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MODERNIZATION OF THE LINEAR MOVEMENT TEST RIG

LINEAARLIIKUMISEGA KATSESEADME MODERNISEERIMINE

MSc thesis

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AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently.

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FOREWORD

This thesis was written for my Master degree in Mechatronics at the Tallinn University of Technology. The work was executed at the Tallinn University of Technology. The work consists of electronic, mechanical, data communication and software fields integration. The purpose of this modernization work is to design a test rig for investigation of friction of materials and machine components. I would like to thank the following people, without whose help and support this thesis would not have been possible. First, I like to show my gratitude to the people of departments of mechatronics. My supervisor Priit Põdra for his suggestions, encouragements, and guidance in writing the thesis and approaching the different challenges during the thesis. I would also like to thank Eren Cizmecioglu for his practical support, vision, and help. Finally, I would like to thank my parents and my girlfriend for their constant support during the time I studied.

Tallinn, June 2016,

Mehmet Deniz

EESSÕNA

Käesolev lõputöö on kirjutatud Tallinna Tehnikaülikooli mehhatroonika õppekava magistrikraadi jaoks. Töö on viidud läbi Tallinna Tehnikaülikoolis ning see põhineb elektroonika, mehaanika, andmeside ja tarkvara valdkondade integratsioonil. Magistritöö eesmärgiks on konstrueerida moderniseeritud katseseade materjalide ja masinaelementide hôôrdumise uurimiseks. Ma sooviksin tänada järgnevaid inimesi, ilma kelle abi ja toetuseta see käesolev magistritöö ei oleks saanud vôimalikuks. Esiteks ma sooviksin avaldada tänu inimestele TTÜmehatroonikainstituudist. Minu juhendajale Priit Pôdrale tema soovituste, julgustuse ja juhendamise eest. Sooviksin ka tänada Eren Cizmecioglut praktilise toe, visiooni ja abi eest. Lôpetuseks tahaksin tänada oma vanemaid ja tüdruksôpra, kannatlikuse ja järjepideva toetuse eest.

Tallinna, juuni 2016,

Mehmet Deniz

1. INTRODUCTION

Friction is a key factor for most of the applications in mechanical systems nowadays. Friction is the resistive force resulting from relative motion of solid surfaces, fluid layers, and material elements sliding against each other [1]. The concept of friction force is illustrated in Figure 1.1. Friction force depends on many parameters and it effects systems.

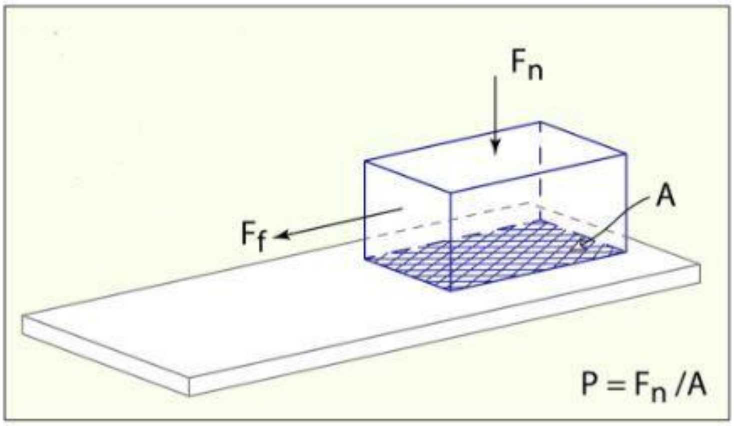


Figure 1.1. Friction forces phenomena[2]

There are mechanisms for example brakes, belt applications, clutches, wheel-road interaction etc. where friction is a reason in order to perform an action. On the other hand, friction always makes unwanted heat and as a result, this worsens the lubrication, materials' parameters change together with possible high wear rates and energy can be wasted in considerable amount. Tribology investigates properties of materials which affect friction and tribometer is the general name of the device where such investigations are conducted [3]. Resulting friction force depends on the properties of materials that are in contact, their relative movement speed, normal load, properties of lubricant, specimens' contact surface parameters etc. For that reason, these parameters must be taken into account when designing rubbing systems. Friction in linear motion systems does not only affect the heat regime and energy consumption but in the case of precision motion systems sets limits to positioning accuracy, etc.

Studying the friction phenomena is an important part of machine elements course in many universities. This is the motivation to develop a modern, computer controlled versatile test rig in the lab of machine elements.

According to Amonton's first law of friction, which states that the friction force is directly proportional to normal force. A friction coefficient can be defined as [4];

$$\mu = \frac{F_f}{F_N},$$

where: μ - friction coefficient

F_F – friction force, N;

F_N – normal force, N.

In most modern tribometers, normal load is applied by a known mass or a measured normal load generated by an external loading system with a force transducer. Friction forces are measured, and a friction coefficient can be determined using the formula above. In given tribometer, a stationary test specimen shall be loaded onto moving one with a known gravity force. The stationary specimen is mounted on a stiff lever. The friction coefficient is determined during the test by measuring the lateral force upon the arm. This simple method facilitates the study of friction behavior of almost every pair of solid materials or reciprocating movement machine component.

Laboratory of machine elements of Tallinn University of Technology has a linear movement friction test rig, which has to be modernized. The rig work principle is based on the simple pre-existing analog from 1960-ies. A few years ago the rebuild of the test rig started but came to the halt with drive and its primary control system partly finished. The modernization task includes:

- the design of a test specimen loading system,
- the design of a friction forces measurement system,
- the design of a drive control algorithm and redesign of a drive control system,
- the design of a data acquisition system
- the design of a rig user computer interface,

The test rig in question must incorporate modern technical solutions and all applicable safety rules must be assumed. It also must be considered in solving design issues, that the rig shall be safely operable by non-trained personnel (students). The test rig shall be possible to easily reconfigure for different types of test objects in the range from pin-on-flat material tests to full component tests.

Chapter 2 presents review of existing test rig configuration. Technical properties of existing test components are studied whether they need to be changed or not. In chapter 3, current commercial available tribometers are reviewed. Their properties are discussed and presented in terms of working principle, measuring system and loading mechanisms. Chapter 4 has an overview of system. It presents subsystems and tasks of system which is to be solved. Defined subsystems includes loading and friction measuring system, motion control, measuring structure and measurement and real time monitoring software. Loading and friction measuring system design is explained in chapter 5. Possible solutions to measuring and loading system are discussed and compared. In chapter 6, motion control system is presented. Motion control system component connections and system set up are explained. Chapter 7 explains how measurement is done and what components are used. In chapter 8, calibration procedure of load cell explained. In chapter 9, Motion control software is explained. measurement, control, and monitoring software has been presented.

2. EXISTING TEST RIG

The current test rig has been configured to provide linear movement by a linear actuator. It has AC motor in order to run linear actuator and a motor driver for controlling motion. Beside it is equipped with limit switches so as to set safety limits. It has been set up and in running condition by manual control of drive mechanism varying the frequency and voltage supplied to the electric motor. Figure 2.1. shows the existing linear movement test equipped with AC motor.

Figure 2.1. Current configuration of linear movement tests rig

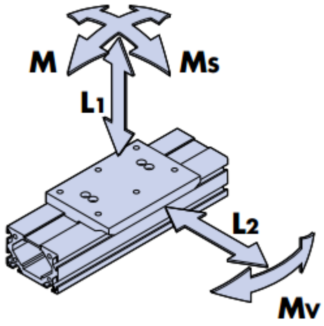
Linear actuator

Linear actuators are used in very wide variety of industrial applications and machine tools such as valves, automation systems and dampers where linear motion is required [1]. This linear movement test rig consists of a toothed belt driven actuator and AC motor in order to provide linear motion. This actuator includes limit switch assembly bracket and fixings. Adjustment of this components is quick and simple and may be repeated several times.

Figure 2.2. HepcoMotion's PDU2 Belt Driven Linear Actuator

This actuator has been designed for use in multi-axis or demanding single axis systems. The table shows the maximum carriage loading capacity properties of this linear actuator.

Table 2.1. Linear Actuator Properties [5]



Carriage load capacity (L_1)	500 N
Max linear force	280 N
Linear move per shaft rev	96 mm
Ms	5 Nm
Mv	14 Nm
M	14 Nm

Motor

AC motors are mostly preferred in industrial applications because of their low costs, and durability. AC motors are driven by alternating current (AC). The AC motor has a stationary stator and inside rotor. Stationary stator has coils to produce a rotating magnetic field with alternating current, and the output shaft connected to inside rotor for producing a second rotating magnetic field [6]. In current test rig, a 3-phase AC motor is used in order to provide motion. The table below shows the properties of a given motor.

Table 2.2. AC Motor Properties [7]

Mains frequency	50 Hz
Input Voltage	(230...400) V
Number of poles	4
Rotational frequency	1310 min^{-1}
Power	0.11 kW

Drive

As a drive, variable Frequency Drive (VFD) which is ACS310-03E-01A Low voltage AC drives by ABB is included in existing rig. A Variable Frequency Drive (VFD) is a kind of controller that drives a motor by varying voltage supplied and the frequency to the electric motor. Other names for a VFD are variable speed drive, adjustable speed drive, adjustable frequency drive, AC drive, and inverter. The table below shows the technical properties of variable frequency drive which has been used.

Table 2.3. Driver (VFD) Properties [8]

Enclosure Class	IP20
Mains frequency	(48 … 63) Hz
Input Voltage (U_{in})	(380 … 480) V
Number of Phases	3
Output Current, Normal Use	1.3 A
Output Power, Normal Use	0.37 kW

Limit switches

Limit switches are used for controlling machinery as part of a control system, as safety interlocks, or to count objects passing a point [1]. The current rig has two limit switches. They are used as safety interlocks. When moving plate of rig reached to the maximum safe location, they come into contact with the actuator, the device operates the contacts to stop motion. Figure 2.3. shows an example of limit switches.

Figure 2.3. Example of limit switch

Chapter summary

Laboratory of machine elements of Tallinn University of Technology has a partly finalised linear movement friction test rig, which has to be modernized. The existing system consists of modern hardware and the possibilities of further development is good.

The rig to be modernized currently has linear actuator, motor and drive. An existing linear test rig is to be designed based on the linear reciprocating principle that provides the functionality to conduct friction force measurement in broader amplitude range and with variable sized materials. For that purpose, the device will include test specimen loading system, friction forces measurement system, drive control algorithm and redesign of a drive control system, data acquisition system, rig user computer interface to be designed.

3. MARKET OVERVIEW

Tribometers are unique instruments designed for wear and friction phenomena investigation. They can conduct both linear reciprocating and rotating experiment modes. The variety of possible test configurations are very large and the most used movement is rotation. Rotation is used for wear and friction testing when a stationary specimens' relative velocity is to be maintained for long testing periods and in the cases when the real rotational movement of a machine component is to be reproduced for testing.

In the case of reciprocating testing, the specimens' relative velocity changes in time, since the system must be stopped and the movement reversed in each movement cycle. However, many machine components incorporate linear movement and reciprocating tribometers should be used in order to study respective components. The tribometers commercially available today that can be compared with each other are manufactured by Nanovea, Anton Paar, Wazzau and Bruker. The following commercially available tribometers were scrutinized in the search of suitable solutions.

Anton Paar Nano Tribometer (NTR2)

Anton Paar is one of the manufacturers of tribometers in the market today. Anton Paar offers Nano and micro tribometers for testing. Although one machine can do both linear and rotational tests, it cannot move in custom 2D paths [9]. Its product range consist of pin on disk tribometers more than linear tribometers. For normal loading, a ball or pin as a counterpart is loaded with dual beam cantilever with capacitive sensor. Figure 3.1 shows the Anton Paar Nano Tribometer (NTR2) and Table 3.1. presents properties.

Table 3.1. Anton Paar tribometer properties [9]

Movement type	Rotation & Reciprocating
Normal load system	Capacitive sensor
Friction measuring system	Capacitive sensor
Control system	Automatic shut-off at selected track length or friction coefficient threshold
Environmental conditions	Temperature and Humidity sensor

Figure 3.1. Anton Paar tribometer [9]

Nanovea T500 High Load Macro Tribometer

Nanovea has linear reciprocating tribometers commercially available. But these devices are not capable of user defined 2D path generation [10]. T500 High Load Macro Tribometer has a continuous stiff arm to ensure measurements at high loads. Loading is applied with dead weights. Friction force measuring is done with a load cell which has a direct contact with the arm. This tribometer has an option for both linear movement and rotational movement. Figure 3.2. presents the Nanovea T500 High Load Macro Tribometer. Table 3.2. presents the properties of this tribometer.

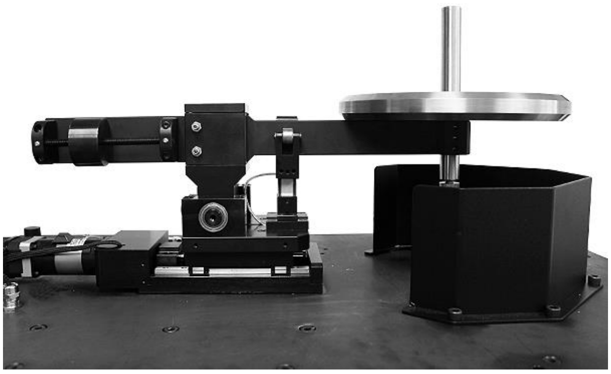


Figure 3.2. Nanovea T500 High Load Macro Tribometer [10]

Table 3.2. Nanovea T500 High Load Macro Tribometer properties [10]

Movement type	Rotation & Reciprocating
Normal load system	Gravity force
Friction measuring system	Load cell

Control system	Automatic shut-off at selected track length
Environmental conditions	Load cell temperature compensation

Wazzau SVT 500 tribometer

Wazzau SVT 500 is a linear reciprocating tribometer. It examines and simulates friction under translational load. It can be used with fluid lubricants or without lubrication with solid objects. The normal force application system of this device is a motor spindle system. Figure 3.3 shows this device. This tribometer is driven by two linear synchronous motors. Table 3.3. presents the properties of this tribometer.

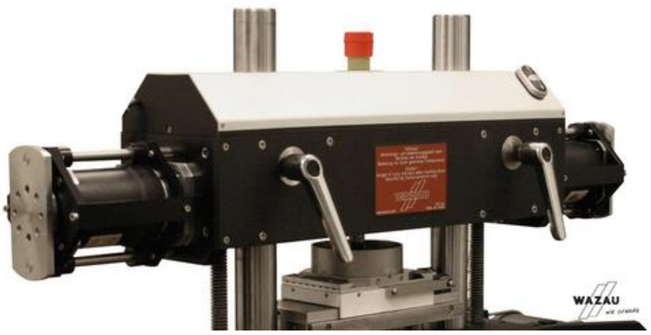


Figure 3.3. Wazzau linear Tribometer SVT 500-1000 [11]

Table 3.3. Wazzau Linear Tribometer SVT 500-1000 properties [11]

Movement type	Linear Reciprocating
Normal load system	Motor spindle system
Friction measuring system	Load cell
Control system	Automatic shut-off at selected track length
Environmental conditions	heating system for specimen bowl

Bruker's Universal Mechanical Tester (UMT)

Bruker Corporation currently has Nano, micro, and macro testing capabilities. The Bruker's Universal Mechanical Tester (UMT) can conduct ball-on-plate, pin-on-plate, and abrasive testing with reciprocating motion [12]. It has capability of the combinations of motions. It can be configured for reciprocating by changing drive. Table 3.4. presents the properties of this tribometer and Figure 3.4. shows the tribometer.

Figure 3.4. Bruker’s Universal Mechanical Tester (UMT) [12]

Table 3.4. Bruker’s Universal Mechanical Tester (UMT) properties [12]

Movement type	Linear Reciprocating & Rotating
Normal load system	Servo-controlled load stage
Friction measuring system	Load cell
Control system	Automatic shut-off at selected track length
Environmental conditions	Temperature controller

It can be concluded here, that versatile friction testing machines with long range of linear movement are not widely commercially available today. But many design ideas can be incorporated into the custom design in question. Table 3.5. presents the comparison of commercially available tribometers.

Table 3.5. Technical properties of Nanovea, Anton Paar, Bruker, and Wazzau tribometers

	Nanovea	***Anton Paar***	***UMT TriboLab***	***Wazzau SVT 500***
Load	…	up to 60 N	(0.01 N to 200) N	(5-500) N
Stroke	35 mm	60 mm	25 mm	(0,1 – 209 mm
Sliding speed	140 mm/s	Up to 100 mm/sec	0.01 m/s to 2 m/s	…
Frequency	2 Hz to 40 Hz	1.6 Hz	0.1 Hz to 60 Hz	(0-40) Hz

4. PROJECT DESIGN CONFIGURATION

To begin the process of designing the tribometer, the device is divided into the subsystems. Characteristics of each subsystem have been identified so as to meet the requirements of the device. Most suitable working principles for each subsystem have been investigated and combined for a number of potential concept designs, that were critically analyzed afterward in order to propose the most suitable option.

Table 4.1. Tribometer subsystem descriptions

Subsystem	Description
Loading and friction measuring system	Applies normal force to the sample. Carries measuring components. Applies measurement principle. Uses load cell in order to measure occurring lateral forces.
Motion Control	Controllable relative motion between samples at sufficient velocities. The mechanism for motion generation and conversation between rotation and translation. Changeable speed and motion profiles. Obtaining motion feedback.
Measuring Structure	Obtaining measurement data and process data. Conversation of gathered information into meaningful manner and registering for analyze
Measurement Software & Real-time Monitoring	Monitoring real-time measuring process through and gives visualized results, charts, graphs etc.

The table above categories subsystems of the work. The software is used for controlling and measurement data recording purposes as well as controlling motion. The mechanical structure is necessary to mount all components and to get a system in motion under load. Mechanical structure involves designing of components of loading system as well as the design of friction measurement component's carriage. The figure below schematizes of subsystems of the project.

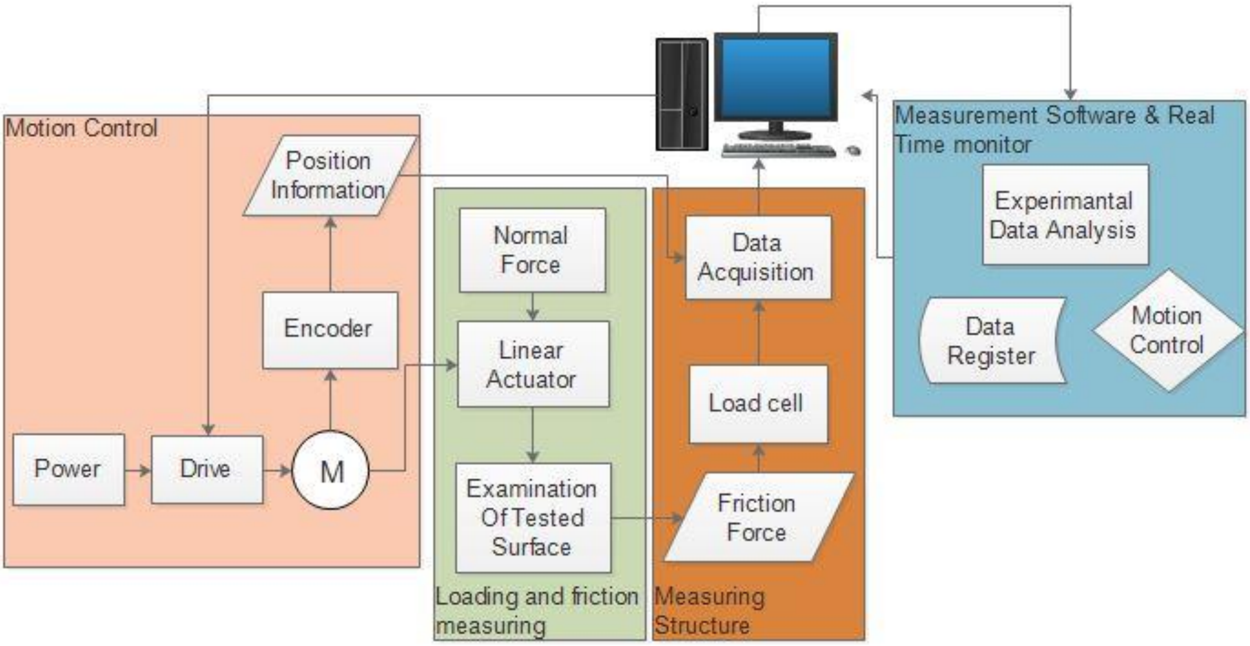


Figure 4.1. Tribometer subsystem configuration

Motion control

The role of motion control is to command system and run based on desired speed and motion of test configuration. It uses the drive to receive commands from PC software that is sent based on user defined test parameters such as speed and distance. Then drive creates a signal in order to run and sends it to the motor. On the other hand, there is position feedback integration for position and speed information of the system. This information is transferred to the software and processed in order to keep motion in control. As a result of getting position feedback, the drive is commanded and it establishes closed loop control mechanism. The motor driven in this control process actuates linear movement of the mechanical structure. In next chapters detailed analysis and discussion of this system will be provided

Loading and friction measuring system

Loading and friction measuring system involves a design of loading system mechanism for application of load in normal direction and friction measurement system. Due to friction force directly related to normal load, versatile loading system is required for different configurations. As well as loading system, friction force measuring mechanism consist of components in order to perform measurement process such as load cell carrier, specimen holders, and fixing parts. Test material holders and fixing mechanisms are also considered in this system. Further detailed discussion will be included in next chapters.

Measuring structure

The objective of measuring is to obtain friction force values of the materials' pairs or machine components which are experimented. But the information, you are seeking is not directly obtained. As a result of measurement principle, the sensor output signal is not directly related to the friction. For that purpose, the measuring structure is designed. Following the design configuration, the measuring structure must have sensor calibration facility. For this work, measuring sensor is a load cell. Load cell creates voltage signal output. Data acquisition board is used to collect voltage signal from load cell output as a result of applied friction force. This signal then transferred to the PC equipped with software.

Measurement software and real-time monitoring

After all measurement and motion system design. In order to track measurement process and observe the result of measurement, it is very important to have a platform. This subsystem involves designing of measurement, control, and monitoring software. The measured signal will be processed, visualized and monitored in real time on the screen. Besides, it will have an interface for defining some parameters by the user, such as the velocity of the test, load, and stroke count. Measured data will be stored and for further analysis and comparison.

Technical specifications

Before the design to begin, the characteristics of work need to be defined. This is important in order to set a clear path what has to be done and how to build a system. Characteristics of this work specified are based on work general objectives and capabilities of existing components. So, it is able to be configured according to geometry and size of the specimen, and normal load range between 10 and 50 N. The table below includes the specifications of the work.

Table 4.2. Technical specifications

Type of motion	Reciprocating
Kind of motion	Continuous - linear
Geometry of specimen	Pin - plate / ball - plate / plate-plate
Lubricant	Without fluids
Loading elements	Normal force (Dead weight)
Sensory functions	Friction Force
Normal force	(10 … 50) N
Speed Range	(0 … 2) m/s - adjustable
Amplitude range	600 mm - adjustable

Chapter summary

Prior to design of a system, it is important to know what kind of characteristics system should have. In order to set clear path, the work has been divided into subsystems. Contents of these divisions are defined and they are presented in this chapter. Motion control system explains how the motion is provided and controlled. Loading system includes application mechanism of normal load and friction measurement system and explains how to measure friction force. Measuring structure explains what kind of sensors are used and how they provide results. Measurement software process input data comes from load cell and it is analysed to convert valuable information. Technical characteristics of the work also have been defined.

5. LOADING AND FRICTION MEASURING SYSTEM

Aforementioned loading and friction measurement has been designed in conceptual level. At first, possible load cell connection and friction force transfer concepts have been reviewed. These concepts include spring joints, rail guided bracket, hinge concept, and rope concept. In addition to that, the measuring experiments need to be carried out with different normal force implementation capacities. Thus, mechanical part of the project must be capable of applying different loads as well. These alternative conceptual ideas are explained in detailed level in coming sections.

5.1. Concept generation

5.1.1. Spring joints

This concept includes lower specimen bracket connected to the plate of the rig with four thin metal parts that serve as spring leafs. This concept has been used in the Wazzau tribometer above. When motion and normal force applied, friction force attempt to move this bracket and spring leafs allows the bracket move. There is a load cell which's end is mounted to this bracket and the other end is connected to the movement plate. And this movement is restricted by the load cell. The force measured by load cell corresponds to friction force. In this concept, the elasticity of spring leafs must be considered when determining the friction force value out of the load cell output signal. A simple illustration of this concept can be seen in Figure 5.1.

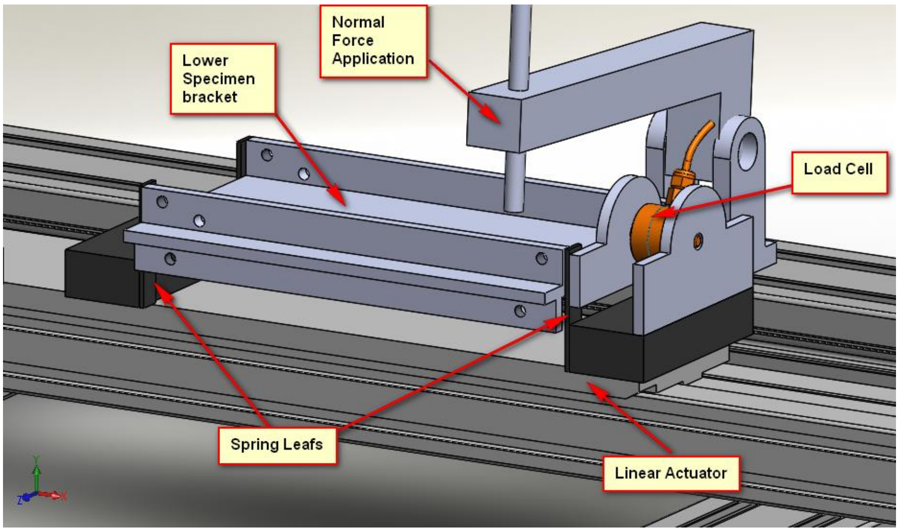


Figure 5.1. Spring leaf joints friction force measurement concept

5.1.2. Linear rail guided bracket

This concept differs from spring based version of a design by replacing springs by linear rail guide mechanism. In this concept specimen bracket connected to linear rail guides. Basically, when linear motion is applied, these linear rails allow the specimen bracket to move. But again this movement is restricted by load cell, which is connected to linear movement plate. Occurring force, because of attempting to move, is transferred to the load cell. In this concept the friction in linear guides must be known and remain relatively constant. This concept is shown in Figure 5.2.

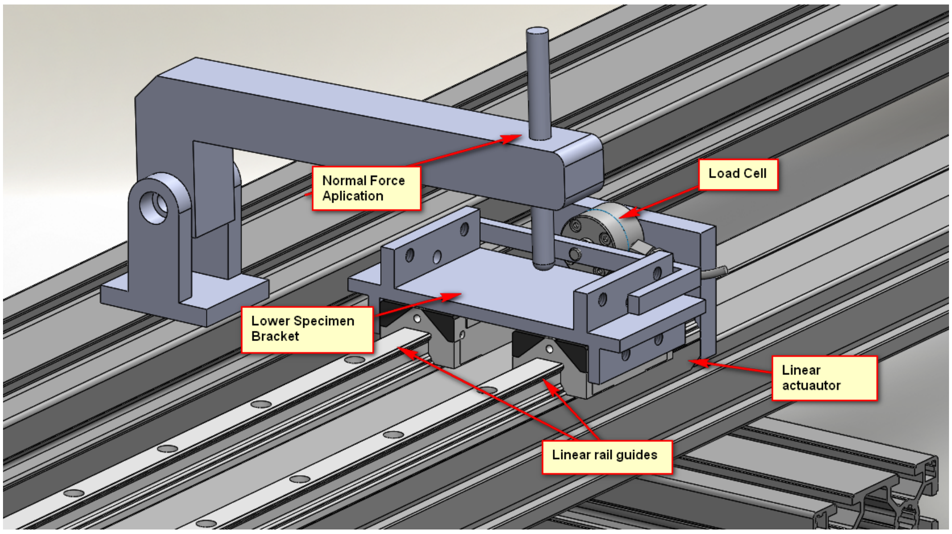


Figure 5.2. Linear guided friction measurement concept

5.1.3. Hinge concept

In this concept the load cell is mounted onto the load carrier and upper specimen holder bar. This bar has a slot configured for mounting load cell and a hinge mechanism. The hinge can be replaced by a thin material section with the hinge movement replaced by elastic deformations. The main disadvantages of that concept are the insufficient structural strength and reliability and clearances in the hinge system, that affect the measuring results. The figure below represents the working principle of the mechanism.

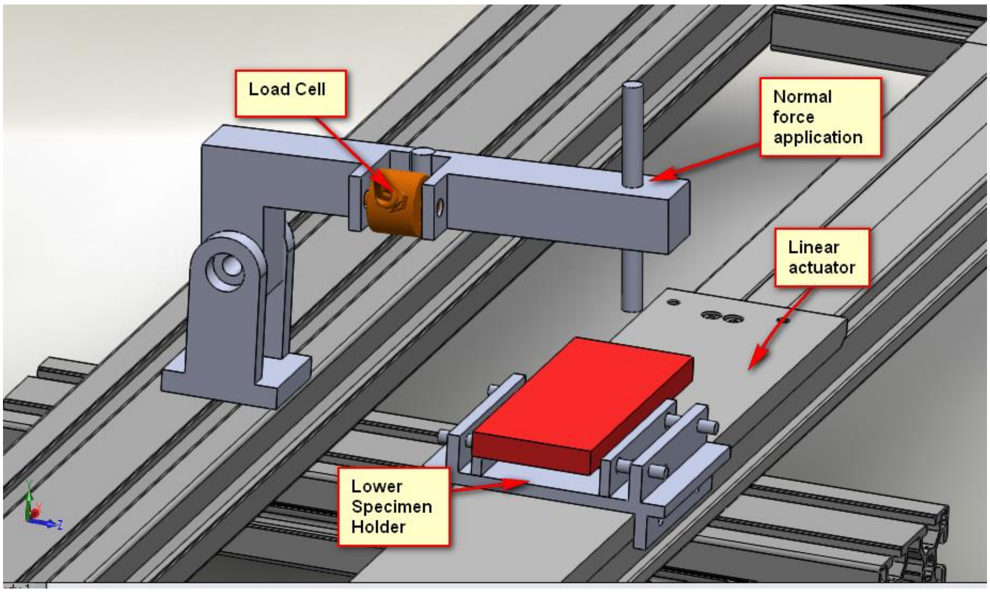


Figure 5.3. Hinged normal force application arm concept

5.1.4. Rope concept

This rope concept has specimen bracket hooked to load cell through the rope in order to transfer friction force to load cell. Compared to the previous concepts, this is more complex in terms of setting it up. It requires more component to build up. On the other hand, in case of the reverse moving condition of test rig, getting friction force needs additional set up. It may not be practical in terms of specimen change and may require more effort. Figure 5.4 illustrates the principle of this mechanism in a simpler manner.

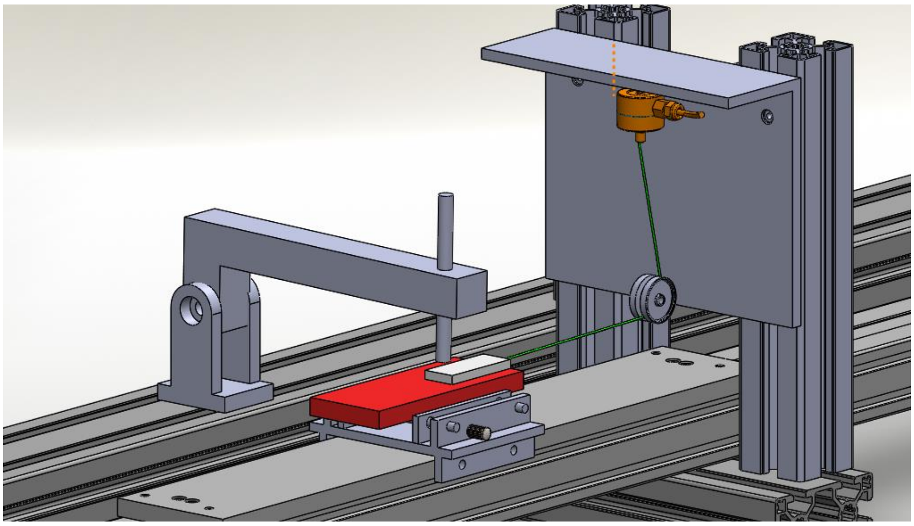
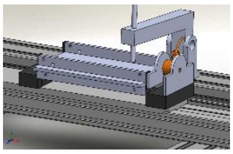
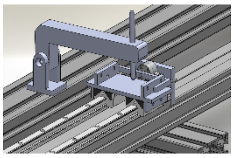
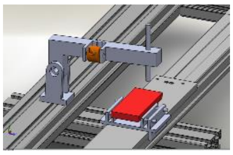
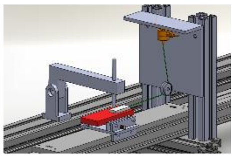


Figure 5.4. Illustration of rope concept

Table 5.1. Comparison of conceptual ideas of loading and friction measuring system

Spring joints	**Linear rail guide**	**Hinge concept**	**Rope concept**	**Final design**
				
Advantages -Easy calibration -less complexity of loading system	**Advantages** -Easy set up -less complexity of loading system	**Advantages** -less complexity of loading system	**Advantages** -Easy calibration	**Advantages** -Reliable measurement
Disadvantages -not flexible for a wide range of shape and sizes - load cell is moving, cabling needs protection	**Disadvantages** -friction between linear guides and specimen bracket -not flexible for a wide range of shape and sizes - load cell is moving, cabling needs protection	**Disadvantages** -bending stress overload cell -precise connection difficulties -damage risk of load cell during loading and unloading, cabling needs protection	**Disadvantages** -Difficult setup -more component -not flexible for a wide range of shape and sizes	**Disadvantages** -more components for loading plate design -calibration difficulty

5.2. Final design description

This concept involves a load cell connected to normal force application mechanism instead of the linear actuator. Through the arm of upper specimen holder, the friction force between materials moving contrary to each other is transferred to the load cell. In this concept, normal force application mechanism built on the rotating mechanism connected with deep groove ball bearing and angular contact ball bearing components. But again another ending of load cell connected to a fixed part in order to restrain rotating of the arm. The figure below shows the concept. Among reviewed concepts, this concept is most feasible due to ease of application and system reliability.

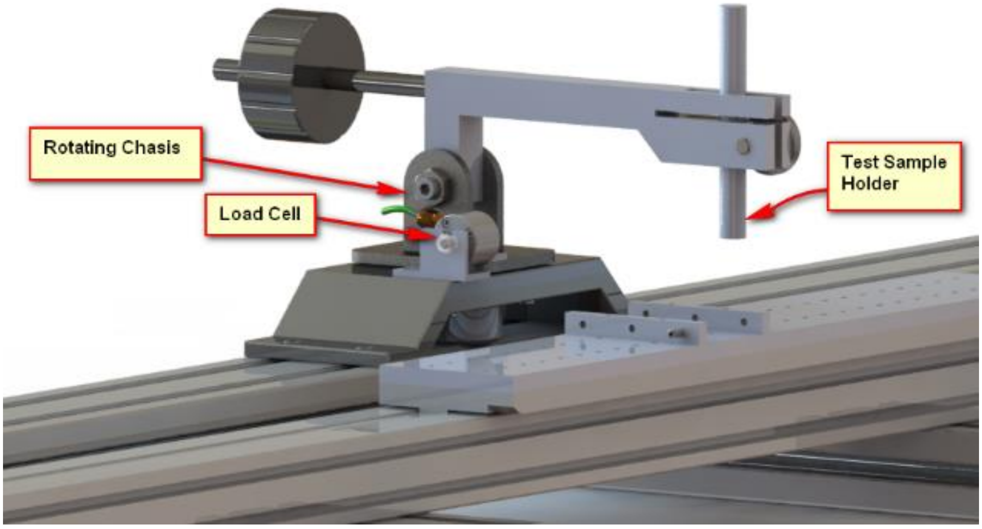


Figure 5.5. Rotational chassis concept

5.2.1. Normal force application system

In order to investigate friction coefficient of materials, experiments are carried out under different normal load values. The normal force applied to the system should be known and it should act onto the materials directly through normal direction. For this purpose, a lever arm is used in order to apply different load variations manually. This arm has counter weight for eliminating the system own mass influence for precise load control. Counterweight is adjustable through the threaded shaft for balancing self-weight of the arm, test specimen holder and test sample itself. Counterweight must also be fixable.

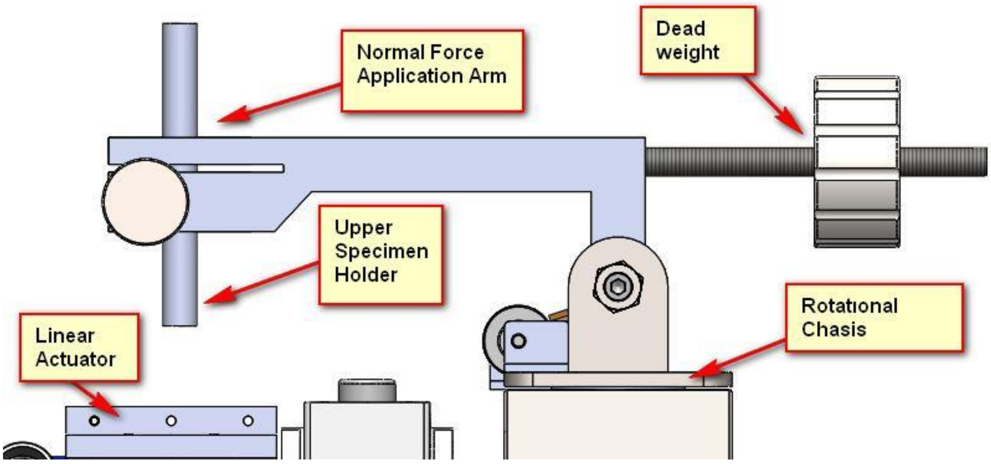


Figure 5.6. Normal force application system

5.2.2. Force measurement

The purpose of this section is to outline in detail how normal and lateral forces exerted on the pin shaft will be measured. Friction force will be measured at load cell mounted on rotational chassis. As the specimens are moved, friction force will occur between materials, this friction force will be exerted to the arm and transferred to the load cell. Load cell has an electrical structure inside, which converts the force to electrical signal. By this circuit, voltage changes occur due to resistance changes in load cell structure. The force applied to the load cell can be determined by measuring voltage changes as a result of resistance change. Figure 5.7. shows the principle of the force measurement.

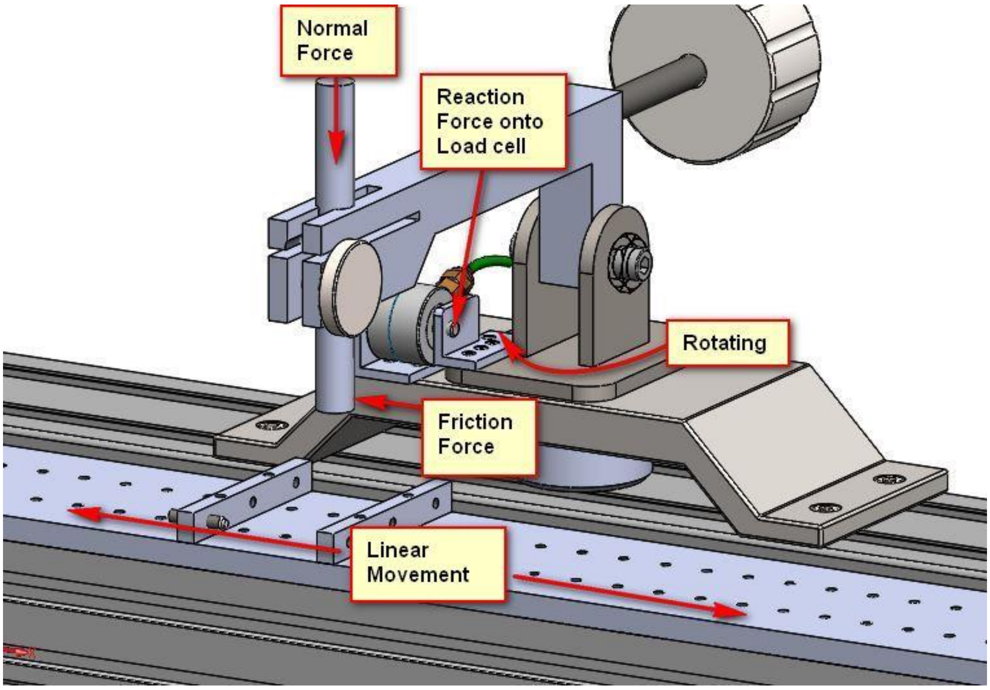


Figure 5.7. Force measurement mechanism

The chassis assembly will consist of a deep groove ball bearing and an angular contact ball bearing in order to allow rotation and carry the load of the chassis, a base plate mounted to the aluminum profiles, a shaft which carries arm of the sample holder and normal load application system. A Cross section of CAD model of this setup is shown below in Figure 5.8. The base plate will be secured to the top of the aluminum profile using 4 bolts. There are side walls which are for mounting load cell. Side walls will be bolted to base plate and carrier of load application arm. These will constrain all motion of the rotation. The slots and bolt holes in the side wall of base plate will be slightly larger to allow for alignment. In mounting process side wall of the rotating shaft will be bolted to load cell prior to the connection. After load cell connected, it can be mounted to the rotating plate. The second side wall will then be secured in place with bolts to the base plate. Afterwards, load cell can be aligned.

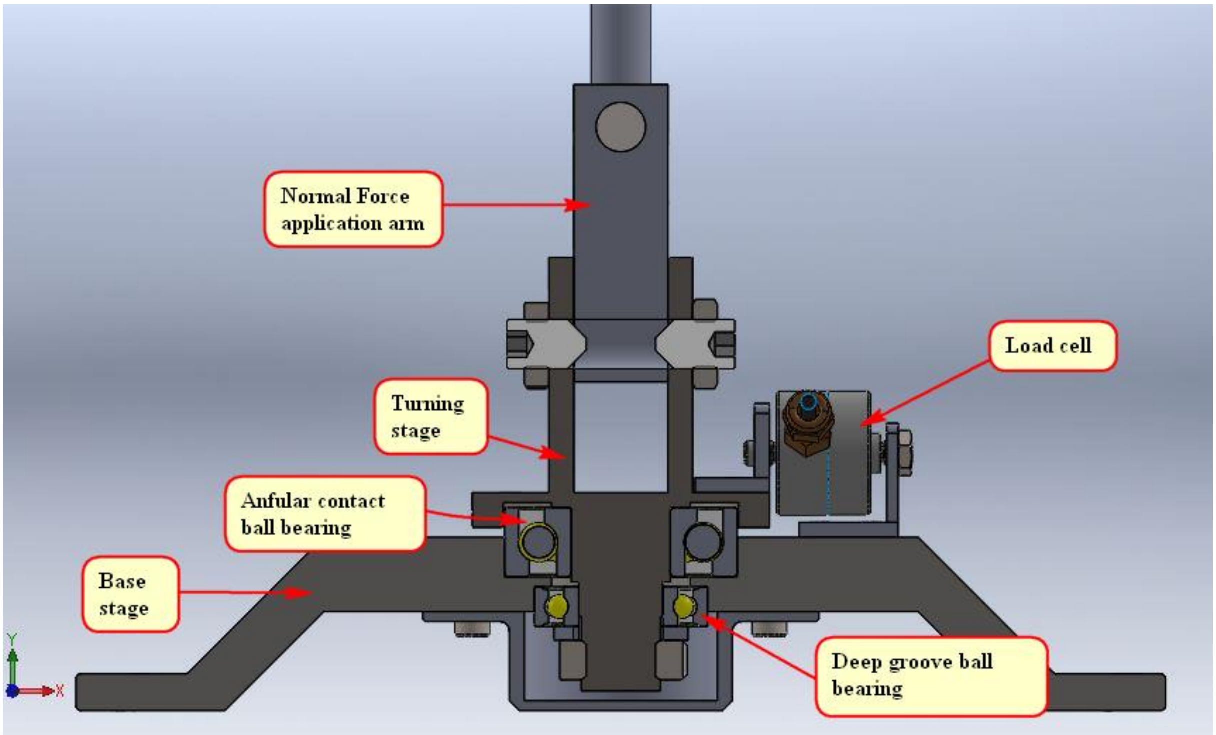


Figure 5.8. Rotational chassis

5.2.3. Sample holding

The system needs to be able to constrain the test samples and components. Machining the test samples themselves is not an option, so the samples must be constrained through an adjustable mechanism.

The parameters affecting our clamp design are:

- Must provide enough constraint to eliminate any slipping
- Must distribute constraint forces to avoid stress concentrations on the samples
- Must not interfere with the path of contact between the samples during the test
- Must be able to accommodate the sample sizes

In order to provide a flexible mounting system, a plate with threaded holes is used for mounting samples to the linear movement plate. This plate has holes along its length for adapting different size and shapes. In order to fix samples, two clamps are used. These clamps are again fixed with screws to the plate. These clamps can be configured for different shapes for different experiment configurations. The Figure below shows the lower sample mounting plate.

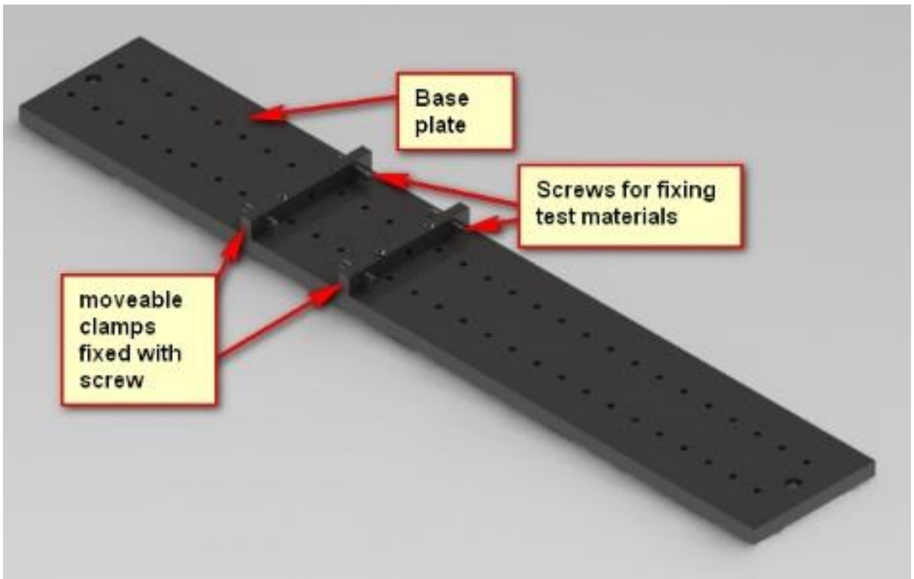


Figure 5.9. Lower test sample holder

In the design of the upper sample holder, the same principle used with lower sample holder. It allows brackets to align with respect to requirements of sample material size and shape. Clamps can be changed if needed with the desired model for the different shape of materials. On the other hand, this upper holder is attached by tightening with the help of screw. It can be removed easily and can be changed with pin holder or ball holder mechanism if needed.

Figure 5.10. Upper test sample holder

Chapter summary

In this chapter possible conceptual ideas of the friction force measurement system and load cell application mechanism as well as specimen holders are presented and detailed. Each of them has advantages and disadvantages in terms of set up, practicality, and reliability. For friction measurement, it is decided to mount load cell on turning plate of loading arm. Threaded shaft is added to balance the weight of the component of loading system by a counterweight. This threaded shaft can provide precise adjusting for balancing. The specimen holders are designed to allow the use of different size and different shape of specimens. They can be removed and changed easily with different models in case of need.

6. MOTION CONTROL SYSTEM AND COMPONENTS

Motion control is the control of the position or velocity of machines using some type of device such as a hydraulic pump, electric motor generally a servo, or linear actuator. Motion control is an important part of robotics, CNC machine tools and laboratory equipment.

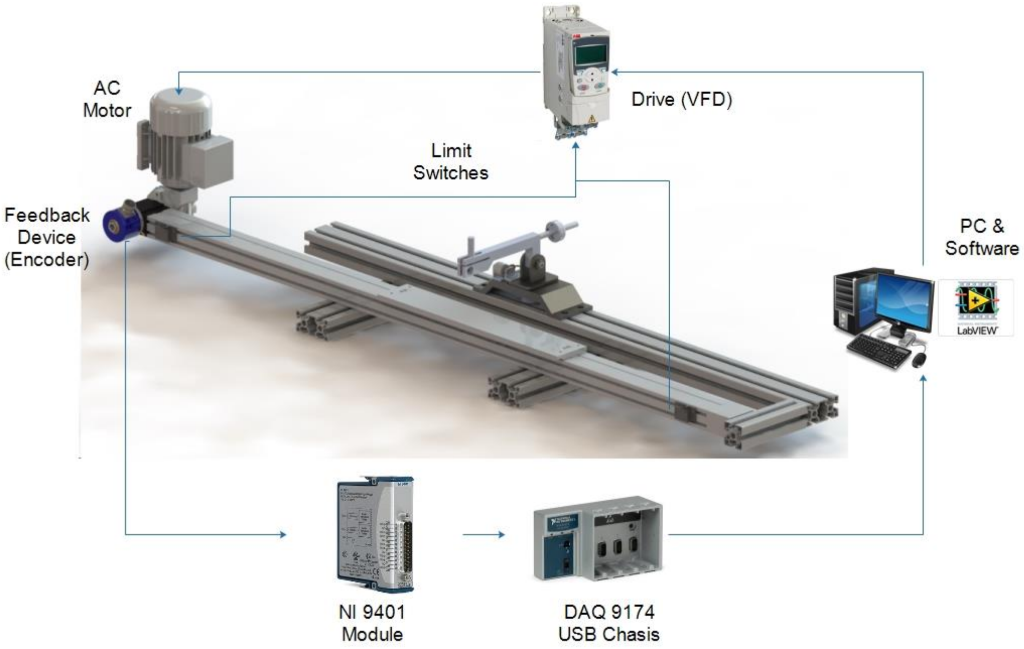


Figure 6.1. Components of a Motion Control System

Mechanical Elements-Parts such as gears, belt, linkages, linear slides and actuators which is driven by motor are constitute mechanical elements. This system has already built toothed belt driven linear actuator with equipped AC motor.

Motor-In motors, electrical energy is turned into mechanical energy and the required torque is produced to move to the desired target position. This work has a 3-phase AC motor previously installed.

Drive-Drives are used to receive commands from the controller and generate the current required to drive or turn the motor. For this work, variable frequency drive which is already installed, is convenient to meet requirements of controlling motion.

Application Software- Application software can be used to command target positions and motion control profiles. There are many platforms that is able to develop software to use for this purpose. In this work, LabVIEW has been chosen because of its easy integration to external hardware.

Feedback device- Rotational motion information is converted into electronic signals needed for precise control of position by feedback devices. The feedback device, usually a quadrature encoder or absolute encoder, senses the position of motor shaft and sends the result to the controller for closing the loop to the motion controller. In this work absolute encoder is used to control position accurately.

6.1. Linear Actuator

In designing phase of the linear motion system, the question is whether to use electro-mechanical actuators or hydraulic. Although the cost of a hydraulic cylinder seems less, because the costs for auxiliary equipment's a hydraulic system, it can still be more expensive than its electromechanical equivalent. Auxiliary equipment consists of a pump, an oil tank, and a filter system, and tubing for distributing the hydraulic fluid. But, electric linear actuators are simpler because they require only cables for power and for transmitting signals. In terms of controlling, electric actuators have more advantages. As the motion produced by the hydraulic drives is not effected by a fluid, and the control response remains constant as long as the machine is in operation. It is however quite different with hydraulic drives.

Thus, it is feasible to use electrical actuator for the system. This linear movement test rig consists of a belt driven actuator PDU2, which has a capacity that meets requirements of this system. There is no need for changing current linear actuator.

6.2. Motor

There are alternatives that can be used for providing motion to the system. These includes stepper motors, DC motors, and AC motors. They have of course advantages and disadvantages in some aspects.

Stepper motor

Stepper motors provide precise position control. They are a special segment of brushless motors. They have high holding torque. This high holding torque provides the ability to incrementally "step" to the next position. This results in a simple positioning system that doesn't require an encoder.

Brushless DC motor

Brushless motors are mostly preferred in actuation and industrial positioning applications. For assembly robots, servo motors or brushless stepper motors are used to position a tool for a manufacturing process or a part for assembly, such as painting or welding. Brushless motors can also be used to drive linear actuators [1].

AC Motor

AC motors are mostly used in domestic and industrial applications due to their durability and relatively low costs. In three-phase induction motors, energy transfer is from the stator to either a short-circuited squirrel cage rotor or a wound rotor [6]. Although most AC motors have been used in fixed-speed load service, they are increasingly being used in variable-frequency drive (VFD) [13]. But AC motors do not provide feedback. Thus, external feedback can be gathered using separate hardware for closed loop control.

Table 6.1. Pros and Cons of motors

Stepper Motor	**Brushless DC Motor**	**AC Motor**
Pros • Excellent position accuracy • High holding torque • High reliability	**Pros** • Reliable • High speed • Efficient • Mass produced and easy to find	**Pros** • low cost • long lifespan • high-efficiency and reliability • simple construction
Cons • Small step distance limits top speed • It's possible to "skip" steps with high loads • Draws maximum current constantly	**Cons** • Difficult to control without specialized controller • Requires low starting loads • Typically require specialized gearboxes in drive applications	**Cons** • Generates a large amount of heat and harmonics

For this work position control is important. Stepper motor would be the convenient choice for this purpose because of its high position feedback accuracy. But, since this system has AC motor, it can be used with the external encoder in order to provide position feedback. Changing current motor results in extra cost and needs to replace the controller. Thus, it is decided to continue with the existing motor.

6.3. Drive

Control applications over a wide range of industry are commonly used today. One of the common applications in performing remote control and monitoring is variable frequency drive system. The drive system is used in order to perform some actions such as control the speed, forward and reverse direction of the motor. Variable frequency drive system often utilizes motors that are designed for operation of fixed-speed. Variable frequency drive operator interfaces allow the user to start and stop the motor and adjust operating speed. The operator interface might also allow the user to switch and reverse between automatic control, or manual speed adjustment [14].

Advantages of a variable frequency drive:

- process can be controlled without a separate controller,
- less maintenance,
- longer lifespan for machinery and the AC motor,
- low operating costs.

In this work, frequency control has been done by variable frequency drive which is ACS310-03E-01A Low voltage AC drives by ABB. VFD control has been chosen specifically because it has the advantages of energy savings, low motor starting current, reduction of mechanical stresses on motors and belts during starts, simple installation, high power factor and lower kVA [14]. Since AC motor does not have feedback hardware, for getting position and speed feedback, encoder application has been chosen. The VFD has a connection via RS-232 serial connection to the computer. Based on encoder feedback VFD commanded by PC equipped with control software.

6.4. Application and monitoring software

The major problem occurs when designing a system with more Hardware Circuits, then we need to go for more wiring connections. It is difficult to design distance control of the system, if more hardware and wirings are needed. In addition, if engineers desire to improve the design, all the irrelevant hardware need to be replaced, which is not sustainable. Due to the rise of the technology, LabVIEW has eased the engineering design. It is because the entire design is implemented in software programming paradigm. LabVIEW had been commonly used in the industry, including controlling induction motor inverter variable drive system. Thus, designing distance control machinery is now possible, even by using Ethernet as the communication device between the Induction motor and the computer. The engineers can use LabVIEW, which has various types of industrial applications which are in the virtual instrument (VI) instead of the real and heavy instrument, to control the Induction motor. The figure below shows the panels of LabVIEW software which makes it easy to program and control systems.

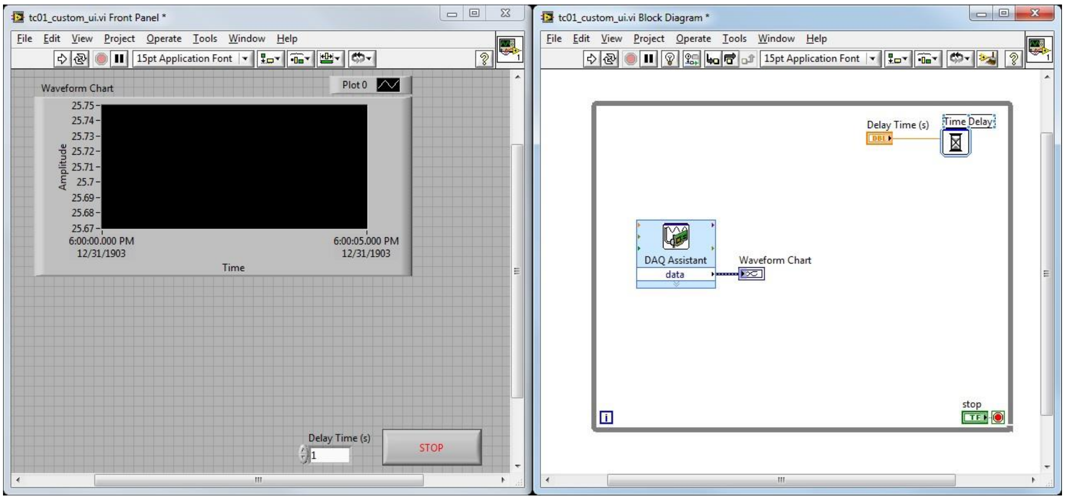


Figure 6.2. LabVIEW panels

In the scope of this work LabVIEW can be used to communicate easily between hardware. The drive used in this work is capable of communicating with RS 232 communication port. For this purpose, LabVIEW MODBUS library is needed for communicating with the drive.

MODBUS Library for LabVIEW

The MODBUS library is a set of Virtual Instruments (VIs) that provide Modbus communication from serial port or any standard Ethernet. The LabVIEW library implements the Modbus protocol in software and offers both master and slave functionality. (PACs) Programmable Automation Controllers can communicate with devices that provide connectivity to a wide variety of industrial networks, for example DeviceNet, PROFIBUS, and EthernetIP by using the Modbus library. Modbus is a commonly used protocol even if the number of new technologies introduced in recent years. It has simple and flexible nature that makes it an excellent choice for some designs.

Due to its easy implementation and easiness of use, LabVIEW is decided to use for motion control. In chapter 9 control algorithm and software interface is given in detailed.

6.5. Feedback Devices

Feedback devices help the motion controller know the location of motor. The most common position feedback device is the incremental encoder. Incremental encoder gives positions relative to the starting point. Most motion controllers are able to work with these types of encoders. Other feedback devices include potentiometers that give analog position feedback, absolute encoders for absolute measurements of position, and resolvers that also give position measurements.

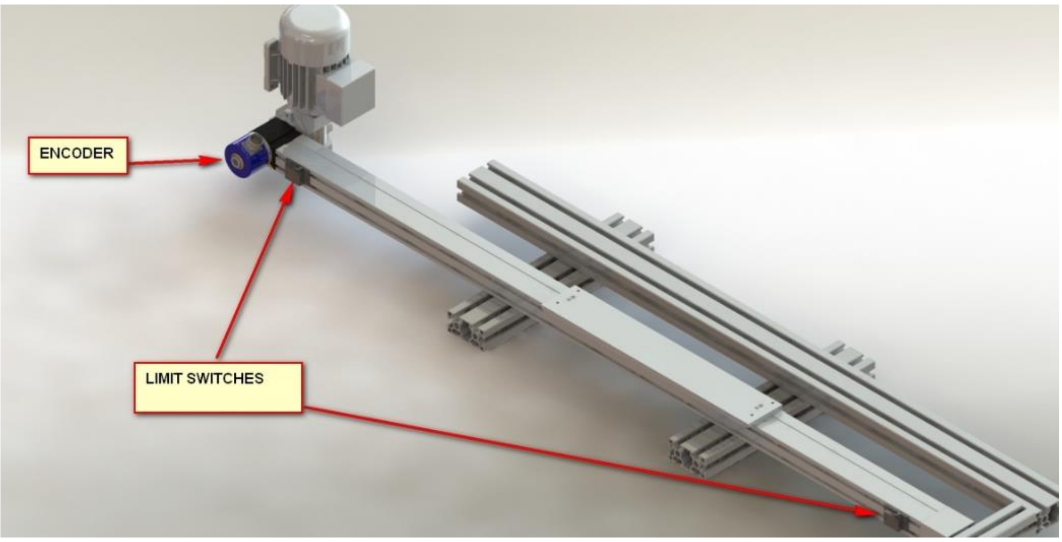


Figure 6.3. Limit switches and encoder

Limit switches provide information about the end of travel to help you avoid damaging your system. When a moving plate or mechanism hits a limit switch, it always halts motor.

Incremental encoder

Rotary encoders measure the rotational motion of a shaft. Figure 6.4. shows the fundamental components of a rotary encoder, which consists of a light detector (LED), a disk, and light-emitting diode on the opposite side of the disk. It consists of two sensors and two tracks whose outputs are called channels A and B. As the shaft rotates, square-wave pulses are generated, which can then be interpreted as motion or position. To make encoder measurements, a basic electronic component is used. It is called a counter. Most counters have three relevant inputs –

up/down gate, and source. The counter counts the registered events in the source input, and, depending on the state of the up/down line, it either increments the count or decrements it.

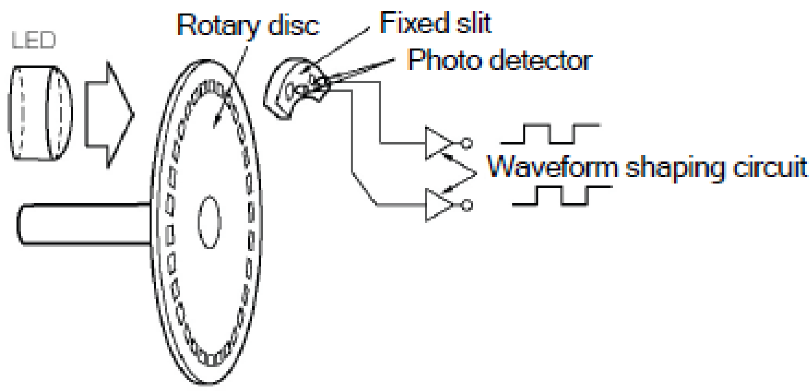


Figure 6.4. Optical Encoder Components [15]

Track A and track B are illustrated in Figure 6.5. By counting the number of pulses and knowing the resolution of the disk, the angular motion is measured. The A and B channels helps to determine the direction of rotation by assessing which channels "leads" the other.

But, since absolute position information is desired in our work. It is not chosen for use. They lost the position of information in case of shut down and failure.

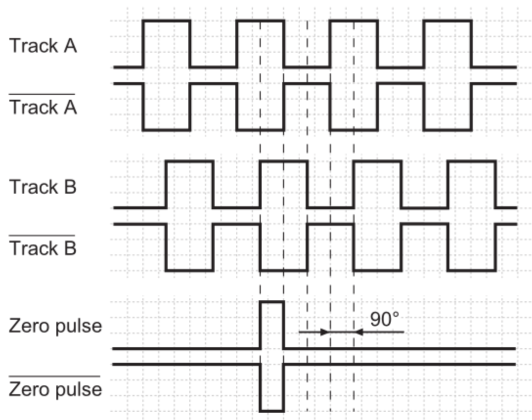


Figure 6.5. Encoder output signals [15]

Absolute Encoder

Absolute encoders typically contain several slots and detectors on a revolving wheel to produce a unique output binary code for each shaft position. Therefore, the shaft position can be obtained absolutely. Moreover, the correct position can always be kept retained before and after a power shut-off. Absolute encoders come in single and multi-turn versions [16].

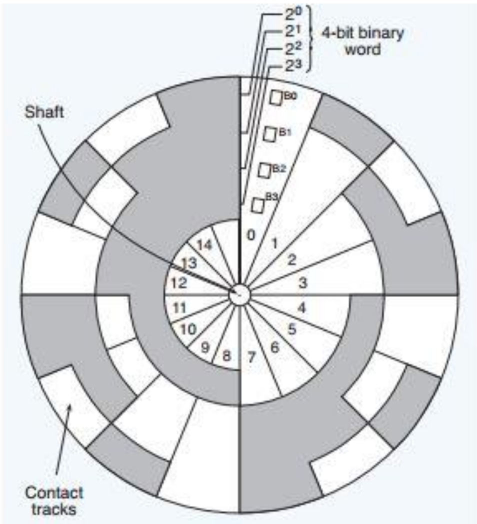


Figure 6.6. Absolute encoder disk

Measuring with the absolute encoder is not done in the same way as a quadrature encoder. More precisely, it is not possible to use an absolute encoder with a counter. An absolute encoder has multiple data wires coming out of it. For example, a 12-bit absolute encoder will have 12 data wires that will produce output of 12 digital signals representing the position in a 12-bit binary number.

In the scope of this work, absolute encoder is more convenient to use due to the importance of tracking position. For variations of test samples and different linear movement distances, it provides precisely position control and monitoring. And it registers position information and does not lose in case of failure.

Baumer GXM2S- SSI 12 bit optical multiturn obsolete encoder has been chosen for this work.

Features of encoder [17]

- multiturn / SSI
- Optical sensing
- Resolution: multiturn 12 bit
- End shaft ø14 mm
- Electronic setting of zero point
- Permanent check of code continuity

- Counting direction input
- Suitable for high positive, negative accelerations

For detailed information, Appendix A includes manual of this encoder.

Limit Switches

Limit switches are important in motion control. Limit switches provide information about the end of travel to help you avoid damaging the system. When a motion system hits a limit switch, a controller needs to stop motion in that direction immediately. Home switches, on the other hand, indicate the system home position to help you define a reference point. Motion system consists of one limit switch at the both ends of the linear actuator. These stop the motion when plate reached its maximum.

A home switch is used to calibrate the position of stage to a known reference. When the stage or motor reaches the location of home switch, position can be reset, so that you will have a known offset. A home switch is important in closed loop stepper and servo systems and open loop systems, with encoder feedback.

6.6. Motion control system set up

6.6.1. Drive connection

ABB ACS310 VFD is equipped with Fieldbus interface to send and receive all of its control information, or the control can be distributed between digital and analogue inputs or the Fieldbus interface and other available sources. The VFD has a connection via RS-232 serial connection to the computer.

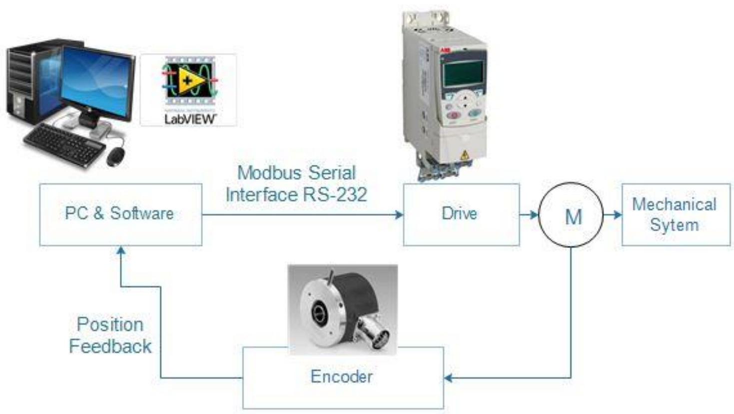


Figure 6.7. Drive control schematic

The drive is connected to an external control system through embedded Fieldbus. The embedded Fieldbus supports Modbus RTU protocol. Modbus Protocol is a messaging structure developed by Modicon in 1979. It is used to establish master-slave/client-server communication between intelligent devices [10]. For the Modbus addresses please check the annex B.

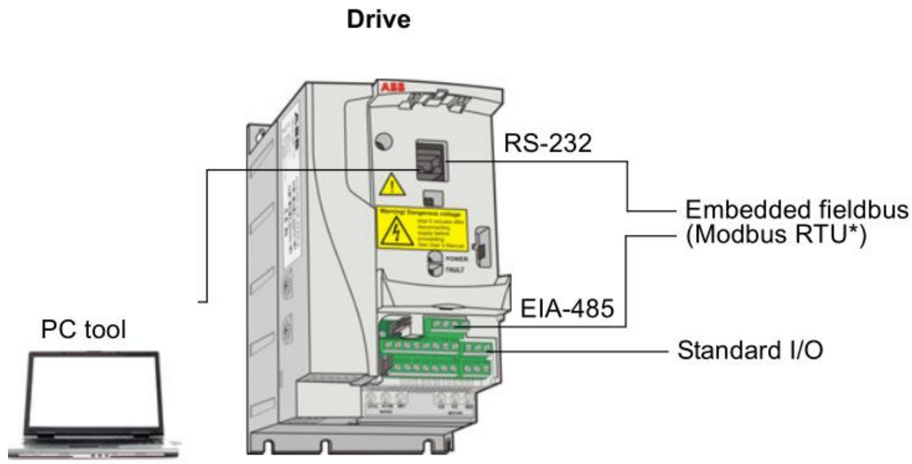


Figure 6.8. ABB ACS310 Variable Frequency Drive communication ports [18]

In order to connect drive to PC, the RJ45 to Serial port conversation is used. It is not possible to directly connect to PC the current connection configuration. Pin arrangements of this conversation are illustrated in Figure 6.9. The drive is capable of communicating with RS 232 communication port. This drive has an advanced technology that allows users to configure for their application requirements [19].

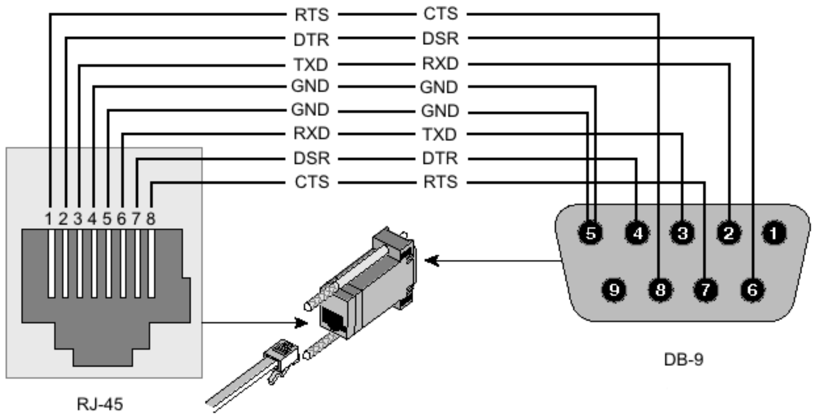


Figure 6.9. RJ45 to Serial Port Conversion for PC connection

In order to control this drive remotely by Modbus, the registers of Fieldbus need to be known. They can be accessed from the manual of this drive from annex B.

6.6.2. Encoder DAQ

An absolute encoder provides signals that represent the absolute position of the encoder. The signals represent the position in a bit binary number. If you place these in sequential order and the typecast this binary number to a 12-bit numerical value, this can be used to get directly the position of the encoder.

Table 6.2. Technical data of absolute encoder [17]

Voltage supply	(10...30)VDC
Initializing time (typ.)	20 ms after power on
Interfaces	SSI, Incremental A 90° B (optional)
Function	Multiturn
Number of turns	4096 / 12 bit
Incremental output	2048 pulses A90°B + inverted
Absolute accuracy	±0.025 °
Sensing method	Optical
Code	Gray or binary

Detailed connection configurations and pin assignments is presented in the annex A.

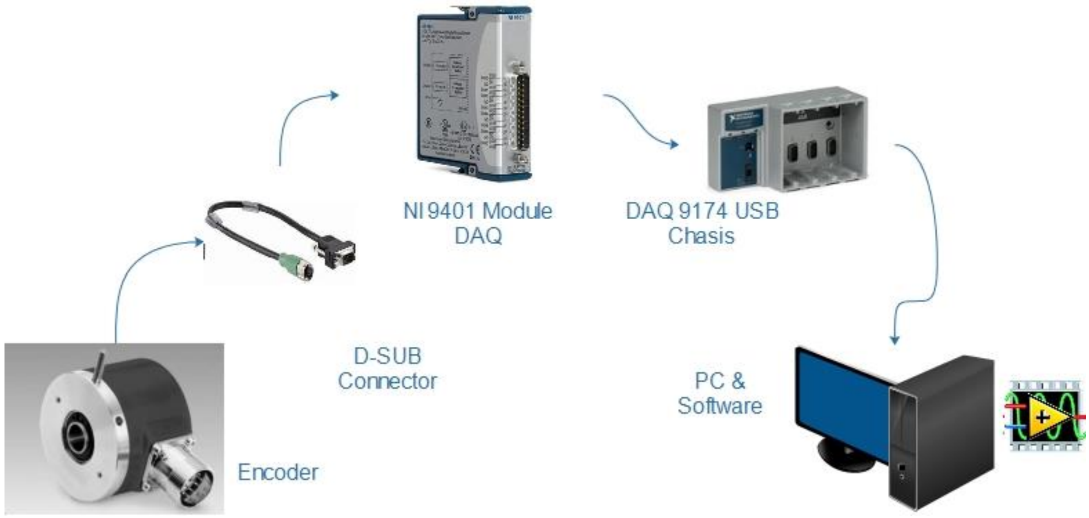


Figure 6.10. Encoder DAQ

Ni 9401 DAQ board

Ni 9401 Bidirectional Digital I/O Module is developed for getting digital inputs in order to make data acquisition of absolute encoder. The NI 9401 has a D-Sub connector, which allows connections for the eight digital channels. It makes easier to integrate encoder to the system without any additional circuit configuration. Through the NI DAQ 9174 USB chassis, it can be configured in LabVIEW environment easily to get signals and position information.

Ni 9401 characteristics [20]

- 8-channel
- 5 V/TTL, sinking/sourcing digital I/O
- Compatible with NI CompactDAQ counters
- 60 VDC, CAT I isolation
- Industry-standard 25-pin D-SUB connector
- -40 °C to 70 °C operating

Chapter summary

In this chapter, structure of motion, control system and components are reviewed. All the component of the current test rig is convenient to implement for building a device for measuring friction force. It is needed to add some additional hardware for example encoder in order to provide a closed loop of motion control. Absolute encoder is chosen for position and speed control. Motion software will be developed in order to provide automatic motion for desired test configuration. The connection of encoder and drive to PC is schematized. Besides, monitoring of AC motor is necessary for operating efficiently. There are many undesirable things that happen to electric motors and other electrical equipment as a result of operating a power system in an over voltage manner. Monitoring of AC motor provides not only reducing the cost of the electricity bill but also extending the life of the electrical motors while preventing unexpected failures [13].

7. MEASURING STRUCTURE AND COMPONENTS

Friction measuring mechanism is the major part of this project. By applying force to the normal direction of the face that specimens contact each other, the friction force occurs between materials. This friction force is transferred to load cell by a mechanism for measuring this force and gain data. This load cell measurement data transferred into software for saving and monitoring desired information.

7.1. Load cell

Load sensors include specially designed structures and circuits that perform in a predictable and repeatable manner when force is applied. The electrical circuit consists of strain gauges or piezo resistors, typically connected in a four-arm (Wheatstone Bridge) configuration [21]. The force helps to create a signal voltage by the resistance change of the strain gauges. This strain gauges have organized an electrical circuit and, applied to the load cell structure. A change in resistance shows the degree of deflection. And this deflection indicates the load on the structure by manipulation of electrical signals. The figure below shows the structure of typical load cell and the figure shows load cell itself.

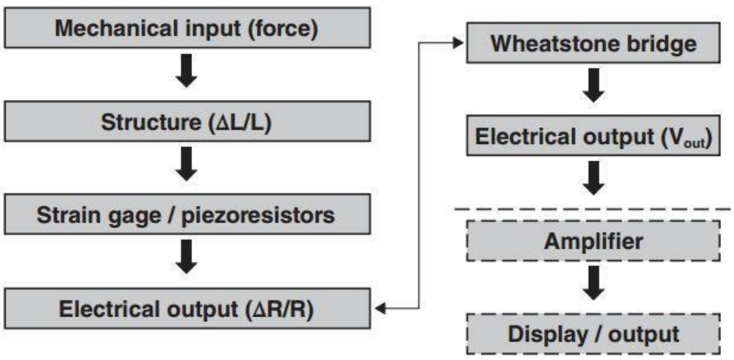


Figure 7.1. Structure of typical load cell [21]

Load cells can be designed to use compression-only forces, or in some applications, they can be designed to measure both a compression and tension (push / pull) force. The tension and compression load cells usually have a centre female threads on top and bottom for fixing, but could also be male to male threads or even a mixture of one female and one male thread. The type of load cell used for an application will relate to the constraints or type of physical mounting requirements.

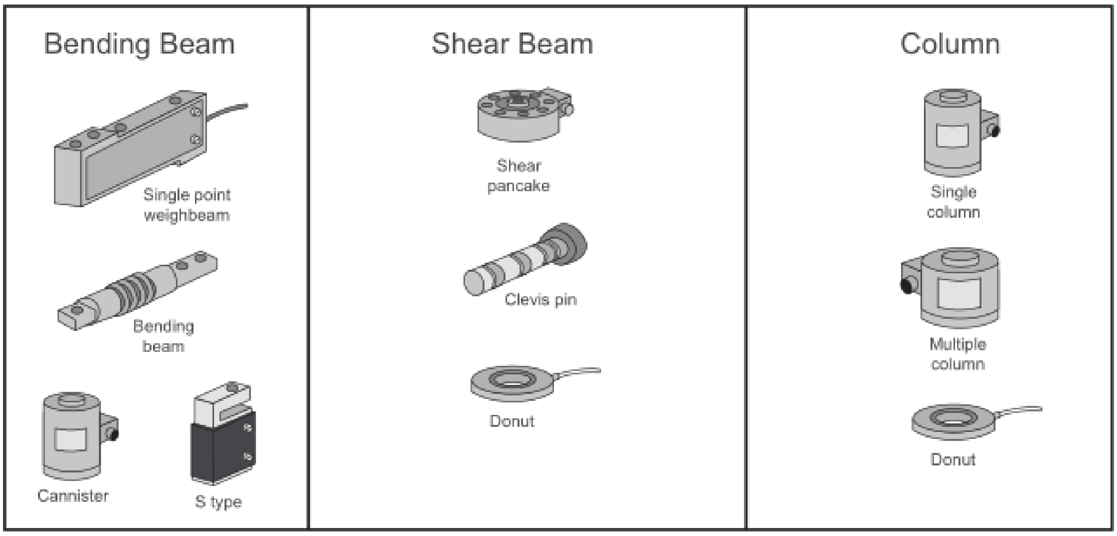


Figure 7.2. Load cell configurations [21]

Load cell types consist of different types of bending beam, shear beam, and column designs. Variations may also be used based on design configurations. The figure above shows variations of the load cells. Load cell type selected for this work is Honeywell model 31 mid-range load cell [22]. Model 31 mid-range precision miniature load cells measure both tension and compression load forces of 1000 grams to 450 kg. These models are highest accuracy, rugged miniature load cells. The Model 31 mid-range load cell has male threads for attachments. High accuracies of 0,15 % to 0,25 % full scale van be achieved. The detailed technical information and manual of this load cell presented in appendix C.

Figure 7.3. Compression-Tension load cell

7.2. Data acquisition (DAQ)

The goal of data acquisition is to measure an electrical or physical entity such as voltage, current, temperature, pressure. Data acquisition uses a combination of software, hardware, and computer for getting measurements. The common goal of every data acquisition system is acquiring, analysing, and presenting information. Data acquisition systems involve signals, data acquisition devices, sensors, signal conditioning, and application software.

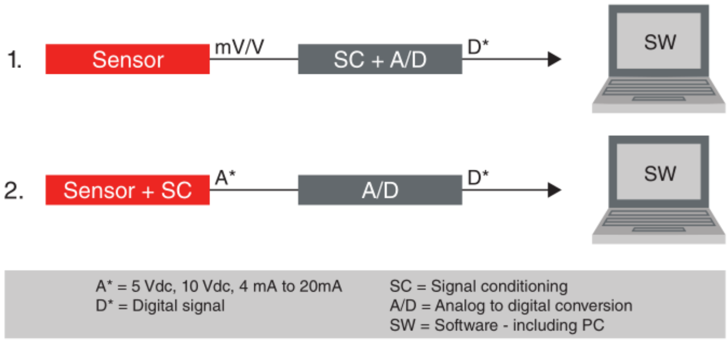


Figure 7.4. Load cell Instrumentation [21]

DAQ contains both ADC & DAC. In automated data acquisition systems, the sensors transmit a voltage or current signal directly to a computer via data acquisition board. Due to inadequate voltage or current some load cell mechanism may require amplification circuit. Software such as Lab VIEW controls the acquisition and processing of such data. Here it has to be considered the following properties of the input signal [23].

- Sampling rate
- Resolution
- Range
- Amplification

7.2.1. DAQ board

ARDUINO

An Arduino board can be an option in the scope of this system. It has its own processor, which can operate independently of a PC, allowing real-time control. The computing power of this processor is significantly less than an FPGA (A field-programmable gate array), which provides a significant price saving. The main drawback to the Arduino board in comparison to an FPGA is that The analogue to digital converters (ADC) on the Arduino have 10-bit [3]. That means the smallest detectable voltage change is high. Besides, Arduino does not do sampling at precise intervals. Arduino uses a certain amount of CPU time being dedicated to looping or calculating those tasks [24]. Data collection is not the primary focus of the Arduino. Since load cell output changes in very small amount, Arduino is not convenient when considering accuracy of the measurement.

Figure 7.5. Arduino board [1]

NI USB – 6009 DAQ

The National Instruments USB-6009 DAQ board provides basic data acquisition functionality for applications such as portable measurements, simple data logging, and academic lab experiments. It is affordable for student use and powerful enough for more sophisticated measurement applications[20]. But, in load cell bridge measurement it needs to be used amplification circuit. This does not have amplification circuit for load cell measurement. On the other hand, in order to make simpler system, it is more convenient to use a system that can integrate both load cell and encoder feedback. Because of this, this board is not much easy to use and requires additional connection port. The figure below shows the input and output map of this DAQ board.

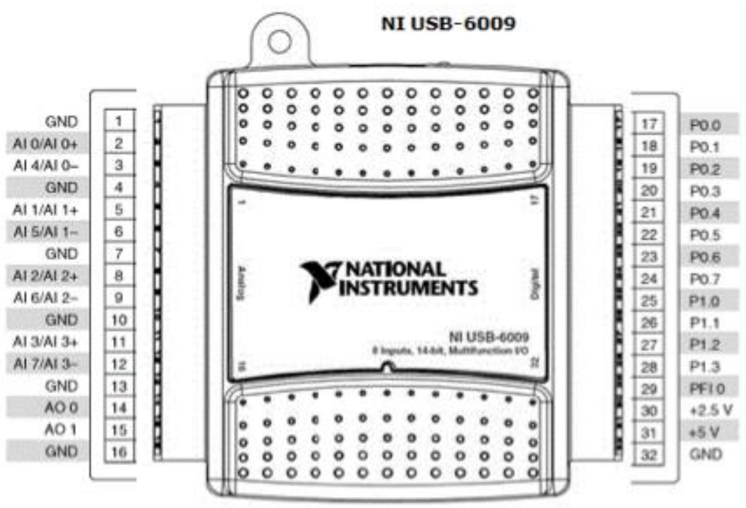


Figure 7.6. USB-6009 - National Instruments DAQ [17]

NI 9237

The NI 9237 bridge module contains all the signal conditioning required to power and measure. It can measure up to four bridge-based sensors simultaneously. The RJ50 jacks provide direct connectivity to most torque or load cells and provide custom cable solutions with minimal tools. The high bandwidth and sampling rate of the NI 9237 offer a high-quality, high-speed load or strain measurement system with zero interchannel phase delay [20].

Figure 7.7. Ni 9237 DAQ board [17]

Properties of this DAQ board is [20];

- 4 channels, 50 kS/s per channel simultaneous AI
- ±25 mV/V input range,
- 24-bit resolution
- Programmable half-bridge and full-bridge completion up to 10 V excitation
- RJ50 connectivity
- -40 ºC to 70 ºC working range

7.3. System set up

The figure below shows the connection schematic of measuring system components. The load cell sends signals to NI9237 DAQ board through the RJ50 connector. The RJ50 connector, also known as a 10P10C connector, features 10 contacts and 10 contact positions [20]. It is similar to the RJ45 connector which is commonly used on network cables. The pinout of the RJ50 connector can be customized for different measurement type. It is not commonly used in every measurement type. RJ50 is a commonly used connector type for communication, such as serial and for bridge-based measurements. It is ideal for bridge-based measurements due to amount of pins needed to provide a quality bridge measurement with Transducer Electronic Data Sheet (TEDS) smart sensors.

Figure 7.8. Load Cell data acquisition system

The connection diagram in Figure 7.9. indicates which pins on your DAQ device should be wired according to the physical channel you selected. For example, a connection load cell which has a full-bridge type I configuration uses pins in Table 7.1, corresponding to EX+, EX- AI+, and AI-, on an NI 9237 C Series module [20].

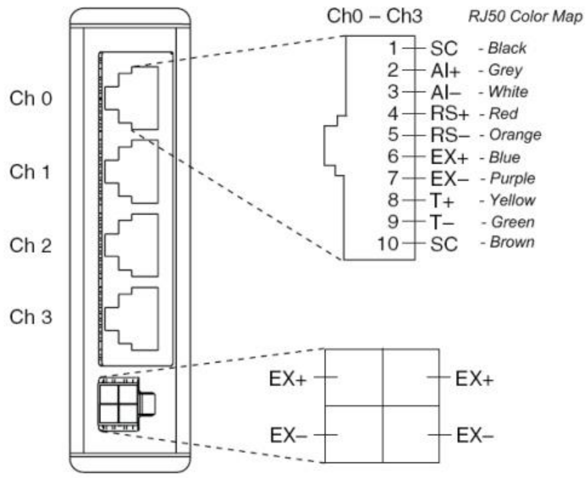


Figure 7.9. NI 9237 Pin assignments and RJ50 Colour Mapping [17]

Load cell pinouts

Table 7.1. Model LCM325 Load Cell Wiring codes [22]

Wiring code	
Red	(+) excitation
Black	(-) excitation
Green	(+) Signal
White	(-) Signal
Shield	(-) Floating

cDAQ-9174CompactDAQ USB Chassis

NI CompactDAQ USB chassis provide the plug-and-play simplicity of USB to sensor and electrical measurements on the benchtop, in the field, and on the production line [17]. The NI CompactDAQ platform delivers high-speed data and ease of use in a flexible, mixed-measurement system.

The main advantage of USB over other PC peripheral buses is simplicity of device detection. Connect NI CompactDAQ USB chassis to a Windows PC with, and the chassis is automatically detected with no additional configuration needed. The device is ready to run with the included LabVIEW software or to be programmed with any of the supported development environments. This ease of setup makes USB a good choice for portable applications that may move from one PC to another.

Figure 7.10. DAQ-9174 CompactDAQ 4-Slot USB Chassis [20]

Chapter summary

In this chapter, components of the measurement system and their set up reviewed. For measuring friction force, it is decided to use a load cell. But load cell needs extra circuit in most circumstances to amplify output signal. Therefore, to remove additional circuit set up and make it more reliable, NI 9237 DAQ board is chosen. Because it has built in amplifier circuit and is specially designed for load cell measurement. It is able to supply all of the components needed in order to extract information from a load cell and convert to a usable format for display and analysis. Besides, DAQ board and load cell connection pinouts are presented. NI 9174 USB Chassis is selected to provide transmission of a signal to Software. The DAQ module and chassis is chosen in order to provide results comparable to that of an actual tribometer, the sampling rate and bandwidth of the module needed to be adequate enough to view multiple frequencies of data.

8. LOAD CELL CALIBRATION

8.1. Overview

The previous chapters have covered the operation, and design of force measurement systems and their installation. But even with suitable sensors and system design, the measurement cannot be trusted without some check on the performance of the system. Some parameters such as component connections, misalignments or user faults can cause uncertainty more than expected or there may appear a need to change the load cell. Consequently, initial calibrations are required to ensure that the force measurement meets the needs of the user and achieves the required degree of uncertainty [26].

8.2. Methodology

There are different calibration options available for constituting the uncertainty of the force measurement system. The first is to have the force transducer in permanently installed position and use a transfer standard to perform the calibrations. The second is to calibrate the force transducer before installation and remove as required for further calibrations. The last option is to calibrate the force transducer before its permanent installation in the force measurement system and then not to recalibrate during the life of the installation.

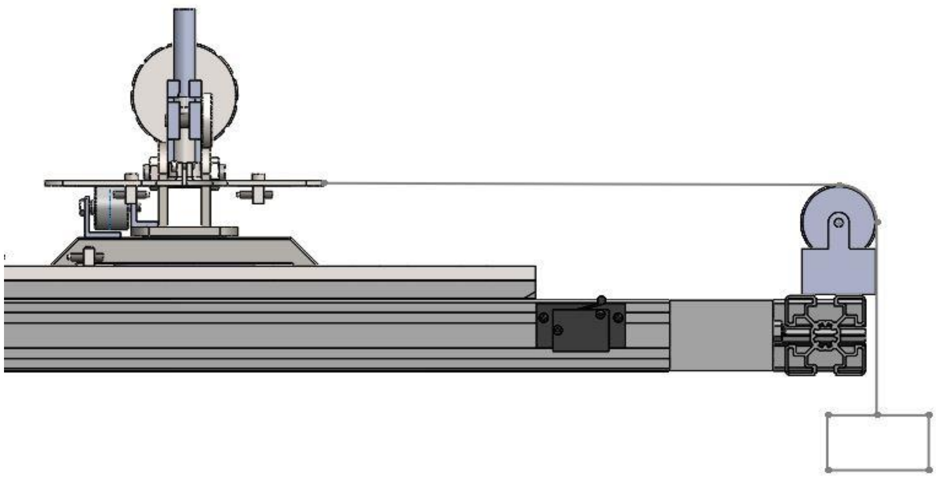


Figure 8.1. Calibration Methodology

However, there are factors that may influence the frequency of needed recalibrations, including:

- environmental conditions,
- the ramifications of operating transducers that do not perform to specification and the consequences of relying on the inaccurate data so produced,
- the frequency and duration of using,
- harsh treatment of the transducer during storage, transportation, or use.

For calibration of this system, it is planned to apply dead weight to the arm of the specimen holder. A pulley can be attached to the system as can be seen in Figure 8.1 with the help of the wire rope, dead weight attached to the arm. Because of known weight, the load cell can be configured easily.

8.3. Standards

Standards in calibration are usually defined at a national or international level by a measuring instrument known as an international standard or a national standard.

Machines capable of performing force calibrations are known as force standard machines and they may be categorized as either secondary or primary [26]. The uncertainty of primary standard machines can be verified through physical principles directly to units of mass, length, and time. Secondary standard machines are can reproduce forces and be compared to standards by the use of a force transfer standard, which is a calibrated force transducer, such as a strain gauge load cell [26]. Types of force standard machines and their characteristics are given in Table 8.1.

Table 8.1. Types of force standard machines[26]

Machine Type	**Principle of operation**	**Uncertainty**	**Category**
Deadweight machines	A known weight is suspended in the Earth's gravitational field and produce a force on the support	0.001 %	Primary or Secondary
Hydraulic amplification machines	A small deadweight machine applies a force to a piston-cylinder assembly and the pressure thus generated is applied to a larger piston-cylinder assembly	0.02 %	Secondary
Lever amplification machines	A small deadweight machine with a set of levers which amplify the force	0.02 %	Secondary
Reference force transducer machines	One or more force transfers standards are placed in series with the	0.02 %	Secondary

	instrument to be calibrated (typically in a materials testing machine		
Strain gauged hydraulic machines	The force applied to an instrument is reacted against by strain gauged columns in the machine's framework	0.05 %	Secondary

8.4. Required uncertainty level

In the calibration of force measurement system, the uncertainty needs to be considered. Some types of uncertainty can be calculated in terms of statistical techniques, such as standard deviation which are known as Type A components. There is Type B uncertainties that is derived by any other method [27]. The combination of these two is combined uncertainty. Thus:

$$\text{Combined Uncertainity} = \sqrt{(u_1)^2 + (u_2)^2 + ...(u_n)^2}$$

where (u_1) ...(u_n) are the individual uncertainty components. In the use of a force measurement system, uncertainties exist at all times, often the only time they are specifically referred to is during the process of calibration.

Chapter summary

The uncertainty level required for the calibration system can be defined by the process, or by standards. Calibration needs to be sufficient to meet these needs, but it would be wasteful to calibrate to more than needed. For this work, during the calibration, it is decided to have the force transducer in permanently installed position and use a transfer standard to perform the calibrations.

9. MEASUREMENT SOFTWARE AND REAL TIME MONITORING

9.1. Measurement module

Data gathered from measurement is often not immediately useful. Much of the time the data is only useful after processing and analysis. You need a software to collect and analysis. For this purpose, LabVIEW is very convenient and useful software. LabVIEW is a software environment for graphical design program and system design environment. Every LabVIEW virtual instrument (VI) has a front panel where you can choose to visualize data or make controls available to your users. It can be easily created a VI with just the controls and displays for your specific need, and provides setting more accurate results while spending less time setting up measurements and interpreting the measured data [28].

The Tribometer software that is to be built (Microsoft Windows platforms) includes a complete set of features for setting up the Tribometer and handling the data. Figure 9.1 explains the software algorithm of the measurement.

By data acquisition board, the signal is gathered and transferred to the software. Software process this signal and converts to force information. This force information is used in order to show on the graph simultaneously and is used to calculate friction coefficient by using user-defined normal load information. At the same this friction force compared to a maximum friction force that is defined for the safety of the system. After this calculated friction coefficient presented on screen by the graph in real time. Afterwards, this data is registered and stored in software for further analysis and exporting.

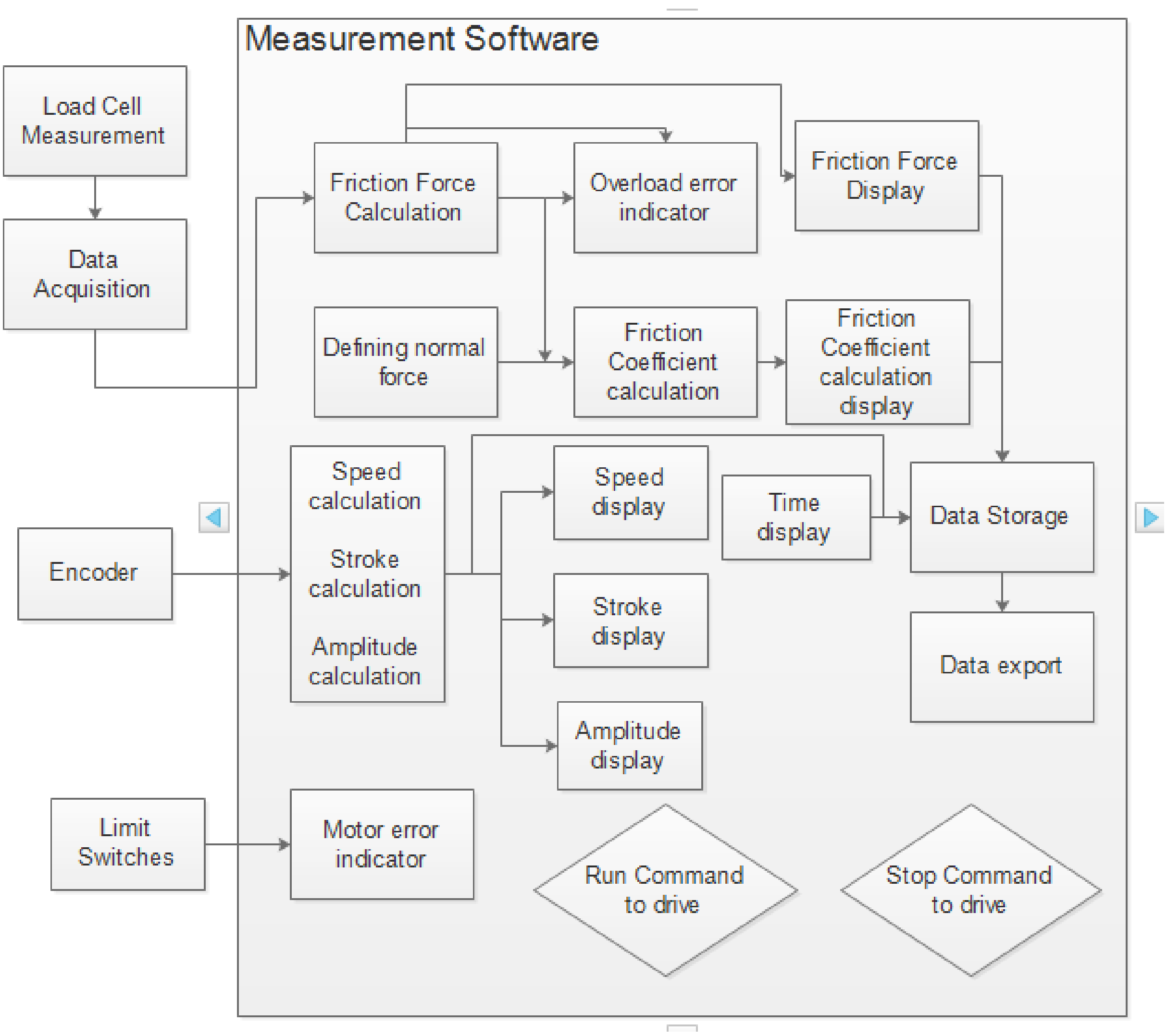


Figure 9.1. Measurement software algorithm

Moreover, software gets information from motion control module and projects onto screen. Encoder for example provides speed and position information. Based on this information motion control module of software generates data of stroke, amplitude, and speed. These data are shown on screen as well. Limit switches provide safety work limits. If it happens and these switches are activated, software projects motor error to the screen. Measurement module has a function to start and stop the motion.

The table below describes the blocks in software algorithm. It explains step by step occurrences of the events. And The Figure 9.2 shows interface of the software.

Table 9.1. Event follow-up of measurement software

1.step	2. step	3. step	4. step	5. step	6. step
	Run Command to drive Execution for running motion after defined parameters				
Defining normal force Based on the experiment, normal load to be defined to the system manually. Following attaching specimens. It is applicable maximum 50N	Load Cell Measurement Reaction force creates resistance to change and gives voltage output which is 1,5 mV/V by load cell.	Data Acquisition Voltage amplified for measuring accurately. Amplified signal is sent to computer through NI 9237 DAQ Input voltage:±25 mV/V	Friction Force Calculation Based on the calibration of the load cell. Voltage signal comes from DAQ corresponds to force	Overload error indicator For safety of system when friction force exceeds maximum force which defined as 330 N. It shuts down and shows error indicator. Friction Force Display Calculated friction force is transferred to the display and shown on graph.	
			Friction Coefficient calculation Friction force measured from load cell is used to calculate friction coefficient using formula $\mu = \frac{F_f}{F_N}$.	Friction Coefficient calculation display Calculated friction coefficient is shown in graph on screen	Data Storage All the information such as friction coefficient, friction force, speed and time of event are registered for further analysis and exporting.
	Encoder During measurement, encoder gets the position information of 12 bit digital signal	Speed calculation Stroke calculation Amplitude calculation In this function block, software	Speed display Calculated stroke from step 4 displayed in software interface.		
			Stroke display Calculated stroke from step 4 displayed in software interface.		

		processes the 12-bit digital signal and calculates speed and position. based on this position information how many stroke completed can be calculated. And again amplitude can be checked.	Amplitude display Calculated amplitude from step 4 displayed in software interface.		
	Limit Switches Limit switches indicate an end of movement, and to prevent a motor from travelling too far. In case of failure and travelling far from defined, limit switches are activated. And stop motor.		Motor error indicator When limit switches stop motor. An indication of error is displayed in screen		

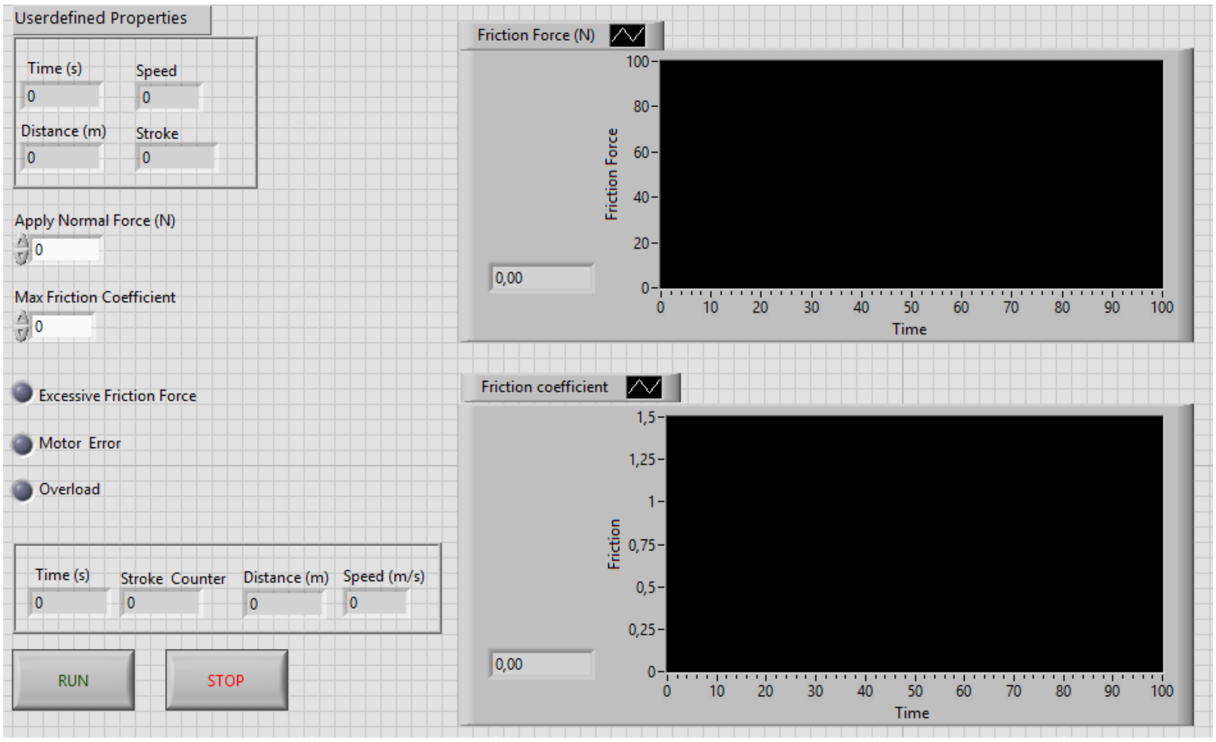


Figure 9.2. Measurement Control Interface

9.2. Motion control module

For measuring process, it is very important to observe experiment conditions. For tribometer, speed is an important factor. For that reason, motion needs to be adjustable in terms of speed and moving distance. In order to meet requirements, Software which is developed needs to have following features;

- adjustable speed,
- adjustable amplitude of movement,
- adjustable home position of the plate in order to attach sample,
- to be able to provide distance and speed information for later analysis and real-time monitoring by values and visualization,
- allowing for manual usage of the linear actuator,
- adjustable stroke number,
- getting position information from feedback device and observe system behaviour and send a command to drive.

Figure 9.3. below represents the interface of motion control software. The interface has subdivisions for defining parameters of motion profile. And it allows user to control manually and specify the initial point for movement by defining the home position. Besides it has a division for monitoring speed, stroke number, test duration and travel distance of plate.

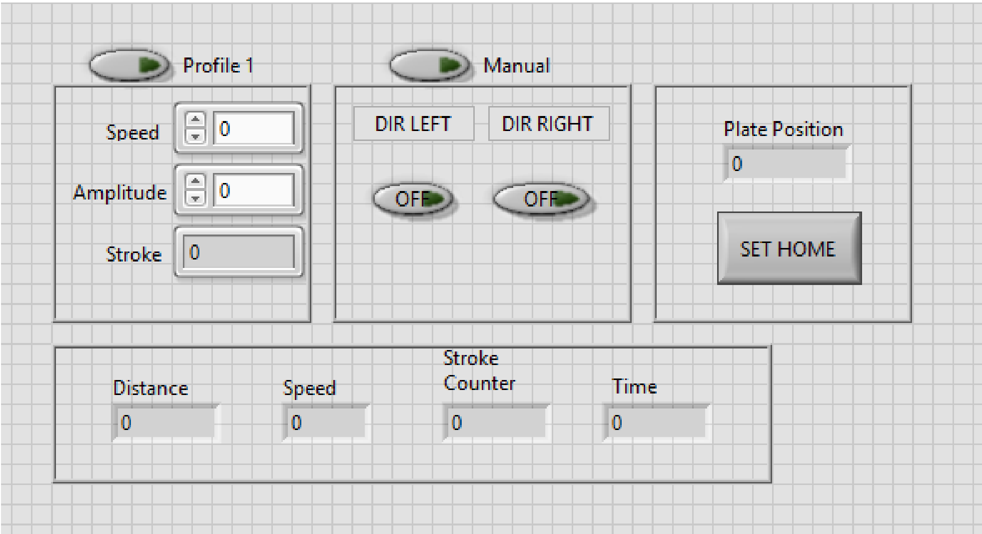


Figure 9.3. Linear motion control and monitoring software user interface

In Figure 9.4 the algorithm of control software is presented. There are parameters such as speed, stroke number and amplitude that is defined by user before the test. Set block is to set the current position of the plate to a home position. After setting home position, based on your amplitude, software calculates the movement both direction and sets the ending position of motion in both side of the linear movement. When speed is defined by the user, it calculates the corresponding frequency which should be provided to the motor. During the motion, the software gets the signal from encoder continuously and compares it with limits of movement. When it reaches the amplitude, it changes the direction of movement. This is repeated for each direction in swinging of movement until it reaches predefined stroke number. It contains start and stop signal which can be controlled from measurement module. When start command is executed, it checks whether parameters are defined and rig plate amplitude in safety range. If the conditions are met, it runs the motion by defined configuration of motion. Otherwise it does not allow the motor run. Moreover, there is a choice for manually run the system when needed. It can be run in both directions manually, for example in the case of testing system setup processes.

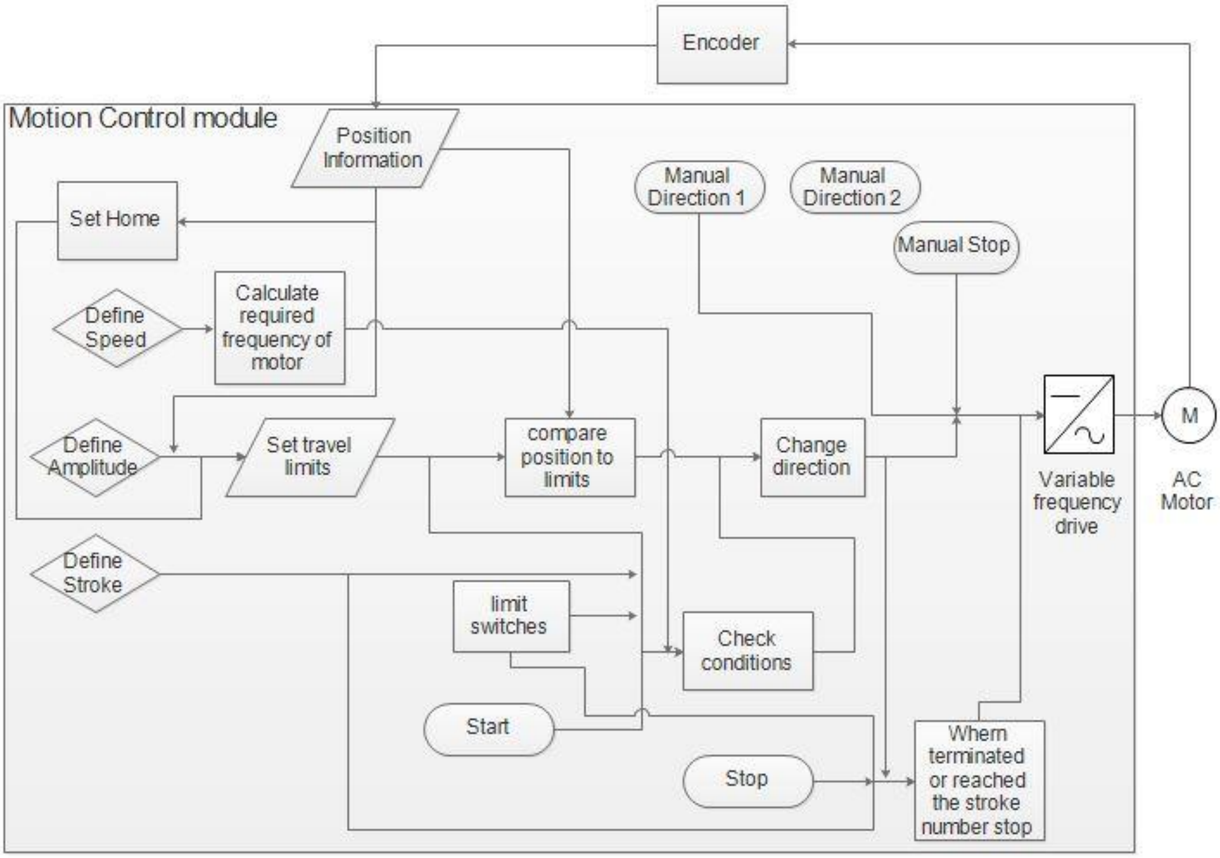
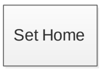
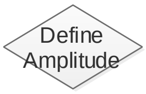
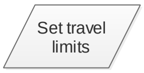


Figure 9.4. Linear motion control algorithm

Example scenario;

1) First step is to connect materials to brackets.
2) Move plate to the position to align material vertically by manual running.
3) Use set home function to specify home position, this registers position of the plate starting point 

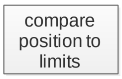
4) Locate limit switches to their places desired amplitude range. These limit switches are used in case of failure and when stage move further than defined.
5) Set the amplitude, 

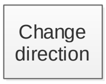
what is the reciprocating distance. When amplitude defined, software calculates the position it will move forward and backward. Then it registers as a travel limit. 

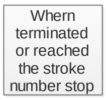
6) Define speed. 

Then it is calculated and required frequency will be provided drive
7) Define the stroke number. 

8) After completing defining speed, stroke and amplitude, press start 

to run the system if all parameters defined it starts.
9) It runs until reaching registered travel limit. During this period, it checks the position via encoder and compare with registered travel limits 

. When it reached forward limit it sends the signal to change moving direction. 

10) When each changing direction it counts and calculate stroke number. When defined value of stroke number reached it stops. 

this terminate function takes signal from measurement module as in case of overload it terminates.

Chapter summary

In this chapter measuring and monitoring software is reviewed. The concept of this software includes a module for the configuration of motion parameters for the experiment. By this software, measured data presented on screen in real time as well as experiment parameters for example speed, amplitude and stroke number. It also allows tracking possible errors that can occur during the measurement process. It includes a graph in order to visualize measurement data. Measurement module is designed as well. By measurement module, software gets signal data through the data acquisition boards and process data. As a result of this software functions friction force and friction coefficient calculated. It has to be assumed, that the configuration above is the first draft only. During the next stages of development, these proposed algorithms, software and user interface configurations shall be optimised and changed based on the results of system practical installation and testing.

SUMMARY

The purpose of this thesis was to develop a tribometer by modernizing existing linear movement test rig. The objectives of the thesis were;

- the design of a test specimen loading system,
- the design of a friction forces measurement system,
- the design of a drive control algorithm and redesign of a drive control system,
- the design of a data acquisition system
- the design of a rig user computer interface,

At first, the current commercially available examples have been reviewed and their working principles were investigated. Then, in order to build linear reciprocating device, existing linear movement test rig was studied and its components were checked whether it had sufficient component or not. It had AC motor which can be used in motion system, toothed belt driven actuator for providing linear reciprocating movement and VFD (Variable frequency drive) as controller of motion. As a result of evaluation of current components, it is determined to build a system based on installed components.

Secondly, work was divided subsystems in order to set specifications and make it easier to study. These subsystems were defined as;

Motion control

Motion control system includes the machine elements such as toothed belt driven stage, an AC motor, and VFD as controller. These components were previously used components in existing test rig. Besides, in order to provide closed loop control and position feedback of test stage, external absolute encoder is used. In this system, connection of this components have been set up. Motion control system was designed to command system and run based on desired speed and motion of test configuration. For that purpose, it was determined to write a PC software, and an algorithm has been developed. On the other hand, a method for remote control of drive was utilized, and connections of encoder and VFD is established.

Loading and friction measuring system

There was need for a normal force application system. It is determined to use dead weight application principle. So, an arm was used to apply normal load by locating dead weight onto it. Friction force measuring mechanism has been designed from scratch. According to this design, upper specimen holder connected to the arm which is located on rotating plate. This rotating plate has connected to a stationary stage through load cell. During experiment, when arm exposed to a friction force, it transfers this friction force to the load cell. Test material holders and fixing mechanisms are also considered in this system.

Measuring structure

In order to measure friction force, a load cell sensor was used. As a result of measurement, the load cell output signal is not directly related to the friction. For that purpose, the measuring structure is designed. NI 9237 Data acquisition board was used to collect voltage signal from load cell output as a result of applied friction force. This signal then transferred to the PC equipped with software. Connections of load cell, DAQ board, and PC were established.

Measurement software and real-time monitoring

After all, in order to track measurement process and observe the result of measurement, it is determined to have a platform for processing, visualizing and monitoring of the measured signal in real time on the screen. Thus, measurement, control, and monitoring software has been decided to write. An algorithm of this software was created. Software programming was left out from the thesis scope due to time limitations.

The project was initially started with a plan that can be completed with couple of months but during the execution process, there were some critical issues faced. Firstly, in motion control, it was very difficult to find out how to connect VFD to computer and establish data communication between them. Moreover, the data communication part is not finally solved. To send and receive commands in practice, it needs practical experimenting with the device in order to get more experience in data communication and fieldbus fields. Algorithm was developed in order to explain it conceptually. This algorithm shall be a basis for practical programming.

Considering the whole process, work has been completed in conceptual level. Components for motion control have been chosen and their connections and motion control method have been established. Mechanical system for loading and friction measurement has been designed. The detail and assembly drawings need to be developed based on given 3D models. Measurement structure components and their connections are presented. Load cell calibration method has been studied and determined. For the future work, these subsystems can be studied in detailed level.

KOKKUVÕTE

Lõputöö oli suunatud tribomeetri väljaarendamisele olemasoleva lineaarliikumisega katseseadme moderniseerimise teel. Lõputöö eesmärgid olid:

- katsekehade koormamissüsteemi konstrueerimine,
- hõõrdejõu mõõtesüsteemi konstrueerimine,
- ajami juhtimisalgoritmi loomine ja juhtimissüsteemi ümberehitus,
- andmekogumissüsteemi konstrueerimine,
- seadme kasutajaliidese loomine.

Esmalt koostati saadaolevate analoogseadmete ülevaade ning uuriti nende tööpõhimõtteid. Seejärel vaadati üle olemasolev lineaarliikumisega katseseade ning selle komponente evalveeriti nende moderniseeritud lahenduses kasutamise otstarbekuse seisukohalt. Olemasoleva katseseadme ajami asünkroonmootor, hammasrihm-veoga reverseeritav lineaarmoodul ja ka sagedusmuundur osutusid sobivaiks moderniseerimisülesande eesmärkidest lähtuvalt. Seega otsustati lähtuda edasiste lahenduste kavandamisel nende, juba olemasolevate, komponentide parameetritest ja võimalustest.

Järgnevalt jagati töö alamsüsteemideks, mida oleks hõlpsam analüüsida ning detailselt kirjeldada. Alamsüsteemid defineeriti alljärgnevalt.

Ajami juhtimissüsteem

Ajam sisladab hammasrihmaga lineaarülekannet kelgu liigutamiseks, asünkroonmootorit ning sagedusmuundurit. Need komponendid olid valitud varasemalt ning ei kuulunud asendamisele. Info saamiseks ajami kelgu asukoha kohta reaalajas ning juhtimissüsteemi tagasiside tagamiseks lisati ajamile absoluutne kooder, mille jaoks oli varasemalt koht jäetud. Kirjeldatud on selle kooderi ühendamist. Ajami juhtimissüsteem annab ajamile käsklusi ning juhib seda vastavalt etteantud kiirusele ja muudele katse liikumisparameetritele. Lõputöös on esitatud juhtimissüsteemi töö algoritm ning selle ellurakendamiseks tuleb kirjutada arvutitarkvara. Välja on töötatud ajami juhtimisprintsiip ning kirjeldatud on kooderi ja sagedusmuunduri ühendusi.

Koormamis- ja hõõrdejõu mõõtmise tarind

Konstrueerida tuli katsekehadele normaalkoormuse rakendamise süsteem, mis põhineb raskusjõul. Normaaljõu rakendamiseks kasutati hooba, millele asetatakse teadaolevate massidega vihid. Hõõrdejõu mõõtesüsteemi konstruktsioon on täielikult loodud autori poolt. See sisaldab ülemist katsekehahoidjat, mis on kinnitatud hoovale, mis omakorda baseerub pöördliikumist võimaldaval alusplaadil. See alusplaat on ühendatud seadme korpusega jõuanduri vahendusel. Katseseadme töö käigus, kui hoovale rakendub katsekehade suhtelise liikumise hõõrdejõud, kandub see üle jõuanduri koormuseks. Katsekehade hoidikud ning kinnitusmehhanismid on samuti leidnud käsitlemist.

Mõõtesüsteem

Hõõrdejõu mõõtmiseks kasutatakse jõuandurit. Jõuanduri väljundiks on elektriline signaal, mis ei ole päris otseselt seotud hõõrdejõu väärtusega. Seetõttu on konstrueeritud mõõtesüsteem. NI 9237 andmekogumismoodulit kasutatakse jõuanduri elektrisignaali (mis tuleneb katsekehade hõõrdumisest) viimiseks vastava tarkvaraga varustatud personaalarvutisse. Lõputöös on kirjeldatud ka jõuanduri, andemekogumismooduli ja personaalarvuti ühendamist.

Mõõtetarkvara ja reaalajas monitooring

Mõõteprotsessi jälgimise ja mõõtetulemuste hindamise eesmärgil tuleb luua platvorm, mis võimaldaks mõõtesignaalide töötlemist, monitoorimist ning visualiseerimist reaalajas personaalarvuti kuvari ekraanil. Selleks vajatakse mõõte-, juhtimis- ja monitooringu tarkvara. Lõputöös koostati selle tarkvara algoritm. Programmide kirjutamine jäeti lõputööst välja ajaliste piirangute tõttu.

Kokkuvõtteks tuleb tõdeda, et lõputöö tegemise alguses said järgnevateks kuudeks paika pandud konkreetsed plaanid, kuid töö tegemisel ilmnesid mõnedki kriitilised asjaolud. Esmalt, ajami juhtimissüsteemi juures osutus aeganõudvaks välja selgitada, kuidas sagedusmuundurit arvutiga tuleb ühendada ning luua andmeside nende vahel. Esitatud töös ei ole andmeside osa lõpuni lahendatud. Tagamaks töökindel andmeside, tuleks seadet praktikas ka katsetada, et saada paremat kogemust andmevahetuse ja tööväljasiini alal. Andmeside kontseptuaalne lahendus on kirjeldatud algoritmiga. Selle algoritmi alusel toimub hilisem programmeerimine.

Kogu protsessi tervikuna hinnates võib tõdeda, et töö tulemus on kontseptuaalsel tasemel. Ajami juhtimissüsteemi komponendid on valitud, nende ühendamisviis on kindlaksmääratud ning ajami juhtimisprintsiip on välja pakutud. Katsekehade koormamise ja hõõrdejõu mõõtmise süsteemi mehaaniline konstruktsioon on loodud. Detaili- ja koostejoonised saab hõlpsasti teha loodud 3D-mudelite alusel. Mõõtesüsteemi komponendid on valitud ning nende ühendamisviis on kindlaks määratud. Välja on pakutud ka jõuanduri kalibreerimise lahendus. Nende alamsüsteemide detailsem väljaarendamine saab toimuda edaspidi.

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Appendix A

Absolute encoders - SSI

End shaft max. ø14 mm

Optical multiturn encoders 14 bit ST / 12 bit MT

GXM2S-SSI

GXM2S with end shaft

Features

- Encoder multiturn / SSI
- Optical sensing
- Resolution: singleturn 14 bit, multiturn 12 bit
- End shaft ø12 mm / ø14 mm
- Electronic setting of zero point
- Permanent check of code continuity
- Counting direction input
- Suitable for high positive, negative accelerations
- Available with additional incremental output

Technical data - electrical ratings	
Voltage supply	10...30 VDC
Reverse polarity protection	Yes
Consumption w/o load	≤50 mA (24 VDC)
Initializing time (typ.)	20 ms after power on
Interfaces	SSI, Incremental A 90° B (optional)
Function	Multiturn
Steps per turn	16384 / 14 bit
Number of turns	4096 / 12 bit
Incremental output	2048 pulses A90°B + inverted
Absolute accuracy	±0.025 °
Sensing method	Optical
Code	Gray or binary
Code sequence	CW/CCW coded by connection
Inputs	SSI clock Control signals UP/$\overline{\text{DOWN}}$ and zero
Output circuit	SSI data: linedriver RS485 Diagnostic and incremental outputs
Interference immunity	DIN EN 61000-6-2
Emitted interference	DIN EN 61000-6-4
Diagnostic functions	Self-diagnosis Code continuity check Multiturn sensing
Approval	UL approval / E63076

Technical data - mechanical design	
Housing	ø58 mm
Shaft	ø12 mm end shaft ø14 mm end shaft
Protection DIN EN 60529	IP 54
Operating speed	≤6000 rpm (mechanical) ≤6000 rpm (electric)
Starting torque	≤0.015 Nm IP 54
Rotor moment of inertia	20 gcm²
Materials	Housing: steel Flange: steel
Operating temperature	-25...+85 °C -40...+85 °C (optional)
Relative humidity	95 % non-condensing
Resistance	DIN EN 60068-2-6 Vibration 10 g, 16-2000 Hz DIN EN 60068-2-27 Shock 100 g, 6 ms
Weight approx.	600 g
Connection	Connector M23, 12-pin

Absolute encoders - SSI

End shaft max. ø14 mm

Optical multiturn encoders 14 bit ST / 12 bit MT

GXM2S - SSI

Part number

Multiturn

GXM2S. [ ][ ][ ][ ]

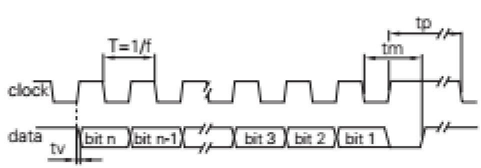
Pulses / Incremental output
- 02 No incremental output
- 04 2048 pulses / push-pull
- 06 2048 pulses / RS422
- 07 2048 periods, Sin/Cos 1 Vpp

Connection
- A1 Connector M23, 12-pin, radial
- A3 Connector M23, 12-pin, radial, for incremental output 04/06/07

Voltage supply / signals
- 10 10...30 VDC / gray code 25 bit
- 12 10...30 VDC / binary code 25 bit
- 20 10...30 VDC / gray code 24 bit
- 24 10...30 VDC / binary code 24 bit
- 90 10...30 VDC / gray code 26 bit
- 92 10...30 VDC / binary code 26 bit

End shaft
- 0 End shaft ø12 mm without pin
- 1 End shaft ø12 mm with pin 15 mm
- B End shaft ø12 mm with pin 9.5 mm
- 4 End shaft ø14 mm without pin
- 5 End shaft ø14 mm with pin 15 mm
- F End shaft ø14 mm with pin 9.5 mm

Data transfer



Clock frequency f	62.5...1500 kHz
Scan ratio of T	40...60 %
Time lag tv	150 ns
Monoflop time tm	25 µs + T/2
Clock interval tp	30 µs

Accessories

Connectors and cables

Z 130.001	Female connector M23, 12-pin, less cable
Z 130.003	Female connector M23, 12-pin, 2 m cable
Z 130.005	Female connector M23, 12-pin, 5 m cable
Z 130.007	Female connector M23, 12-pin, 10 m cable
Z 182.001	Female connector M23, 12-pin, less cable (incr.)
Z 182.003	Female connector M23, 12-pin, 2 m (incr.)
Z 182.005	Female connector M23, 12-pin, 5 m (incr.)

Mounting accessories

Z 119.023	Spring coupling for encoders with ø58 mm housing
Z 119.024	Torque support and spring washer for encoders with 9.5 mm pin
Z 119.041	Torque support by rubber buffer element for encoders with 15 mm pin
Z 119.050	Spring coupling
Z 119.053	Spring coupling height 19.1 mm
Z 119.070	Spring coupling height 29.1 mm
Z 119.072	Spring coupling for encoders with ø58 mm housing, hole distance 73 mm
Z 119.073	Spring coupling for encoders with ø58 mm housing, hole distance 68 mm
Z 119.076	Spring coupling for encoders with ø58 mm housing
Z 119.082	Spring coupling for encoders with ø58 mm housing, hole distance 63 mm

Absolute encoders - SSI

End shaft max. ø14 mm

Optical multiturn encoders 14 bit ST / 12 bit MT

GXM2S - SSI

Terminal significance	
UB	Encoder voltage supply.
GND	Encoder ground connection relating to UB.
Data+	Positive, serial data output of differential linedriver.
Data-	Negative, serial data output of differential linedriver.
Clock+	Positive SSI clock input. Clock+ together with clock- forms a current loop. A current of approx. 7 mA towards clock+ input means logic 1 in positive logic.
Clock-	Negative SSI clock input. Clock- together with clock+ forms a current loop. A current of approx. 7 mA towards clock- input means logic 0 in positive logic.
Zero setting	Input for setting a zero point anywhere within the programmed encoder resolution. The zero setting operation is triggered by a High impulse and has to be in line with the selected direction of rotation (UP/$\overline{\text{DOWN}}$). Connect to GND after setting operation for maximum interference immunity. Impulse duration $\geq$100 ms.
$\overline{\text{DATAVALID}}$	Diagnostic output. An error warning is given at level Low. Important: Interferences must be drained by the downstram electronics.
DATAVALID MT	Diagnostic output for monitoring the multiturn sensor voltage supply. Upon dropping below a defined voltage level the $\overline{\text{DV MT}}$ output is switched to Low.
UP/$\overline{\text{DOWN}}$	UP/$\overline{\text{DOWN}}$ counting direction input. This input is standard on High. UP/$\overline{\text{DOWN}}$ means ascending output data with clockwise shaft rotation when looking at flange. UP/$\overline{\text{DOWN}}$-Low means ascending values with counterclockwise shaft rotation when looking at flange.
Incremental Outputs	Incremental tracks A 90° B and inverted.

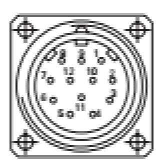
Terminal assignment

GXM2S

Connector	Core colour	Assignment
Pin 1	brown	UB
Pin 2	black	GND
Pin 3	blue	Clock+
Pin 4	beige	Data+
Pin 5	green	Zero setting
Pin 6	yellow	Data-
Pin 7	violet	Clock-
Pin 8	brown/yellow	$\overline{\text{DATAVALID}}$
Pin 9	pink	UP/$\overline{\text{DOWN}}$
Pin 10	black/yellow	$\overline{\text{DATAVALID MT}}$
Pin 11	–	–
Pin 12	–	–

GXM2S with incremental tracks

Connector	Core colour	Assignment
Pin 1	brown	UB
Pin 2	white	GND
Pin 3	blue	Clock+
Pin 4	green	Data+
Pin 5	grey	Zero setting
Pin 6	yellow	Data-
Pin 7	red	Clock-
Pin 8	red/blue	Track B inv.
Pin 9	pink	UP/$\overline{\text{DOWN}}$
Pin 10	violet	Track A inv.
Pin 11	black	Track A
Pin 12	grey/pink	Track B



Please use cores twisted in pairs (for example clock+ / clock-) for extension cables of more than 10 m length.

Absolute encoders - SSI

End shaft max. ø14 mm

Optical multiturn encoders 14 bit ST / 12 bit MT

GXM2S-SSI

Trigger level

SSI	Circuit
SSI-Clock	Optocoupler
SSI-Data	Linedriver RS485

Control inputs	Input circuit
Input level High	>0.7 UB
Input level Low	<0.3 UB
Input resistance	10 kΩ

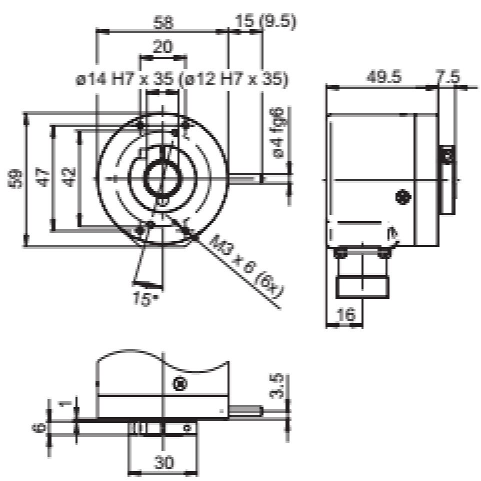
Diagnostic outputs or Incremental outputs	Output circuit Push-pull circuit-proof
Output level High	>UB -3.5 V (I = -20 mA)
Output level Low	<0.5 V (I = 20 mA)
Load High / Low	<20 mA

Incremental outputs	Linedriver RS422
Output level High	>2.5 V (I = -20 mA)
Output level Low	<0.5 V (I = 20 mA)
Load High / Low	<20 mA

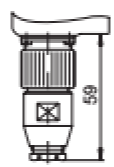
Outputs	Sine / Cosine
Output level	1 Vpp ±10 %
Load	<10 mA

Dimensions

GXM2S



Connector dimensions



Appendix B

Setting up communication through the embedded Modbus

Before configuring the drive for fieldbus control, install the fieldbus according to instructions given in section *Connecting the embedded fieldbus* on page *54*.

The communication through the fieldbus link is initialized by setting parameter *9802 COMM PROT SEL* to *STD MODBUS* or *MODBUS RS232*. The communication parameters in group *53 EFB PROTOCOL* must also be adjusted. See the table below.

Parameter	Alternative settings	Setting for fieldbus control	Function/Information
COMMUNICATION INITIALIZATION			
9802 COMM PROT SEL	*NOT SEL* *STD MODBUS* *MODBUS RS232*	STD MODBUS (with EIA-485) MODBUS RS232 (with RS-232)	Initializes embedded fieldbus communication.
ADAPTER MODULE CONFIGURATION			
1611 PARAMETER VIEW	*FLASHDROP* *SHORT VIEW* *LONG VIEW*	*LONG VIEW*	Selects the long view.
5302 EFB STATION ID	0…65535	Any	Defines the station ID address of the EIA-485/RS-232 link. No two stations on line may have the same address.
5303 EFB BAUD RATE	1.2 kbit/s 2.4 kbit/s 4.8 kbit/s 9.6 kbit/s 19.2 kbit/s 38.4 kbit/s 57.6 kbit/s 76.8 kbit/s		Defines the communication speed of the EIA-485/RS-232 link.
5304 EFB PARITY	*8 NONE 1* *8 NONE 2* *8 EVEN 1* *8 ODD 1*		Selects the parity setting. The same settings must be used in all on-line stations.
5305 EFB CTRL PROFILE	*ABB DRV LIM* *DCU PROFILE* *ABB DRV FULL*	Any	Selects the communication profile used by the drive. See section *Communication profiles* on page *302*.
5310 EFB PAR 10 … … *5317 EFB PAR 17*	0…65535	Any	Selects an actual value to be mapped to Modbus register 400xx.

After the configuration parameters in group *53 EFB PROTOCOL* have been set, the *Drive control parameters* on page *291* must be checked and adjusted when necessary.

The new settings take effect when the drive is next powered up, or when parameter *5302 EFB STATION ID* setting is cleared and reset.

Drive control parameters

After the Modbus communication has been set up, the drive control parameters listed in the table below should be checked and adjusted when necessary.

The **Setting for fieldbus control** column gives the value to use when the Modbus interface is the desired source or destination for that particular signal. The **Function/Information** column gives a description of the parameter.

Parameter	**Setting for fieldbus control**	**Function/Information**	**Modbus register address**	
CONTROL COMMAND SOURCE SELECTION			ABB DRV	DCU
1001 EXT1 COMMANDS	*COMM*	Enables *0301 FB CMD WORD 1* bits 0…1 (*START/STOP*) when EXT1 is selected as the active control location.		40031 bits 0…1
1002 EXT2 COMMANDS	*COMM*	Enables *0301 FB CMD WORD 1* bits 0…1 (*START/STOP*) when EXT2 is selected as the active control location.		40031 bits 0…1
1003 DIRECTION	*FORWARD* *REVERSE* *REQUEST*	Enables rotation direction control as defined by parameters *1001* and *1002*. The direction control is explained in section *Reference handling* on page *297*.		40031 bit 2
1102 EXT1/EXT2 SEL	*COMM*	Enables EXT1/EXT2 selection through *0301 FB CMD WORD 1* bit 5 (with ABB drives profile *5319 EFB PAR 19* bit 11).	40001 bit 11	40031 bit 5
1103 REF1 SELECT	*COMM* *COMM+AI1* *COMM*AI1*	Fieldbus reference REF1 is used when EXT1 is selected as the active control location. See section *Fieldbus references* on page *294* for information on the alternative settings.	40002 for REF1	
1106 REF2 SELECT	*COMM* *COMM+AI1* *COMM*AI1*	Fieldbus reference REF2 is used when EXT2 is selected as the active control location. See section *Fieldbus references* on page *294* for information on the alternative settings.	40003 for REF2	
OUTPUT SIGNAL SOURCE SELECTION			ABB DRV	DCU
1401 RELAY OUTPUT 1	*COMM* *COMM(-1)*	Enables relay output RO control by signal *0134 COMM RO WORD*.	40134 for signal *0134*	
1501 AO1 CONTENT SEL	135	Directs the contents of fieldbus reference *0135 COMM VALUE 1* to analog output AO.	40135 for signal *0135*	
SYSTEM CONTROL INPUTS			ABB DRV	DCU
1601 RUN ENABLE	*COMM*	Enables the control of the inverted Run enable signal (Run disable) through *0301 FB CMD WORD 1* bit 6 (with ABB drives profile *5319 EFB PAR 19* bit 3).	40001 bit 3	40031 bit 6

Parameter	Setting for fieldbus control	Function/Information	Modbus register address	
1604 FAULT RESET SEL	*COMM*	Enables fault reset through fieldbus *0301 FB CMD WORD 1* bit 4 (with ABB drives profile *5319 EFB PAR 19* bit 7).	40001 bit 7	40031 bit 4
1606 LOCAL LOCK	*COMM*	Local control mode lock signal through *0301 FB CMD WORD 1* bit 14	-	40031 bit 14
1607 PARAM SAVE	*DONE SAVE...*	Saves parameter value changes (including those made through fieldbus control) to permanent memory.	41607	
1608 START ENABLE 1	*COMM*	Inverted Start enable 1 (Start disable) through *0302 FB CMD WORD 2* bit 18	-	40032 bit 18
1609 START ENABLE 2	*COMM*	Inverted Start enable 2 (Start disable) through *0302 FB CMD WORD 2* bit 19	-	40032 bit 19
LIMITS			ABB DRV	DCU
2201 ACC/DEC 1/2 SEL	*COMM*	Acceleration/deceleration ramp pair selection through *0301 FB CMD WORD 1* bit 10	-	40031 bit 10
2209 RAMP INPUT 0	*COMM*	Ramp input to zero through *0301 FB CMD WORD 1* bit 13 (with ABB drives profile *5319 EFB PAR 19* bit 6)	40001 bit 6	40031 bit 13
COMMUNICATION FAULT FUNCTIONS			ABB DRV	DCU
3018 COMM FAULT FUNC	*NOT SEL* *FAULT* *CONST SP 7* *LAST SPEED*	Determines drive action in case fieldbus communication is lost.	43018	
3019 COMM FAULT TIME	0.1…60.0 s	Defines the time between communication loss detection and the action selected with parameter *3018 COMM FAULT FUNC*.	43019	
PID CONTROLLER REFERENCE SIGNAL SOURCE SELECTION			ABB DRV	DCU
4010/ 4110/ 4210 SET POINT SEL	*COMM* *COMM+AI1* *COMM*AI1*	PID control reference (REF2)	40003 for REF2	

Modbus mapping

The following Modbus function codes are supported by the drive.

Function	Code Hex (dec)	Additional information
Read Coil Status	01 (01)	Reads discrete output status. The individual bits of the control word are mapped to coils 1...16. Relay outputs are mapped sequentially beginning with Coil 33 (eg, RO1 = Coil 33).
Read Discrete Input Status	02 (02)	Reads discrete input status. The individual bits of the status word are mapped to inputs 1...16 or 1...32, depending on the active profile. Terminal inputs are mapped sequentially beginning with input 33 (eg, DI1 = Input 33).
Read Multiple Holding Registers	03 (03)	Reads the contents of registers in a slave device. Parameter sets, control, status and reference values are mapped as holding registers.
Read Multiple Input Registers	04 (04)	Reads multiple input registers. The 2 analog input channels are mapped as input registers 1 and 2.
Force Single Coil	05 (05)	Writes a single discrete output. The individual bits of the control word are mapped to Coils 1...16. Relay outputs are mapped sequentially beginning with Coil 33 (eg, RO1 = Coil 33).
Write Single Holding Register	06 (06)	Writes to a single register in a slave device. Parameter sets, control, status and reference values are mapped as holding registers.
Diagnostics	08 (08)	Provides a series of tests for checking the communication between the master and the slave devices, or for checking various internal error conditions within the slave. The following subcodes are supported: 00 Return Query Data: The data passed in the request data field is to be returned in the response. The entire response message should be identical to the request. 01 Restart Communications Option: The slave device serial line port must be initialized and restarted, and all of its communication event counters cleared. If the port is currently in Listen Only Mode, no response is returned. If the port is not currently in Listen Only Mode, a normal response is returned before the restart. 04 Force Listen Only Mode: Forces the addressed slave device to Listen Only Mode. This isolates it from the other devices on the network, allowing them to continue communicating without interruption from the addressed remote device. No response is returned. The only function that is processed after this mode is entered is the Restart Communications Option function (subcode 01).
Force Multiple Coils	0F (15)	Writes multiple discrete outputs. The individual bits of the control word are mapped to Coils 1...16. Relay outputs are mapped sequentially beginning with Coil 33 (eg, RO1 = Coil 33).
Write Multiple Holding Registers	10 (16)	Writes to the registers (1 to approximately 120 registers) in a slave device. Parameter sets, control, status and reference values are mapped as holding registers.
Read/Write Multiple Holding Registers	17 (23)	Performs a combination of one read operation and one write operation (function codes 03 and 10) in a single Modbus transaction. The write operation is performed before the read operation.

Register mapping

The drive parameters, Control/Status word, references and actual values are mapped to the area 4xxxx so that:

- 40001…40099 are reserved for drive control/status, reference and actual values.
- 40101…49999 are reserved for drive parameters *0101*…9999. (Eg 40102 is parameter *0102*). In this mapping, the thousands and hundreds correspond to the group number, while the tens and ones correspond to the parameter number within a group.

The register addresses that do not correspond with drive parameters are invalid. If there is an attempt to read or write invalid addresses, the Modbus interface returns an exception code to the controller. See *Exception codes* on page *301*.

The following table gives information on the contents of the Modbus addresses 40001…40012 and 40031…40034.

Modbus register		**Access**	**Information**
40001	Control Word	R/W	Control word. Supported only by ABB drives profile, ie when *5305 EFB CTRL PROFILE* setting is *ABB DRV LIM* or *ABB DRV FULL*. Parameter *5319 EFB PAR 19* shows a copy of the Control word in hexadecimal format.
40002	Reference 1	R/W	External reference REF1. See section *Fieldbus references* on page *294*.
40003	Reference 2	R/W	External reference REF2. See section *Fieldbus references* on page *294*.
40004	Status Word	R	Status word. Supported only by ABB drives profile, ie when *5305 EFB CTRL PROFILE* setting is *ABB DRV LIM* or *ABB DRV FULL*. Parameter *5320 EFB PAR 20* shows a copy of the Control word in hexadecimal format.
40005 … 40012	Actual 1…8	R	Actual value 1…8. Use parameter *5310*… *5317* to select an actual value to be mapped to Modbus register 40005…40012.
40013 … 40014	MDB DATA IN 1...2	R	Modbus Data IN 1 and 2. Use parameter *5321* and *5322* to select an actual value to be mapped to Modbus register 40013 and 40014. Supported only by *STD MODBUS*.
40031	Control Word LSW	R/W	*0301 FB CMD WORD 1*, ie the least significant word of the DCU profile 32-bit Control word. Supported only by DCU profile, ie when *5305 EFB CTRL PROFILE* setting is *DCU PROFILE*.
40032	Control Word MSW	R/W	*0302 FB CMD WORD 2*, ie the most significant word of the DCU profile 32-bit Control word. Supported only by DCU profile, ie when *5305 EFB CTRL PROFILE* setting is *DCU PROFILE*.
40033	Status Word LSW	R	*0303 FB STS WORD 1*, ie the least significant word of the DCU profile 32-bit Status word. Supported only by DCU profile, ie when *5305 EFB CTRL PROFILE* setting is *DCU PROFILE*.
40034	ACS310 STATUS WORD MSW	R	*0304 FB STS WORD 2*, ie the most significant word of the DCU profile 32-bit Status word. Supported only by DCU profile, ie when *5305 EFB CTRL PROFILE* setting is *DCU PROFILE*.
40080 … 40089	MB Data OUT 1...10	W	Modbus Data OUT 1...10. Use parameter *5323*...*5332* to select an actual value to be mapped to Modbus register 40080...40089. Supported only by *STD MODBUS*.

Note: Parameter writes through standard Modbus are always volatile, ie modified values are not automatically stored to permanent memory. Use parameter *1607 PARAM SAVE* to save all changed values.

Function codes

Supported function codes for the holding 4xxxx register are:

Code Hex (dec)	Function name	Additional information
03 (03)	Read 4X Register	Reads the binary contents of registers (4X references) in a slave device.
06 (06)	Preset single 4X register	Presets a value into a single register (4X reference). When broadcast, the function presets the same register reference in all attached slaves.
10 (16)	Preset multiple 4X registers	Presets values into a sequence of registers (4X references). When broadcast, the function presets the same register references in all attached slaves.
17 (23)	Read/Write 4X registers	Performs a combination of one read operation and one write operation (function codes 03 and 10) in a single Modbus transaction. Write operation is performed before the read operation.

Note: In the Modbus data message, register 4xxxx is addressed as xxxx -1. For example register 40002 is addressed as 0001.

Exception codes

Exception codes are serial communication responses from the drive. The drive supports the standard Modbus exception codes listed in the following table.

Code	Name	Description
01	Illegal Function	Unsupported command
02	Illegal Data Address	Address does not exist or is read/write protected.
03	Illegal Data Value	Incorrect value for the drive: • Value is outside minimum or maximum limits. • Parameter is read-only. • Message is too long. • Parameter write is not allowed when start is active. • Parameter write is not allowed when factory macro is selected.

The table below and the state diagram on page *306* describe the Control word content for the ABB drives profile. The upper case boldface text refers to the states shown in the diagram.

ABB drives profile Control word, parameter *5319 EFB PAR 19*			
Bit	**Name**	**Value**	**Comments**
0	OFF1 CONTROL	1	Enter **READY TO OPERATE.**
		0	Stop along currently active deceleration ramp (*2203*/*2206*). Enter OFF1 ACTIVE; proceed to READY TO SWITCH ON unless other interlocks (OFF2, OFF3) are active.
1	OFF2 CONTROL	1	Continue operation (OFF2 inactive).
		0	Emergency OFF, drive coast to stop. Enter **OFF2 ACTIVE**; proceed to **SWITCH-ON INHIBITED**.
2	OFF3 CONTROL	1	Continue operation (OFF3 inactive).
		0	Emergency stop, drive stops within time defined by par. *2208*. Enter **OFF3 ACTIVE**; proceed to **SWITCH-ON INHIBITED**. **WARNING:** Ensure motor and driven machine can be stopped using this stop mode.
3	INHIBIT OPERATION	1	Enter **OPERATION ENABLED**. (**Note:** The Run enable signal must be active; see parameter *1601*. If par. *1601* is set to *COMM*, this bit also activates the Run enable signal.)
		0	Inhibit operation. Enter **OPERATION INHIBITED**.
4	**Note:** Bit 4 is supported only by *ABB DRV FULL* profile.		
	RAMP_OUT_ ZERO (*ABB DRV FULL*)	1	Enter **RAMP FUNCTION GENERATOR: OUTPUT ENABLED**.
		0	Force Ramp function generator output to zero. Drive ramps to stop (current and DC voltage limits in force).
5	RAMP_HOLD	1	Enable ramp function. Enter **RAMP FUNCTION GENERATOR: ACCELERATOR ENABLED**.
		0	Halt ramping (Ramp function generator output held).
6	RAMP_IN_ ZERO	1	Normal operation. Enter **OPERATING**.
		0	Force Ramp function generator input to zero.
7	RESET	0=>1	Fault reset if an active fault exists. Enter **SWITCH-ON INHIBITED**. Effective if par. *1604* is set to *COMM*.
		0	Continue normal operation.
8…9	Not in use		
10	**Note:** Bit 10 is supported only by *ABB DRV FULL*.		
	REMOTE_CMD (*ABB DRV FULL*)	1	Fieldbus control enabled.
		0	Control word ≠ 0 or Reference ≠ 0: Retain last Control word and Reference. Control word = 0 and Reference = 0: Fieldbus control enabled. Reference and deceleration/acceleration ramp are locked.
11	EXT CTRL LOC	1	Select external control location EXT2. Effective if par. *1102* is set to *COMM*.
		0	Select external control location EXT1. Effective if par. *1102* is set to *COMM*.

Appendix C

Model 31 Mid

PERFORMANCE SPECIFICATIONS

Characteristic	Measure
Load ranges[6]	1000 g, 5 lb, 10 lb, 25 lb, 50 lb, 100 lb, 250 lb, 500 lb, 1000 lb
Linearity 1000 g to 250 lb	±0.15 % full scale
Linearity 500 lb to 1000 lb	±0.2 % full scale
Hysteresis 1000 g to 250 lb	±0.15 % full scale
Hysteresis 500 lb to 1000 lb	±0.2 % full scale
Non-repeatability 1000 g	±0.1 % full scale
Non-repeatability 5 lb to 1000 lb	±0.05 % full scale
Tolerance on output 1000 g	1.5 mV/V (nominal)
Tolerance on output 5 lb to 1000 lb	2 mV/V
Operation	Tension/compression [3]
Resolution	Infinite

ENVIRONMENTAL SPECIFICATIONS

Characteristic	Measure
Temperature, operating	-53 °C to 121 °C [-65 °F to 250 °F]
Temperature, compensated	15 °C to 71 °C [60 °F to 160 °F]
Storage temperature	-73 °C to 148 °C [-100 °F to 300 °F]
Temperature effect, zero	0.005 % full scale/°F
Temperature effect, span	0.005 % full scale/°F

ELECTRICAL SPECIFICATIONS

Characteristic	Measure
Strain gage type	Bonded foil
Excitation (calibration) 1 kg to 10 lb	5 Vdc
Excitation (calibration) 25 lb to 1000 lb	10 Vdc
Insulation resistance	5000 Mohm @ 50 Vdc
Bridge resistance	350 ohm
Zero balance	1 % max.
Electrical termination (std)	Teflon cable (1524 mm [60 in])

MECHANICAL SPECIFICATIONS

Characteristic	Measure
Maximum allowable load	150 % FS[1]
Weight	See table
Material	17-4 PH stainless steel
Deflection full scale	See table
Natural frequency	See table

RANGE CODES

Range codes	Range
AR	1000 g
AT	5 lb
AV	10 lb
BL	25 lb
BN	50 lb
BR	100 lb
CN	250 lb
CR	500 lb
CV	1000 lb

WIRING CODES

Cable	Unamplified
Red	(+) excitation
Black	(-) excitation
Green	(-) output
White	(+) output

DEFLECTIONS AND RINGING FREQUENCIES

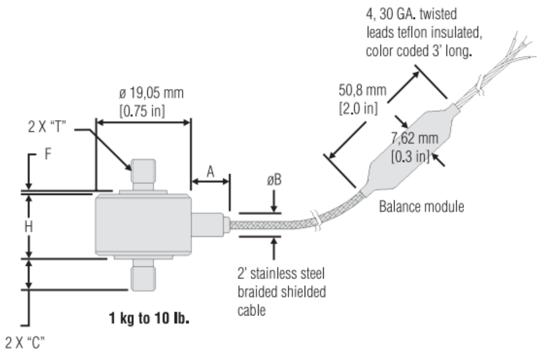
Capacity (lb)	Deflection at full scale (in)	Ringing frequency (Hz)	Weight (g)
1000 g to 10 lb	0,03 mm [0.001 in]	3000 Hz	21 g
25 lb to 100 lb	0,03 mm [0.001 in]	10000 Hz	63 g
250 lb to 1000 lb	0,04 mm [0.0015 in]	12000 Hz	80 g

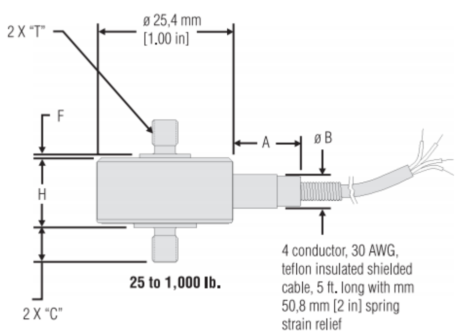
Honeywell

Mid Range Precision Miniature Load Cell

MOUNTING DIMENSIONS

Ranges (lb)	T	H	C	F	A	B
1000 g, 5 lb, 10 lb	#6-32 UNC	11,43 mm [0.45 in]	6,35 mm [0.25 in]	1,27 mm [0.05 in]	7,87 mm [0.31 in]	4,83 mm [0.19 in]
25 lb, 50 lb, 100 lb	#10-32 UNF	13,21 mm [0.52 in]	6,35 mm [0.25 in]	0,76 mm [0.03 in]	12,7 mm [0.50 in]	6,35 mm [0.25 in]
250 lb, 500 lb, 1000 lb	1/4-28 UNF	13,21 mm [0.52 in]	9,65 mm [0.38 in]	0,76 mm [0.03 in]	12,7 mm [0.50 in]	6,35 mm [0.25 in]





OPTION CODES

	Many range/option combinations are available in our quick-ship and fast-track manufacture programs. Please see http://sensing.honeywell.com/TMsensor-ship for updated listings.
Load range	1000 g, 5 lb, 10 lb, 25 lb, 50 lb, 100 lb, 250 lb, 500 lb, 1000 lb
Temperature compensation	1a. 60 °F to 160 °F 1b. 30 °F to 130 °F 1c. 0 °F to 185 °F 1d. -20 °F to 130 °F 1e. -20 °F to 200 °F 1f. 70 °F to 250 °F 1g. 70 °F to 325 °F 1h. 70 °F to 400 °F 1i. -65 °F to 250 °F 1j. 0 °C to 50 °C 1k. -20 °C to 85 °C 1m. -25 ° to 110 °C
Internal amplifiers	2u. Unamplified, mV/V output
Overload stops	4a. Overload stops
Electrical termination	6a. Bendix PTIH-10-6P - 6 pin (max. 250 °F)[5] 6d. Microtec DR-4S-4H 4 pin 6e. Integral cable: Teflon 6f. Integral cable: PVC 6h. Integral cable: Silicone 6i. Integral underwater cable (max. 180 °F) 6v. Phoenix connector on end of cable 15d. Connector on end of cable
Special calibration	9a. 10 point (5 up/5 down) 20 % increments @ 20 °C 9b. 20 point (10 up/10 down) 10 % increments @ 20 °C
Special calibration	30a. Compression only calibration, positive in compression 30b. Tension and compression calibration, positive in tension 30c. Compression only calibration, negative in compression
Shock and vibration	44a. Shock and vibration resistance
Interfaces[4]	53e. Signature calibration[7] 53t. TEDS IEEE 1451.4 module