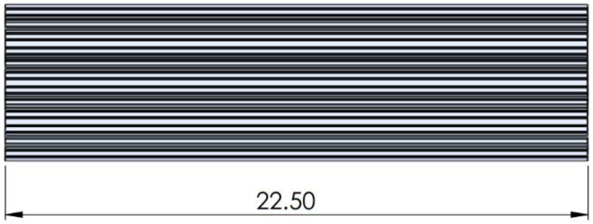
| | | |
|---|---|---|
| DESCRIPTION | BME SPEC NUMBER | |
| ITEM 9<br>80_20 to Actuator Mount | FIX-0001 | |
| DRAWN BY: Aaron Stone | DATE: 5/2/2017 | |
| SCALE: 1:5 | DO NOT SCALE DRAWING | MATERIAL:<br>304 Stainless Steel | Sheet:<br>11 of 13 |

BIOMECHANICAL
ENVIRONMENTS
LABORATORY

| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| | DCO-0007 | |







DIMENSIONS ARE IN INCHES UNLESS OTHERWISE STATED.

TOLERANCES:
FRACTIONAL ± 1/16
ANGULE ± 1 degree
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.005
X.XXXX ± 0.0005
CENTIMETER: ± 0.2cm
MILIMETER: ± 0.5mm

BIOMECHANICAL
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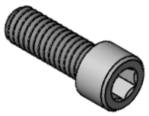
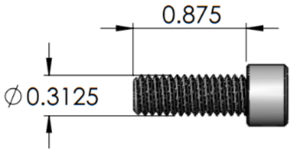
| DESCRIPTION | BME SPEC NUMBER |
|---|---|
| ITEM 10<br>80_20 Inc. 3060 Profile 22.5in | FIX-0001 |
| DRAWN BY: Aaron Stone | DATE: 5/2/2017 |
| DO NOT SCALE DRAWING | MATERIAL:<br>6105-T5 Aluminum |

SCALE: 1:5

Sheet: 12 of 13

| REVISION | DESCRIPTION OF CHANGE | APPROVAL |
|---|---|---|
| 00 | Inital Version | |
| | DCO-0007 | |





BIOMECHANICAL
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|---|---|---|
| DIMENSIONS ARE IN INCHES<br>UNLESS OTHERWISE STATED.<br>TOLERANCES:<br>FRACTIONAL ± 1/16<br>ANGULE ± 1 degree<br>X.X ± 0.1<br>X.XX ± 0.01<br>X.XXX ±0.005<br>X.XXXX ± 0.0005<br>CENTIMETER: ± 0.2cm<br>MILIMETER: ± 0.5mm | DESCRIPTION<br>ITEM 11<br>0.3125-18 Socket Head Cap Screw | BME SPEC NUMBER<br>FIX-0001 |
| | DRAWN BY: Aaron Stone | DATE: 5/2/2017 |
| SCALE: 1:1 | DO NOT SCALE DRAWING | MATERIAL:<br>18-8 Stainless Steel<br>Sheet:<br>13 of 13 |

# RTS Bill of Materials

| Category | Part # | Company | Part Name | Description | Qty | Unit Cost | Cost |
|---|---|---|---|---|---|---|---|
| Actuators | N-0437005 | Hartfiel | DTR115-010-GIF004322 11- RM115-40 | Custom Configured Right Angle Gear Head | 1 | $3,915.16 | $3,915.16 |
| Actuators | N/A | Hartfiel | AKM43E-ACC2AB01 | AKM series brushless servomotor | 1 | $1,545.84 | $1,545.84 |
| Actuators | N/A | Hartfiel | ECT09-B53R03PB-2510 | Linear Actuator (LA), converts servo motor motion to linear actuation. | 1 | $4,816.00 | $4,816.00 |
| Connectors | 92196A541 | McMaster Carr | 18-8 Stainless Steel Socket Head Screws 1/4-20 7/8" | Fasteners | 1 | $10.53 | $10.53 |
| Connectors | 92196A583 | McMaster Carr | 18-8 Stainless Steel Socket Head Screws 5/16-18 1" | fasteners | 1 | $10.04 | $10.04 |
| Connectors | 92196A584 | McMaster Carr | 18-8 Stainless Steel Socket Head Screws 5/16-18 7/8" | fasteners | 1 | $8.29 | $8.29 |
| Connectors | 91292A225 | McMaster Carr | 18-8 Stainless Steel Socket Head Screws M12-18 | fasteners | 1 | $7.61 | $7.61 |

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|---|---|---|---|---|---|---|---|
| Connectors | | McMaster Carr | Clevis Bracket | bore 1" with height 2-1/4" | 2 | $122.22 | $244.44 |
| Connectors | | McMaster Carr | 18-8 Stainless Steel Socket Head Screw | 1/4-20 Diameter and 3/4" in length | 1 | $9.53 | $9.53 |
| Connectors | | McMaster Carr | 18-8 Stainless steel adjustable length clevis pin | 1/2" Dia. And 2 1/2" length | 7 | $20.00 | $140.00 |
| Connectors | 90669A342 | McMaster Carr | 18-8 Stainless Steel Brass-Tip Set Screws 10-32 Thread, 1/2" Long | 4-Point Bending Fixture | 1 | $12.25 | $12.25 |
| Connectors | 92311A242 | McMaster Carr | 18-8 Stainless Steel Cup-Point Set Screw 10-24 Thread, 1/2" Long | 4-Point Bending Fixture | 1 | $5.75 | $5.75 |
| Connectors | 92196A582 | McMaster Carr | 18-8 Stainless Steel Socket Head Screw 5/16"-18 Thread Size, 7/8" Long | 4-Point Bending Fixture | 1 | $8.29 | $8.29 |
| Connectors | 92196A152 | McMaster Carr | 18-8 Stainless Steel Socket Head Screw6-32 Thread Size, 7/8" Long | 4-Point Bending Fixture | 1 | $6.36 | $6.36 |
| Connectors | 92390A395 | McMaster Carr | 18-8 Stainless Steel Clevis Pin 1/2" Diameter, 2-3/4" Usable Length | 4-Point Bending Fixture | 3 | $4.49 | $13.47 |

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|---|---|---|---|---|---|---|---|
| Electronics | FSH02214 | Futek | LCF456 , 500 lb , Fatigue Rated Pancake Load Cell with Tension Base | 500lb Load Cell | 1 | $1,200.00 | $1,200.00 |
| Electronics | FSH02215 | Futek | LCF456 , 1000 lb , Fatigue Rated Pancake Load Cell with Tension Base | 1000lb Load Cell | 1 | $1,200.00 | $1,200.00 |
| Electronics | FSH02573 | Futek | LCF456 , 2500 lb , Fatigue Rated Pancake Load Cell with Tension Base | 2500lb Load Cell | 1 | $1,550.00 | $1,550.00 |
| Electronics | FSH01757 | Futek | 15 ft Long , 6 Pin Bendix PT06A106SSR to Cable Assembly | Load Cell Connection Cable | 1 | $90.00 | $90.00 |
| Electronics | FSH03863 | Futek | IAA100 , Full Bridge Strain Gage Signal Conditioning Voltage Amplifier | Signal Conditioner for Load Cells | 3 | $425.00 | $1,275.00 |
| Electronics | SBA00435 | Futek | #28 Awg , 10 ft Cable , 6 Cond. Braided Shielded | Connection Cable from Signal Conditioner to DAQ | 3 | $30.00 | $90.00 |
| Electronics | SLB00023 | Futek | NIST Calibration | Calibration for each load cell and paired signal conditioner | 3 | $300.00 | $900.00 |
| Electronics | FSH03935 | Futek | APA100 , Power Supply Kit for IAA100/IAA200/IAA300 | Power supply for IAA100s | 1 | $75.00 | $75.00 |

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|---|---|---|---|---|---|---|---|
| Electronics | 782677-01 | Hartfiel | AKD-P01206-NBEC-0000 | Servo Driver, EtherCAT based servo driver for integration with LabVIEW SoftMotion | 1 | $1,385.10 | $1,385.10 |
| Electronics | 70355K106 | McMaster Carr | Power Cord Turn Lock, NEMA L6-30 Plug x Wire Leads, 8 Feet Long | Power Cord | 1 | $30.24 | $30.24 |
| Electronics | 779519-01 | National Instruments | NI-920532-Channel ±10 V, 250 kS/s, 16-Bit Analog Input Module | Analog input module for cRIO 9064 | 1 | $810.00 | $810.00 |
| Electronics | 781529-03 | National Instruments | VF-DA0474N-03 Smart Feedback Cable, AKM Motor to AKD Drive, 3m | Ethernet Connection Cables | 2 | $78.30 | $156.60 |
| Electronics | | National Instruments | cRIO-9064 | Controller, allows integration with LabVIEW and master-slave configuration of AKD servo drivers. | 1 | $900.00 | $900.00 |
| Electronics | 781093-01 | National Instruments | NI PS-15 Power Supply, 24 VDC, 5 A, 100-120/200-240 VAC Input | Power Supply, for controller and driver | 1 | $198.00 | $198.00 |
| Electronics | 779097-01 | National Instruments | NI 9904 Horizontal Panel Mounting Kit of 4-slot Chassis | | 1 | $54.00 | $54.00 |

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|---|---|---|---|---|---|---|---|
| Electronics | 170405-335584 | SSC | 240V 30A Power Outlet in VMR Lab | Outlet with necessary power for large AKM Servo Motor | 1 | $425.00 | $425.00 |
| Electronics | 0221-00000 | Trans-Tek | ACDT .75 OD +/-7.5" STROKE | 15" Full stroke LVDT for Linear Actuator position control | 1 | $513.00 | $513.00 |
| Electronics | 1000-0014 | Trans-Tek | OSC/DEMOD 7.0 KHZ VDC OUTPUT | Signal conditioner for LVDT | 1 | $315.90 | $315.90 |
| Electronics | C006-0180 | Trans-Tek | Core Extension .187 DIA x 19.24L | LVDT core extension | 1 | $40.00 | $40.00 |
| Electronics | D15.200 | Trans-Tek | POWER SUPPLY +/-15 VDC .200 AMP | Dual DC Power Supply | 1 | $218.70 | $218.70 |
| Fabrication | N/A | Machine Shop (Carl Johnson BMEL) | Fabrication costs for fixtures and adaptor plates as of 07.24.17 | N/A | 1 | $2,360.00 | $2,360.00 |
| Frame | 3060 | 80/20 Inc | 3" x 6" 15 Series Frame | 60" length with 3/8-16 dual tapped ends | 2 | $217.00 | $434.00 |
| Frame | 3060 | 80/20 Inc | 3" x 6" 15 Series Frame | 14" length | 2 | $44.20 | $88.40 |
| Frame | 3364 | 80/20 Inc | 90 Degree Inside Corner Connector | Holds 14" sections perpendicular to 40" lengths to create frame shape | 32 | $9.00 | $288.00 |

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|---|---|---|---|---|---|---|---|
| Frame | 3364 | 80/20 Inc | 15 Series 5/16-18 Standard Slide-In T-Nut | Holds actuator adapter to 80/20 14" frame pieces | 10 | $0.79 | $7.90 |
| Frame | MB2436 | Thorlabs | Aluminum Breadboard 24" x 36" x 1/2", 1/4"-20 Taps | Modular surface for testing fixtures and mounting frame and actuator | 1 | $667.00 | $667.00 |
| Material | 8992K158 | McMaster Carr | Multipurpose 304 Stainless Steel Bar 24"x5"x0.75" | Fixture Material | 1 | $197.66 | $197.66 |
| Material | 8992K162 | McMaster Carr | Multipurpose 304 Stainless Steel Bar 24"x6"x0.75" | Fixture Material | 1 | $229.79 | $229.79 |
| Material |  | McMaster Carr | 304 Stainless Steel Rod | 2 1/2" diameter and 1ft in length | 1 | $80.30 | $80.30 |
| Material |  | McMaster Carr | 304 Stainless Steel Rod | 1 7/8" diameter and 1 ft in length | 1 | $59.51 | $59.51 |
| Material | 2780T39 | McMaster Carr | High-Load Bearing Double Shielded, for 1/2" Shaft Diameter, 1-3/8" OD | 4-Point Bending Fixture | 4 | $14.25 | $57.00 |
| Material | 92391A140 | McMaster Carr | 18-8 Stainless Steel Hairpin Cotter Pin for 1/4" to 1/2" Clevis Diameter, 3/32" Wire Diameter | 4-Point Bending Fixture | 1 | $7.32 | $7.32 |
| Material | 8992K906 | McMaster Carr | 304 Stainless Steel Bar 1/2" Thick, 4" Wide, Hot Rolled, 1' Long | 4-Point Bending Fixture | 1 | $55.92 | $55.92 |

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|---|---|---|---|---|---|---|---|
| Material | 8992K903 | McMaster Carr | 304 Stainless Steel Bar 1/2" Thick, 2-1/2" Wide, Hot Rolled, 2' Long | 4-Point Bending Fixture | 1 | $66.26 | $66.26 |
| Material | 8992K171 | McMaster Carr | 304 Stainless Steel Bar 1" Thick, 1-1/2" Wide, Hot Rolled, 1/2' Long | 4-Point Bending Fixture | 2 | $31.25 | $62.50 |
| Material | 89535K45 | McMaster Carr | 304/304L Stainless Steel Rod 1-1/4" Diameter, 1/2' Long | 4-Point Bending Fixture | 1 | $16.36 | $16.36 |
| Material | 8992K149 | McMaster Carr | 304 Stainless Steel Bar 3/4" Thick, 3" Wide, Hot Rolled, 2' Long | 4-Point Bending Fixture | 1 | $130.43 | $130.43 |
| Material | 8992K149 | McMaster Carr | 304 Stainless Steel Bar 3/4" Thick, 3" Wide, Hot Rolled, 1/2' Long | 4-Point Bending Fixture | 2 | $45.02 | $90.04 |
| Material | 89535K12 | McMaster Carr | 304/304L Stainless Steel Rod 3/4" Diameter, 1/2' Long | 4-Point Bending Fixture | 1 | $6.01 | $6.01 |
| Material | 8974K11 | McMaster Carr | 6061 Aluminum 3/4" Diameter, 1/2' Long | 4-Point Bending Fixture | 1 | $3.17 | $3.17 |
| Material | 8627K199 | McMaster Carr | White Delrin® Acetal Resin TubeTight-Tolerance, 3/4" OD x 1/2" ID, 1' Long | 4-Point Bending Fixture | 1 | $6.38 | $6.38 |

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|---|---|---|---|---|---|---|---|
| Material | 8992K154 | McMaster Carr | 304 Stainless Steel Bar 3/4" Thick, 4" Wide, Hot Rolled, 1' Long | Fixture Material | 1 | $94.51 | $94.51 |
| Material | | McMaster Carr | 304 Stainless Steel Rod | 13/16" diameter and 1/2 ft. in length | 1 | $7.09 | $7.09 |
| Safety Screen | 1010 | 80/20 Inc | T Slot Profile | 48 Inches; End Tap Right Side; 2 Access Holes .5" from Left Side | 4 | $11.04 | $44.16 |
| Safety Screen | 1010 | 80/20 Inc | T Slot Profile | 37.17 Inches; Two End Taps | 2 | $8.55 | $17.10 |
| Safety Screen | 1010 | 80/20 Inc | T Slot Profile | 25.17 Inches; Two End Taps | 2 | $5.79 | $11.58 |
| Safety Screen | 1010 | 80/20 Inc | T Slot Profile | 46.875 Inches | 2 | $10.78 | $21.56 |
| Safety Screen | 2062 | 80/20 Inc | 10 Series Plastic Door Handle | Plastic Door Handle | 2 | $4.20 | $8.40 |
| Safety Screen | 2090 | 80/20 Inc | 10 & 15 Series Magnetic Door Catch | Magnetic Catch | 2 | $6.85 | $13.70 |
| Safety Screen | 2496 | 80/20 Inc | 10 Series Single Arm Narrow Panel Retainer | Panel Mounting Bracket | 6 | $3.95 | $23.70 |
| Safety Screen | 2609 | 80/20 Inc | Polycarbonate Panel: .200 - .236" Thick, Clear | Polycarbonate Panel 46.875" x 17.747" | 2 | $47.95 | $95.90 |

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|---|---|---|---|---|---|---|---|
| Safety Screen | 2609 | 80/20 Inc | Polycarbonate Panel: .200 - .236" Thick, Clear | Polycarbonate Panel 47.25" x 25.736" | 2 | $70.09 | $140.18 |
| Safety Screen | 2609 | 80/20 Inc | Polycarbonate Panel: .200 - .236" Thick, Clear | Polycarbonate Panel 47.25" x 37.736" | 1 | $102.77 | $102.77 |
| Safety Screen | 2830 | 80/20 Inc | 10 Series Economy Lift-Off Hinge Left Hand with Short Pin | Short Lift-Off Hinge Left | 2 | $6.15 | $12.30 |
| Safety Screen | 2831 | 80/20 Inc | 10 Series Economy Lift-Off Hinge Left Hand with Long Pin | Long Lift-Off Hinge Left | 1 | $6.15 | $6.15 |
| Safety Screen | 2837 | 80/20 Inc | 10 Series Economy Lift-Off Hinge Right Hand with Short Pin | Short Lift-Off Hinge Right | 2 | $6.15 | $12.30 |
| Safety Screen | 2838 | 80/20 Inc | 10 Series Economy Lift-Off Hinge Right Hand with Long Pin | Long Lift-Off Hinge Right | 1 | $6.15 | $6.15 |
| Safety Screen | 3342 | 80/20 Inc | 1/4-20 x .500" Flanged Button Head Socket Cap Screw (FBHSCS) | 1/4-20 x .5" Flanged Button Head Socket Cap Screw | 6 | $0.30 | $1.80 |
| Safety Screen | 3382 | 80/20 Inc | 1/4-20 Slide-in Economy T-Nut - Centered Thread | 1/4-20 Slide-In Economy T-Nut | 32 | $0.21 | $6.72 |
| Safety Screen | 3383 | 80/20 Inc | Single Tab End Fastener, 1/4-20 | Single Tab End Fastener | 8 | $1.20 | $9.60 |

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|---|---|---|---|---|---|---|---|
| Safety Screen | 3390 | 80/20 Inc | 1/4-20 x .375" Flanged Button Head Socket Cap Screw (FBHSCS) | 1/4-20 x .375" Flanged Button Head Socket Cap Screw | 26 | $0.39 | $10.14 |
| Safety Screen | 2015-Plain | 80/20 Inc | 10 Series End Cap with Push-In Fastener | End Cap with Push-In Fastener | 4 | $1.20 | $4.80 |
| Software | 777844-35 | National Instruments | LabVIEW Real-Time Module | Single Seat License with 1 Year Service | 1 | $672.75 | $672.75 |
| Software | 781158-35 | National Instruments | LabVIEW SoftMotion Module | Single Seat License with 1 Year Service | 1 | $1,799.10 | $1,799.10 |
| Work Hours | N/A | Graduate Student | N/A | Hours spent on project | 2,400 | $6.67 | $16,008.00 |
| Workstation | KE3060 | BenchDepot | Kennedy Series 30"x60" with Formica Laminate | Table to mound load frame on (order bench height at 29" with 6" adjustable legs) 6,000lb capacity | 1 | $354.00 | $354.00 |
| Workstation | BS1858 | BenchDepot | 18"x58" Standard Formica Laminate Bottom Shelves | Bottom shelf for all electrical and controller hardware | 1 | $103.00 | $103.00 |
| Workstation | LP | BenchDepot | Dewey Series Adjustable Leg Sets | Adjustable legs for ergonomic reasons | 1 | $44.00 | $44.00 |
| Workstation | U48 | BenchDepot | Upright Sets 48" height for 1.25" thick table | Table mounted columns for mounting of lights, cameras, and any | 1 | $78.00 | $78.00 |

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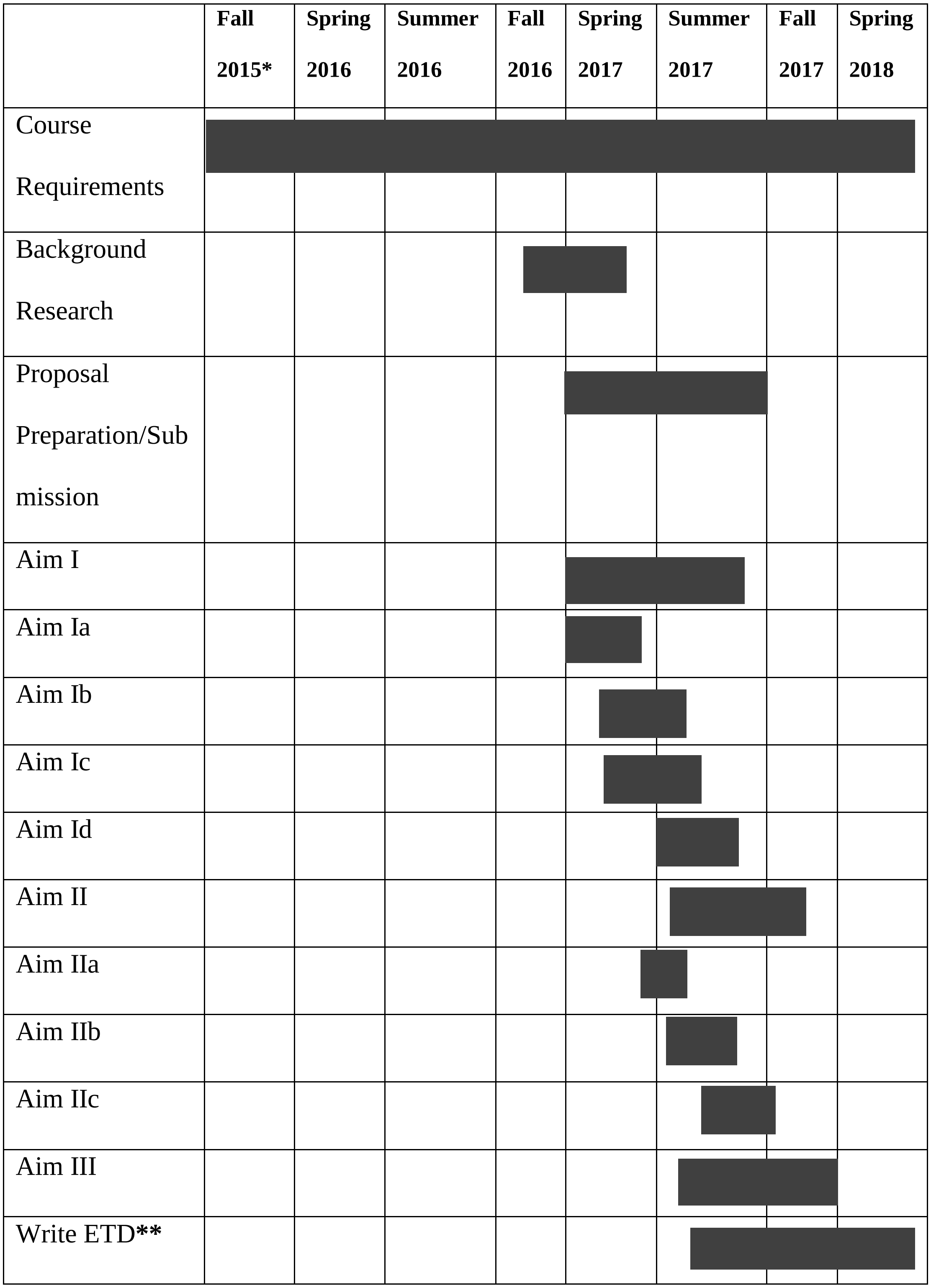
| | | | | other extraneous hardware. | | | |
| Workstation | N/A | BenchDepot | Shipping | Shipping Cost | 1 | $220.37 | $220.37 |
| | | | **Total** | | **2635** | | **$ 47,023.88** |

## Study Timeline



| | **Fall 2015*** | **Spring 2016** | **Summer 2016** | **Fall 2016** | **Spring 2017** | **Summer 2017** | **Fall 2017** | **Spring 2018** |
|---|---|---|---|---|---|---|---|---|
| Course Requirements | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Background Research | | | | ■ | ■ | | | |
| Proposal Preparation/Submission | | | | | ■ | ■ | | |
| Aim I | | | | | ■ | ■ | | |
| Aim Ia | | | | | ■ | | | |
| Aim Ib | | | | | ■ | ■ | | |
| Aim Ic | | | | | ■ | ■ | | |
| Aim Id | | | | | | ■ | | |
| Aim II | | | | | | ■ | ■ | |
| Aim IIa | | | | | ■ | ■ | | |
| Aim IIb | | | | | | ■ | | |
| Aim IIc | | | | | | ■ | ■ | |
| Aim III | | | | | | ■ | ■ | |
| Write ETD** | | | | | | ■ | ■ | ■ |

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|---|---|---|---|---|---|---|---|---|
| Final Defense | | | | | | | | ■ |
| Thesis Submission | | | | | | | | ■ |
| Graduation | | | | | | | | ■ |

*Start of program

**ETD – Electronic Thesis/Dissertation