Reformer Tube Internal Diameter Measuring System

A Thesis in the partial fulfilment of the requirements for the Degree of

Master of Engineering

In

Mechatronics

At Massey University, Turitea Campus
Palmerston North
New Zealand.

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2010

ABSTRACT

A Reformer Tube is a device used in chemical engineering, commonly in the fuel cell technology, used to perform chemical reactions to produce chemicals products. Commonly the process involves heating the introduced chemicals in the tube to ultra-high temperatures at pressures around 20 bars encouraging rapid reactions. Reformer tube construction is described within which both the desired endothermic catalysed chemical reaction and heat transfer from the reaction products to the incoming reactants are accomplished [10]. The service life of these devices is primary ended when Creeps Shear damage is detected. Due to the complex combination of multiple factors between temperature, stress and aggressive environment during service influencing the generation of Creep damage, it is of significant benefit for process companies using condition-based assessment rather than time-based estimation to judge the retirement of reformer tubes.

The aim of this research is to investigate a low-cost, mechatronic reformer tube inspection system that can replace the conventional expensive laser based system employed by New Zealand Methanex Ltd. The system must be a non-destructive examination (NDT) instrument capable of making a full inspection of a vertically standing, 110mm bore, 14m reformer tube within 5 minutes duration. Specification requirements set by the company state that the new system must be able to make measurement of at least 2 diametrical axes at axial increments of 25mm. The measurements are to be of 0.5mm accuracy or better. The nature of the tube stands to handle processing of Methanol stored at temperature of 500 degrees Celsius, gathering internal pressure of up to 20 bars. Due the cyclic repetition of these thermal and pressure changes, the tube will overtime result in internal cavity adaption causing tube failure through Creeping Shear. The device will be used to inspect the internal diameter change caused by creep damage and thus forecast the remaining service life of the tubes to help schedule the retirement of the reformer tubes at the most efficient timing.

The project commended with a research investigating the variety of reformer tube inspection techniques available for modern furnaces and reviewed the application methodologies and limitations. Based on the findings, the project proceeded to develop a low cost, mechanical reformer tube inspection system. The new system is branded Reformer Tube Internal Diameter Measuring (RTIDM) system. In the final part of this research, field testing was conducted at the Methanex Ltd furnace to examine the RTIDM systems performance. Analysis performed on the collected data from the field test revealed that the RTIDM system is a working system capable of making diametrical measurement at the precision of +/-0.1668mm.

Documented in this thesis is an in-depth discussion on the development of the Reformer Tube Internal Diameter Measuring (FTIDM) system. Conclusively, the RTIDM system developed in this research provided new method for reformer tube inspection. With the cost of the prototype is under $2000 NZD, the design is a much cost friendly instrument compared with its rival devices while capable of making diametrical inspection at competitive precision and accuracy.

ACKNOWLEDGEMENTS

I would like to express my appreciation and gratitude to my supervisor Dr Liquong Tang who has given valued guidance, suggestions and greatly appreciated enthusiasm throughout this research. I have been fortunate to have a supervisor who possess so great a knowledge of her subject areas, and who were always willing to spend the time to import that knowledge.

I would also like to extend my thanks to Mrs Trish O'Grady, Mrs Linda Lowe, Mr Colin Plaw and Mr Bruce Collins for their assistance in compiling this research. And also, much thanks to the technicians at the Massey University Institute of Technology and Engineering workshop for their help and support.

Finally, I would like to owe my deepest gratitude to my wife and parents for their unconditional love, support and encouragements. And importantly, would like to thanks the Massey University and TechNZ foundation for their continuing efforts in providing opportunities and experience for students such as myself.

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CHAPTER 1 INTRODUCTION

This project was conducted in partnership with Methanex New Zealand through the funds from postgraduate internships programme provided by TechNZ. Methanex is the world's largest supplier of methanol to major international markets and their product is used to make countless industrial and consumer products increasingly in the energy sector.

Methanex's proposition to this project lies in the company's very interest to develop a new system which will be placed in their routine inspection of the Reformer Tubes in the Methanex Plant. The new system branded as Reformer Tube Internal Diameter Measuring (FTIDM) system, once completed, will be replacing their current system which has proven to be problematic due to its high production cost and being over engineered for the tasks required. This new low cost system will minimise their current down-time period of their furnace required during Reformer Tube inspection thus will benefit the company efficiently both financially and time wise.

A reformer is a high cost, critical equipment used in chemical engineering, commonly in the fuel cell technology, used to perform chemical reactions in production of chemical products. It is a rectangular insulated structure containing vertical supported tubes commonly classified as Reformer Tube. The endothermic heat of reaction is supplied from downward firing burners situated in the roof of the Reformer. These are fired on a mixture of combined process waste gas streams supplemented with natural gas [19]. Commonly the process involves heating the introduced chemicals in the reformer tube to ultra-high temperatures at pressures around 20 bars encouraging rapid reactions. Reformer tube construction is described within which both the desired endothermic catalysed chemical reaction and heat transfer from the reaction products to the incoming reactants are accomplished [10]. The service life of these devices is primary ended when Creeps Shear damage is detected. Due to the complex combination of multiple factors between temperature, stress and aggressive environment during service influencing the generation of Creep damage, it is of significant benefit for process companies using condition-based assessment rather than time-based estimation to judge the retirement of reformer tubes. To reduce the occurrences of furnace tube removal for condition-based assessment and to improve overall reliability of tube life, the use of conventional non-destructive examination (NDE) techniques on a regular basis during reformer furnace turnarounds is thought to be beneficial [7]. It is not rare to see company performing destruct testing methods on small number of reformer tube removed from the furnace to try estimating the absolute life remaining. But it is a fact that results collected from sample testing on small number of specimen are not statistically valid. To this it is preferable that all the tubes are tested with a NED technique to characterise their relative condition in order to make sense of the absolute condition assessment provided by the destructive testing [6].

Of the many inspection method available, the most commonly used technique is the detection of internal creep damage based on diametrical growth. The principle rationale behind this technique is that, as creep damage occurs, the tube bulges [7]. Although recent studies reported that there are reformer tubes apparent to significant diametrical growth with absence of internal damage, this technique gives an early detection of creep damage and can be used to indicate the need for performing further tube inspection.

The aim of this research is to investigate a low-cost, mechatronic reformer inspection system that can replace the conventional laser based system. The system to be developed must be a NDT instrument capable of making a full inspection of a vertically standing, 110mm bore, 14m reformer tube within 5 minutes duration. Specification requirements set by the company state that the new system must be able to make measurement of at least 2 diametrical axes at axial increments of 25mm. The measurements are to be of 0.5mm accuracy or better. The nature of the tube stands to handle processing of Methanol stored at temperature of 500 degrees Celsius, gathering internal pressure of up to 20 bars. Due the cyclic repetition of these thermal and pressure changes, the tube will overtime result in internal cavity adaption causing tube failure through Creeping Shear. The new system will be used to inspect the internal diameter caused by creep damage and thus forecast the remaining service life of the tubes to help schedule the retirement of reformers at the most efficient timing.

The project commended with a research investigating the variety of reformer tube inspection method available for modern furnaces. The research revealed that only two techniques are popularly used in reformer tube inspection, Laser based and photo based tube profiling commonly referred to as Profilometry. The research concluded that methodologies employed in both systems are over engineered for some applications, resulting in unnecessary inspection precision and expense. Based on these finding, the Reformer Tube Internal Diameter Measuring (RTIDM) system was developed. Presented in the following chapters of this thesis focuses on outlining the methodology, mechanical construction and design consideration taken in the development of the RTIDM. To conclude the research, a prototype of the system was made and the field experiment was performed to examine the performance of the design. The result was used to make the final review and recommendation for future development.

The structure of this thesis closely follows the research conducted. Chapter two contains the literature review. The review investigated the technology and methodology behind the reformer tube and the inspection methodologies available. A more detail study on the Laser Profilometry and the Photo Profilometry inspection method were carried out as these two are the most popular technologies used for reformer tube inspection. Based-on the literature study a mechatronic Reformer Tube Internal Diameter Measuring (RTIDM) system was designed. The development work is presented in Chapter Three. From Chapter Four to Chapter Eight, the design consideration, principles and mechanical/software structure of the final RTIDM system is discussed in detail with some experiment analysis performed during development. Outlined in Chapter nine is the fielding test along with the result analysis and review. Finally, Chapter Ten contains an evaluation of the RTIDM system, and the conclusions that have been drawn based on the findings from this research. Further, future development and recommendation of the system is discussed in the last section of chapter ten.

CHAPTER 2 LITERATURE REVIEW

A Reformer Tube is a device commonly used in chemical process industry to perform controlled chemical reactions to produce selective chemicals. In the case of Methanex Ltd, the chemical product is methanol. The process commonly involves heating of chemicals in the reformer to ultra-high temperatures with the presence of catalyst at pressures around 20 bars encouraging rapid reactions as in the chemical reaction shown in Equation 2.1.

$$CH_3OH_{(g)} + H_2O_{(g)} \rightarrow CO_2 + 3H_2 \qquad \Delta H^0_{R\ 298} = 49.2kJ/moll$$

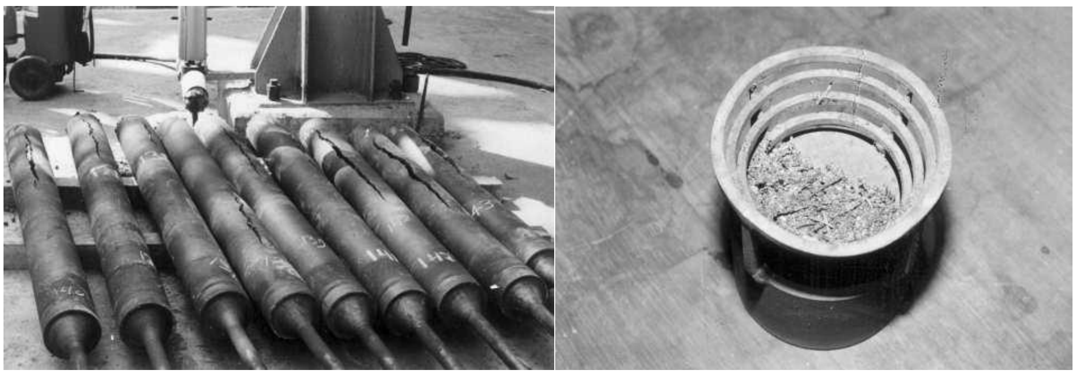
Equation 2.1

The heating is taken place usually in a gas burner furnace. The furnace is a large refractory lined box with gas burners heating multiple vertically supported reformer tubes as shown in Figure 2.1. In a large reformer cell a few hundred reformer tubes are installed with continuous production of chemical quantity up to several tons per hour [11].

Figure 2.1 Reformer Cell at Methanex Ltd

2.1 Reformer Tube Inspection

One of the major concerns in the operation and maintenance of a primary reformer is being able to monitor and predict the behaviour of the reformer tubes. To this it is of great benefit to be able to determine the condition of the reformers. Common causes of failure of these devices are from Creep Shear arising as a consequence of high operating temperature and pressure stresses which primarily dictates the service life of reformer tubes. In the past, the scheduling for reformer tube retirement has been based on the time-based criteria of the reformer tube design life, which is about 100,000 service hour. But in actual fact, the service life can vary largely between individual reformers as factors like rapid rate of temperature changes during start-up/shut-down through cyclic condition all has influences to the material deterioration degree. To this, it is desirable to change the maintenance philosophy for tube retirement from time-based assessment to condition-based assessment. At a cost of several thousands of dollars per reformer tube, with equal cost in the replacing process, a significant amount of the capital can be inadvertently applied if tubes are retired either too early or too late.



(a) Nine retired Reformer tube due to longitudinal shear on the retaining ring ***(b) Broken pieces of Catalyst***

Figure 2.2 Retired Reformer Tubes

In 2002, an article was published in the Science Direct magazine stating that an research was performed by National Metallurgical Laboratory group on the failure mechanism and life evaluation of a Reformer Tube. The project investigated the devices through tensile, hardness, dimensional, microscopy and acceleration test and revealed that longitudinal cracks found in the tubes were caused by overheating due to inadequate feed flow caused by choking of damaged catalysts [1]. The overheated material resulted in significant reduction in tensile strength, hardness and creep rupture strength, and thus ruling out serviceability to regain the reformer tube condition. The project concluded that avoidance of such choking incident can be achieved through precautions taken that there is no material remains left in the reformer tube after the shutdown period of the reformer tube. With respect to these finding, this project will consider the importance of securing the device parts so that no external materials is left behind in the tube during the tube inspection process. This will require that the system implements a stability feature to stabilize the apparatus while travelling within the tube to minimise unpredicted contact between the device and the internal wall.

There have been number of approaches and methods taken to assess the condition of reformer tube but the most effective and common technique used is based on the diametrical variation of the tubes. The principle behind this technique is that as creep damage occur the tube bulges resulting in a tube diameter change. Therefore, by measuring diametric growth in the tube, an estimation of the tube condition can be made. For reformer tubes made from different materials, the nominal value of diameter changes, where creep is considered to have occurred, is different For example, reformer tubes made from HK-40 and HP-40, the corresponding nominal values are:

HK-40 = 2.3% HP-40 = 5.7%

It should be noted that past findings shows that creep damage assessment by the diametrical growth measurement alone is not reliable enough to make conclusion. In some cases, significant growth maybe apparent to tube while shows absence of internal damage. The diametrical growth may provide a very general indication of the tube condition but alone may lead to a significant false call on the actual condition of the tube. To this, this method should be used as a primary process taken to indicate the need for performing further testing. Below is a list of inspection techniques that are used in industry to infer the condition of Reformer Tube [4]:

· Wall Thickness Measurement (apparent decrease in wall thickness with creep)

· Replication (final stages of creep damage; i.e., macro-cracking)

· Radiography (final stages of creep damage; i.e., macro-cracking)

· Eddy Current (responds to chromium migration due to overheating and conductivity changes)

· Ultrasonic (responds to attenuation and scattering)

These techniques are only able to identify creep damage after it had reached the point of micro cracking and macro cracking. Many process plants consider these last two stages illustrated with red colour in Figure 2.3 as the retirement point of a reformer tube [5].

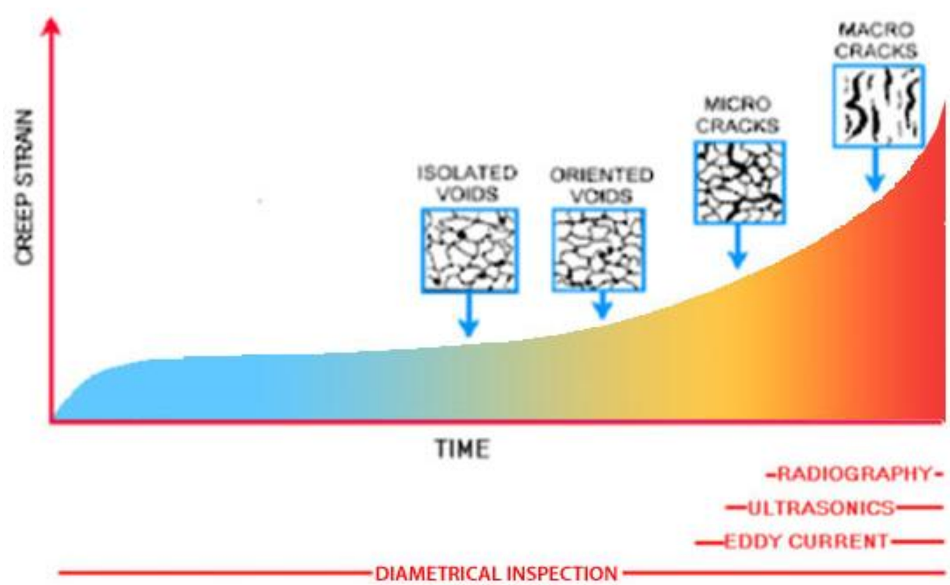


Figure 2.3 Creep Strain vs Time [5]

The diametrical inspection is commonly performed through reformer tube sectional profilometry analysis. There are two forms of profilometry inspection methods commonly found in modern industry are image processing and laser based.

2.2 Laser Profilometry

The most recent technique developed in inspecting internal or external tube diameter growth is the laser mapping method referred as 'laser profilometry'. The laser mapping probe is able to transmit several thousand diameter readings of the entire tube with the accuracy of +/- 0.05mm, allowing this method to gain acceptance as a viable inspection method for early detection of creep [2]. Laser based profilometry can be categorised as being one of the most common non-destructive testing method found in many high-tech instruments such as the Laser Optic Tube Inspection System (LOTIS) manufactured by QUEST Integrity Group. LOTIS technology utilizes laser profilometry to inspect the internal surface of reformer tubes. The data captured by LOTIS is exceptionally powerful when combined with the LifeQuest™ remaining life assessment capabilities, providing an integrated solution set for the process and syngas industries. LOTIS is internationally recognized by the NDT industry and the American Society of Non-destructive Testing (ASNT) as a time-proven NDT method. [12]

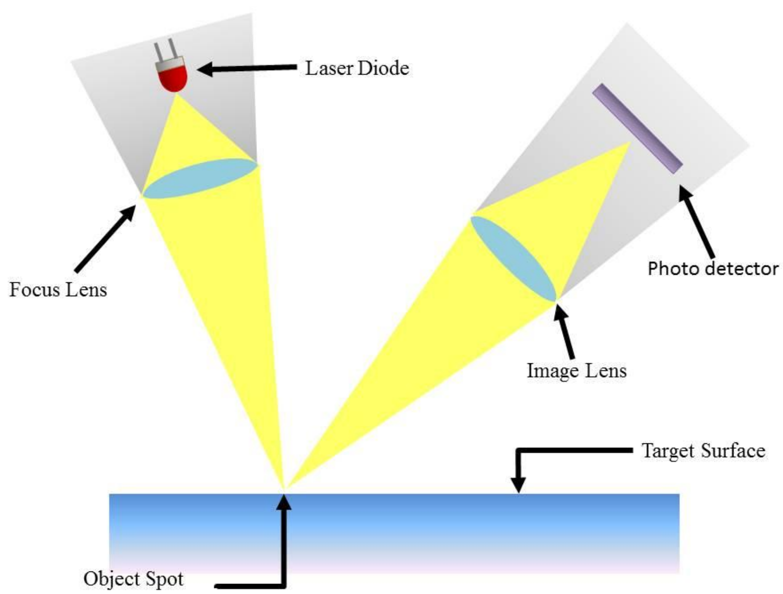


Figure 2.4 Illustration of Laser Profilometry mechanisms

LOTIS laser probe contains a rotating head, spinning at 1800rpm, acquiring 360 readings per revolution along the internal surface of a tube and has a helical path as small as 0.01inches.

Reformer Tube internal diameter available for inspection range between 0.43 inches to 6.0nches with varying probe size. The basic principle behind the laser Profilometry utilized device is the optical triangulation. It makes use of a light source, imaging optics and a photo detector to measure the target surface height by observing the shift in the reflection spot of light due to the parallax. The LOTIS is known to provide highly accurate and repeatable result, collecting over million data points during typical inspection. But in most circumstances, the instrument is thought to be over engineered, making too much needless measurements for standard furnace maintenance resulting in unnecessary expense.

2.3 Photo Profilometry

In-situ inspection is another form of non-destructive inspection method offering an acceptable, low cost alternative to the laser Profilometry systems. This method is currently being employed by Methanex. The method uses photo detector to visually inspect the reflected light beam from the tube internal wall emitted from a laser diode. With the use of focusing lens the laser diode emitted light is focused onto appoint of the interior of the tube. The focus lens along with the laser diode is rotated to form a ring. With the distance between the photo detector and the diode fixed the diode, photo detector and the surface of the tube forms a triangle. This results in the reflected spot to move on the surface of the photo detector in proportion to the distance to the internal surface of the tube [6]. With the means of signal processing the collected information, substantially ring shaped image, can be reconstructed into a three-dimensional image of the tube internal geometry.

With present technology a 15m tube can be inspected within three minutes providing over 1 million radius readings with this method. The raw image data output is pre-processed with the host PC computing the actual radius values and converts the output to engineering units such as inches or millimetres. Data is sent from the probe to the host PC via a high-speed interface; suitable methods include serial interfaces such as RS232, RS485, USB, or IEEE-1394.

One disadvantage of this method is that the system is vulnerable to unsanitary environment. In reliant to photo detectors and light beams, when subjected to scratches or dust/dirt, the reflection path for light can be interfered or blocked. These light leakage paths cause false readings and result in errors in the radius measurements.

Another disadvantage is in the system processing rate. A typical optic sensor output imagery data built of 512x512 arrays which is equivalent to 272,144 elements or pixels. With the system making 120Hz frame rate the system is not able make fast enough processing rate to allow for real-time data acquisition.

2.5 Literature Review Conclusions

Laser and Photo Profilometry inspection systems are both an accurate method in inspecting the reformer tube for internal creeps. It is clear that there is a relationship between price and accuracy. The current reformer tube inspection instruments, claimed from Methanex Ltd, are over engineered for some applications resulting in unnecessary cost. As mentioned previously, standard figure of 2%-3% increase in tube diameter must be detected to indicate a potential sign of creep damage. In a typical 110mm reformer tube, accuracy of +/-0.05mm found in the Laser Profilometry may be more than enough resolution to detect 2.2mm increase (2%) of the diametrical measurement. Therefore, the Laser Profilometry system is over engineered for the purpose of some applications. Diametrical measurements taken from the outer walls of the tube require adequate inspection conditions as the inside reformer cells cannot be seen. Hence internal inspection seems to be preferred. Also with high data processing required in many inspection instruments, there appears that real-time data acquisition is not yet a common feature. The chemical engineering industry would benefit from a cheap, automated system with real-time data acquisition. Mechanical system are known for its durability with little effect from operating environments therefore it is plausible to design a non-destructive Reformer Inspection system based on mechanical means.

CHAPTER 3 RTIDM SYSTEM DESIGN PROPOSAL

As mentioned in Chapter 1, the aim of this research is to develop a measuring instrument capable of profiling the internal geometry of a 110mm Reformer Tube. As the minimum requirement, the device must analysis at least two geometrical features of the reformer tube of depth and two different diametrical measurements. Finally the system must be capable of recording the measurement data so that it can be used to plot a Diameter vs. Depth line graph such that the percentage of diametrical expansion can be analysed.

Based on the literature study, this research developed a mechatronic reformer tube measuring instrument that uses mechanical means to measure the internal diameter of reformer tube ranging from 100mm to 125mm. This chapter will focus on the prototype design that leads to the initiation of this research. The basic construction and layout of the system is discussed along with the methodology of the automatic reformer analysis.

3.1 RTIDM system layout

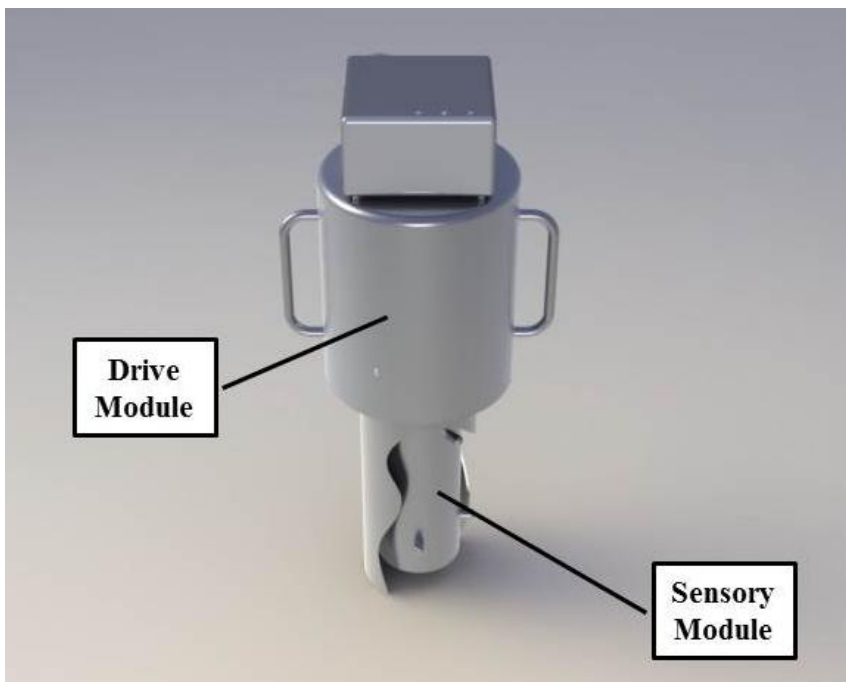


Figure 3.1 Prototype Design – Partial section view

Figure 3.1 is a 3-D illustration of the proposed *Reformer Tube Internal Diameter Measuring* (RTIDM) system created on a 3D mechanical *computer-aided design* (CAD) package called Solidworks. RTIDM is a portable instrument. The prototype is made mainly of aluminium with some steel parts. The overall dimension of the design is within 50cm height x 30cm diameter. Large portions of the components constructed out of Aluminium resulting in a net weight of less than 10kg. It is intended to be operable by single operator through a Control Software on the host computer (Figure 3.1.2). The hardware is a two part instrument made up of two modules; Sensory Module and Drive Module. Sensory module is design to travel through the reformer tube making diametrical measurements while the Drive Module rests on top of the reformer tube, driving the Sensory Module via a steel wire. A wireless radio communication is established between the Sensory and Drive modules where diametrical and depth data is fed back to the control software on the host computer enabling a *real-time* data acquisition. The collected data is ultimately stored onto the computer as an excel file used to generated a Diameter vs Depth graphical analysis.

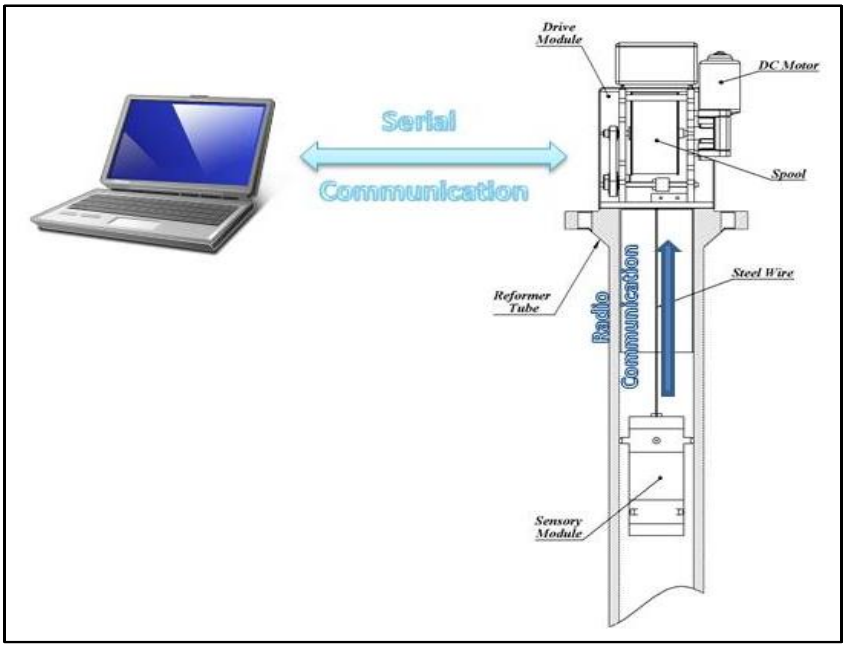


Figure 3.2 Simple RTIDM Diagram

3.2 Drive Module

The Drive Module is designed to control and monitor the depth location of the Sensory Module. It is design to rest on top of the reformer tube with the Sensory Enclosure, along with the Sensory Module, fitted inside the top opening of the reformer tubes as illustrated in Figure 3.3. A simple reel design is used to lower/raise the Sensory Module with a geared DC motor driving the aluminium spool winding the steel wire. *Motor control* signals are generated by the Control Software to drive the motor via *motor driver* hardware, allowing for software motor control. The angular movement of the spool is monitored using a rotary encoder to approximate the length of the wire between the two modules, estimating the axial location of the Sensory Module. The driver module is fitted with a radio receiver to retrieve diametrical data from the sensory module. A microcontroller chip is used to pre-process the sensory measurements along with its associating depth measurement before it is transmitted to the computer.

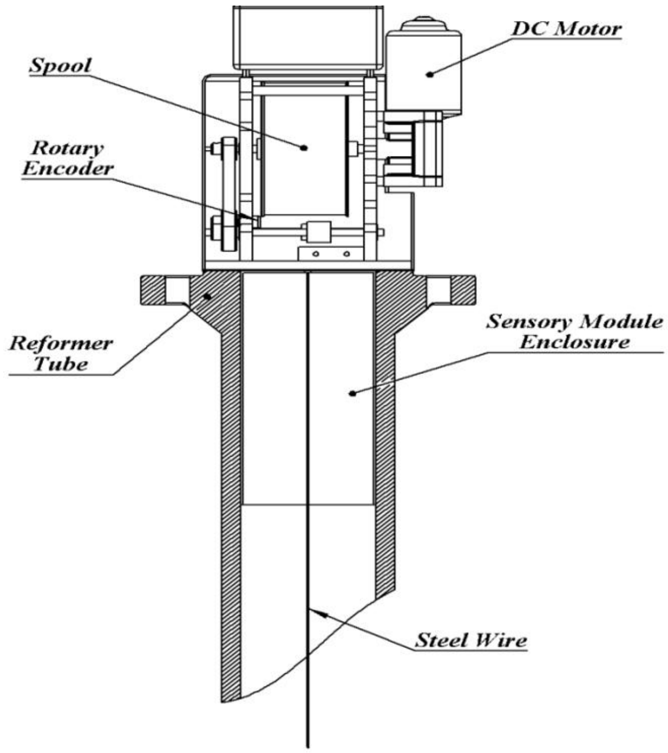


Figure 3.3 Drive Module & Reformer Tube

3.3 Sensory Module

The Sensory Module is a cylindrical system with overall geometrical dimensions of approximately 100mm in height and 60mm in diameter. It is designed to travel through a reformer tube while making internal diametrical measurements through mechanical means. When the system is not in use the module is stationed inside the Sensory Enclosure of the Driver Module. Within the sensory module, there is a radio transmitter module. This transmitter module is integrated with a microcontroller and is used to transmit the collected data to the *Drive Module* through wireless communication.

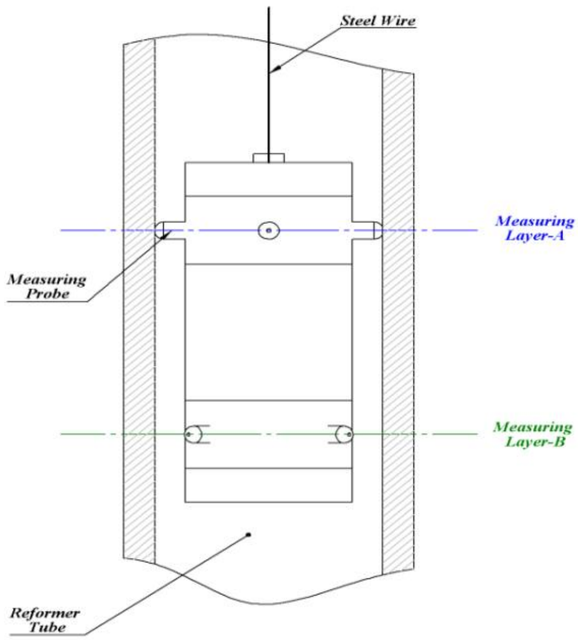


Figure 3.4 Sensory Module – CAD Model

In geometry a diameter of a circle is any straight line that passes through the centre of the circle with the two end points of the line lying on the circle circumference. In more modern usage, diameter can also refer to the length of a diameter. When characterizing a circle only one diameter is needed to be determined as the diameter is constant with a perfect circle. When profiling a deformed reformer tubes it is important to note that the cross section profile never traces a perfect circle. With small variation in the wall thickness and different processing temperature the reformer tube will deform in an uneven manner, resulting in a random sectional profiles as illustrated in Figure 3.5.

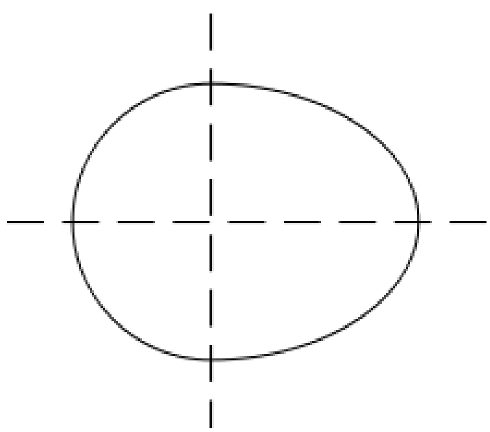


Figure 3.5 An illustration of a possible deformed reformer tube cross-section profile

In such type of deformation, unlike circle where all diameters are equal, the diameter is different between each angle or in more extreme deformation there may not be a so called diameter. In such cases at least two diameters measurement of different axis must be known to make sectional profile estimation. But obviously with more known diameter of different axis the better estimate can be made.

With this understanding the sensory module is designed to make four diametrical measurements at two measuring layers**;** *Measuring Layer A & B* (illustrated in Figure 3.4 in blue and green dotted lines). The measurement is performed using a mechanical *linear-to-angular transducer* and a Rotary Encoder. The design of the *linear-to-angular transducer* is based on the outcome of a research titled “Reformer Tube Internal Diameter Measuring Device” [4] performed prior to this project.

CHAPTER 4 INTERNAL DIAMETER MEASURING UNIT

This chapter will centre on the design and mechanics of the Internal Diameter Measuring Unit (IDMU) developed from the prototype design discussed in the previous chapter. The main discussion will focus on the mechanical construction, design considerations and the mathematics implemented into the system. And finally will analyse the result collected from *accuracy* and *precision* experiment performed to evaluate the validity of the design.

4.1 Mechanical Design

Internal Diameter Measuring Unit (IDMU) developed for this research utilizes mechanical means to measure the internal diameter of the reformer tube. As illustrated in Figure 4.1, IDMU is a cylindrical device measuring 50mm in height and 76mm in diameter, made of aluminium and steel parts weighing just over 300g. Four symmetrically moving stainless steel probes extend out the side of the body allowing the device to make two diametrical measurements simultaneously while making minimal contact with the tube internal wall.

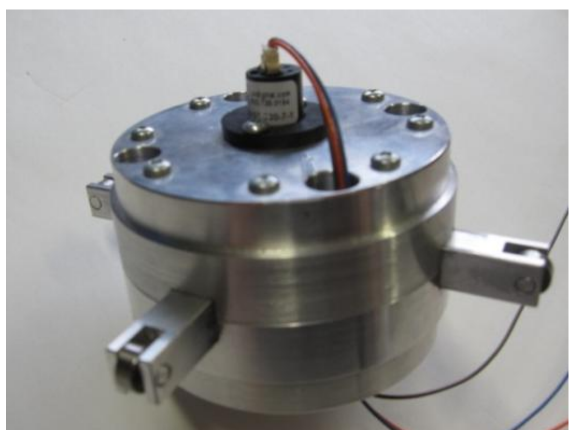


Figure 4.1 Internal Diameter Measuring Unit

Two Digital Absolute Encoders are used to generate analogue voltage signals that are proportional to the linear movement of the stainless steel probes. IDMU is essentially an assembly of two *Linear-to-Angular Transducers* unit each making diametrical measurements independent to one another (As shown in Figure 4.2). The two transducers are positioned 90-degree apart and are fixed together with M3 size machine screws.

Figure 4.2 IDMU Assembly

4.1.1 Linear-to-Rotary Transducer

The basic principle adopted in the Linear-to-Rotary Transducer is illustrated in Figure 4.3. The design composes of three key components; Encoder Disc and two Encoder Shafts. The main parts of the Linear-to-Rotary Transducer are list in Table 4.1.

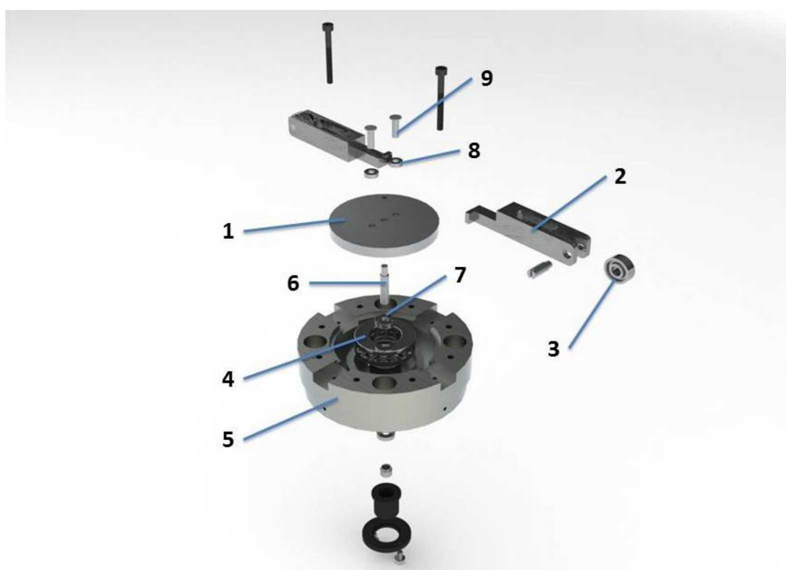


Figure 4.3 Linear-to-Rotary Transducer assemblies

1	Encoder Disc	6	Rotary Encoder Shaft
2	Encoder Shaft	7	4-9-2.5 Bearing
3	Probe Bearing	8	3-6-3 Bearing
4	15-28-9 Thrust Bearing	9	Bearing Pin
5	Body		

Table 4.1 Linear-to-Angular Transducer Parts List

The *Encoder Disc* (ED) is a 5mm thick disc located in the centre of the liner-to-angular transducer. The ED is loaded with a continuous angular force generated by a mechanical tension spring connected between the ED and the aluminium body. Two 4mm mechanical bearing is mounted on to the top face of the ED, via Bearing Shaft-A, making contacted with the flat face of the *Encoder Shafts* (ES). The two *Encoder Shafts* (ES) of equal length *L* is aligned along the diametrical axis making contact with the internal walls of the Reformer Tube.

Different mechanical bearings are considered into the design. Every moving component has been braced with precision machine bearing. To counter the unbalanced loading on the ED generated by the mechanical spring, a thrust bearing is used. A 10mm machine bearing is mounted to the end of the Encoder Shafts significantly reducing the friction and contact surface area between the probe and the Reformer internal wall.

The torque on the ED is transferred through the Encoder Shaft (ES) as a linear outwards force; via the two contacting points between the Encoder Shaft and the ball bearing distant 7mm from the ED axis (marked by green line in Figure 4.4). With the change of the internal diameter, the spring will rotate the ED. As a result, the two ES is shifted symmetrically so that the shaft stays in contact with the internal wall of the reformer tube. Hence **the internal diameter of the Reformer Tube can be directly mapped to the angular displacement of the ED**. Equation 4.1 is a simple formula mapping angular displacement and the change of the internal diameter.

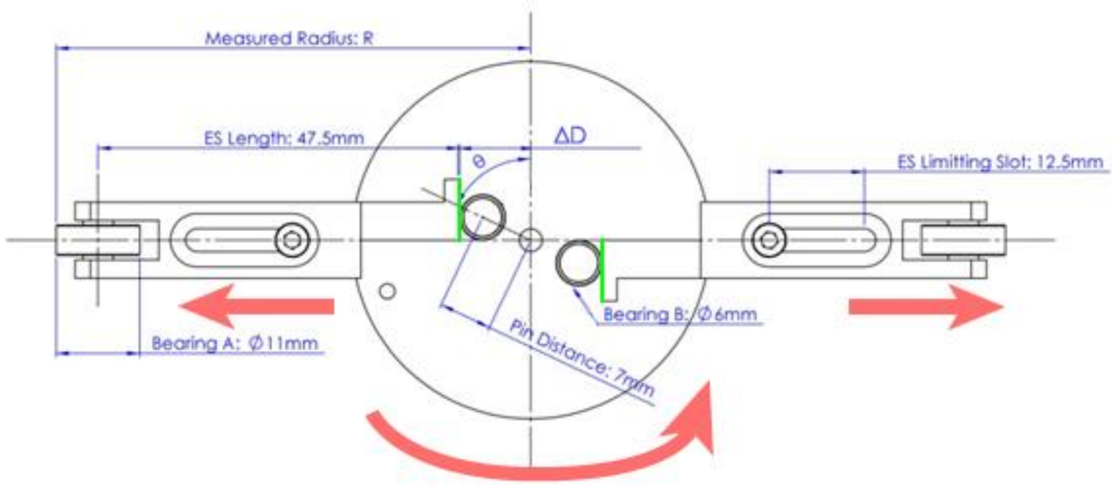


Figure 4.4 Mechanical Construction

R_1 = Bearing A Radius (mm)

R_p = Pin Distance from Axis (mm)

R_2 = Bearing B Radius (mm)

ΔD = ES distance from centre axis (mm)

ES = Encoder Shaft Length (mm)

D = Reformer Tube Diameter (mm)

θ = Encoder Disc Angle (degree)

$$D = 2 \times R$$

$$D = 2(L + \Delta D)$$

$$D = 2(R1 + ES + (R2 + R_P . \sin\theta))$$

$$= 2(5.5mm + 47.5mm + (3mm + 7mm \ \times \sin\theta))$$

Equation 4.1:

$$\boldsymbol{D = 112 + 14\sin\theta}$$

Following the equation deriving steps above, the diameter of the reformer tube (the maximum distance between the outer face between the two Bearing A) is a sum of twice the Measured Radius measurements on figure 4.4. Measured Radius (R) is a sum of the Encoder Shaft assembly and the distance between the centre axis and the contact point of the encoder shaft (ΔD). The distance ΔD is a variable value that can be determined using simple trigonometry substituting the angular displacement of the ED (θ). The assembly of the Encoder Shaft (ES) of Bearing A and Encoder Shaft components have a fixed dimension equivalent to the sum of measurements R_1 (radius of Bearing A) and ES (distance between the contact face of the Encoder Shaft and the centre axis of Bearing A). Finally, by substituting the known values into the third equation and simplifying the equation by summing the constants, equation 4.1 can be derived.

Observing this equation, one can quickly recognize the Sine relationship between the two elements of Encoder Disc angle ϑ and Reformer Tube diameter *D*. To this, the measurable diametrical range can be determined to be 98mm and 126mm by substituting -90° and 90° into the Equation 4.2.

Equation 4.2:

$$\boldsymbol{Dmax = 112 + 14\,sin(90}\,°)$$
$$= 126mm$$

$$Dmin = 112 + 14\sin(-90\,°)$$

$$= 98mm$$

IDMU Diameter Measuring Range: 98~126mm

Obviously, the assembly will mechanically lock together at Encoder Disc angle of both -90° and 90°. To this the movement of the encoder disc has been limited to -80° and 80° via limiting the length of the Encoder Shaft Slot length. The relationship between the diameter and the encoder disc angle is illustrated in Figure 4.5.

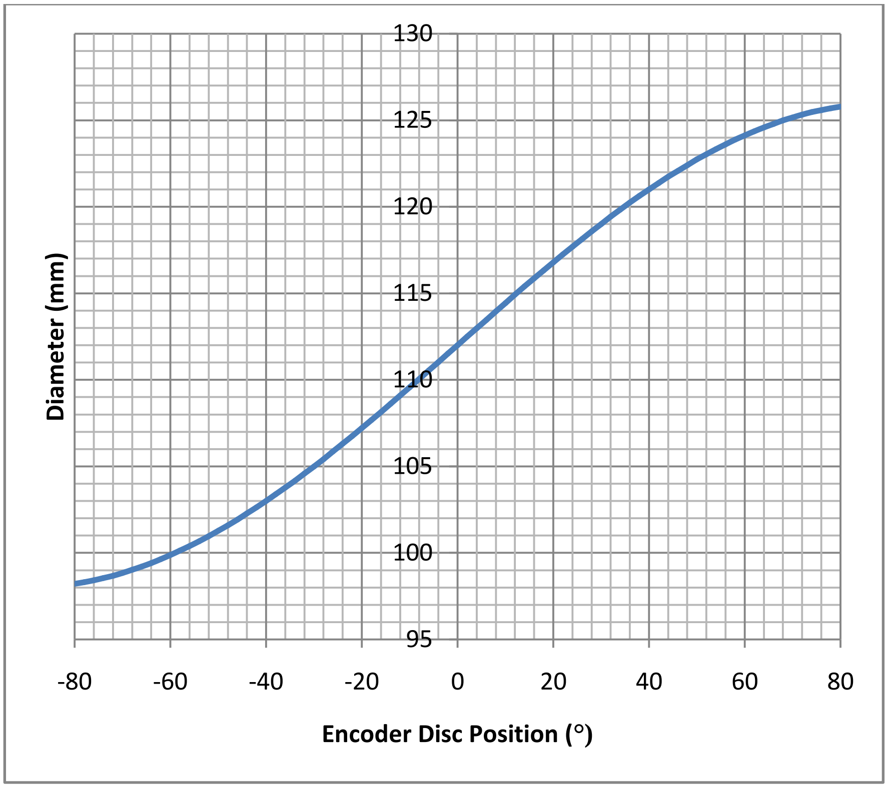


Figure 4.5 Diameter (mm) vs Encoder Position (°)

One of the key characteristics Linear-to-Angular Transducer design is the *Self-Centring* nature of the system. With the symmetric movement of the Encoder Shafts, the device is always pushed towards the centre of the reformer tube allowing for stable and accurate diametrical measurement.

4.1.2 Digital Absolute Rotary Encoder

The rotary encoder used in the IDMU is an electromagnet absolute rotary encoder developed by US Digital coded MAE3 (Magnetic Absolute Encoder Kit). US Digital is a design engineer company settled in Los Alamitos, CA. From the early 1980 the company has been manufacturing multiple off-the-shelf motion control components world-wide. “Our mission is to make our customers successful by inventing, manufacturing, and quickly delivering the most practical motion control components “[20]. Of their wide selections of motion encoders, the MAE3 is one of the most compact rotary encoder provided user friendly and practical functionality and competitive price.

MAE3 encoder is designed to be easily mounted to shaft and provide shaft rotary position information over 360° with no stops or gaps. The optional analogue output provides a 5 volts analogue signal that is proportional to the absolute shaft position in 10-bits precision at sampling rate of 2.6 kHz (illustrated in Figure 4.7). More specifications regarding this sensory can be found in the Datasheet provided in Appendix C of this thesis.

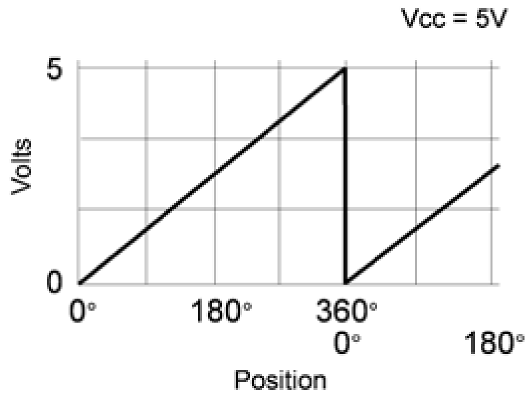
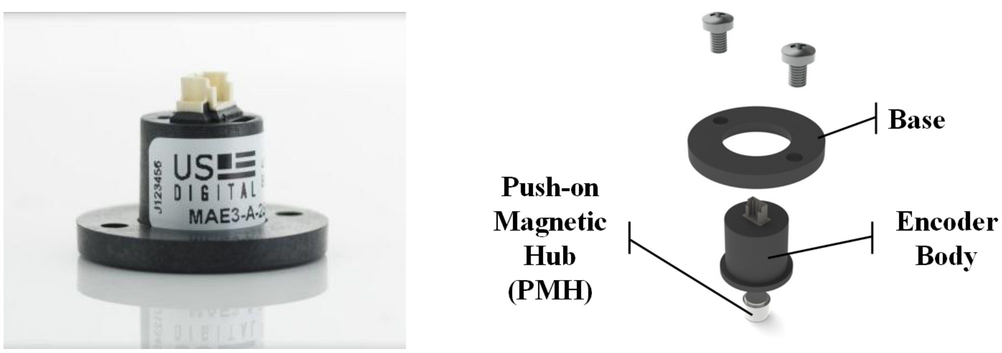


Figure 4.7 MAE3 Encoder Output graph (Voltage vs Angular Position)

The MAE3 kit consists of three components as shown in Figure 4.8: *base, **p**ush-on **m**agnet **h**ub* (PMH), and encoder body. The push-on, collet gripping hub is directly mounted to the 4mm **E**ncoder **D**isc **S**haft (EDS) of the IDMU. The Encoder Body is fitted over the top of the magnet hub with the base component holding down encoder body in place.



(a) **(b)**

Figure 4.8 MAE3 Sensory Assembly

As seen in Figure 4.7, the output voltage jumps between 0v to 5v when a full revolution is made. This kind of sudden change in voltage is a common cause of electric noise requiring more complex noise cancelling circuitry for effective processing, often resulting with larger circuitry boards. This type of sudden changes has to be avoided for the use of this project. For the ease of software interaction, during assembly the encoder body is aligned with the PMH so that the MAE3 roughly output 2.5v when the Encoder Disc is at centre (θ at 0° in Formula 4.1). By doing this, the system is able to work within single revolution phase without the sudden jumps as illustrated in Figure 4.9.

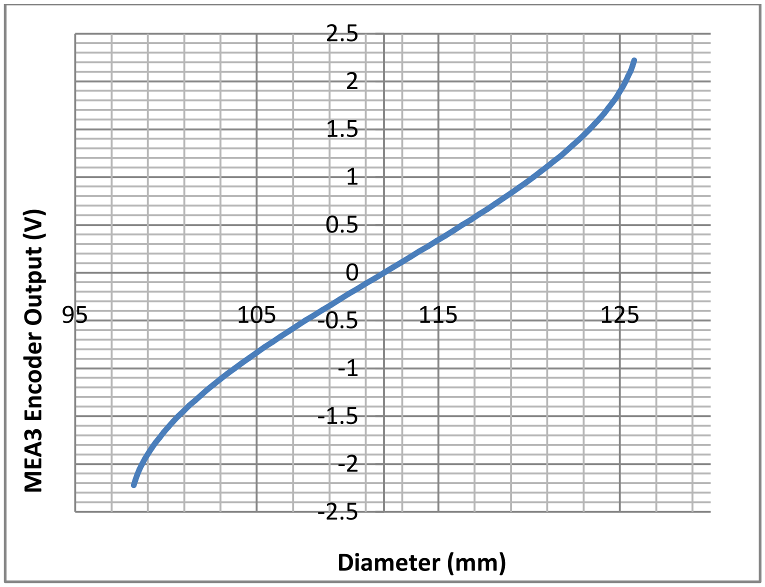


Figure 4.9 MAE3 Encoder Output (V) vs Diameter (mm)

4.2 Theoretical precision

When considering the precision and accuracy of a measuring instrument design, three aspects must be considered; manufacturing tolerance, sensory resolution and components clearance tolerance. In this chapter, the dimension and tolerance of the IDMU assembly along with the precision of the MEA3 rotary encoder is analysed. Based on the discussion, the theoretical precession of the system is formulated.

4.2.1 Tolerance Stack up

Tolerance is the limit of variation allowance of physical dimensions occurring during fabrication. As these variations occurring independently to each part, in an assembly with multiple interactions between features the tolerances are accumulated resulting in inaccuracy in the measuring instrument. There are four geometric characteristics that describe feature geometry and the interrelationship of parts features; size, orientation, form and location. And consequently, there are four types of tolerances that are possible for each feature; Size, form, orientation, and location tolerances. Every feature on a part, however, does not necessarily possess all four characteristics. The definition of tolerance can be described by the following two options.

Option 1: A Tolerance specifies how closely to the nominal (or exact) location, size, form, or orientation that a feature on a part must lie.

Option 2: A Tolerance specifies the range of acceptable deviation permitted in maintaining a specified dimension in machining a piece.

Discussed in Table 4.2 are the four types of geometric characteristics along with its associative feature tolerances.

Feature	Description
Size	Size can be considered as the magnitude of the straight-line distance between two points on one or two surfaces whose surface normal vectors are collinear and point in opposite directions.
Form	Form can be considered as the shape of a feature. Ever feature has form, regardless of whether it is nominally a flat plane, a cylinder, a width, a sphere, a cone etc.
Orientation	Orientation can be considered as the angle between features, or more precisely, orientation is the amount a feature may tilt relative to a datum reference frame.
Location	Location can be considered as where a feature lies relative to another feature, or more precisely, location is where a feature lies relative to a datum reference frame.

Table 4.2 Geometric characteristics [17]

In considering the mechanical tolerance, the fabrication method and design consideration must be first discussed. The intended fabrication processes affects the way a part should be designed [14]. The shop drawing used during fabrication of some key component of the IDMU can be found in the appendix D. Each component has been designed with simple features with minimum use of complex 3D geometry, allowing for quality fabrication through Milling and Turning. For hand-sized parts, turning and milling can be used to easily create feature sizes that are accurate to within 0.01mm, whereas accuracy to be within 0.001mm is considered difficult [14].

To eliminate some of the accumulation of tolerances the baseline dimension technique is used. Baseline dimensioning is a system of dimensioning in shop drawings where each feature is dimensioned from the same origin. As shown in Figure 4.10, the features on the Encoder Shaft have been dimensioned from the flat face making contact with the bearing. Although not shown in the figure, each dimension is tolerance to the same default tolerance of 0.01mm.

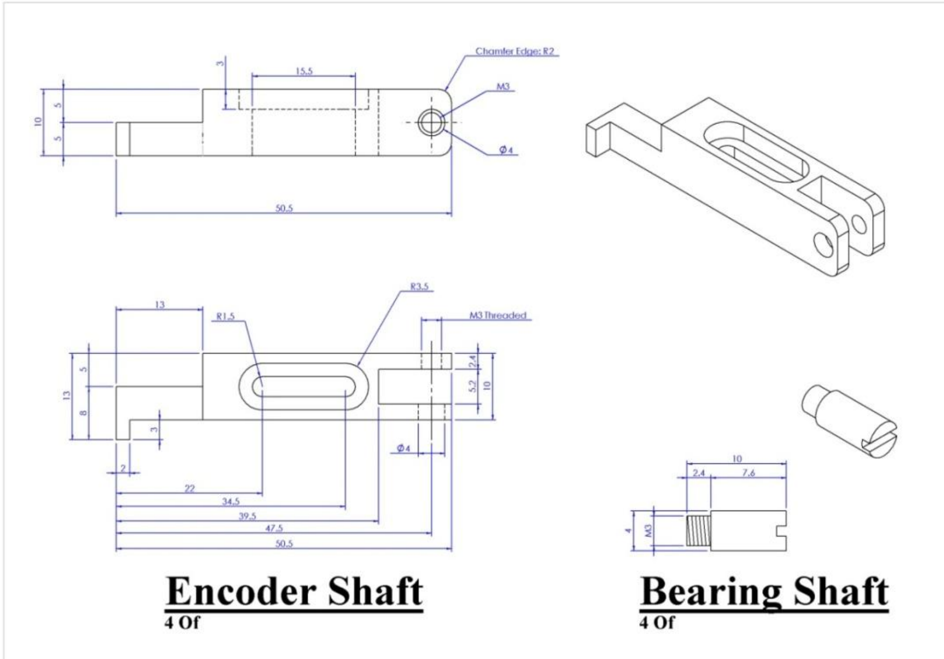


Figure 4.10 Encoder Shaft construction drawing

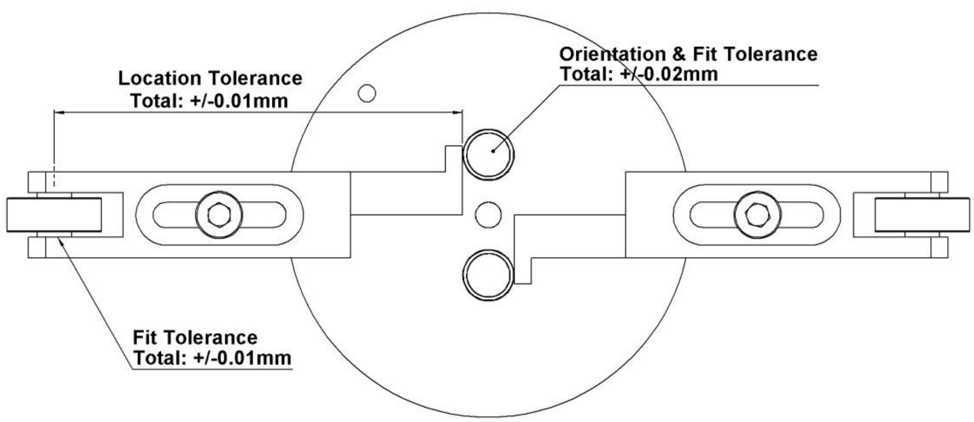


Figure 4.11 IDMU Tolerance distributions

Figure 4.11 is an elevation drawing of the IDMU assembly identifying the type of interaction and tolerance between each component. Assembly will be greatly affected by the outwards force generated from the mechanical spring and the equal and repelling force from the reformer wall, pushing the mechanicals bearings outwards against its associative pins. The pins will in turn be pulled outwards against the hole of the bearings. This will add assembly shift to the chain of Dimensions and Tolerances twice, for the holes in the encoder shaft and for the bearing fitted to the pin. Locational interference fit is used for every shaft-hole fit. Equation 4.3 formulates the theoretical tolerance in the IDMU (derived from Equation 4.1). The machine bearings manufactured by the SNK Roller Bearings Ltd used in the design are assumed to be of perfect geometry. As the equation states, the IDUM will experience constant +/-0.08mm to measurement deviation.

Equation 4.3:

$$= 2(5.5\text{mm} \mp 0.01 + 3\text{mm} \mp 0.02 + 47.5\text{mm} \mp 0.01 + 7\text{mm} \ \times \sin\theta)$$
$$\mathbf{Diameter = 112 \mp 0.08mm + 14sin\theta}$$

4.2.2 Sensory Precision

With the 10bit resolution, the MAE3 encoder is potentially capable of detecting angular variation of 0.035° (shown in Equation 4.4). By equating with the Equation 4.1, the sensory precision of the system can be determined to formulate the theoretical precision of the IDMU based on the encoder. Figure 4.12 is a plot illustrating the precision distribution across measuring range.

$$Encoder\ Resolution = \frac{360}{MAE3\ Resolution}$$

$$0.35° = \frac{360°}{2^{10}}$$

Equation 4.4:

$$\text{D iameter} = 112 \mp 0.08\text{mm} + 14\sin(\theta \mp 0.35°)$$

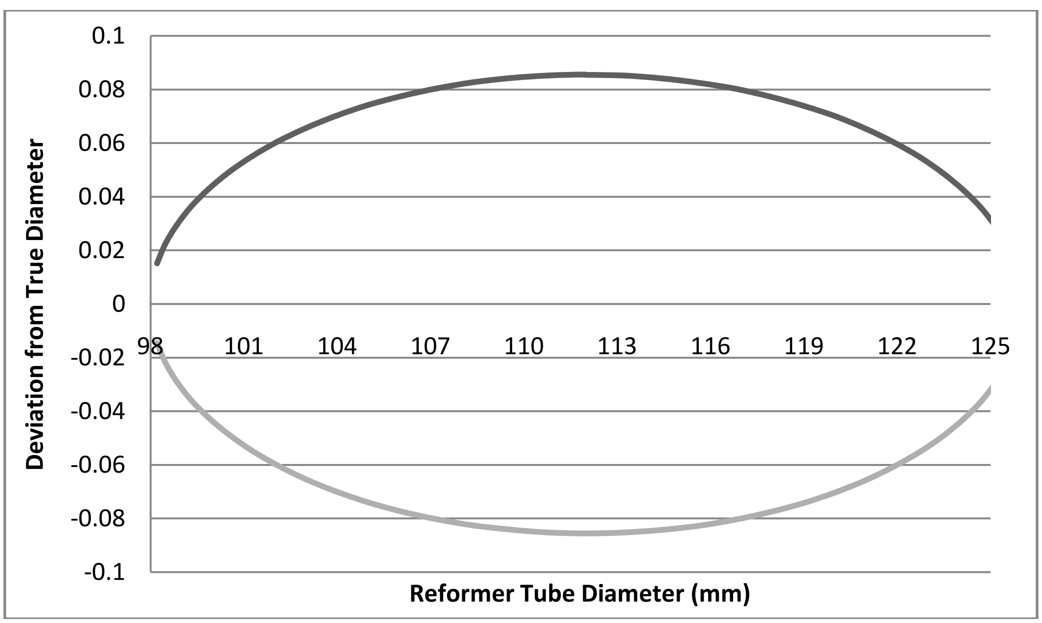


Figure 4.12 Precision Distribution

The plot shows that the error from the encoder deviate across the measuring range. Error ranges from minimum +/-0.0146mm, at diameter of 98mm and 125mm, and maximum error of +/-0.0852mm, at 112mm diameter

4.2.3 IDMU Tolerance

$$\mathbf{Diameter} = \mathbf{112} \mp \mathbf{0.08mm} + \mathbf{14sin}(\boldsymbol{\theta} \mp \mathbf{0.35°})$$

Equation 4.5 IDMU Theoretical Tolerance

Formula above is the overall system precision derived from integrating the tolerance and precision equation (Equation 4.4 & Equation 4.3). The formula is used to calculate the theoretical precision of the IDMU system over the measuring range of 98mm to 125mm. Data has been made more meaningful by creating a Deviation vs Diameter plot (Figure 4.13). Clearly, the graph shows a change in precision at changing diameter. The maximum deviation is seen at 112mm diameter, where the Encoder Disc is perpendicular to the diametrical measuring axis, at precision of +/-0.166mm. The minimum tolerance is seen at the two limit of diameter of 98mm and 125mm where the precision increases to +/-0.095mm. Conclusively, from manufacturing tolerance and MAE3 Rotary encoder resolution, the reformer tube diameter determined by the IDMU system will have an error of maximum 0.166mm and hence the theoretical precision of the system is determined to be +/-0.166mm.

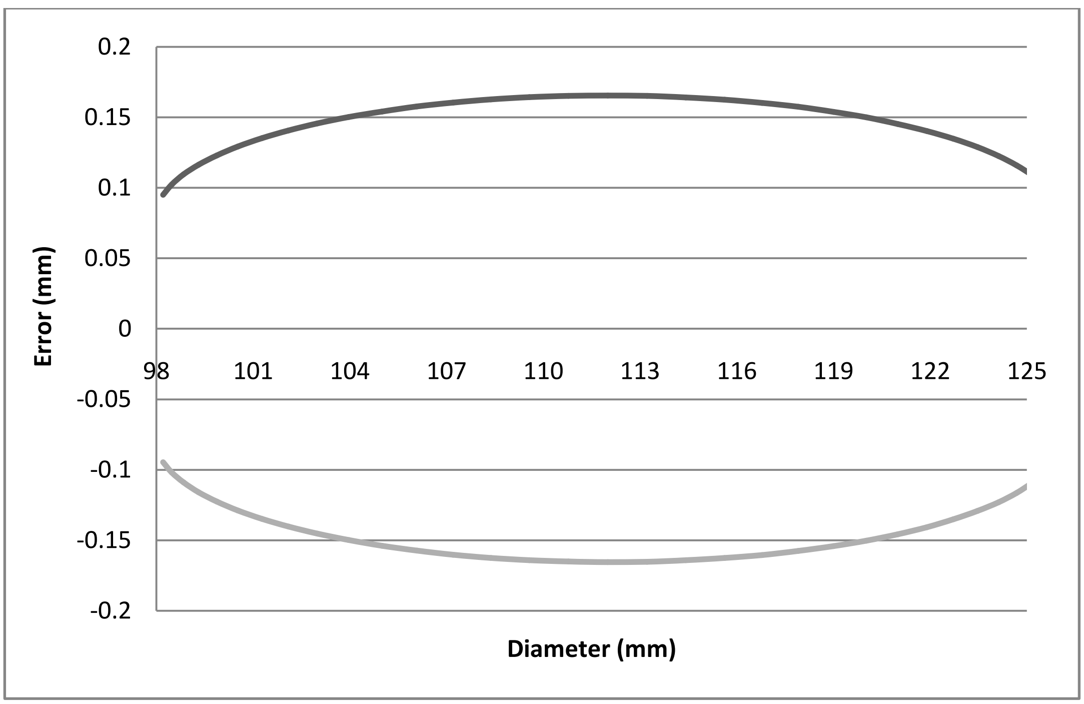


Figure 4.13 IDMU Deviation vs Diameter plot

4.3 IDMU Precision & Accuracy Experiment

The IDMU is tested for accuracy before it can be used for any real-world applications. An experiment was performed to test the accuracy and precision by making repeated measurements of a known diameter. A segment of 110mm reformer tube was made available for this experiment.

Aim:
To test the diametrical measurement precision and accuracy of the Internal Diameter Measuring Unit (IDMU) using a 109mm reformer tube segment.

Figure 4.14 Segment of Reformer Tube

Procedure and Data Collection:

1. Figure 4.10 is a photo of the segment of reformer tube used for the experiment. First two diametrical measurement of the specimen reformer tube opening is carefully measured using a precision calliper as shown in Figure 4.3.2. These values are used as the *known value x* for the accuracy and precision calculation.

2. The IDMU is carefully placing into the reformer tube with the two measuring access aligned with the two diametrical axis measured in set 1.

3. Measure and record the voltage seen at the output pins of each Rotary Encoder.

4. Remove system and repeat the process 30 times.

All the raw data is converted into diametrical measurement using Equation 4.1. The collected voltage readings collected from IDMU Precision & Accuracy experiment along with its associative diametrical measurement is tabulated onto Table 4.2. The sample mean has also been included into the table.

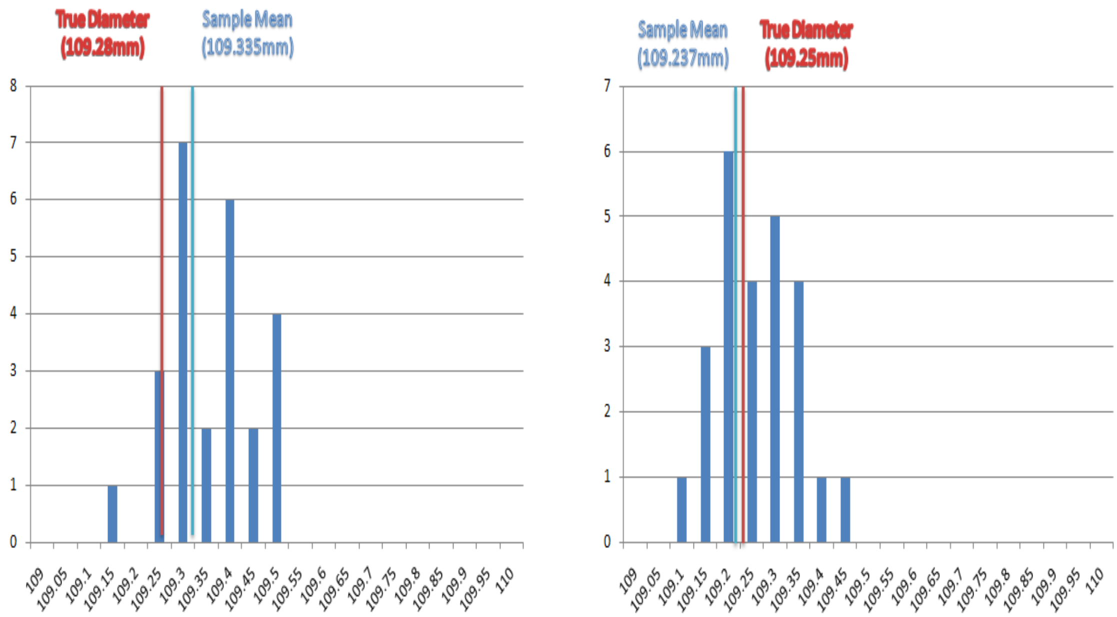
Table 4.2

a) Diameter 1

Trial No.	Sensor 1 (V)	Encoder Disc Angle (°)	Diameter 1
1	2.469	-0.198	109.251
2	2.471	-0.180	109.498
3	2.470	-0.189	109.363
4	2.470	-0.190	109.353
5	2.469	-0.193	109.320
6	2.469	-0.193	109.309
7	2.470	-0.190	109.361
8	2.469	-0.197	109.258
9	2.469	-0.197	109.265
10	2.470	-0.188	109.384
11	2.469	-0.195	109.292
12	2.470	-0.187	109.393
13	2.470	-0.187	109.391
14	2.471	-0.183	109.453
15	2.469	-0.195	109.291
16	2.471	-0.182	109.470
17	2.471	-0.184	109.439
18	2.468	-0.200	109.218
19	2.468	-0.198	109.245
20	2.468	-0.199	109.236
21	2.469	-0.194	109.294
22	2.469	-0.195	109.283
23	2.467	-0.207	109.125
24	2.471	-0.184	109.433
25	2.471	-0.183	109.455
	Sample Mean	-0.192	109.335

b) Diameter 2

Trial No.	Sensor 2 (V)	Encoder Disc Angle (°)	Diameter 2
1	2.471	-0.185	109.424
2	2.466	-0.212	109.057
3	2.468	-0.198	109.245
4	2.468	-0.203	109.177
5	2.469	-0.192	109.331
6	2.469	-0.194	109.295
7	2.468	-0.200	109.220
8	2.468	-0.201	109.202
9	2.469	-0.195	109.283
10	2.467	-0.206	109.142
11	2.469	-0.194	109.294
12	2.467	-0.208	109.113
13	2.468	-0.202	109.186
14	2.469	-0.196	109.274
15	2.467	-0.206	109.130
16	2.468	-0.199	109.232
17	2.469	-0.194	109.304
18	2.469	-0.194	109.303
19	2.468	-0.202	109.193
20	2.469	-0.194	109.298
21	2.469	-0.193	109.317
22	2.467	-0.204	109.161
23	2.470	-0.188	109.386
24	2.468	-0.202	109.186
25	2.468	-0.203	109.178
	Sample Mean	-0.199	109.237



(a) Diameter 1 **(b) Diameter 2**

Figure 4.15 Histogram of Collected Diameter

Figure 4.11 presents a histogram of the data on Table 4.2. The sample mean and the reference diameter have been added onto the graph. The sample mean of the data collected from diameter one is 109.335mm which is slightly greater than its true dimension of 109.28mm. The sample mean calculated from diameter two is 109.237mm which is slightly less than its true value of 109.25mm.

The accuracy of a measuring instrument is simply the degree of closeness of measurements to it true value. It can be calculated by subtracting the sample mean from the true value (Equation 4.6). As seen in the calculation below, the accuracy the two data collection resulted with different accuracy output of 0.055mm & -0.013mm.

Equation 4.6:

$$Accuracy = \bar{x} - x$$

Accuracy calculated from data collected from diameter 1;

Sample mean (x-bar) =109.335mm, True Diameter = 109.28mm

$$= 109.335mm - 109.28mm$$

$$= 0.055mm$$

Accuracy calculated from data collected from diameter 2;

Sample mean (x-bar) =109.237mm, True Diameter = 109.25mm

$$= 109.237mm - 109.25mm$$

$$= -0.013mm$$

The precision of a measurement system is the degree to which repeated measurements resulting with same value. It is commonly estimated by the sample standard deviation derived in Equation 4.7. As seen in the calculation below, the precision the two data collection resulted with two precision of 0.0929mm and 0.0878mm.

Equation 4.7:

$$Precision = s = \sqrt{\frac{1}{n-1}\sum(x_i - \bar{x})^2}$$

Precision calculated from data collected from diameter 1;

$\sum(\boldsymbol{x_i} - \boldsymbol{\bar{x}})^2$ **=0.207074, n = 25**

$$= \sqrt{\frac{\mathbf{1}}{\mathbf{25-1}} \times \mathbf{0.207074}}$$

$$= \mathbf{0.0929}\boldsymbol{mm}$$

Precision calculated from data collected from diameter 1;

$\sum(\boldsymbol{x_i} - \boldsymbol{\bar{x}})^2$ **=0.184887, n = 25**

$$= \sqrt{\frac{\mathbf{1}}{\mathbf{25-1}} \times \mathbf{0.184887}}$$

$$= \mathbf{0.0878}\boldsymbol{mm}$$

The data collected in the experiment suggest that the Internal Diameter Measuring Unit has an accuracy of +/-0.055mm and precision of +/-0.0929mm which is much better than the theoretically calculated tolerance of +/-0.166mm. The outcome is very acceptable with accuracy being much below the objective accuracy of this research of +/-0.1mm (Discussed in Chapter 1). Precision & Accuracy Experiment has shown that the IDMU has a very good level of both accuracy and precision.

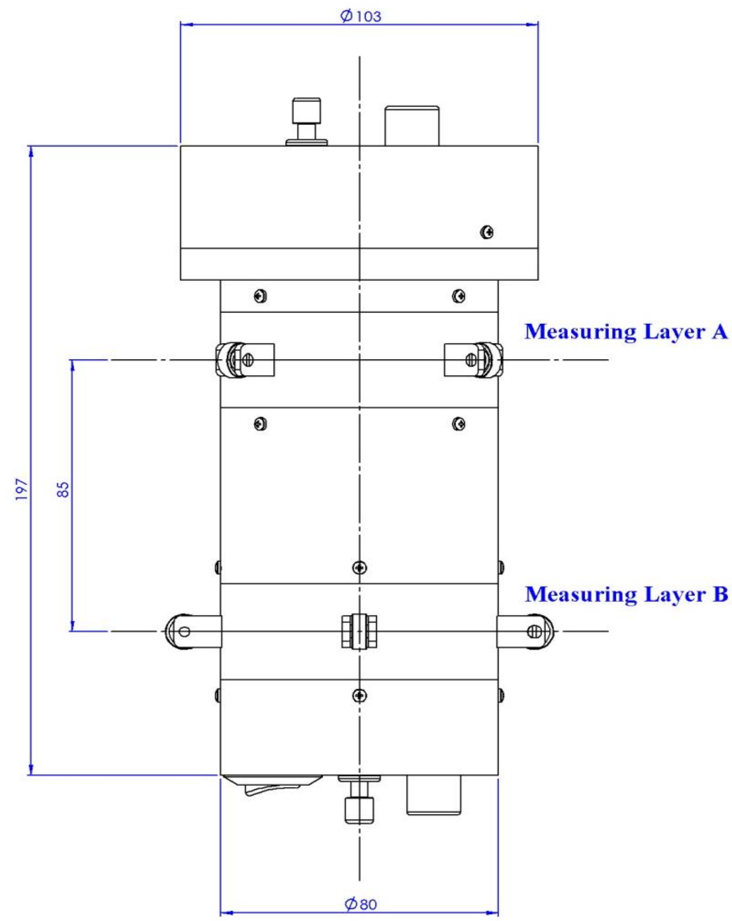
CHAPTER 5 SENSOR MODULE

The Sensory Module of the Reformer Tube Internal Diameter Measuring (RTIDM) system designed to make four diametrical measurements through mechanical means via the use of Linear-to-Angular Transducer. This chapter will focus on the mechanical construction, design considerations and the uses of PICAXE Microcontroller of the Sensory Module developed from the prototype design discussed in chapter 3. It will also discuss the range detection scheme used to detect the end of the reformer tube.

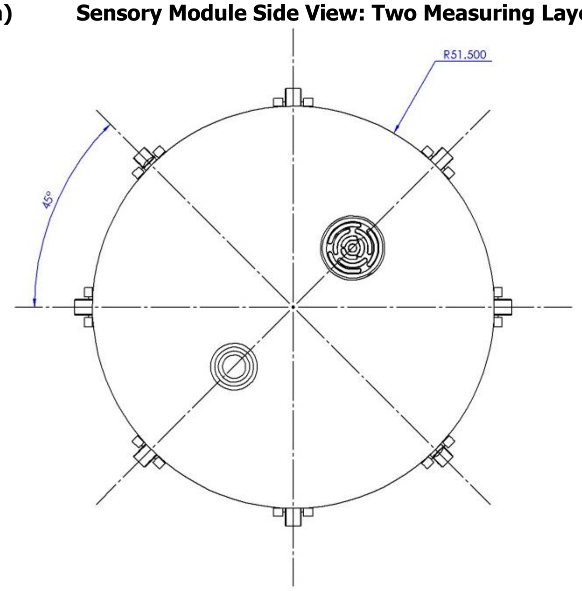
5.1 Mechanical Construction

Figure 5.1 is a photo of the Sensory Module. The cylindrical aluminium body is 200mm in height and 100mm in diameter, weighing a little over 3kg. It is designed to travel through the internal cavity of a vertically standing reformer tube, utilizing two *Internal Diameter Measuring Units* (IDMU), discussed in the previous chapter, to making (in total) four diametrical measurements ranging between 98mm to 125mm. Two IDMUs are spaced 85mm apart creating two measuring layers identified as *Measuring Layer A* & *Measuring Layout B* as illustrated in Figure 5.2a. As shown in Figure 5.2b four *diameter measuring axes* are equally oriented about the radial axis at 45°. Multiple sensors are located on both end of the sensory module to detect the top and the bottom of the reformer tube. The Self-Aligning characteristic featured of the IDMU help to stabilize the instrument against the reformer wall improving the analysis performance while minimizing the contact surface.

Figure 5.1 Sensory Module



(a) Sensory Module Side View: Two Measuring Layer



(b) Sensory Module Top View: Four Measuring Axis

Figure 5.2 Sensory Module Technical Drawing

The Sensory Module is essentially an assembly of five components; circuit compartment, Inner Diameter Measuring Unit A (IDMU-A), Inner Diameter Measuring Unit – B (IDMU-B), Mid

Compartment, and Power Supply (refer to Figure 5.3). Each component is assembled via M2 machine screws, allowing for simple onsite disassemble.

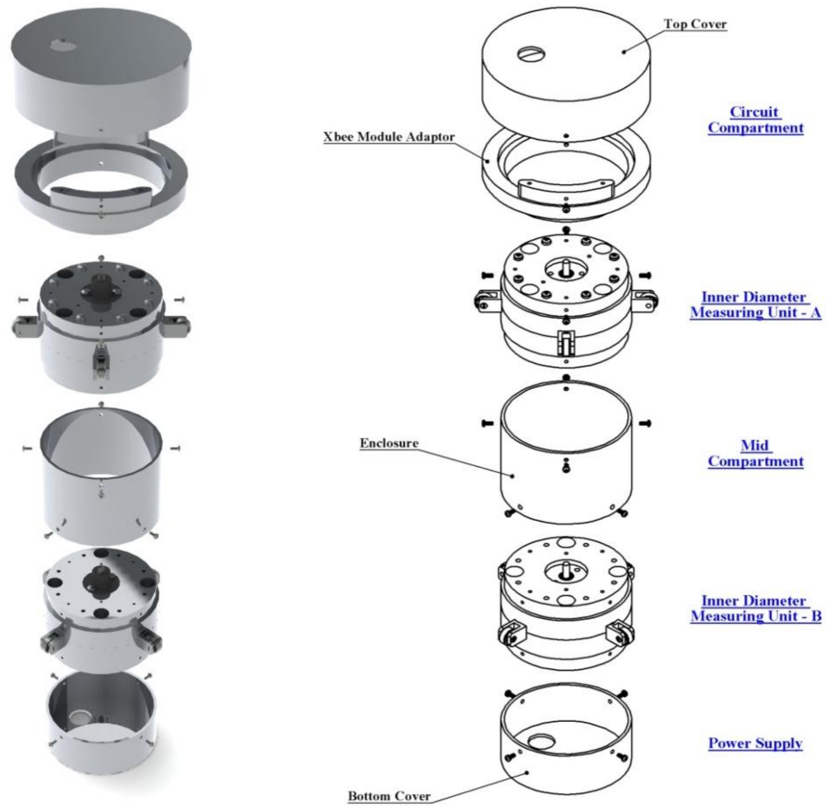


Figure 5.3 Sensory Module – Assembly Drawing (ISO View)

The Circuit Compartment is a cavity located at the top of the module created between the Top Cover and XBee Module Adaptor components. This cavity is designed to enclose the main circuit board consisting of a microcontroller and the XBee Radio Module (see Chapter 7). A miniature ultrasonic sensor and press-switch sensors are mounted on the *Top Cover* for detecting the top of the reformer tube. Identical sensors can also be found mounted to the Bottom Cover.

Two Internal Diameter Measuring Units are spaced by an *Enclosure* component which creates the *Mid Compartment* cavity. The Enclosure is simply a cylindrical shell made out of rolled 2mm aluminium steel. Mid Compartment is used to run multiple electrical wires between the power supply, IDMU and the main circuit board. The wires and its colour codes are tabulated in Table 5.1 included with a description of the type of signal it is carrying.

Name	Colour	Description
Sensor 1	BLUE	5V Analogue Signal
Sensor 2	PINK	5V Analogue Signal
Sensor 3	GREEN	5V Analogue Signal
Sensor 4	YELLOW	5V Analogue Signal

Ultrasonic 2	PURPLE	4.5V Analogue Signal
Bottom Detect 2	WHITE	4.5V Analogue Logic Signal
Power Supply +v	RED	Constant 4.5V
Power Supply GND	BLACK	Common Ground
Sensor Supply	RED (Strip)	Constant 4.5V
Sensor GND	BROWN	Common Ground

Table 5.1 Sensory Module wire list

The bottom cover encloses three AAA battery cells used to power the module with 4.5v. The cell output is regulated using the *power supply circuit* located in the *mid compartment.* Details on the *power supply circuit* can be found in Chapter 5.3. The battery is fitted into the four openings found on the IDMU as illustrated below (Figure 5.4). The operator must remove the Bottom cover when replacing the batteries.

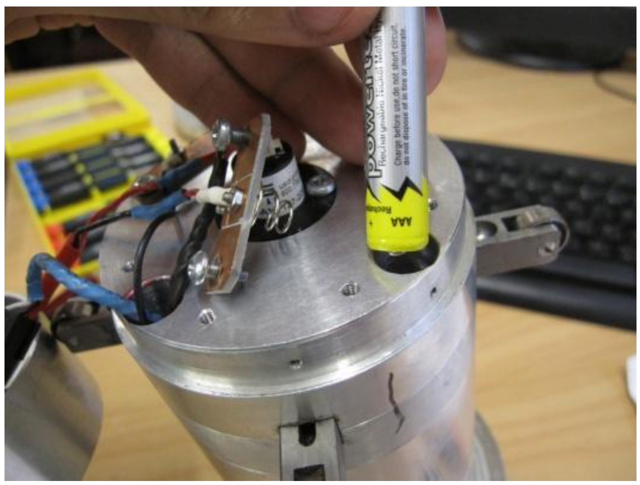


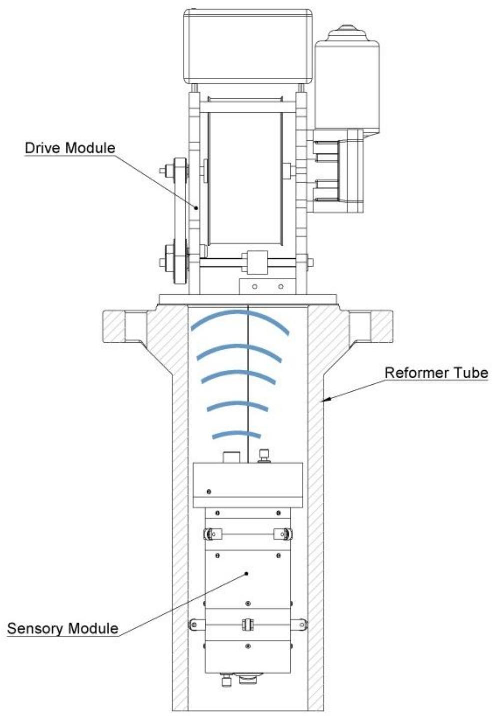
Figure 5.4 Battery Cell

5.2 Reformer Tube End Detection

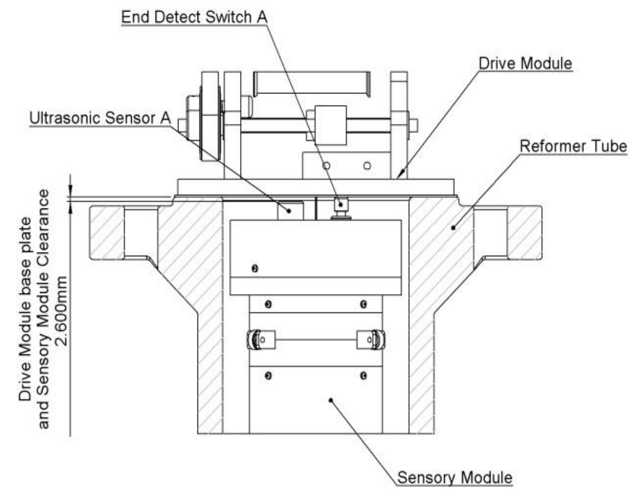
In successfully monitoring the reformer tube profile characteristic, the RTIDM system must be able to accurately detect the top and bottom end of the reformer. This will allow the system to aid the sensory module move to the very tip of the tube with crashing into the bottom of the reformer tube while inspecting the entire length. Two ultrasonic and mechanical switch sensors have been selected for this purpose. The ultrasonic is used to detect the end of the tube at range before the mechanical switch sensor makes contact.

5.2.1 End Detect Sensor

In the RTIDM system, an *End Detection* is an important aspect that must considered to successful inspect the entire length of the reformer tube. The RTIDM system must accurately detect the top and the bottom ends of the tube to guide the Sensory Module to the very tips without causing hazardous collision or behaviour. During the reformer tube inspection cycle it is intended for the Sensory Module to move at its fastest speed allowed by the radio communication without making false reading. However the system must be able to detect the two ends of the reformer tube prior the sensory module reaches the top of the tube or bottoming out, slow down the DC motor and stop the sensory module leaving minimum clearance between the bottom of the Sensory Module and the tube end.



(a) Ultrasonic End Detect



(b) End Detect Switch

Figure 5.5 Sensory Module End Detect Mechanism

To achieve this, two sensors has been selected from the wide range of sensory components available; an Ultrasonic Range Sensor and a mechanical press switch. The two sensory has been prefixed to the top and bottom faces of the Sensory Module facing towards the two ends of the reformer tube. The Ultrasonic Sensors continuously monitor for approaching object (tube end) in both directions of the Sensory Module. When the tube end is detected, the system will go into a “tracking” phase, slowing down the DC motor until the End Detect Switch makes contact with the tube end signalling the motor to stop. At this point, there is approximately 5mm clearance between the Sensory Module and the end of the tube.

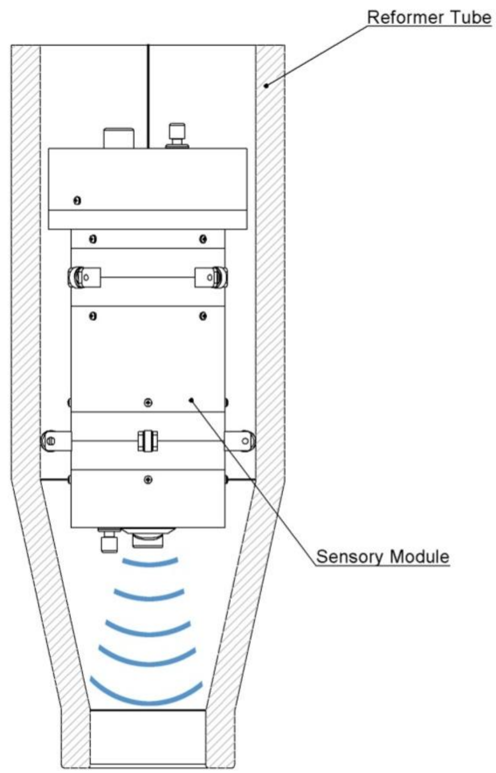


Figure5.6 Ultrasonic Bottom End Detect

Obviously depending on the design of the reformer tube the end section of the tube will have varying shape, where the End Detect Switch may not work. In such case, the DC motor is stopped dependent solely on the Ultrasonic sensor.

5.2.2 SONAR

Ultrasonic is the name given to a sound wave having a frequency above the human hearing range, which is approximately 20 kHz. It has been used in many fields typically for measuring and non-destructive testing purposes. Of which the name *Sound Navigation and Range* (abbreviated SONAR) is given to measuring instruments using ultrasonic waves for range finding application.

SONAR is an optoelectronic transducer converting physical measurements into electric signal through emission and reception of acoustic energy. The methodology is very similar to a RADAR system commonly known to be used in submarine navigation. It is typically a two part sensor of a transmitter and a receiver. Transmitter is used to generate ultrasonic pulse in particular direction. If object is within the transmitted ultrasonic detection range, the pulse is reflected back as an echo and can be detected through the receiver (as illustrated in Figure 5.7). The object distance is measure based on *time-of –flight* (TOF) or frequency phase shift of the ultrasonic pulse. The range of a SONAR application in open space can range from centre meter to few meters but it is common that object in contact or closer than the minimum distance cannot be detected.

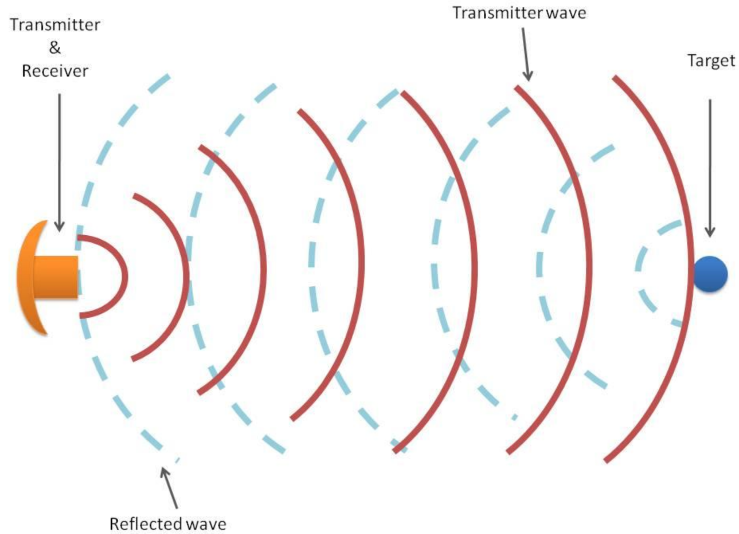


Figure 5.7 Active sonar illustration

The SONAR used in this design is the LV-MaxSonar sensor distributed by Maxbotic® Technology. Of the line of LV Product range, the LV-MaxSonar-EZ4 (Figure 5.8) balances robust people detection ability with a significantly narrow beam width. The MaxSonar ultrasonic inducer is mounted onto a prebuilt PCB footprint of 20mmx22mm. The integrated with active components consist a PIC16f1676 microcontroller allowing for interface output in pulse width, analogue voltage and serial digital format.

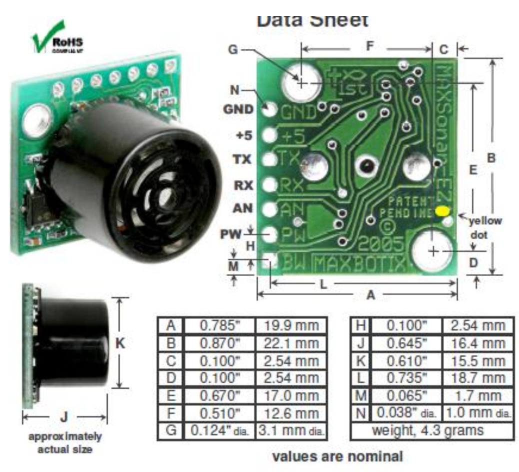


Figure 5.8 LV-MaxSonar®–EZ4

The 5v operating device allow object detections from 0-inches to 254-inches (6.45m) and provides sonar range information from 6-inches out to 254-inches with 1-inch resolution. More details can be found in the datasheet provided in Appendix C of this thesis. This sensor will enable the RTIDM system to detect the ends of the reformer when the Sensory Module is within 500mm. This information will be used to aid the gradual decent of module speed.

5.3 Sensory Module Circuit Design

The Sensory Circuit Board is designed to process the analogue signal using low cost integrated circuit (IC). This IC is for processing the digital signal prior to radio transition. The circuit is built on a circular PCB board cut out measuring 80mm diameter. A programmed PICAXE microcontroller is used to pre-process the sensory output, preparing the analogue sensory signal into ASCII language for 'chip' level analysis and editing. The microcontroller is also used to encode and generate serial data for the radio transition, investigated in chapter 7. The block diagram of the Sensory Circuit is illustrated in Figure 5.9.

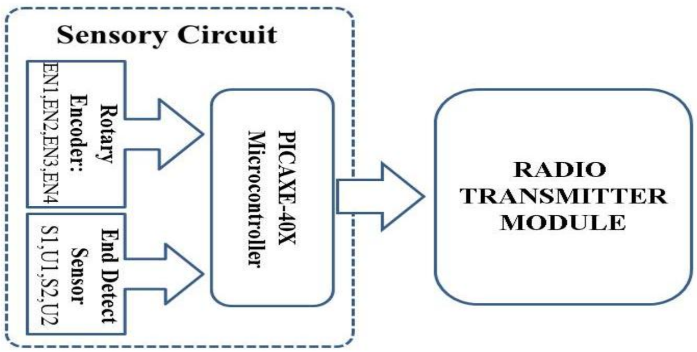


Figure 5.9 Sensory Circuit block diagram

5.3.1 PICAXE Microcontroller

Figure 5.10 PICAXE-40X1 Chip

A PICAXE micro-controller has been integrated in the Sensory Module to act as a data acquisition unit. The low cost PIC chip is pre-programmed with a special booth-strap code created by PICAXE®. The bootstrap code enables the PICAXE microcontroller to be re-programmed directly using a simple serial connection via the featured universal asynchronous receiver/transmitter (UART) component. This programming technique eliminates the need for the conventional expensive microcontroller programmer thereby making the whole download method easy and low cost [13]. The PICAXE microcontrollers are programmed used the PICAXE ® Programming Editor software via the use of serial interface. Figure 5.11 is the interface of PICAXE Programming Editor.

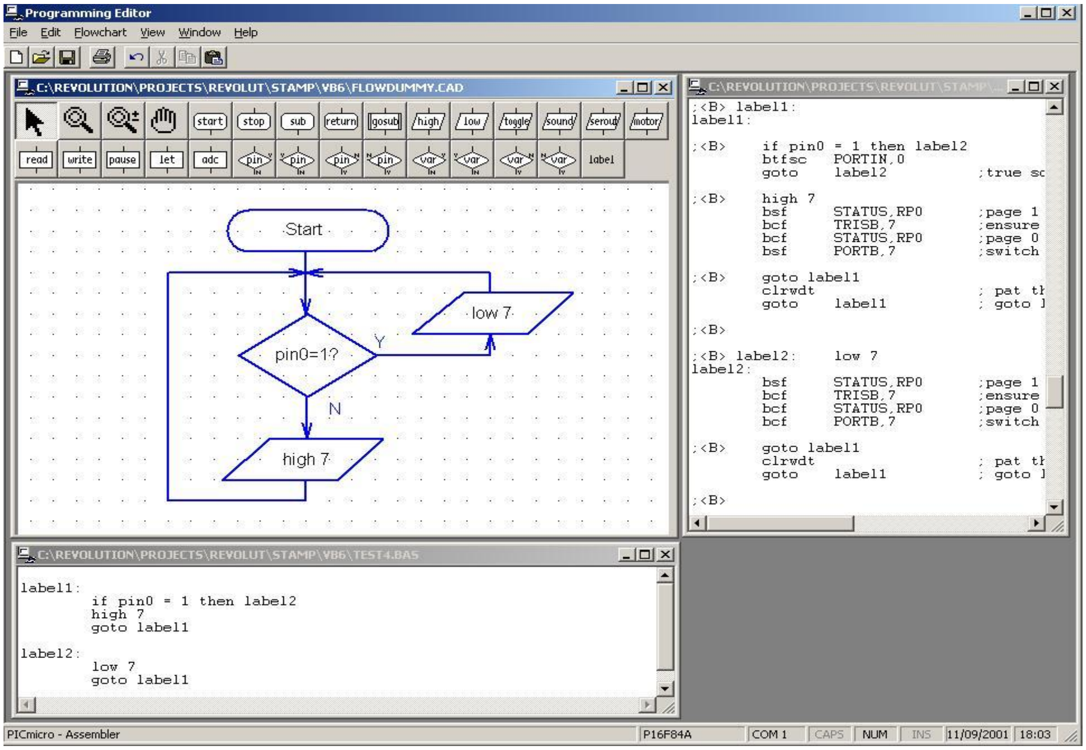


Figure 5.11 PICAXE Programming Editor Screenshot

5.3.2 Sensory Circuit Design

In this chapter, the design of the *Sensory Circuit,* found in the *Circuitry Compartment* of the Sensory Module is discussed (Figure 5.12). The final circuit uses a PICAXE-40X1, an indicator LED, two capacitors, three press-buttons, and ten resistors. Illustrated in Figure 5.13 is the circuit diagram of Sensory Circuit.

Figure 5.12 PICAXE & XBee Radio Circuitry photo

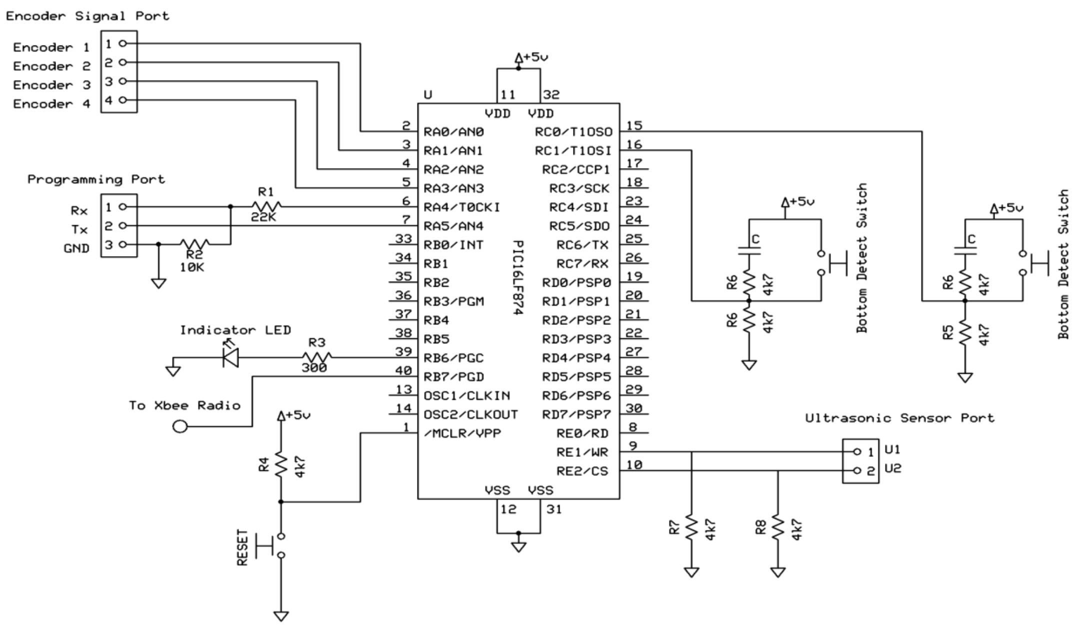


Figure 5.13 Sensory Circuit diagram

With the PICAXE facility to use allocated I/O pins as sink ("absorb") or source ("give out") small amount of current, the indicator LEDs has been directly connected to the output pin via 330Ω current limiting resistor. The output wire carrying analogue voltage signal from the four rotary encoders are directly connected to the PICAXE input ports 1~4. The Ultrasonic end-detect sensors are connected to the input pins 1~2 via 4.7kΩ pull-down resistors. The end-detect switches are connected to the PICAXE input ports via a *de-bounce* network. De-bounced single-throw switch is composed of 10kΩ and a 0.47μF capacitor, smoothing the voltage signal reducing error due to the mechanical bouncing nature inhibited with switches.

The 470uf electrolytic capacitor is connected across the 5-volt supply to the PICAXE acting as a decoupling capacitor, reducing noise caused by the *radio circuit* sharing the same 5-volt supply (more on the Radio Circuit in chapter 7).

The two resistors (R1 & R2) are used to create a serial interface between the PC and PICAXE, opening a Program Download port for program writing and downloading. 9pin Custom serial cable is used illustrated in Figure 5.14. The ground wire provides a common reference, the RX wire sends signals from the computer to the PIC microcontroller, and the TX wire sends signals from the PIC microcontroller to the computer.

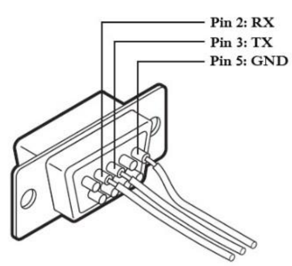


Figure 5.14 PICAXE Download Cable

The circuit is powered by three alkaline AAA cells supplying 4.5V protected from voltage polarity with the use of a diode. For long period experimental purposes the *Power Supply* circuit shown in Figure 5.15 has been integrated. L7805CP voltage regulator is used to regulate up to 9Volts input voltage to 5Volts. Multiples capacitors are used before and after the regulator to help stabilise the output along with a diode for reverse connection protection.

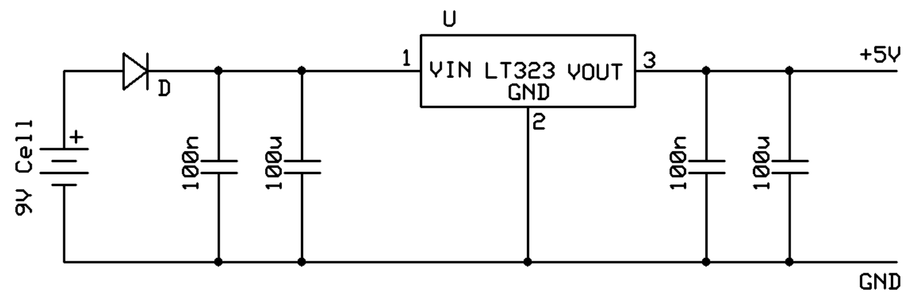


Figure 5.15 Power Supply Circuit

5.3.3 Code Description

The low cost chip has been programmed to run a simple route in reading the four Rotary Encoders outputs, two End-Detect Switches outputs, and the two ultrasonic sensor output and packaging the data in a workable format.

The part of the code used in the PICAXE-40X microcontroller is shown in Code 5.1. The code commences by defining symbols for constants and variables and then initializes the internal clock speed to 8 megahertz via the '*setfreq*' command. Then the code enters a permanent loop 'main' that reads the analogue voltage signal received from each sensors to generate a single string output in ASCII format. The high resolution 10-bit Analogue-to-Digital (ADC) is used to read the four Rotary Encoder outputs via "readadc10" command. Each reading is written into their allocated word variables. With the lower resolution ultrasonic range sensors the standard 8-bit ADC is used. A simple *"if-else"* statement is used to monitor the state of the End-detect switches to assign Boolean high (1) or low (0). Finally, the *sertxd* command is used to organise the collected variable into a single ASCII string package and transmitted out the serial programming port (pin7). Figure 5.16 shows the output data format.

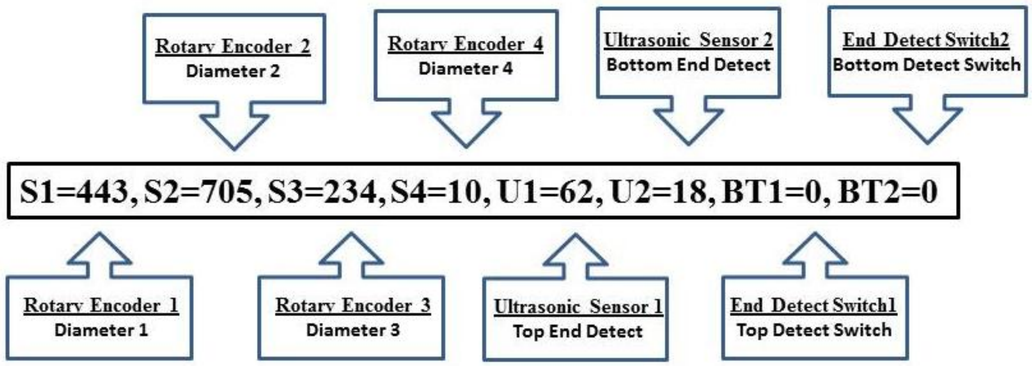


Figure 5.16 Sensory output format

Code 5.1: PICAXE-40X Sensory module code

```
Symbol S1=w0          'define word variable w0 as S1 (Sensor 1)
Symbol S2=w1          'define word variable w1 as S2 (Sensor 2)
Symbol S3=w2          'define word variable w2 as S3 (Sensor 3)
Symbol S4=w3          'define word variable w3 as S4 (Sensor 4)
Symbol U1=b8          'define byte variable b9 as U1 (Ultrasonic 1)
Symbol U2=b9          'define byte variable b10 as U2 (Ultrasonic 2)
Symbol BT1=b10        'define byte variable b11 as BT1 (Button 1)
Symbol BT2=b11        'define byte variable b12 as BT2 (Button 2)
Init:
setfreq m8
'input PortC pin1
'input PortC pin2
high PortC 0

Main:
ReadADC10 6,S1                'Read Encoder 1 via 10bits ADC
ReadADC10 1,S2                'Read Encoder 2
ReadADC10 2,S3                'Read Encoder 3
ReadADC10 3,S4                'Read Encoder 4
ReadADC 7,U1          'Read Ultrasonic Sensor 1
ReadADC 0,U2          'Read Ultrasonic Sensor 2
if PortC pin1 = 1 then        'If Stopper Button is High, set BT1=1
        BT1 = 0
else
        BT1=1
Endif
if PortC pin2 = 1 then        'If Stopper Button is High, set BT2=1
        BT2 = 0
else
        BT2=1
Endif
sertxd ("S1 =",#S1," S2 =",#S2," S3 =",#S3," S4 =",#S4," U1 =",#U1," U2 =",#U2," BT1 =",#BT1, " 
BT2 =",#BT2,13,10)
goto Main:
```

CHAPTER 6 DRIVE MODULE

The Drive Module uses a simple Reel & Wire design to accurately control the axial movement of the Sensory Module through the Reformer Tube. The main discussion of this chapter will focus on the mechanical construction, design considerations and the methodologies implemented are discussed. The last part of the chapter will focus on the Motor Driver circuitry design along with the integration of PICAXE microcontroller and the LMD18200 motor controller chip.

6.1 Mechanical Construction

Figure 6.1 Driver Module

The mechanical construction of the Drive Module (D-Module) uses the same principle of an electric fishing reel (illustrated in Figure 6.1). The D-Module assembly is uniquely suited for a 1.5 gauge steel wire. Spool and the drive shaft assembly are fitted between two 10mm aluminium side plates braced with a heavy duty ball bearing. The geared DC motor is affixed to the side plate (B) driving the spool via the drive shaft. On the opposing side on plate (A) is a three-way timing belt system setup to connect the spool, Rotary Encoder and the lead screw. The rotary encoder is fitted along the slot. The structure is able to be adjusted to take-up the belt tension. The pulleys are of different tooth count giving 1:2 mechanical advantages between the spool shaft and the lead screw. The majority of the assembly components are made of aluminium, resulting in overall weight of approximately 8kg.

The Sensory Module Enclosure component originally included in the prototype design was never realized in the final design (refer back to Chapter 3). The component was designed to bring together the Sensory and Drive Module during transport, and was also intended to aid for *software calibration*. The disadvantage of having this design is that it will limit the range of reformer tube size capable for inspection. Obviously reformer tube of smaller ID than the Sensory Module Enclosure diameter will not be inspectional while too bigger size will result in a step incapable for the sensory module to roll over. Also the component will add to the total weight of the instrument, not preferable for a portable system.

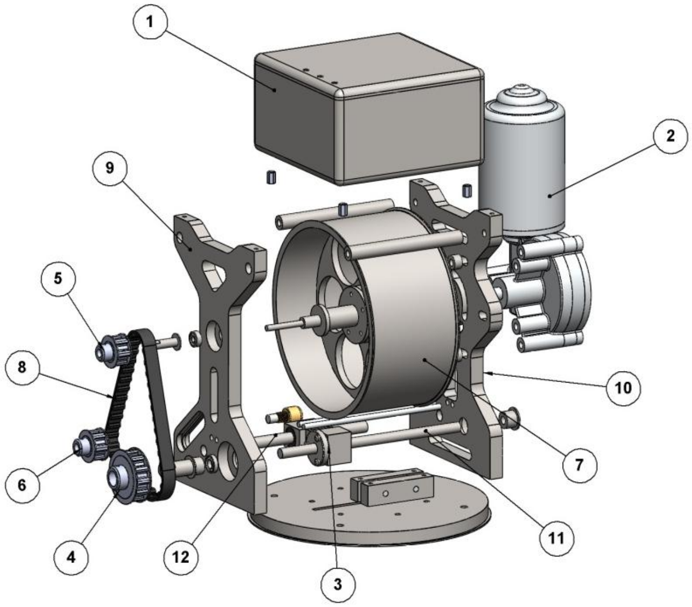


Figure 6.2 Drive Module Assemblies

1	Circuitry Enclosure	**7**	Spool
2	Geared DC Motor	**8**	Timing Belt
3	Traversing Pulley Carriage	**9**	Side Plate A
4	Lead Screw 12 teeth Pulley	**10**	Side Plate B
5	Drive Shaft 6 teeth Pulley	**11**	Lead Screw
6	Encoder 6 teeth Pulley	**12**	Precision Shaft

Table 6.1 Drive Module Part List

As illustrated in Figure 6.2, when the motor rotates clockwise the wire is wound onto the spool. As the spool turns the traversing carriage is shifted approximately 1.5mm per resolution in the relative direction, guiding the steel wire onto the spool in an orderly manner. The digital rotary encoder is used to monitor angular position of the spool. The 10bit encoder is able to accurately measure the angular position of the spool to the nearest 0.1° at a sample rate of 2.6 kHz. From this, the system is able to formulate the length of wire that has been lead out and remaining on the spool and therefore able to estimate the position of the Sensory Module. Equation 6.1 is used to estimate the amount length that has been unwounded out of the spool, the depth at which the top of the Sensory Module is located (depth D). By adding the two constant value ‘a’ and ‘b’, the depth of the two measuring plane on the Sensory Module can be determined. The two values 'a' & 'b' is the distance from the top of the Sensory Module to the two measuring plane.

$$D = 2\pi r(n + \frac{\theta}{360^{\circ}})$$

$$\mathbf{Measuring\ Layer\ A} = \mathbf{2\pi r}\left(\mathbf{n} + \frac{\boldsymbol{\theta}}{\mathbf{360^{\circ}}}\right) + \mathbf{a}$$

$$\mathbf{Measuring\ Layer\ B} = \mathbf{2\pi r}\left(\mathbf{n} + \frac{\boldsymbol{\theta}}{\mathbf{360^{\circ}}}\right) + \mathbf{b}$$

Equation 6.1

The word "estimate" is used as Equation 6.1 does not take into account all the factor that determines the actual length of wire between the reel and the Sensory module, such as the deviation in wire length due to stretching, change in thermal property, elastic bouncing and change in the spool radius from wire over lapping.

This assembly utilizes purely mechanical means to control both the linear speed and the direction of the Traverse Carriage from the single take-up motor, thus eliminating the need of clutches, gears, programming and complex control. Even during severe speed change, the system is able to maintain synchronises.

6.1.1 Spool Design

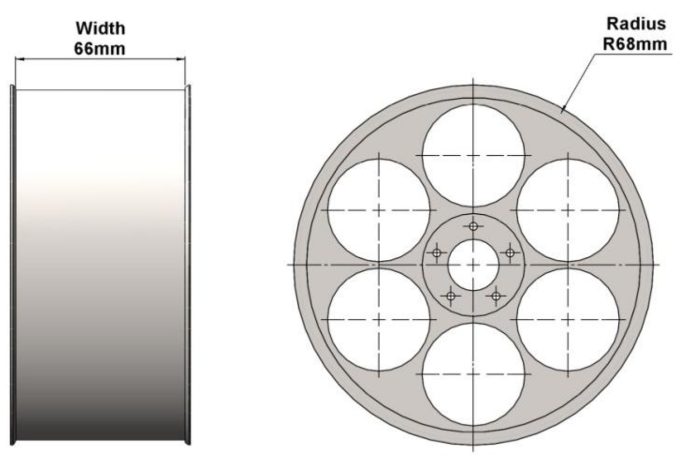


Figure 6.3 Spool Dimension

The design of the reel is a curial factor in successfully meeting the goal of this research. The radius must be of ideal size to achieve appropriate winding speed while having sufficient amount of strength to left the Sensory module. The spool must have enough width so that the full 14m of 1.5mm gauge wire can be wound without overlapping. Referring back to Chapter 1 of this thesis, the system must be able complete a full inspection cycle of one reformer tube within 2~3minutes, recording diametrical measurement at maximum 15mm vertical step. As discussed later in this thesis, with the limit of X-bee radio and the PICAXE microcontroller processing rate the sample rate of the system is limited to net sample rate of 8Hz (Chapter 8). From this value it can be calculated that the maximum speed of the Sensory Module during the inspection cycle is 0.12m/s, at which taking at least 2minutes to travel 14m.

$$Inspection\ Duration\ (s) = \frac{Reformer\ Length\ (m)}{Measuring\ Step\ (m)} \times Frequency(Hz)$$

$$\mathbf{117sec = \frac{14m}{0.015} \times 8Hz \cong 2\ minutes}$$

Equation 6.2 Inspection Period

To this, the Sensory module must travel to the bottom of the reformer tube with the remaining 1minute or faster. Although the selected DC motor is specified to output 5Nm of torque at 5A input current, the LMD18200 motor driver chip used in this project is limited to maximum 3A output. According to the data sheet found in Appendix C, this will limit the motor output just over 2Nm or torque. With the Sensory Module weighing 5.5kgs, the following calculation has been used to determine the absolute limit of the reel radius and width dimensions.

$$\boldsymbol{r = \frac{\tau}{F}, \qquad 0.09m = \frac{2Nm}{55N}}$$

$$\boldsymbol{r = \frac{v}{\omega}, \qquad 0.029m = \frac{0.12m/sec}{2\pi \times \frac{40rpm}{60sec}}}$$

Equation 6.3 Spool Radius Calculation

$$\boldsymbol{w = t \times \frac{14000}{2\pi r} \qquad , \qquad 49mm = 1.5mm \times \frac{14000mm}{2\pi \times 68mm}}$$

Equation 6.4 Spool Width Calculation

With the 80N of tangential force of the Sensory Module and, the radius of the spool must be in range of 29-90mm (Equation 6.3). Taking the mid value of 68mm radius, an appropriate width of the spool is calculated to be 50mm (Equation 6.4). Based on these values, and some visual balance aspects, **68mm** radius and **66mm** width was used in the final spool design.

6.1.2 Traversing Pulley System

(1) L1318 Lead Screws - Round nut **(2) DryLin® Linear Plain Bearing RJUM-01**

Figure 6.4 Linear Motion Components

Traversing Pulley is intended to lead the steel wire accordingly on the spool. The carriage will shift precisely 1.5mm relative to the spool direction, avoiding the over lapping of wire on the spool. As illustrated in Figure 6.5, 1.5mm pitch Anti-backlash lead screw and a circular nut is used to control the linear movement of the traversing carriage. The Traversing Carriage body is fitted with a DryLin Linear Plain Bearing to provide free motion along a stainless steel precision shaft.

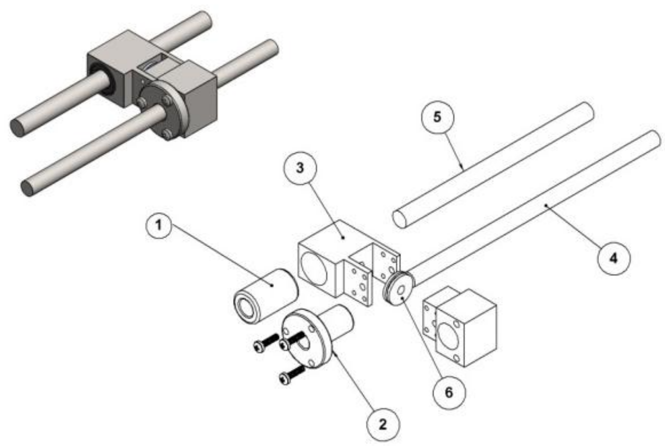


Figure 6.5 Traversing Carriage Assembly

The two pulleys located on the base plate of the Drive Module and the Traversing Pulley is used to guide the steel wire from the centre of the base plate to the spool as shown on the Figure 6.6. Each pulley is fitted with a miniature machine bearing.

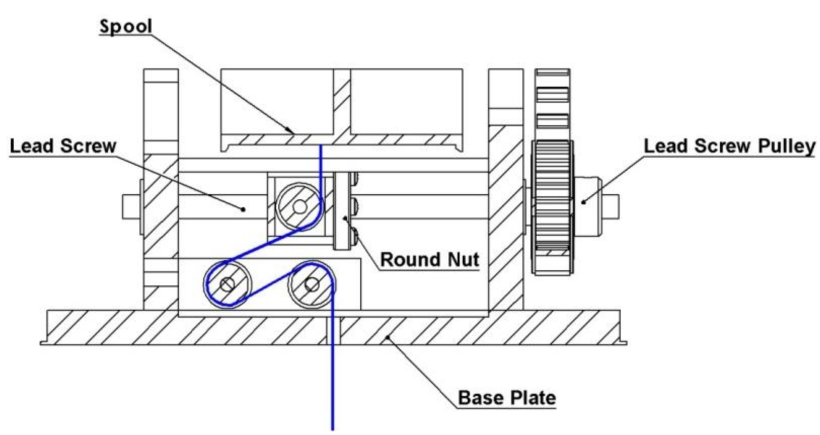


Figure 6.6 Steel Wire Path Illustration

6.2 DC Motor Control

The addition of a motor driver component is an important part in the development of this module. The Driver Circuit will create a method to digitally control the DC motor to achieve accurate motion control of the Sensory Module. Shown in Figure 6.7 is the block diagram the motor Driver Unit. This section of the chapter will evaluate the integration of LMD18200 H-bridge DC motor controller chip and PICAXE microcontroller.

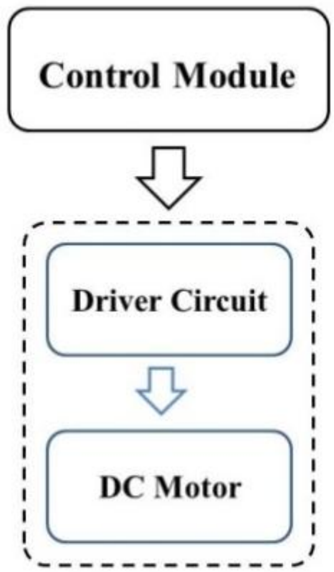
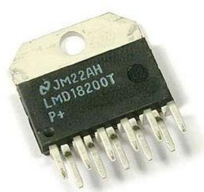


Figure 6.7 Simple Motor Control Block Diagram



(a) LMD18200 3A, 55V H-Bridge

(b) PICAXE-08x Microcontroller

Figure 6.8 Motor Driver Circuitry Components

The motor driver circuit is made up of two key driver chip; LMD18200T motor driver (Figure 6.8a) and the Picaxe-08x microcontroller (Figure 6.8b). With the universal asynchronous receiver/transmitter component featured on the PICAXE chips, the Driver Circuit is able to receive digital command signals encoded with the motor direction and speed data. The signal is received through a stereo 3.5mm jack socket affixed to the Circuit Enclosure. The LMD18200T is a very capable H-bridge driver integrated with an internal Thermal and current sensor used to help protect the system overloading. A red LED indicator is used to give visual warning when the LMD18200T reaches 145°C while automatically shutting down at 170°C. This simple but rather clever Driver Circuitry is more able for this project, likely achieving more control resolution than can be realized by the motor itself. Figure 6.9 illustrates the layout of the driver board.

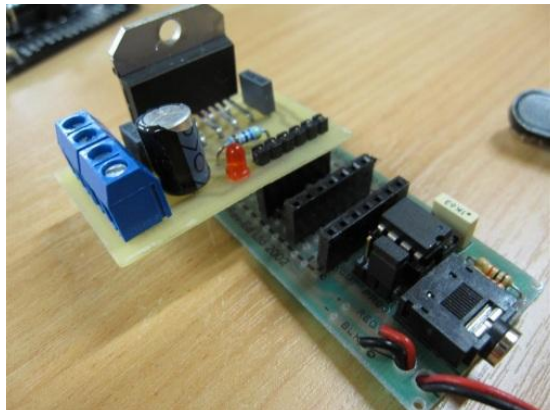


Figure 6.9 Driver Circuitry Layout

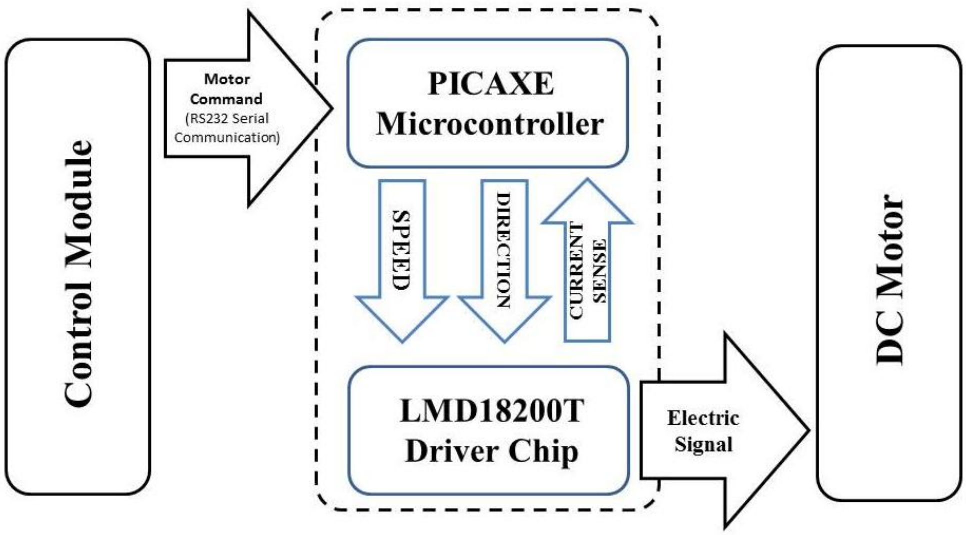


Figure 6.10 Motor Driver data flow diagram

Diagram shown in Figure 6.10 is a block diagram demonstrating the data flow between Control PC, PICAXE microcontroller and the LMD18200T Driver Chip. The *Motor Command* signal generated by the *Control Program* is received by the PICAXE microcontroller through a serial communication. The chip translates this digital data into two independent electrical signals of direction and speed. These signals are used by the LMD18200T driver chip to regulate the two output terminals connected to the DC motor. The *Current Sensor* signal from the LMD18200T is transmitted back to the PICAXE chip to monitor the amount of the current sourced to the motor. This data along with the motor speed detected from the rotary encoder can be further used to determine the amount of load the motor is under or if the motor is stalling.

The *Motor Command* is a RS-232 standard serial data encoded in ASCII character-encoding scheme. In this application, only the "receive data" pin of the minimal "3-sire" RS-232 connection is used as the full facilities of RS-232 is not required as there is no data feeding back through the serial cable. The signal is made up three components of parity code, speed and direction as illustrated in Figure 6.11.

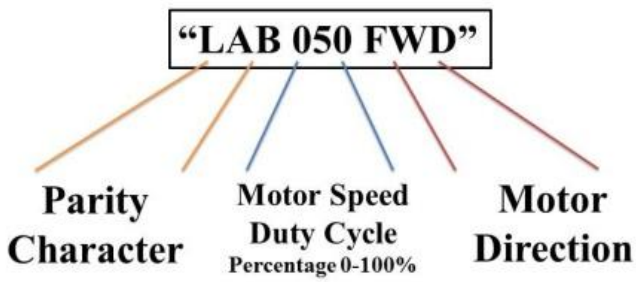


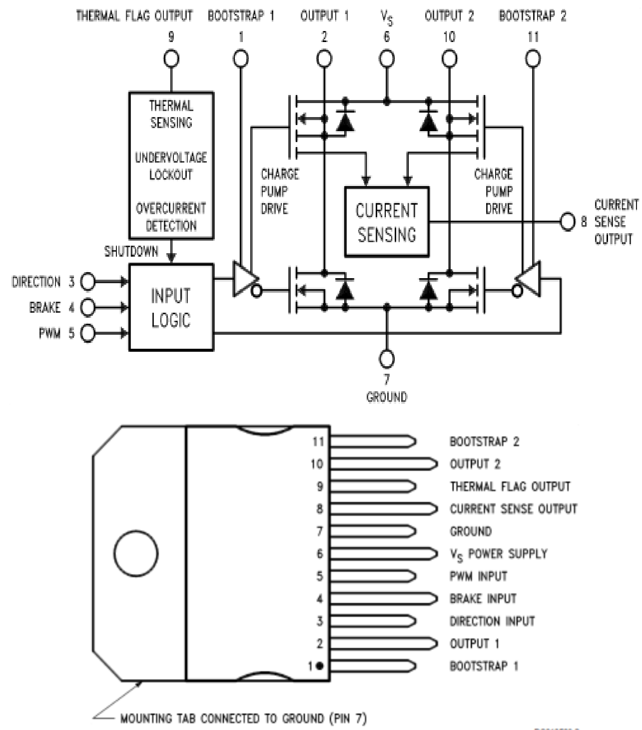
Figure 6.11 Motor Command format

Each transmitted data is preceded by the character set "LAB". This is a simple parity method to ensure that only valid data is accepted by the PICAXE. The second component, speed, is a three digit string integer representing the speed or the power output of the motor in percentage (100% for full power and 0% to stop the motor). The final character contains the direction of motor ("FWD" = clockwise, "REV" = anti-clockwise).

The Direction output signal from the PICAXE chip is a 5v high-low logical controlling the current flow between the two output terminals connected to the motor. Thus, it controls which way the motor turns. At logic High voltage (+2v and above) the motor while turn in clockwise direction, lowing the Sensory Module and vice versa lowering the Sensory Module at Logic Low voltage (-0.1 – 0.8 volts). The Speed is a Pulse Width Modulated (PWM) signal outputting maximum power to the motor at 100% PWM Duty Cycle.

6.2.1 LMD18200

The LMD18200 is a 3A H-Bridge designed for motion control applications. The device is built using a multi-technology process which combines bipolar and CMOS control circuitry with DMOS power devices on the same monolithic structure (Reference). As mentioned before the LMD18200 chip has an on-board current sensor and thermal sensor shown in Figure 6.12a. When the temperature of the chip reaches 145°C thermal high flag is provided at pin 9 (Figure 6.12b). This flag is essentially used as a protection circuit but it is not used in this research as the temperature will not reach such high temperature at 2A operation current used in our system. The "Current Sense Output" pin 8 provides the sourcing current signal detected by the current sensor. This pin will output as signal with current proportional to the sourcing current to the DC Motor (Figure 6.12b) at typically 377µA/A. It should be noted that the recirculating current (freewheeling current) are ignored by the current sense circuitry. Therefore, only the currents in the upper sourcing output are sensed (reference). When logic high is detected at "BRAKE INPUT" (Pin 5) the output terminals are effectively shorted which is used for braking. Obviously this braking method will result in high power loss and therefore is not used in this system. The worm gear used in the DC Motor gear box will give enough braking force.



(a) LMD18200 Block Diagram ***(b) LMD18200 Pin layout***

Figure 6.12 LMD18200

The LMD18200 driver readily interfaces with different forms of PWM signals. Pulse width modulation (PWM) is a method used to digitally encode an analogue signal level through modulation of the duty cycle. PWM is used in a variety of situations, from controlling the intensity of a light bulb with a dimmer switch to transmitting data across a fibre optic line. Through the use of this technique, analogue circuits can be controlled digitally, thus reducing system costs and power consumption.

LMD18200T is able to work with two of the more popular forms of PWM signals detected at PWM pin 5 (Figure 6.12b); Lock Anti-Phase PWM and Signal/magnitude PWM. With a Lock Anti-phase PWM, single variable duty-cycle signal transmitted at the “DIRECTION INPUT” (pin 3). The signal is encoded with both direction and amplitude information. At duty-cycle below 50% the average load current will flow from Output 1 to Output 2 while at duty-cycle above 50% the average load current will flow from Output 2 to Output 1. A 50% duty-cycle PWM signal represents zero drive as the net value of voltage integrated over one period is zero as illustrated in Figure 6.13.

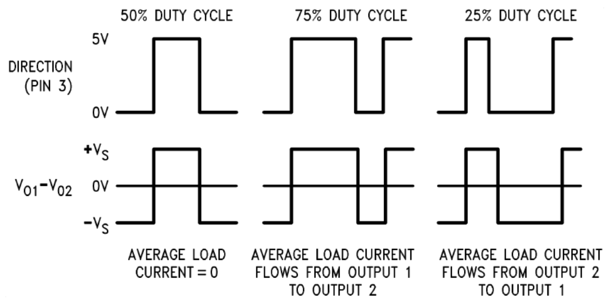


Figure 6.13 Lock Anti-phase PWM control

Unlike the Lock Anti-phase PWM, the Signal/magnitude PWM control method require two separate signals of direction and speed. The speed is modulated by the PWM duty-cycle received at “PWM INPUT” pin (Pin 5) while the direction of the load current is determined with the logic signal at “DIRECTION INPUT”. Absence of PWM signal represents zero drive as shown in Figure 6.14.

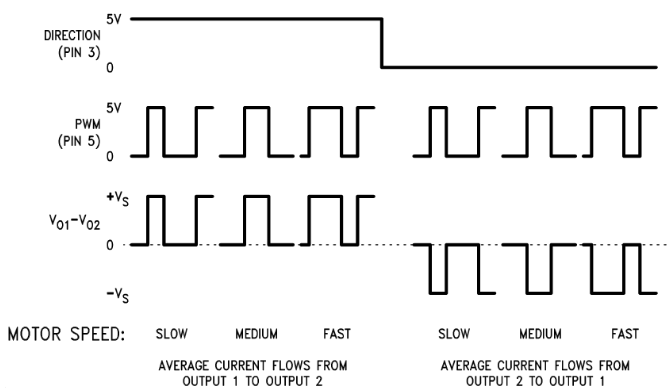


Figure 6.14 Signal/Magnitude PWM Control

At first Lock Anti-Phase PWM seems somewhat counter intuitive in alternately driving the motor forward and then reverse to stop the motor. Although it may seem to burn up a lot of power, because the motors inductance low pass filters the current to a DC value zero current is sourced at 50% duty-cycle. But obviously the motor does not act as a perfect lo pass filter and the resulting output waveform will ripple resulting in power loss. This ripple will increase if the inductance of the motor is too little for the PWM frequency resulting with greater power loss and vibration in the motor.

Comparing the power consumption benefits, the Signal/Magnitude PWM control method was selected for the Motor Driver system. Although it is a disadvantage of having more signal line compared with the Lock Anti-phase PWM control method, speed modulation at higher resolution is achievable, although it may be of higher resolution than the motors response time.

6.2.2 Circuit Design

The circuit provided in the LMD18200 3A, 55V H-Bridge datasheet, found in Appendix C of this thesis, has been modified to design the motor driver circuit. The motor drive circuit is built on two separate boards of Driver Chip board and PICAXE Board as shown in Figure 6.15.

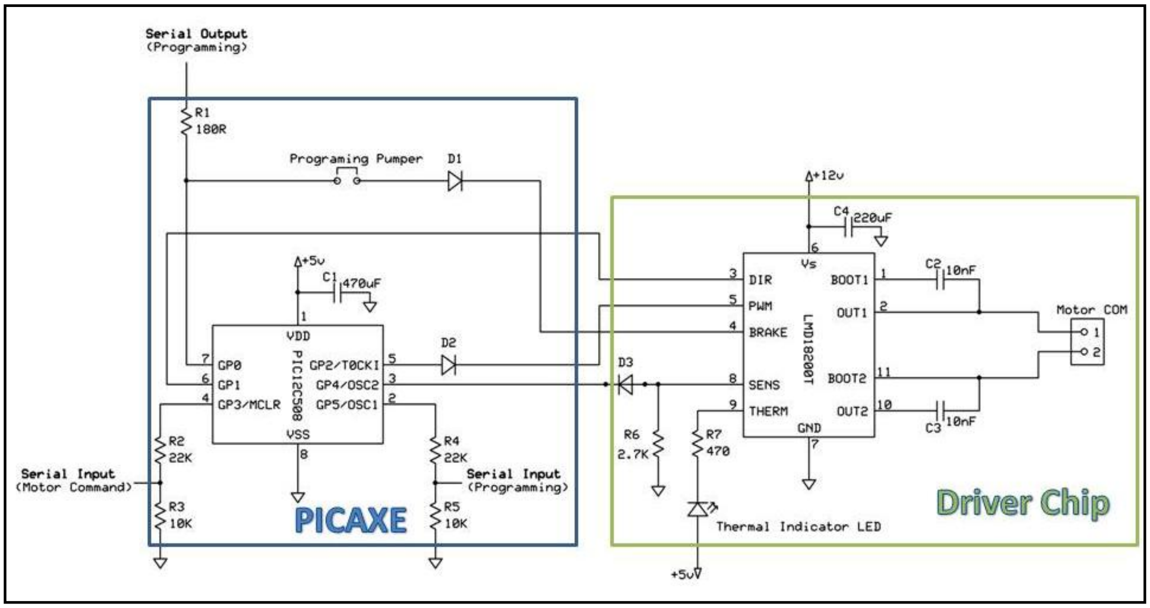


Figure 6.15 Motor Drive Circuit

The two input ports 3 & 5 on the LMD18200T are directly connected to the two output pins 5 and 6 on PICAXE. The BRAKE input port 4 is grounded as it is not used for this research. The Thermal output pin is connected to the Thermal Warning LED via current limiting resistor (R1). LMD18200T is supplied with regulated 12v source conditioned through a STMicroelectronics 12v regulator. Although not shown in the figures, the power supply circuit identical to the one used for the Sensory Module is used (more in chapter 5) sourcing the PICAXE and the radio module (Chapter 7). The two resistors R1 & R2 is used to create a Program Download interface discussed in Chapter 5.

6.2.3 Program

This section of the chapter will look into the BASIC code programmed into the Pic-08M microcontroller. It is a simple program used to receive motor command from the LabVIEW Motor Control VI (discussed in Chapter 8) to control the DC Motor accordingly. The code commences by defining symbols for constants/variables and then setting the internal clock speed to 8 megahertz in the *'Init'* routine via the *'setfreq'* command.

Code 6.1 PIC-08M 'Initi' Routine

```
Symbol DutyCycle = W0
Symbol Direction = W1
Symbol DC = W2
Symbol Current = W3
Symbol CurrentLimit = B8

Init:
Setfreq M8
DC = 0
CurrentLimit = 2/5*1024
pause 500
```

The first part of the routine reads the voltage across the *Current Sense* resistor using the 10bit Analogue-to-Digital converter. When the reading in above 2V, that's when the output current of the LMD18200T output current is above 2A, the *ShutDown* routine is activated, shutting down the circuitry (Code 6.2)

Code 6.2 Current Sense

```
ReadADC10 1, Current
if Current >= CurrentLimit then ShutDown


ShutDown:
pwmout 3,0,0
High 1
```

The program used *'serin'* command to receive the *'direction'* and *'Duty cycle'* values from the motor command received through pin 2 while using the qualifier characters "LAB" to filter out noises. Using the two control values the program flows a simple logic code to select the three states; Brake, Clockwise and Anti-clock. In each state the values of the two output pins are set. The 'pwmout' command is used to generate appropriate PWM signal with the frequency of 1000 Hz. The *motor start*-up routine is used to ramp the PWM duty cycle slow to avoid circuit damage caused from motor start-up current (Code 6.3).

Code 6.3 Read & State control

```
Main:
high 4
serin 2, N4800_8, ("LAB"),Direction,#DutyCycle  'Receive Command from LabView
low 4

ReadADC10 1, Current
if Current >= CurrentLimit then ShutDown

if DC < Dutycycle then
        DC = DC +1
endif

‘Motor Start-up Routine
if DC > Dutycycle then
        DC = DutyCycle
endif

if Direction = "B" then     Brake
if Direction = "F" then  Clockwise
if Direction = "R" then     CounterClockwise

Brake:
        High 1          'Brake ON
        Low 2                   'Direction Forwards (NOT IMPORTANT)
        pwmout 3,0,0    'Set PWD
        DC=0                    'STOP Motor
goto Main

Clockwise:
        Low 1                                           'Brake OFF
        High 2                                  'Direction Forwards
        pwmout 3,199,DutyCycle
goto Main

CounterClockwise:
        Low 1                                           'Brake OFF
        Low 2                                   'Direction Reverse
        pwmout 3,199,DutyCycle
goto Main
```

CHAPTER 7 RADIO

The implementation of a radio component is an important part in the development of the RTIDM system explored in this research. The radio module allows for real-time data acquisition between the Sensory Module, Motor Drive Module and the Computer Control Program. This chapter will evaluate the implementation of the XBee/PICAXE Radio Module (AXE210) and the way it has been setup to suite this research. Shown in Figure 7.1 is a block diagram demonstrating the implementation of radio module.

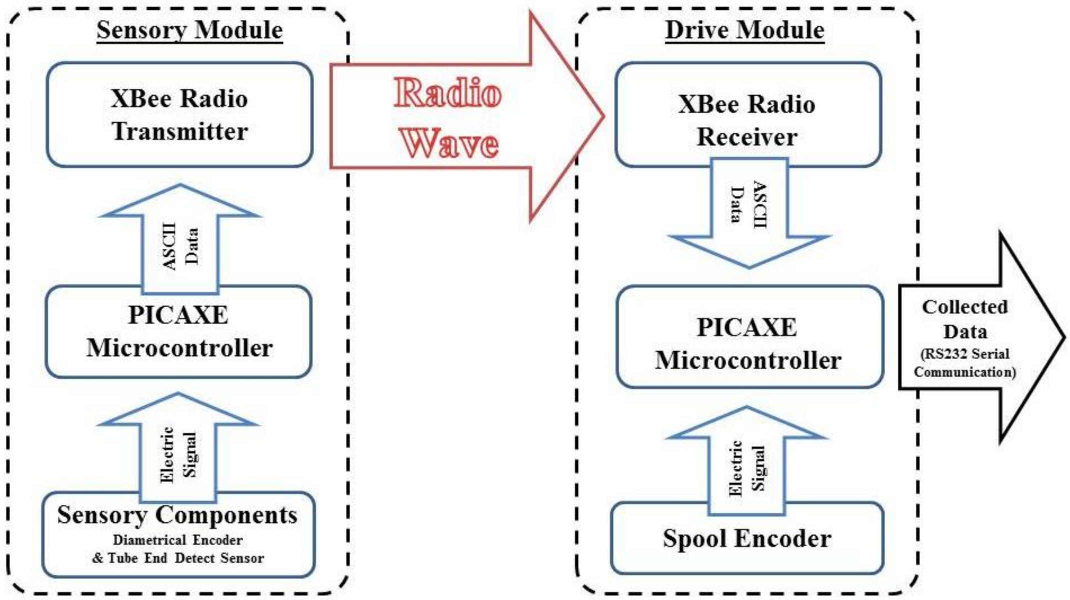


Figure 7.1 Radio Implementation Block Diagram

7.1 Radio

Radio is the transmission of information by the oscillation of electromagnetic waves transmitted through air and vacuum space. A radio instrument is normally a two-part system composed of a transmitter and a receiver. The transmitter radiates electromagnet wave encoding information commonly by modulating the frequency, amplitude and the phase of the carrier frequency. The receiver unit is able to detect the radio information by demodulating the alternating current in the receiver antenna induced from the transmitter radio.

Radio waves can travel between two points either by propagating in free space or by being guided in a medium as a coaxial cable, wave guide or optic fibre. In the case of this research, radio wave is radiated between the transmitter and the receiver propagated inside a cylindrical tube potentially acting as a radio guide medium. in principle, when a radio wave is carried inside a guiding medium there is not likely to be any interference with other radio users allowing for full usage of the radio frequency [15].

7.1.1 Closed Wave Guide

Lumped resistors, capacitors, and inductors are not the “pure” components they are assumed to be at lower frequencies. Their true nature at higher frequencies has undesirable resistances, capacitances, and inductances, which result in energy losses which must be taken into account during design of any wireless circuit [16]. The classical inverse square law found in many other fields of physics state that energy from an isotropic source propagates outward in a spherical fashion and therefore the power is smeared or distributed over the whole surface area of the sphere [16]. To this at distance *d* the power density of the receiver module is equal to the power transmitted divided by the surface area of the sphere (Equation 6.1). That is, as the distance between the transmitter and the receiver module is doubled, the power seen by the receiver is reduced by quadrupled.

$$p = \frac{p_T}{4\pi d^2}\mathrm{Wm}^{-2}$$

Equation 7.1 Free Space Propagation

Compared with open space radio propagation it is a common practice to make use of wave guides to dramatically amplify the radio wave propagation distance. It is sufficient to note that enclosed guiding media, such as those in figure 6.2, performs as a type of high-pass filter and will only allow the passage of signals with wavelengths above a certain minimum, the cut off frequency. The cut-off frequency is largely influenced by the dimension of the wave guide media and can be roughly determined by the following two equations (Equation 6.2a & 6.2b).

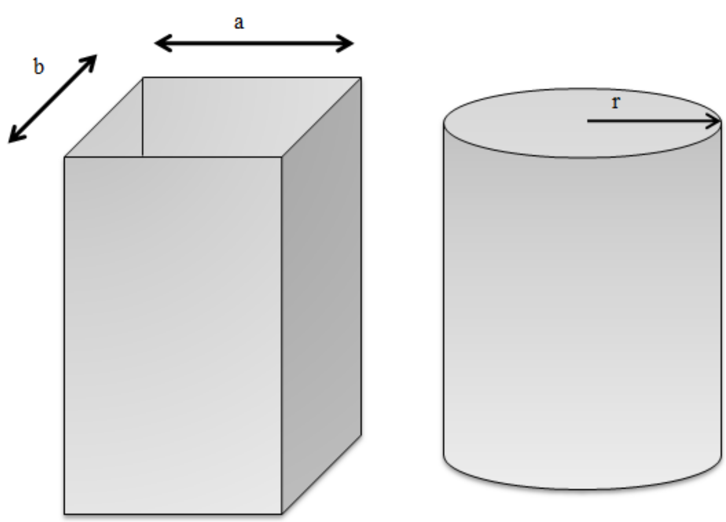


Figure 7.1 Type of Wave Guide

$$f_c = \frac{150}{b}\mathrm{MHz}$$

Equation 7.2 Rectangular cross-section wave guide media

$$f_c = \frac{87.9}{r}\text{MHz}$$

Equation 7.3 Circular cross-section wave guide media

By substituting the 55mm into the equation 7.2b the cut-off frequency of the 110mm bore reformer tube can be determined to be 1.6GHz. Although the wave guide theory state that signal below the tunnel cut-off frequency will not radiate, there are some energy penetration near the opening. Ignoring any reflections caused by the discontinuity from free space to the tunnel, a signal below the cut-off frequency, in attempting to penetrate the tunnel, will decay exponentially with the distance along the tunnel [15]. It is thus important to select a radio module that support radio frequency above 1.6GHz to be able to successfully propagate the radio wave through the 110mm reformer tube. Waveguide theory has been developed extensively and it is possible to find the lowest operation frequency to guide other reformer tube size.

7.2 X-bee Radio

For the FIDM system, the Transmitter/Receiver pair must transmit radio data reliably over a distance of at least 14m within a 110mm bore reformer tube. The system will be used as the primary communication stream to transmit sensory data retrieved by the Sensory Module to the User Interface GUI operated on a Laptop Computer (see Chapter 7). For the purpose of this research a modified Picaxe AXE210 Connection Project Board has been used fitted with an X-Bee Radio module and a Picaxe Microcontroller.

Figure 7.3 X-Bee RF Module

The X-Bee Radio Frequency (RF) Module is a pre-assembled wireless communication module that operates on the 2.4GHz frequency baud. The module utilizes ZigBee/Mesh topologies incorporating IEEE 802.15.4 networking protocol providing quick, robust communication in point-to-point, peer-to-peer, and multipoint/star configuration (Figure 6.4). Whilst the more common 433MHz modules are low cost and may be suitable for some very simple PICAXE application, the XBee module offers considerable advantages in this research (see the previous section on Wave Guide).

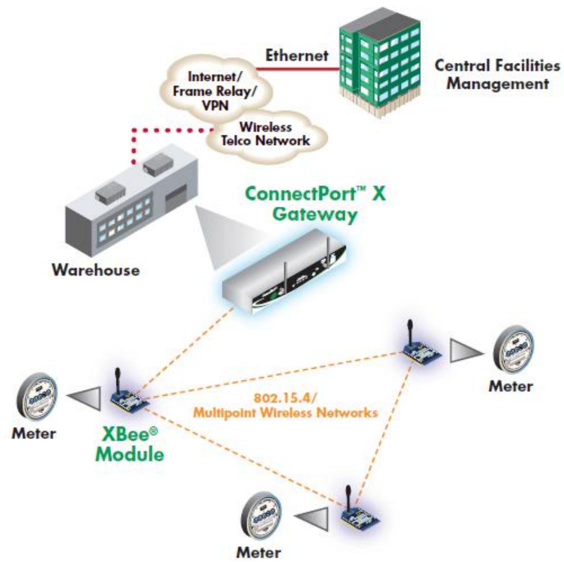


Figure 7.4 XBee Multipoint/Star Configurations (Appendix C)

One of the primary advantages of the XBee module is its capability for 'bi-directional' communication allowing single module to act as a receiver and transmitter simultaneously without the need for pre-configuration. The module also allows simple module addressing and channelling for multipoint product communication, enabling robust end-point connectivity with ease. Finally the XBee protocol has an in-build 'data-packet' building and error-checking employing 128-bit AES encryption ensuring reliable and secure data transmission over the range of 100ft (30m) indoor/urban range and 300ft (90m) Outdoor RF line-of-sight range.

7.2.1 Circuit Design

The pre-assembled Picaxe AXE210 Connection Project Board allows simple interfacing between the XBee and PICAXE microcontroller. The transmitter and receiver circuits illustrated in Figure 7.5 and 7.6 are designed based on the modified Connection Project board circuitry provided in the PICAXE AXE210 "PICAXE Connection (AXE210)" found in Appendix of this thesis. The AXE210 project board used for radio transmitter has been modified to fit a PICAXE-40X microcontroller discussed in the Chapter 5. The receiver board has been modified to read the analogue reading from the spool rotary encoder (see Chapter 6). The detail information of the circuit can be found in the AXE210 Datasheet.

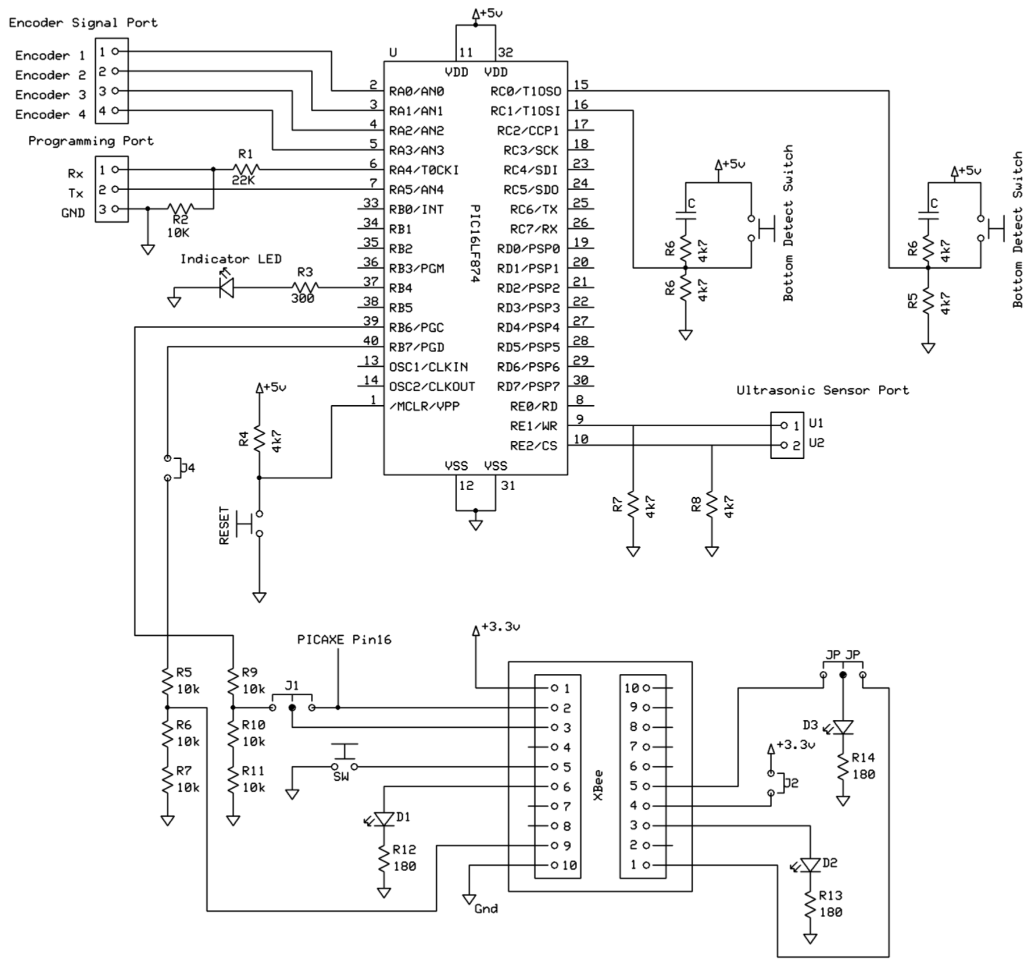


Figure 7.5 Radio transmitter circuit

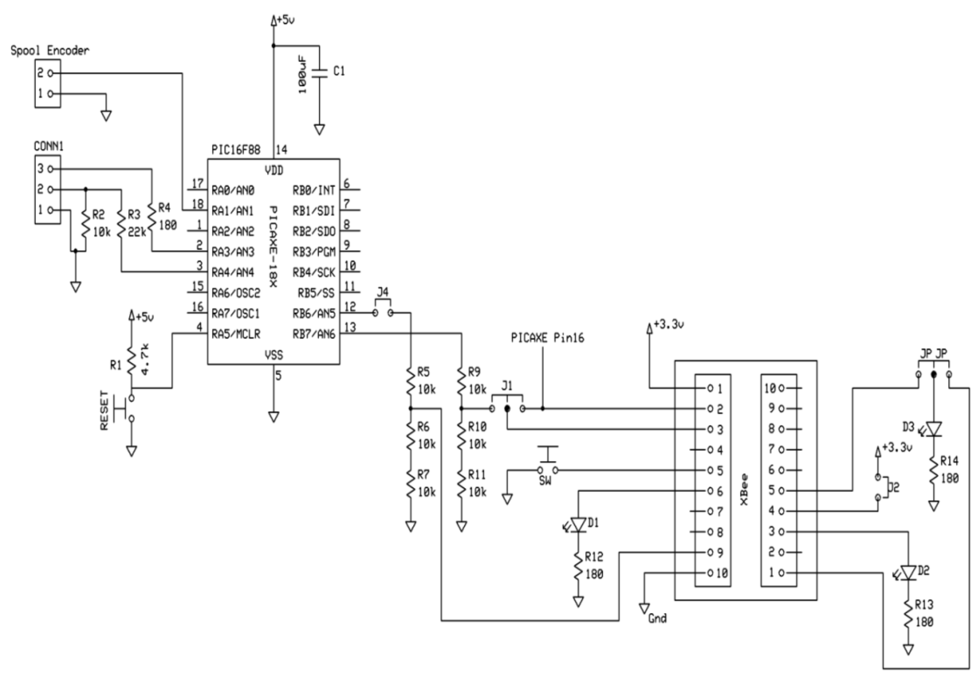


Figure 7.6 Radio Receiver circuit

7.2.1.1 Addressing

One of the main advantages of the XBee module is that they can be setup for selective communication between multiple modules, ignoring information from inadequate XBee module running in the same environment. Each XBee module can be addressed with network nicknaming and network Group ID for selective communication with unique devices. Table 7.1 list the available configurable components on the XBee module. This detail along with more XBee module data can be found in the PICAXE AXE210 Datasheet in Appendix C.

Broadcast Channel (CH) The XBee modules can communicate on different 'broadcast channels'. All XBee modules in the same network must be on the same channel. By placing different networks on different channels, interference can be reduced. By changing channel you may also reduce interference from, for instance, a home computer WiFi setup.
Baud Rate (BD) To communicate, all XBee units must be operating at the same baud rate. For PICAXE setups it is recommended to use a baud rate setting of 2400, as this is compatible with all PICAXE chips. Although this is fairly slow by modern standards, it is quite adequate for most PICAXE projects.
Network Group (ID) The XBee modules can be configured to work in 'Network Groups' (referred to as 'PAN ID' in the XBee documentation). Each module will only respond to devices in its own group. The group is defined by a 16-bit number.
Serial Number (SH)(SL) Each XBee unit has a unique 64-bit serial number (aka 'long address'). This serial number is factory loaded and cannot be changed. When transmitting data you can choose to address the data to a unique device, identified by its serial number. The serial number is printed on the bottom of the XBee module.
Nickname (MY) Each XBee unit can also be set with a user configurable 16-bit 'my nickname' (aka 'short address'). The advantage of the 'nickname' over the serial number is that it uses less memory in a PICAXE program. It also allows XBee units to be easily interchanged within an existing system by re-programming a replacement module (which would have a different serial number) with the existing nickname.

Table 7.1 XBee module configurable components

With the use of PICAXE Programming Editor Software and the MAX3232 chip, the two receiver/transmitter modules have been setup with the address configuration presented in figure 6.10. The two modules are setup to work in the upper Broadcast Channel 9600 in channel "AA" with the default "Network Group" 3332. The transmitter module located in the Sensory Module has been nicknamed "TRAN" in long serial mode (64bit) and is configured to communicate with the unique receiver module located in the Driver Module nicknamed "RECE" and vice versa.

	Receiver Module	**Transmitter Module**
Baud Rate	9600	9600
Broadcast Channel	AA	AA
Network Group	3332	3332
Destination Nickname	'RECE'	'TRAN'
My short Nickname	'TRAN'	'RECE'

Table 7.2 XBee Module Configurations

7.3 Picaxe Code

The Transmitter/Receiver XBee pair is both integrated with its associated PICAXE microcontroller. The receiver module needs to receive and transmit useful information to the monitory system with minimal noise at optimum rate. Discussed in this section of the chapter is the PICAXE Receiver/Transmitter code used for the XBee radio modules. Some of the key programming commands and qualifier constant implementation is discussed.

7.3.1 PICAXE-40X Transmitter Module

The code is similar to the code discussed in chapter 4. The definition of the first bulk of the code can be found in the preceding chapter (Chapter 4.4.2 PICAXE-40X Sensory Module Code). The main difference is that the collected data is sent out from pin 7 via ‘serout’ command instead of ‘sertxd’ on pin 2. In using the ‘serout’ command, more sophisticated data transmissions are possible by dedicating transmission modes and qualifier components.

The command is commenced with the syntax ‘serout 7,T9600_8’ as illustrated in Code 7.1 which specifies true serial data output at port 7 at 9600 baud rate. Then a qualifier constant string ‘HEY’ is transmitted followed by the 12 byte variables. It should be noted that by default the serial transmission in PICAXE has no parity with eight data bits, and one stop bit.

Code 7.1: PICAXE-40X Transmitter Sensory module

```
Symbol S1=w0          ‘define word variable w0 as S1 (Sensor 1)
Symbol S2=w1          ‘define word variable w1 as S2 (Sensor 2)
Symbol S3=w2          ‘define word variable w2 as S3 (Sensor 3)
Symbol S4=w3          ‘define word variable w3 as S4 (Sensor 4)
Symbol U1=b8          ‘define byte variable b9 as U1 (Ultrasonic 1)
Symbol U2=b9          ‘define byte variable b10 as U2 (Ultrasonic 2)
Symbol BT1=b10        ‘define byte variable b11 as BT1 (Button 1)
Symbol BT2=b11        ‘define byte variable b12 as BT2 (Button 2)

Init:
setfreq m8
'input PortC pin1
'input PortC pin2
high PortC 0

Main:
ReadADC10 6,S1              'Read Encoder 1 via 10bits ADC
ReadADC10 1,S2              'Read Encoder 2
ReadADC10 2,S3              'Read Encoder 3
ReadADC10 3,S4              'Read Encoder 4
ReadADC10 7,U1              'Read Ultrasonic Sensor 1
ReadADC10 0,U2              'Read Ultrasonic Sensor 2
```

```
if PortC pin1 = 1 then          'If Stopper Button is High, set BT1=1
        BT1 = 0
else
        BT1=1
Endif

if PortC pin2 = 1 then          'If Stopper Button is High, set BT2=1
        BT2 = 0
else
        BT2=1
Endif

‘sertxd ("S1 =",#S1," S2 =",#S2," S3 =",#S3," S4 =",#S4," U1 =",#U1," U2 =",#U2," BT
=",#BT,13,10)
serout 7,T9600_8,("HEY",b0,b1,b2,b3,b4,b5,b6,b7,b8,b9,b10,b11,BT)
goto Main:
```

7.3.2 PICAXE-18x Receiver Module

The code used in the receiver PICAXE-18X is shown below in Code 6.2. The code commences by defining symbols for constants and variables and initializes the internal clock speed to 8 megahertz via the ‘setfreq’ command. Then the code enters a permanent loop ‘main’ that reads the received serial data and the ADC analogue reading from the Spool Encoder and transmits a packaged serial data via the serial programming port.

Using the “serin” command the serial data received from the XBee radio module is through pin 7. The ‘T9600_8’ set the transmission mode to 9600 baud rate at over clocked chip rate of 8MHz. With confirmation of qualifier string ‘HEY’, 12 8bit serial data received is stored to their allocated byte variables. The analogue signal received at pin 1 from the Spool Rotary Encoder sensor is read into the variable ‘EN’ via the High-resolution 10-bit Analogue-to-Digital converter.

Finally, the filled variables are transmitted out from pin 2 to a computer for further processing via ‘sertxd’ command. The serial out is transmitted at 2400 baud rate, with no parity, 8 data bits, one stop bit, and an inverted logic level. Figure 7.15 is the raw receiver output transmitted through the serial cable.

Communication between the PICAXE-08M microcontroller and the computer is established by serial communication using the RS232 port and LabVIEW software interface. The microcontroller has predefined BASIC commands to output serial information from any of the Input/output (I/O) pins available on the PICAXE-08M. With this method the information received from the sensors are transmitted to the computer via a RS232 cable as illustrated in figure 6.16. With every cycle of the ”main” routine the raw data stored in the internal memory of the Microcontroller is converted into ASCII characters and sent to the computer by using the "serout" BASIC command. The interpretation of this information is discussed in chapter 6.

Code 7.2: PICAXE-18X Receiver XBee & Serial Out

```
Symbol S1=w0        ‘define word variable w0 as S1 (Sensor 1)
Symbol S2=w1        ‘define word variable w1 as S2 (Sensor 2)
Symbol S3=w2        ‘define word variable w2 as S3 (Sensor 3)
Symbol S4=w3        ‘define word variable w3 as S4 (Sensor 4)
Symbol U1=b9        ‘define byte variable b9 as U1 (Ultrasonic 1)
Symbol U2=b10       ‘define byte variable b10 as U2 (Ultrasonic 2)
Symbol BT1=b11      ‘define byte variable b11 as BT1 (Button 1)
Symbol BT2=b12      ‘define byte variable b12 as BT2 (Button 2)
Symbol EN=w6        ‘define word variable w6 as EN (Encoder)

init:
setfreq M8          ‘set chip clock to 8 megahertz
Pause 100           ‘pause 100ms

main:
    serin 7,T9600_8,("HEY"),b0,b1,b2,b3,b4,b5,b6,b7,b8,b9,b10,b11      ‘receive Data
    readadc10 1,EN                                   ‘read ADC 1 value (Spool Encoder)
    'pause 20
    sertxd ("S1=",#S1,", S2=",#S2,", S3=",#S3,", S4=",#S4,", U1=",#U1,", U2=",#U2,",
    BT1=",#BT1,", BT2=",#BT2,", EN=",#EN,$D, CR,LF)  ‘send data via serial out port
goto main                                            ‘loop back to main
```

Figure 7.7 Sample Receiver Output

```
S1=443, S2=705, S3=234, S4=10, U1=62, U2=18, BT1=0, BT2=0, EN=491

S1=443, S2=705, S3=234, S4=10, U1=62, U2=18, BT1=0, BT2=0, EN=491

S1=443, S2=704, S3=234, S4=10, U1=62, U2=18, BT1=0, BT2=0, EN=491

S1=443, S2=705, S3=234, S4=9, U1=62, U2=18, BT1=0, BT2=0, EN=491

S1=443, S2=705, S3=234, S4=10, U1=62, U2=18, BT1=0, BT2=0, EN=491

S1=443, S2=705, S3=233, S4=10, U1=62, U2=18, BT1=0, BT2=0, EN=491

S1=443, S2=705, S3=234, S4=10, U1=62, U2=18, BT1=0, BT2=0, EN=491

S1=443, S2=705, S3=234, S4=10, U1=62, U2=18, BT1=0, BT2=0, EN=491

S1=443, S2=704, S3=235, S4=10, U1=62, U2=18, BT1=0, BT2=0, EN=491
```

CHAPTER 8 LABVIEW SOFTWARE

For the ease of operators' interaction with the FTIDM system National Instrument LabVIEW programmer has been used to develop a Control Software Graphical User Interface (GUI). The software allows the users to control the RTID system through a laptop computer while retrieving real-time data and making system configuration. This chapter will discuss the software architecture and layout of the Control Program.

8.1 National Instrument LabVIEW

LabVIEW is short for Laboratory Virtual Instrument Engineering Workbench. It is a powerful and flexible graphical development environment used by millions of engineers and scientists to develop sophisticated measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart. It offers unrivalled integration with thousands of hardware devices and provides hundreds of built-in libraries for advanced analysis and data visualization – all for creating virtual instrumentation. The LabVIEW platform is scalable across multiple targets and OSs, and, since its introduction in 1986, it has become an industry leader [8].

LabVIEW programs are called Virtual Instruments or **VI**s for short. LabVIEW is different from text-based programming languages (such as FORTRAN and C) in that LabVIEW uses graphical programming language, known as the G programming language [8]. In this chapter, multiple screen shots of the G Program are illustrated. The programming language used by LabVIEW is referred to as dataflow programming languages were execution is determined by the structure of a graphical block diagram on which the programmer connects different function-nodes by drawing wires. An extensive library of virtual instruments and functions is proved.

8.2 LabVIEW Virtual Instrument

The RTIDM Control Program is an interactive computer system providing visual means to operate the RTIDM system through a Personal Computer (intended for a Laptop computer). Figure 8.1 illustrates the block diagram of the LabVIEW control software interaction with the hardware. To design a computer system that meets the needs of this project, the aims or goals the user has towards the system must be identified. Below is six key tasks that has been identified and the program must perform.

- Provide simple means to control the movement of the Sensory Module
- Provide safety features (e.g. Sensory Module Movement limit)
- Display visual information so that the user is able to verify the state of the system.
- Log inspection data into an electronic file for documenting.
- Able to be adjust system configuration

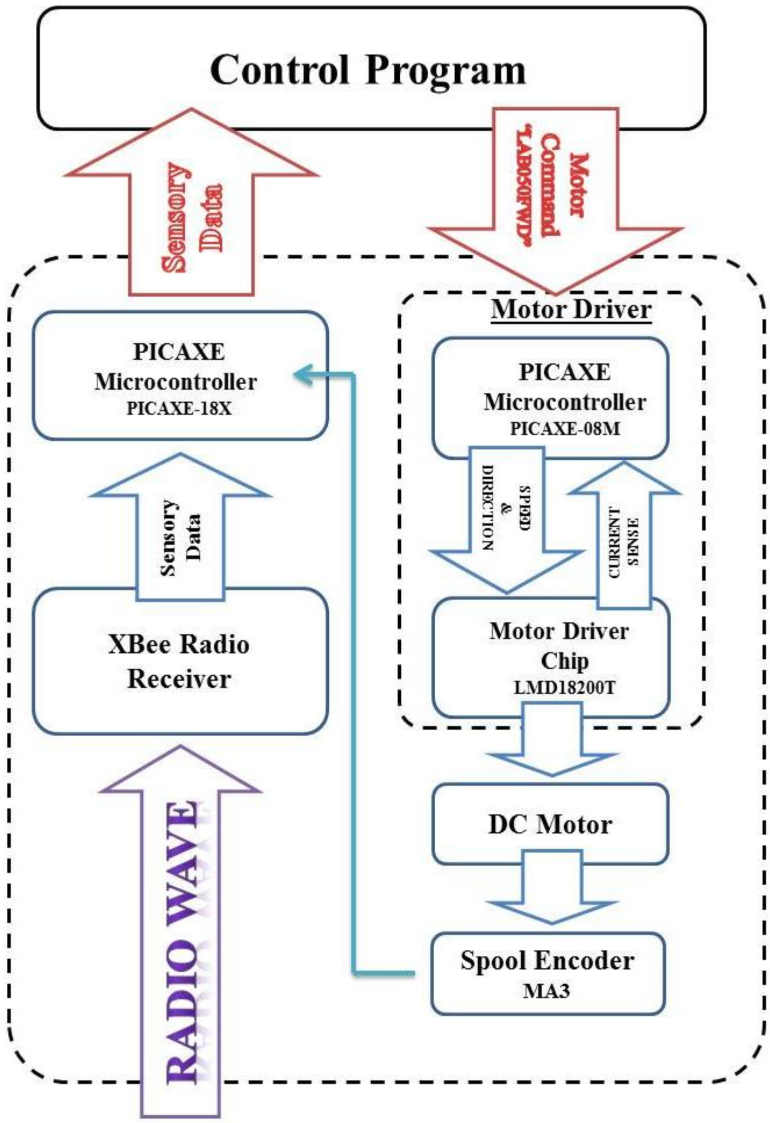


Figure 8.1 RTIDM system block diagram

LabVIEW Virtual Instrument program is comprised of Front panel and a block diagram. Both components consist of graphical objects that are the G programming elements. Front panels is essentially a graphical control panel contain various types of controls and indicators for human interactions. Block diagrams containing terminals corresponding to front panel controls and indicators, as well as constants, functions, subVIs, structures, and wires that carry data from one object to another [8]. The front panel of the RTIDM control program and its associative block diagram window is shown in Figure 8.2.

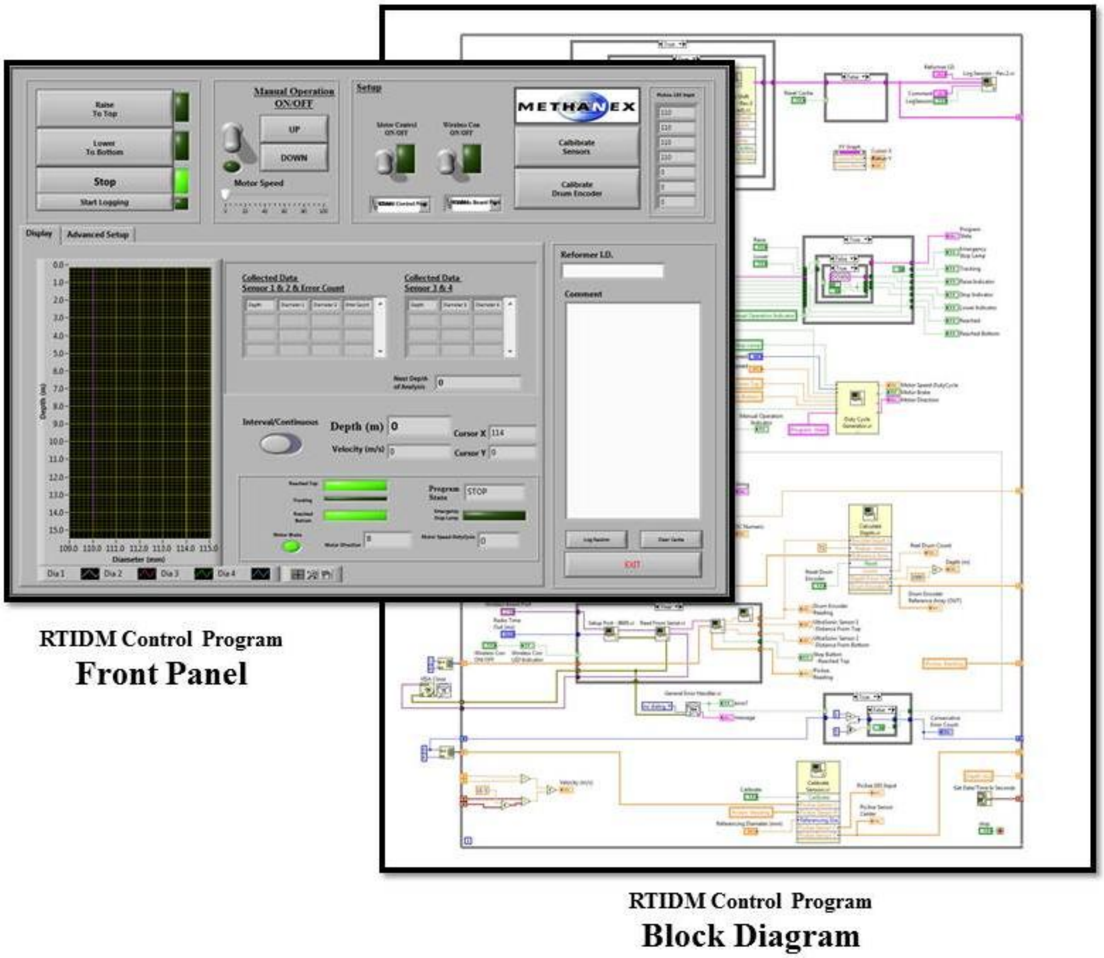


Figure 8.2 RTIDM Control Program front panel & block diagram

8.3 Graphical User Interface (GUI)

As illustrated in figure 8.3, the Front Panel of the Control Program is made up of four interface panels - Data Display, Control panel, System Setup and Data Entry panels. The advanced setup menu can be accessed by clicking on the tab located above the Graph display. Using the controllers and indicator the user is able to interact with the code. In this section of the chapter each component of the RTIDM Control Program is discussed.

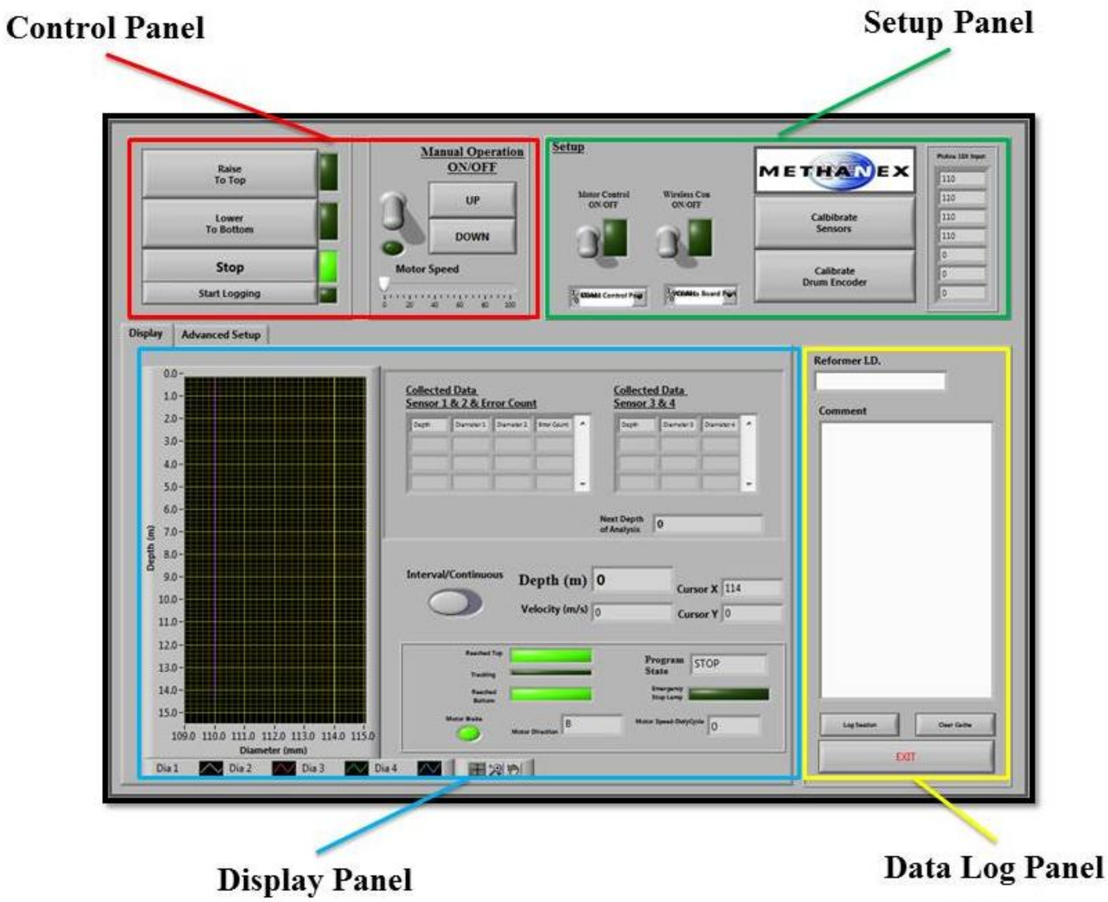


Figure 8.3 Software Interface

8.3.1 Data Display panel

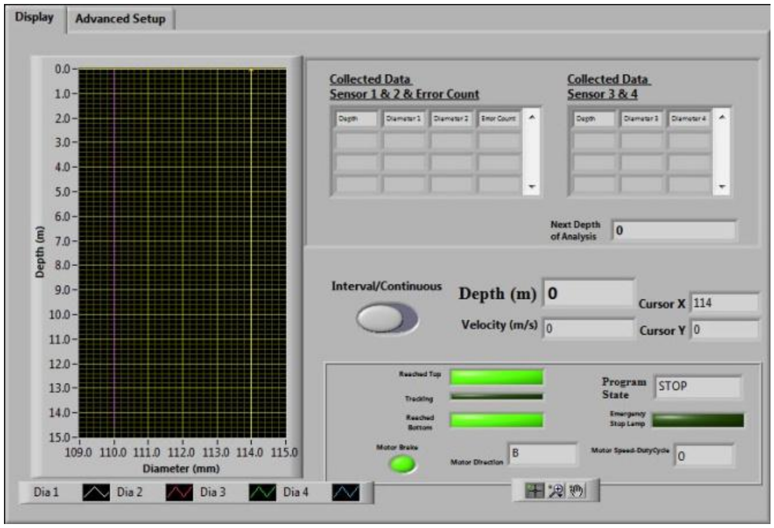


Figure 8.4 Display Panel indicator locality

The Data Display panel consists of multiple type of indicator to indicate the current behaviour of the system. With simple indicator the user is able to visually confirm the state of the system during the period the hardware is inside the reform tube and out of sight. Illustration above (Figure 8.4) shows the location of the 13 indicators located on the Data Display panel.

8.3.1.1 Motor Brake Indicator

Motor Brake – Round LED Indicator

As described in chapter 6, the Motor driver chip LMD18200 integrated in the Motor Driver Circuitry is capable of shortening the output terminals effectively “braking” the DC motor. This Indicator is potentially used to indicate when the motor is “braked” but is not used for this project.

8.3.1.2 Reached Top

Reached Top – Square LED Indicator

On the Sensory Module, an End Detect Switch is located on the top face of the hardware used to determine when the module has reached the top of the reformer tube (refer back to chapter 4). This indicator turns on when the Sensory Module has made contact with the base of the Drive Module.

8.3.1.3 Reached Bottom

Reached Bottom – Square LED Indicator

On the Sensory Module, an End Detect Switch is located on the bottom face of the hardware used to determine when the module has reached the bottom of the reformer tube and has made contact with the tube end (refer back to chapter 4). This indicator turns on when the sensory module makes contact with the reformer tube base.

8.3.1.4 Tracking

Tracking – Square LED Indicator

The ultrasonic sensor mounted to the sensory module is used to determine when the module is around 500mm from the end of the reformer tube (refer back to Chapter 4). This indicator turns on when the Sensory Module is within 500mm from the base of the Drive Module.

8.3.1.5 Motor Direction

Motor Direction – String Indicator

This text box displays the direction of the DC motor using single character code (see Chapter 6).

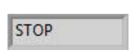
R = Anti-clockwise, B = at Halt, F = Clockwise

8.3.1.6 Motor Speed

Motor Speed (Duty Cycle) - Numeric Indicator

The speed of the DC Motor is controlled by Pulse Width Modulated signal (refer back to chapter 5). This indicator displays the duty cycle percentage transmitted to the motor driver hardware.

8.3.1.7 Program State



Program Sate – String Indicator

The state of the program can be separated into four states: Lowering, Raising, Stop, and Analysing (discussed in later chapter). This indicator displays the four program state of the software.

8.3.1.8 Emergency Stop

Emergency Stop – Square LED

Initially the Driver Unit was designed with an "emergency stop" button allowing the user to shut down the system in case of emergency, but was not implemented in the prototype. This indicator is potentially used to indicate when this "Emergency Stop" button is pressed.

8.3.1.9 Next Depth of Analysis

Next Depth of Analysis (m) – Numeric Indicator

During "Interval" analysis mode (discussed later in this chapter), this indicator displays the next depth at which the system will record the sensory output.

8.3.1.10 Depth

Depth (m) - Numeric Indicator

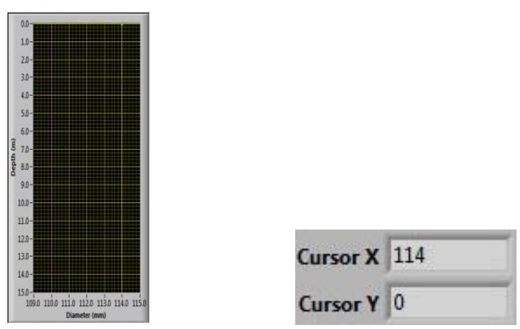
The "Depth (m)" numeric indicator displays the length or steel wire between the Driver Unit and the Sensory Module and can be seen as a Yellow horizontal line on the "Graph Display".

8.3.1.11 Velocity

Velocity (m/s) – Numeric Indicator

The "Velocity (m/s)" numeric indicator displays the rough estimation of the velocity at which the Sensory Module is travelling through the Reformer Tube. Positive speed (+) indicates that the module moving towards the bottom of the reformer and vice versa.

8.3.1.12 Depth vs Diameter Plot



Depth vs Diameter Plot & Cursor Value – XY Graph & Numeric Indicator

The radio component of this research enables the system for real-time data acquisition to retrieve sensory data. Using these collected data a Depth vs Diameter plot is drawn. With the cursor function the user is able to analyse the collected data and display on the "Cursor X" and "Cursor Y" numeric indicator

8.3.1.13 Data Analysis

Data Analysis – Numeric Array Indicator

In the centre of the GUI are two Collected Data array display the collected data stored in the computer memory. The serial communication consecutive error count between each data acquisition is also displayed. In this way the user is able to view the data collected before logging into a "Text" file. The collected data are stored in the following format.

Depth (m), Diameter 1, Diameter 2, Diameter 3, Diameter 4, Consecutive error count

8.3.2 Control Panel

The control panel is built upon multiple control nodes used to run the system. There are two basic control modes, Manual and Automatic operation. Correspondingly, the interface is made up of two sub-panels as shown in Figure 8.5. The system is capable of working with only one mode at a time, selected by the toggle switch. The round LED indicates the current mode that is activated: ON = Manual Operation, OFF = Automatic Operation

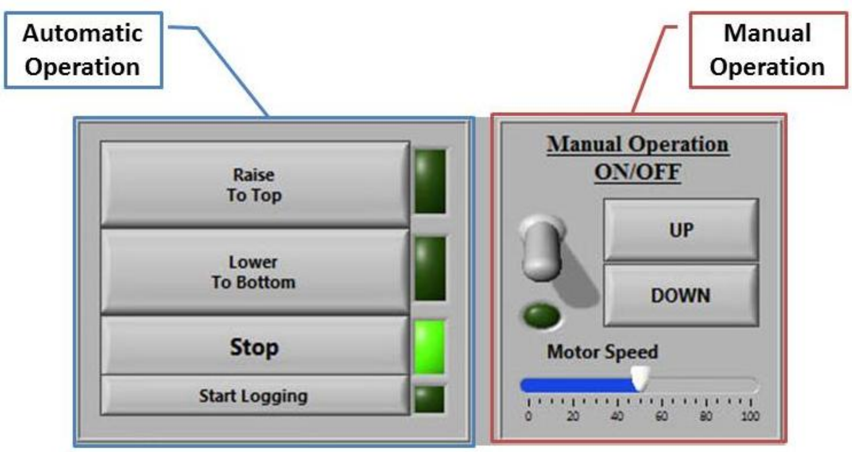
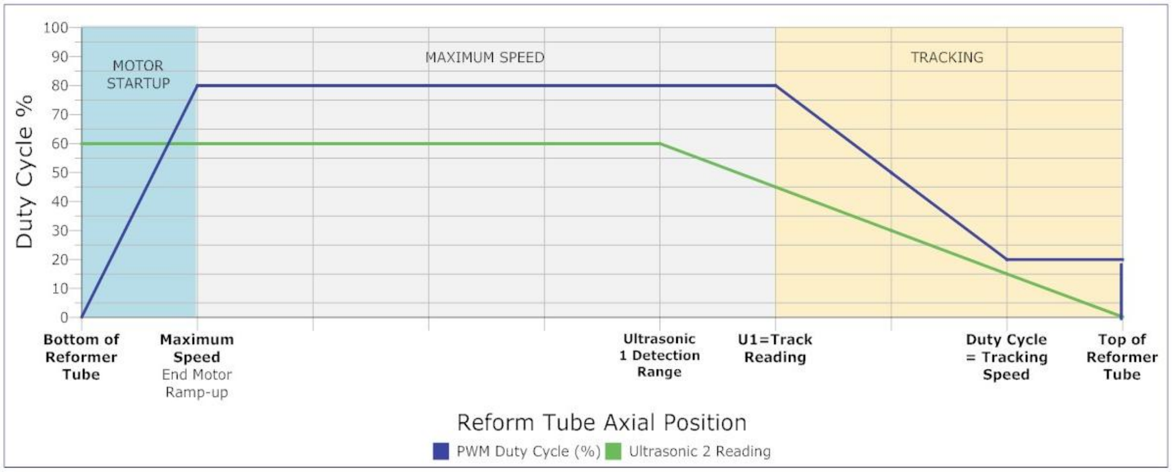


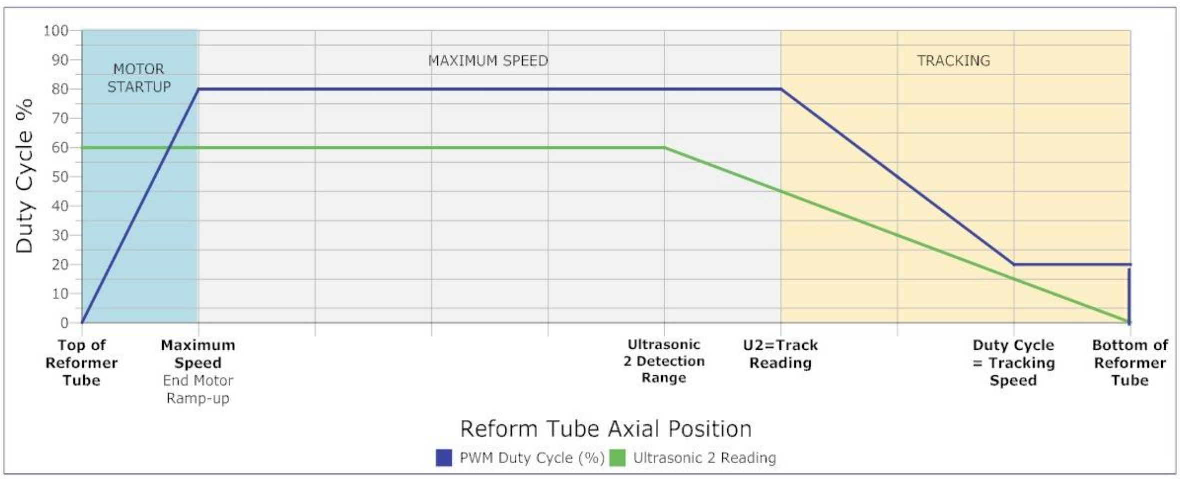
Figure 8.5 Control Panel

During Automatic Control mode, the four control buttons in the Automatic Operation sub-panel are activated. Under Automatic Control mode, the program will run a predefined control routine indicated by the associated LED indicator.

When the "Raise to Top" routine is active the system will raise the Sensory Module to the top of the reformer tube from its current position. When the initial position of the module is at the top of the reformer tube nothing will happen. When the "Lower to Bottom" button is pressed the system will lower the Sensory Module to the bottom of the reformer tube. Figure 8.6 represents a Depth vs Duty Cycle plot with associated sensory outputs for the two routines.



(a)"Raise to Top" Routine structure



(b) "Lower to Bottom" Routine structure

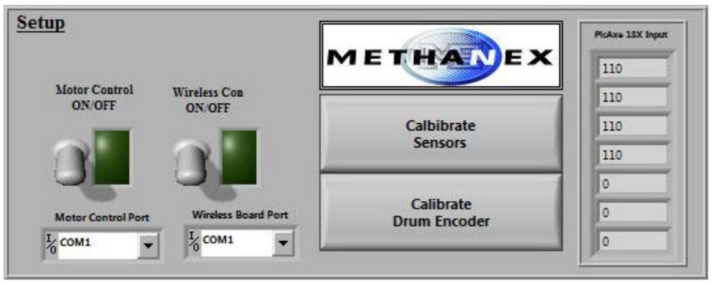
Figure 8.6 Routine Characteristic Diagrams

The maximum speed at which the system raises/lowers the module is determined by the "Max Duty-cycle" set by the operator in the "Advanced Setup" menu (80% in the diagram). Both routines include the motor start-up (Discussed in Chapter 6) and a tracking phase, and will automatically come to a halt with the aid of the End Detect Sensor 1. The blue area in Figure 8.6 shows the motor start-up phase where the motor speed is linearly increased to maximum speed at a constant rate (ramping). During the 'raising to top' routine, when the *Ultrasonic Sensor 1* output reading is below the "Tracking Reading" threshold, the tracking phase is activated, indicated as a yellow area on Figure 8.6. In this phase, the speed of the DC motor is decreased to the "Tracking Speed" value set by the user in the "Advanced Setup" panel (20% in the illustration). This speed is kept until the motor is stopped when the bottom of the reformer tube is detected by the *End Detect Switch 1*.

The *Lower to Bottom* routine is very similar to the *Raise to top* routine described above. Ultrasonic Sensor 2 is used to detect the bottom of the reformer tube to put the system into tracking phase and End Detect Switch 2 is used to end the routine.

8.3.3 System Configuration

System Setup panel is used to configure system setting to suit the user's application. Here the user is able to change the default system setting from simple serial port selection in the *Setup* panel (Figure 8.7a) to Ultrasonic tracking threshold values in the *Advanced Setup* panel (Figure 8.7b). For the advanced users, multiple raw data output can also be confirmed on the *Advanced Setup* panel.

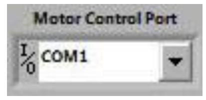


(a) 'Setup' Panel

(b) 'Advanced Setup' Panel

Figure 8.7 System Configuration Panel

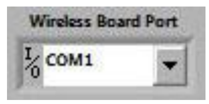
8.3.3.1 Motor Control Port



Motor Control Port – I/O Source Controller

The Motor Control Port controller allows the user to select the PC serial port that will be used for motor control unit. Upon start-up, the user must select the appropriate port before the Motor Control port is turned on.

8.3.3.2 Wireless Communication Port



Wireless Communication Port - I/O Source Controller

The Wireless Communication Port controller allows the user to select the PC serial port that will be used for wireless data acquisition. Upon start-up the user must select the appropriate port before the Wireless Communication port is turned on.

8.3.3.3 Motor Control ON/OFF

Motor Control ON/OFF – Toggle switch & LED Indicator

This toggle switch allows the user to turn on the PC serial port that is selected on the Motor Control Port. The square LED is used to indicate the activation of this port. This port must be activated for the program is able to control the DC Motor.

8.3.3.4 Wireless Communication ON/OFF

Wireless Communication ON/OFF – Toggle Switch & LED Indicator

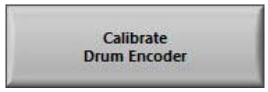
This toggle switch allows the user to turn on the PC serial port that is selected on the Wireless Communication Port. The square LED is used to indicate the activation of this port. This port must be activated for the program to retrieve sensory data from the hardware.

8.3.3.5 Calibrate Sensors

Calibrate Sensors – Control Button

As discussed in Chapter 4, during assembly of the Linear-to-Rotary Transducer the encoder body is aligned with the PMH so that the MAE3 rotary encoder roughly output 2.5v when the Encoder Disc is at centre at 112mm reformer tube diameter (θ at 0° in Formula 4.1). With the *Calibrate Sensor* button, the user can calibrate the diameter calculation equation (Equation 4.1) to compensate for this alignment offset.

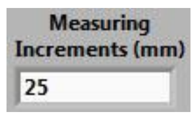
8.3.3.6 Calibrate Spool Encoder



Calibrate Spool Encoder – Control Button

With the *Calibrate Spool Encoder* button the user is able to perform a software calibration to synchronize the *Spool Encoder* output and the software setting. The depth counts to zero when the Sensory Module is in contact with the Drive Module.

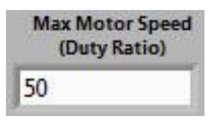
8.3.3.6 Measuring Increment



Measuring Increment (mm) – Numeric Indicator

The *Measuring Increment* allows the user to set the depth interval at which the data is collected during *Interval* data collect mode.

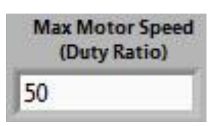
8.3.3.7 Maximum Motor Speed



Maximum Motor Speed (Duty Cycle %) – Numeric Indicator

The maximum speed at which the motor runs during automatic operation mode can set in Duty cycle percentage.

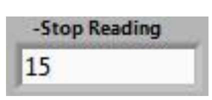
8.3.3.8 Tracking Reading



Tracking Reading – Numeric Indicator

Here the user is able to set the ultrasonic sensor output reading at which the tracking phase is activated during automatic control mode.

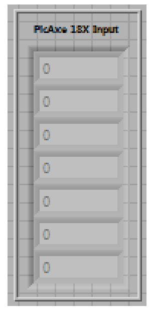
8.3.3.9 Stop Reading



Stop Reading – Numeric Indicator

In some situation the bottom detecting sensor on the Sensory Module may not be able to accurately detect the bottom of the tube. In such situation, the user is able to set the bottom ultrasonic sensor output to detect the bottom. That is, the bottom of the reformer tube is detected when the ultrasonic sensor output is less than the *Stop Reading* value.

8.3.310 Sensory Reading



Sensory Reading – Numeric Array Indicator

Sensory Reading displays the raw sensor output received from the Wireless Communication port. The sensor outputs are as follow:

- Rotary Encoder 1
- Rotary Encoder 2
- Rotary Encoder 3
- Rotary Encoder 4
- Ultrasonic 1
- Ultrasonic 2
- Top Detect Sensor
- Bottom Detect Sensor
- Spool Rotary Encoder

More information on these sensors can be found in the preceding chapter throughout Chapter 3~6.

8.4 Block Diagram

Block diagram is a pictorial representation of the LabVIEW program code. It is built upon interactions of execution icons connected with wires. The art of successful programming in LabVIEW is an exercise in modular programming [8]. The code is divided into a series of simpler tasks and a VI is constructed to accomplish each subtask (these VIs are identified as subVIs and are analogous to subroutines). The resulting subVIs is included into the top-level block diagram to form the complete program. The benefit of modularity is that each subVI is executed independently to one another allowing for easier debugging and verification [8].

The top-level block diagram of the RTIDM Control program is shown in Figure 8.8. The program can be divided into four subtasks - State Control, Motor Control, Data Logging and Sensory Calibration. Each consists of its associative subVIs.

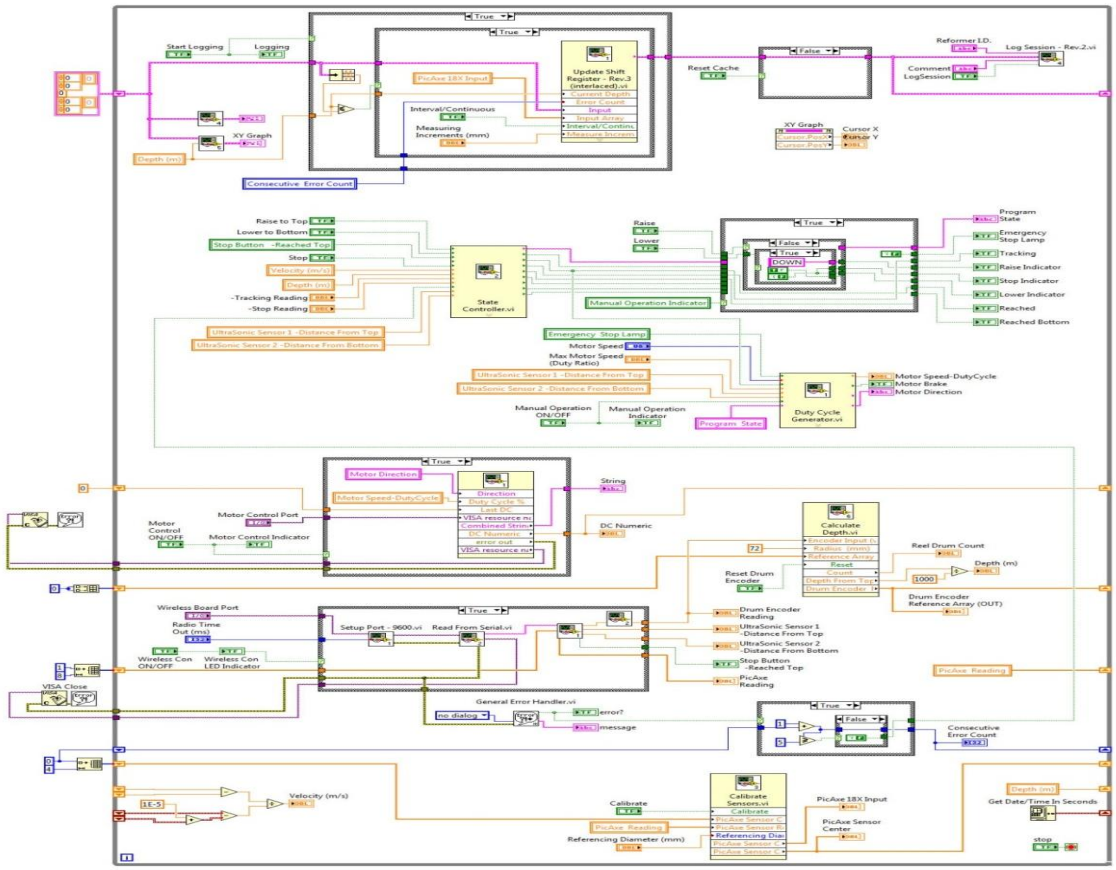


Figure 8.8 RTIDM Control Program block diagram subtasks

8.4.1 RS232 Data Input/output

As discussed in the preceding chapter, two serial communications are established between the PICAXE micro controller and the RS232 port. One port is used to receive a sensory reading transmitted from the Receiver PICAXE-18X microcontroller and another to transmit motor control command from the computer to the Motor Control PICAXE-08M microcontroller. The interface program compiled by LabVIEW makes advantage of the *Virtual Instrument Software Architecture* (VISA) to configure the *Communication Port* (COM Port). This allows information to be transmitted and received with the use of serial communication between the microcontroller and computer. Figure 8.9 shows the area of LabVIEW code used for COM Port configuration with its associative sub-VI. With the reference on the COM Port number and the *Timeout* values selected by the operator in the *Setup* panel (discussed earlier in this chapter), the *Setup Port – 9600* VI configures the corresponding COM Port with the configuration in

Table 7.3. Here, the VISA Configure Serial Port and the VISA Set I/O Buffer Size VI are used which are both predefined LabVIEW functions. The COM Port configuration is defined into the "*reference output"* node which is used by the *VISA Write/Read* VI for serial communication.

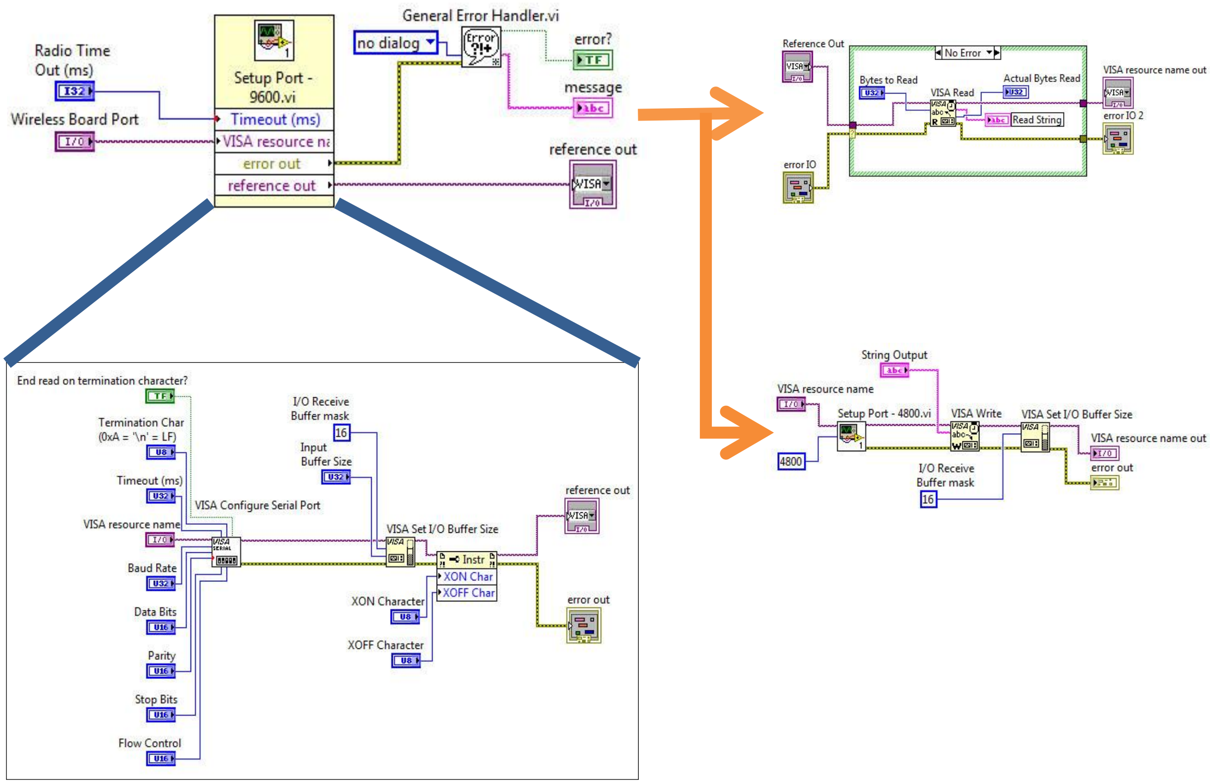
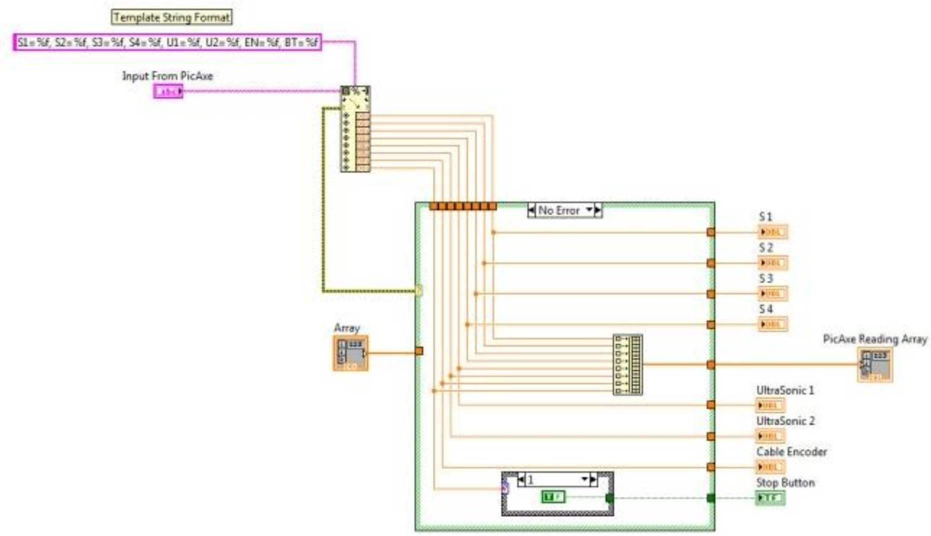
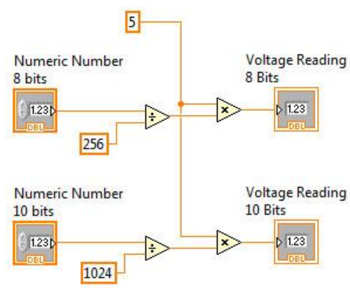


Figure 8.9 Serial Communication Setup and Read/Write

The string package received from the PICAXE-18M is first scanned through the *Scan from String* VI. Here the raw string input is compared with the "*Template String Format"* and separated into individual sensor component. These outputs are used to build a single "*PICAXE Reading Array"* string array (Figure 8.10). For any meaning full operation, these raw data must be converted into voltage readings from there associative *Analogue-to-Digital* converter is used. This conversion is performed by the "10/8bits to Voltage Converter" program with simple mathematics.



(a) Serial Communication Setup and Read/Write



(b) Bit Converter

Figure 8.10 Serial Communication Setup VI Block Diagram

8.4.2 State Control

The Control Program has two basic states, *Manual* and *Automatic* operation. Each made up of several sub-states. During Manual operation, the system operates mainly in aspects to the user control, with minimal interaction with the sensory readings while in the Automatic operation the state is controlled soley with the sensory reading with the operator only starting the sub-state initiation. Figure 8.11 is a screenshot of the block diagram accosiated with the State Control.

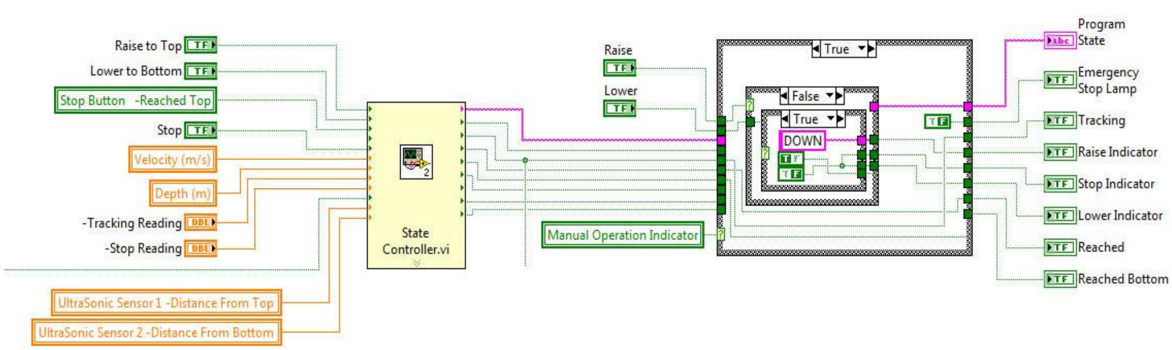


Figure 8.11 State Control block diagram

The most prominent component in the Automatic Operation section of the block diagram is the State Controller subVI. The VI is made up of complex condition state controller to automatically switch between the three sub-states using the sensory readings. Below in table 8.1 lists the control components used by the VI. Figure 8.12 is a State Diagram for the State Controller.

End Detect Sensor 1	Spool Encoder	Raise to top Button
End Detect Sensor 2	Velocity	Lower to Bottom Button
End Detect Switch 1	Tracking Reading	Stop Button
End Detect Switch 2	Stop Reading	

Table 8.1 Control Variable

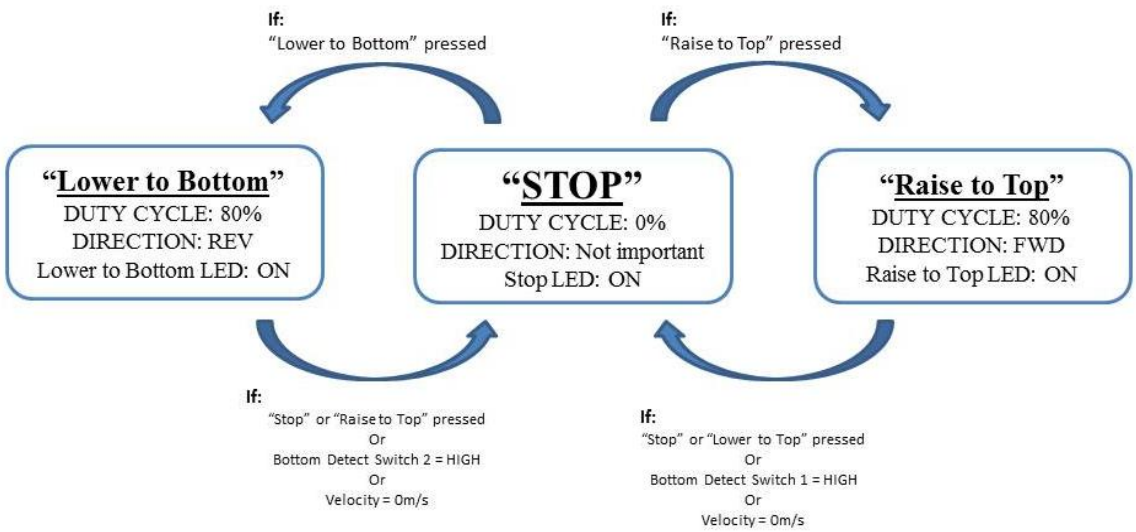


Figure 8.12 Automatic Operation state Diagram

In manual operation, the sub-states are predominantly controlled by the operator. As shown in the State Diagram below (Figure 8.13), on the Bottom Detection sensors are used to loop out of the state to limit the movement of the Sensory Module.

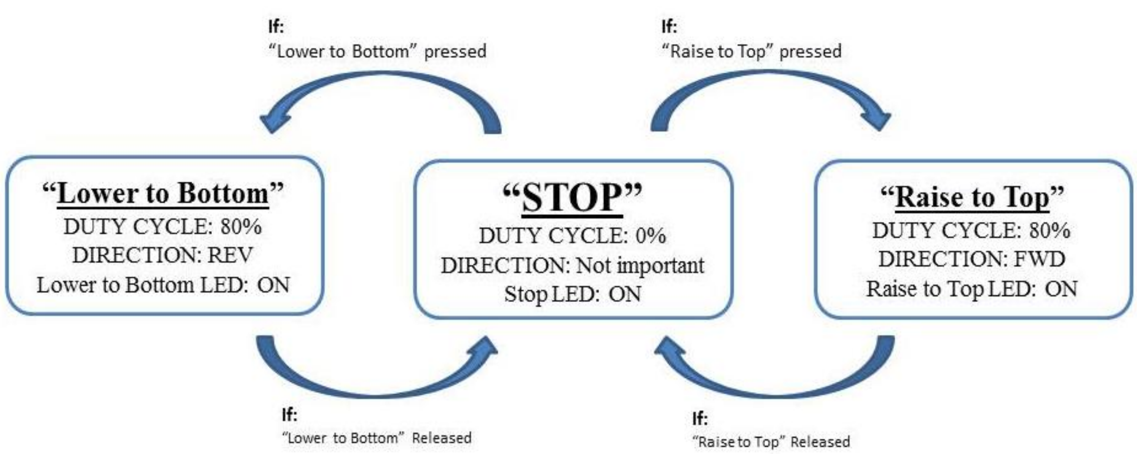


Figure 8.13 Manual Operation state diagram

8.4.3 Real-time Data Acquisition and Logging

In developing a program that is capable of making real-time data acquisition and data logging, the program must be able to access data collected from it preceding iteration of the loop. The LabVIEW interface has to temporary store the collected data processed from the microcontroller into the computer memory. With the confirmation from the operator, File I/O functions must be used to pass the data to a file, available to other applications. To achieve this (screenshot of the LabVIEW program in Figure 8.14) two subVIs (*Update Shift* Register and *Log Session*) has been developed along with the use of the *Shift register* function.

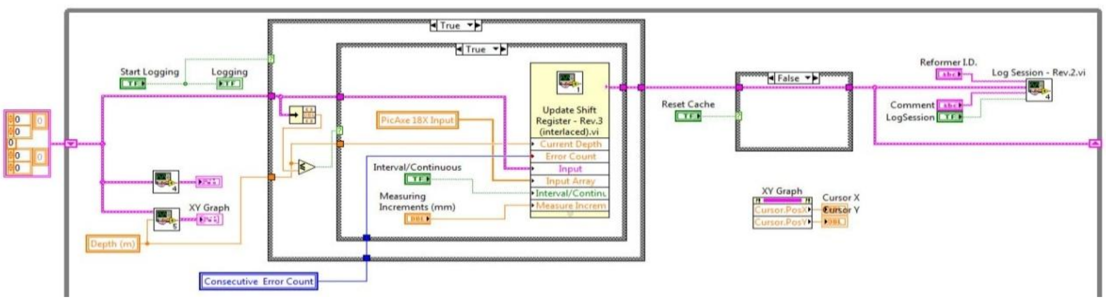


Figure 8.14 Register Update & Data Log Block Diagram

Shift registers allows for data to be transferred from one iteration of a program loop to the next. It comprises of a pair of terminals directly opposite each other on the vertical sides of the loop border as illustrated in Figure 8.14. A value can be passed through the right terminal at the end of each iteration cycle and can be accessed from the left terminal in the next. A shift register can hold any data type. In the case of this research, a Custer data made up of three data elements. The makeup of the Cluster is shown in Table 8.2.

Element No.	Name	Type
1	Measurement Array 1	Numerical array
2	Next Depth	Numeric Value
3	Measurement Array 2	Numerical array

Table 8.2 Bundle Data Elements

The Measurement Array 1 is a 2-dimensional numeric array made up of depth and diametrical measurements collected from Measuring Layer A on the sensory module (see chapter 5). The second element stores the *Next Depth* numeric value indicating the depth at which the next measure should be taken during *Incremental* mode. The final element (Measurement Array 2) is a 2-dimensional numeric array storing the diametrical measurement collected from Measuring Layer B (see Chapter 5).

8.4.3.1 Update Shift Register

Shown in figure 8.15 is a screenshot of the LabVIEW code used to update the Cluster element. The most prominent component of the code is the Update Shift Register subVI. As the name implies, with execution the subVI the Cluster elements are updated with new diametrical and depth measurement collected from the PICAXE-18X Input and Depth (m) variable.

The Update Shift Register subVI is embedded within two Case Structures to create a conditional execution. This is analogous to the common If…Then…Else statements in conventional, text-based programming languages. The conditional loop looks at two control element; Start Logging and Depth elements. During 'continuous' collection mode the shift register is updated at every iteration during the *"Inspection"* phase. During *'incremental'* inspection mode, the shift register is updated relative to incremental step size determined by the operator within the *'Advanced Setup Panel'*. Within the Update Shift Register subVI, the Depth (m) element and the Increment Step size is compared to determining the 'Next Depth' value. The code can be found Appendix C of this report.

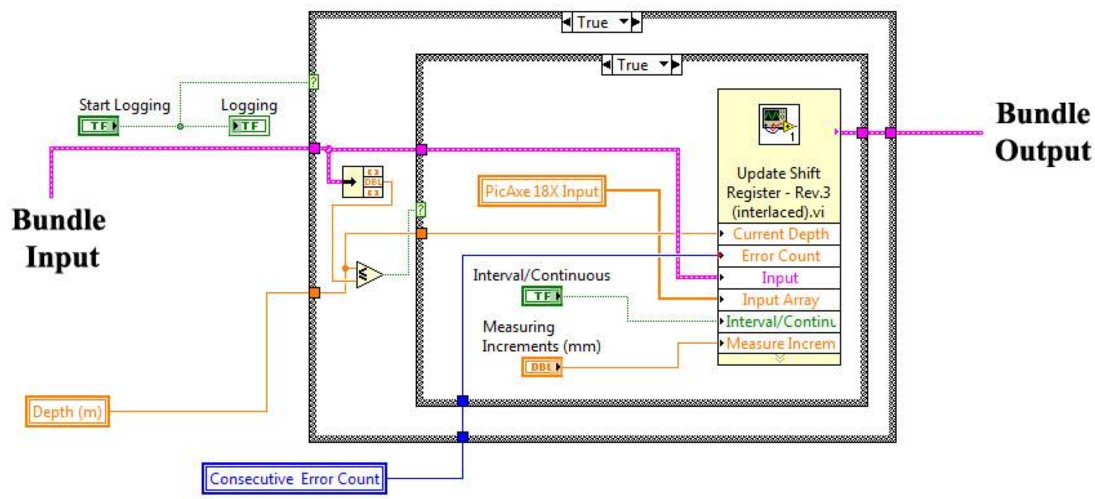


Figure 8.15 Update Shift Register Code

8.4.3.2 Data Log

The objective of the Data Log VI is to append collected data to a txt file in ASCII format. This VI uses a Case Structure to execute the routine on press of the Log button on the front panel. During each execution, the VI converts the numeric data stored in the Cluster to a string, adding tab space as a delimiting character, and then appends the string to a file.

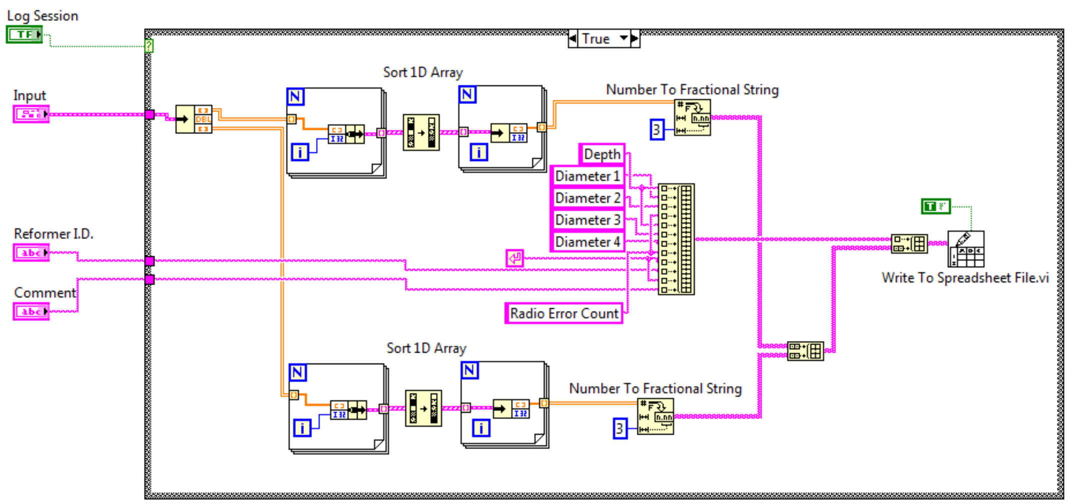


Figure 8.16 Log Data code

During each program cycle, the code commences by sorting the *Measurement Array 1 & 2* in depth ascending order using the *Sort 1D Array* function. Then the numeric data is converted into fractional string. The Build array function is used to create a Title array for labelling each data element. The inspected Reformer I.D and the comments determined by the operator are also added. Finally the *Write-To-Spreadsheet File* function to convert the 2D array of string to a text string writes the string to a new byte stream file or appends the string to an existing file. Figure 8.17 is a sample output text file created by the VI.

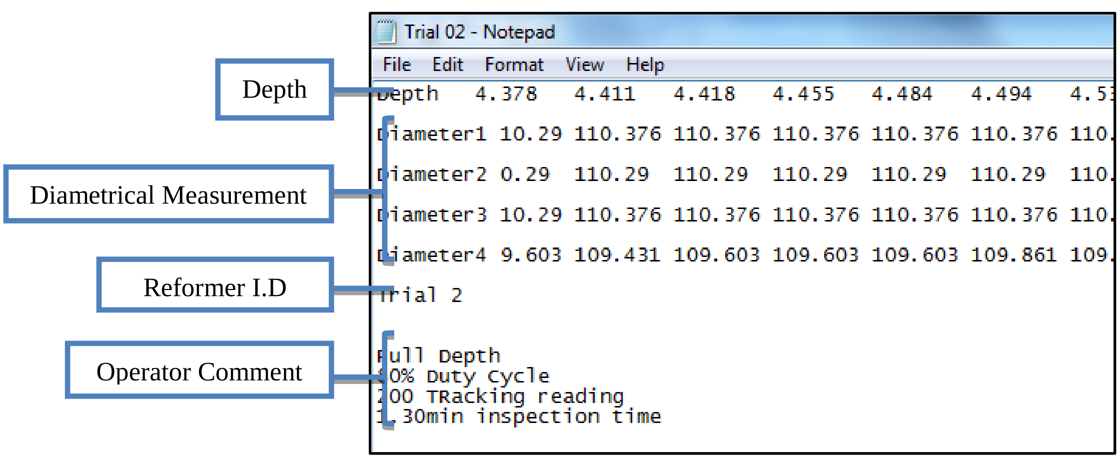


Figure 8.17 Log Data VI sample output

CHAPTER 9 TESTING OF THE RTIDM SYSTEM

The Reformer Tube Internal Diameter Measuring (RTIDMS) system must be tested for performance before it can be used for any real-world application. In October of the year 2009, the RTIDM system was taken to Methanex Furnace plant for field testing. While the main area of interest is in the systems precision and usability, factors such as data drift over time and mechanical design capabilities were also assessed.

9.1 Field Testing Structure

The system was tested on a full 14 meter, 109mm bore, vertically standing reformer tube that is currently been used for company testing facility (Figure 9.1). The tube had been in use for the past few years for methanol production and had been brought out for replacement. There is no recorded data made available on the condition of the specimen but it has been vulnerable to excessive diametrical expansion damage caused from general service.

(a) Experiment Reformer Tube

(b) Experiment cycle in progress

Figure 9.1 Fielding Testing Site Photo

The experiment is to perform numerous Reformer Tube inspection cycle and perform in-depth data analysis based on the collected data. For experiment purpose a Laptop PC and a DC power supply unit was made available to run the system. To make each analysis cycle identical as possible care was taken that same process was taken between each cycle. The experiment structure is as follow.

Procedure and Data Collection:

1. **Set Device**
   Insert Sensory module into the tube and rest the Drive Module on the reformer opening.
2. **Perform Software Calibration**
   Calibrate Sensory module at 109mm. Raise Sensory Module to the top of the tube, via manual operation, and calibrate the Spool Encoder.
3. **Lower Sensory Module**
   Lower the sensory module to the bottom of the tube via "Lower to Bottom" button in automatic operation mode.
4. **Raise Sensory Module and Record Data**
   Press the LOG button and raise the sensory module to top of the tube via "Raise to Top" button in automatic operation mode.
5. **Make Comment & Log Data**
   Insert trial number into the Reformer I.D and the configuration used during the inspection section into the comment box. Log data into text file.
6. **Remove**

With the coned shape extraction tip of the reformer tube, the *Bottom Detect Sensor* was not able to be used for detection of the bottom of the reformer tube hence the *ultrasonic sensor 2* was used. The 'stop reading' value was set to 15 which would theoretically stop the Sensory Module at 50mm from the bottom of the reformer tube. On the day of the experiment 30 full analysis trials were able to be performed. Of which, 26 trials had resulting with adequate data for analysis. Trial 9, 10, 11 and 12 resulted in inadequate result and was not included in this analysis. The reasons for the failed trails are described in table shown in Table 8.1.

Figure 9.2 Specimen Reformer Tube Extraction End

Trial No.	Description
9	Motor stopped at 1.21m. Suspected loss power connection
10	Forgot to log the collected data by the operator
11	Failed to Calibrate Sensors.
12	Failed to Calibrate Cable Drum Sensor

Table 9.1 Table of Failed Trials

The collected data is stored onto the Laptop computer memory as a text file. Part of the raw data collected in trial 3 is shown in Table 9.2. Data is made more meaningful by plotting the logged data against a Diameter vs Depth graph with ***Microsoft Excel*** (MS Excel). Graph illustrated in Figure 9.3 is a plot generated from data collected during trail 4. As visually observable the specimen reformer tube is presented to diametrical expansion obvious from around 1.5meter depth from the top of the tube. The raw data and excel plot collected from the 30 trials can be found in Appendix B.

Depth	**-0.006**	**-0.006**	**0**	**0**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
Diameter 1	108.914	108.914	108.914	108.914	108.914	108.914	108.914	108.914	108.914
Diameter 2	108.827	108.914	108.827	108.914	108.827	108.827	108.827	108.827	108.827
Diameter 3	109	108.914	109	109	108.914	109	109	109	109
Diameter 4	109	108.914	109	108.914	108.914	108.914	108.914	108.914	108.914

Table 9.2 Raw Data from Trial 4

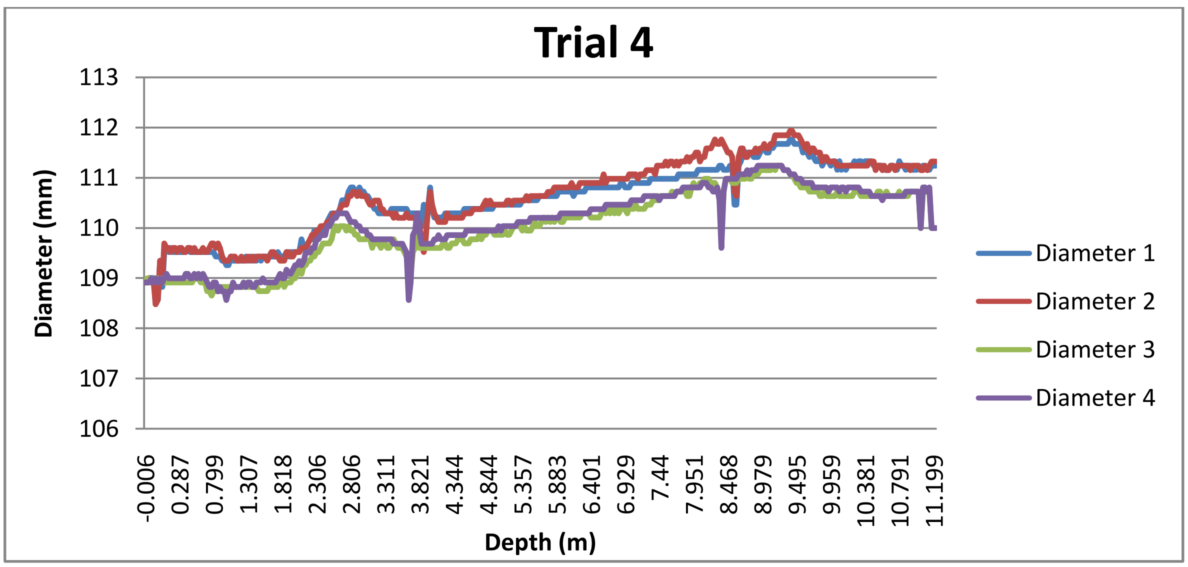


Figure 9.3 Trial 4 data plot

9.2 Simple Analysis and Data Interpolation

Looking at the Diameter vs Depth plot generated from the data collected during the experiment (Appendix B) it is observable that the system has accurately detected the 2mm increase in the specimen reformer tubes internal diameter at reasonable resolution. Throughout the 30 trials similar curve can be seen tracing a common path. For every trial the system was able to detect the two welded rings inside the reformer tube at the depth of approximately 4m and 8.5m which indicate that the radio communication is fast enough when the maximum motor speed is set to 80% duty cycle.

Figure 9.4 Reformer Tube plot Characteristic

As mentioned before, the ultrasonic sensor signal was used to detect the bottom of the reformer tube. The depth at which the system detected the bottom is tabulated in Table 9.3. Included in the table are the variances and error percentage. The variance is the difference between the detected distance and the true length of the reformer tube. Unfortunately there is no official data record of the true length of the tube to compare the data to; therefore the estimate length of 14m was used. The Error Percentage is the percentage error between the variance value and the estimate true length. The Error Percentage values are charted onto a scatter chart (Figure 9.4) to examine the data distribution.

Trial No.	Depth (m)	Variance (m)	Error %
2	12.662	1.338	9.56
3	12.426	1.574	11.24
4	11.225	2.775	19.82
5	12.489	1.511	10.79
6	12.727	1.273	9.09
7	11.790	2.210	15.79
8	11.371	2.629	18.78
13	12.789	1.211	8.65
14	12.807	1.193	8.52
15	12.553	1.447	10.34
16	12.709	1.291	9.22
17	12.773	1.227	8.76
18	12.477	1.523	10.88
19	13.084	0.916	6.54
20	12.397	1.603	11.45
21	12.456	1.544	11.03
22	12.420	1.580	11.29
23	12.695	1.305	9.32
24	11.730	2.270	16.21
25	12.421	1.579	11.28
26	12.245	1.755	12.54
27	12.618	1.382	9.87
28	12.482	1.518	10.84
29	12.840	1.160	8.29
30	12.557	1.443	10.31
Average	12.430	1.57	11.216

Table 9.3 Bottom Detect depth

The tabulated data show that the error associated with the *bottom detect* depth is consistent seem throughout the experiment trials at average of 11.216%. Figure 9.5 suggests that the error percentage vary between 6.5% and 18.78% with statistically no sign of *special cause*. Assuming that the Reformer Tube has no blockage, the results show that the depth measured by the system is always around 10% less than the true depth. With no indication of software or hardware error present in the system, it is thought that this deviation is caused by elastic property of the steel wire used to suspend the Sensory Module (see Chapter 5).

Figure 9.5 Bottom detect Error Percentage

Because the system is set-up independently between each experimental trial the angular orientation of the Sensory Module may differ between trials. Hence slight deviation in the each diametrical measurement is expected but observing the trial plots, there is a definite gap between two measuring layer on the Sensory Module; diametrical measurement 1, 2 (blue and red plot) is almost always greater than the measurements 3, 4 (green and purple plot) by approximately 0.51mm. To this, it is feasible to say that there is a mechanical error resulting from the Angular-to-Linear Transducers in the sensory module.

Another important aspect that can be seen from the plots is the depth offset existing between the two measuring layers. Looking at the first weld location detected in the plots there is a definite and a constant difference between the two measuring layer. The depth at which the weld is detected by the two sensors on *Measuring Layer B (Diameter 1 & 2)* are always at a deeper location than the depth detected by the two sensors on *Measuring Layer A (Diameter 3 & 4)* by around 140mm. These factors are illustrated in Figure 9.6.

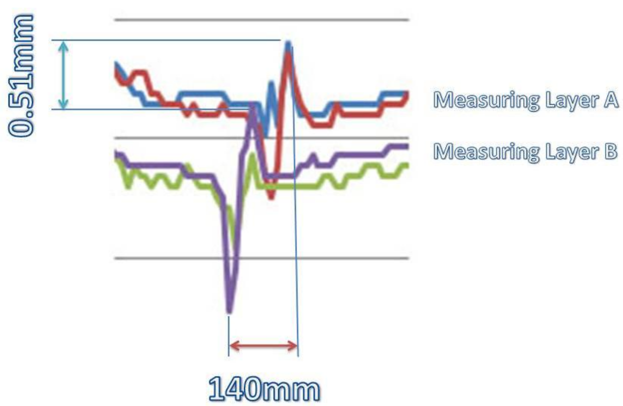


Figure 9.6 Measuring Layer Deviation

For the purpose for further analysis, all the data collected on the day was interpolated through *MS Excel*. Interpolation was done simple by shift the measurement collect on *Measuring Layer B* to over lay with the *Measuring Layer A* plot by adding additional 0.51mm and 140mm to the diameter and depth. All the analysis discussed in this chapter is done upon the newly interpolated data plots, which can be found in Appendix B. Figure 9.7 is a plot of the interpolated data generated from the data collected during trial 16.

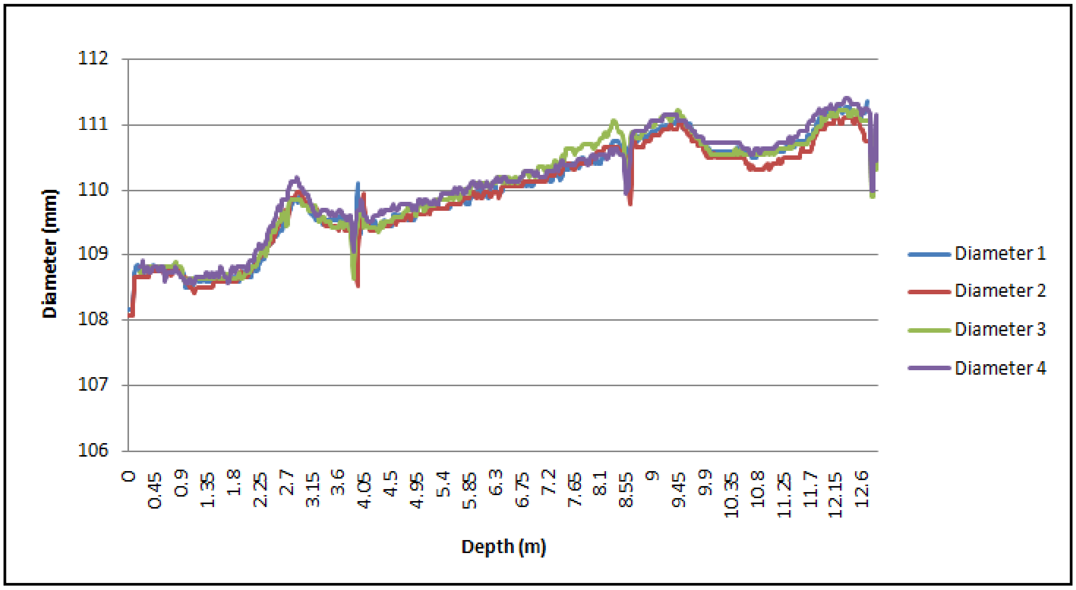


Figure 9.7 Trial 16 - Interpolated

9.3 Accuracy & Precision

In engineering, the measure of accuracy and precision of an instrument gives a good indication of its performance. A measurement system is called *valid* if it is both *accurate* and *precise.* The concept of accuracy and precision of a measuring instrument are statistical in nature. Accuracy refers to the degree to which repeated measurements of a known quantity value agree with x. Given several repeated measurements $x_1, x_2, x_3..., x_n$ of some known value x, the accuracy of the readings can be determined by measuring the difference between x and the average of the n reading. As mentioned previously there is no data available for the specimen reformer tube. To this there is no technique available at this point to access the systems *accuracy* from the collected data.

$$\boldsymbol{Accuracy = \bar{x} - x}$$

The precision of an instrument describes the extent to which repeated measurements tend to agree with one another. They do not necessarily have to agree with the true value that is being measured (Applied Statistic). Precision, then, is a measure of variation and is estimated by the sample standard deviation (s) of n repeated measurements x_1, x_2, x_3..., x_n defined by the Formula 9.1. RTIDM system makes depth and diameter measurement independent to one another. To this, the two elements must be analysed for precision separately.

$$\boldsymbol{Precision = s = \sqrt{\frac{1}{n-1}\sum(x_i - \bar{x})^2}}$$

Equation 9.1

For the purpose of this analysis, a set of measurement must be collected from a common point of the reformer tube. To achieve these five points were selected on the Diameter vs Depth plot to gather data for the precision analysis. The five points are shown in Figure 9.8 and describe in Table 9.4.

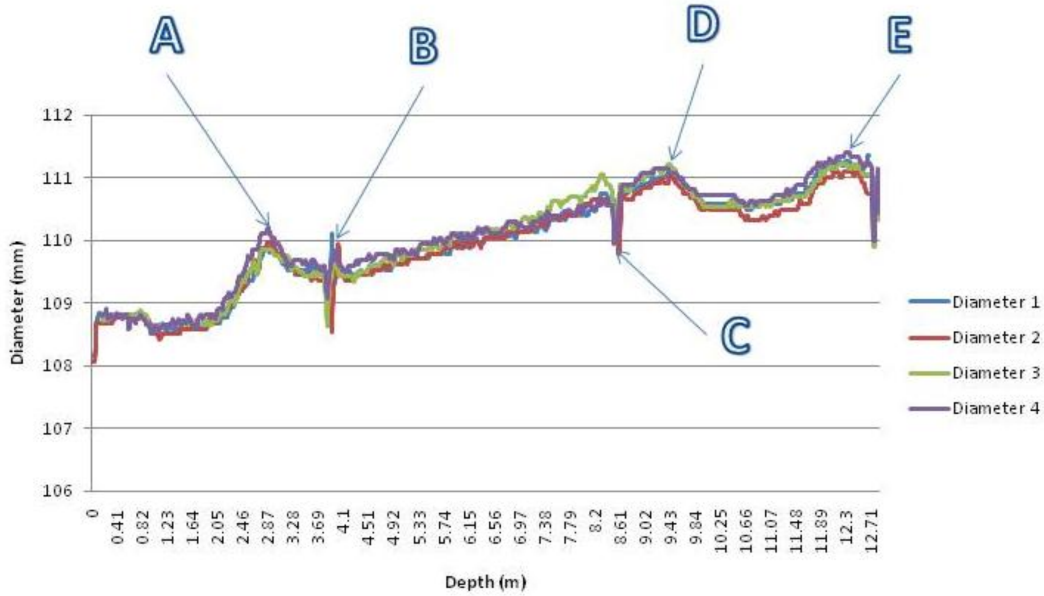


Figure 9.8 Data Collect Point

Table 9.4 Data Collection point Description

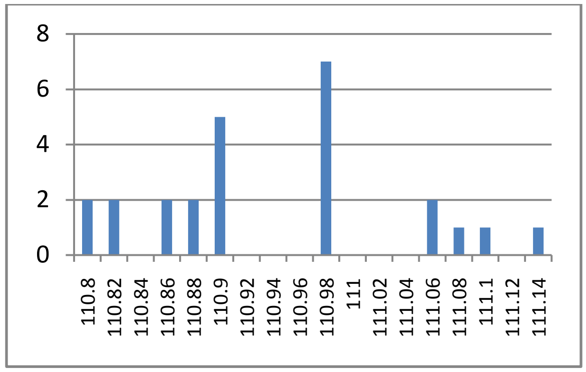
Point ID	Description
A	The first diametrical maximum seen at around 3m depth before the first weld set. Here the relative diametrical and depth measurements are collected.
B	The maximum depth at which the first weld step is seen
C	The maximum depth at which the second weld step is seen
D	The second maximum point located around 9m little past the second weld step. Here relative diametrical measurement is collected.
E	The last diametrical maximum at 12m depth

9.3.1 Diametrical Precision analysis

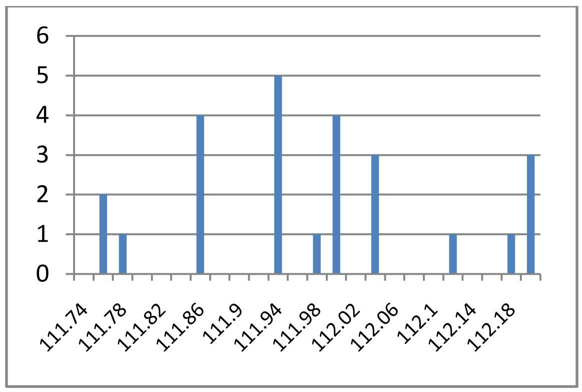
The diametrical data collected from the experiment trials is shown in Table 9.5. Included in the table are the *sample mean* and the *squared deviation* of each diameter. Figure 9.9 is a histogram displaying the spread of the data.

Table 9.5 Diametrical Data

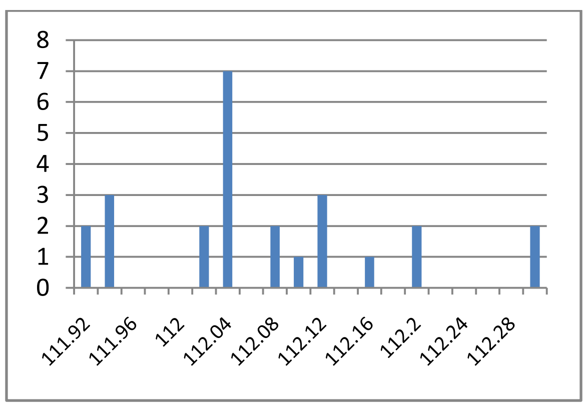
Trial No.	Diameter		
	A	D	E
2	110.85	111.765	111.937
3	110.866	111.996	112.001
4	110.772	111.741	112.11
5	110.893	111.981	112.022
6	111.059	112.188	112.19
7	110.893	111.935	112.022
8	110.89	111.93	111.412
13	110.869	112.022	112.1
14	110.966	111.847	112.022
15	110.807	111.847	111.847
16	111.065	112.188	112.15
17	110.975	112.022	112.286
18	111.128	112.173	112.005
19	110.772	111.965	111.935
20	110.851	111.995	112.022
21	111.059	112.198	112.283
22	111.082	112.022	112.074
23	110.893	111.935	112.022
24	110.979	112.11	112.11
25	110.893	111.923	112.022
26	110.962	111.991	112.187
27	110.979	111.847	112.11
28	110.807	111.741	111.923
29	110.979	111.847	112.022
30	110.979	111.922	112.074
Sample Mean	110.9307	111.9652	112.0355
Squared Sum	0.235693	0.4334	0.667866



(a) Diameter A Histogram



(a) Diameter B Histogram



(c) Diameter C Histogram

Figure 9.9 Diameter Histogram

Following is the calculation performed in deriving the system precision at the three locations.

Precision calculated from data collected from *Diameter A*;

Squared Sum = 0.235693, n = 25

$$= \sqrt{\frac{1}{25-1} \times 0.235693}$$

$$= 0.0991mm$$

Precision calculated from data collected from *Diameter B*;

Squared Sum = 0.4334, n = 25

$$= \sqrt{\frac{1}{25-1} \times 0.4334}$$

$$= 0.1348mm$$

Precision calculated from data collected from *Diameter C*;

Squared Sum = 0.667866, n = 25

$$= \sqrt{\frac{1}{25-1} \times 0.667866}$$

$$= 0.1668mm$$

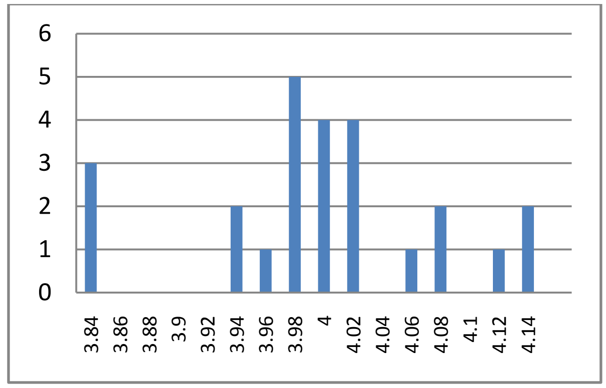
The data collected in the experiment suggests that the precision of the system is +/-0.0991mm and increases to +/-0.1668mm as the distance between the Drive Unit and the Sensory Module increases.

9.3.2 Depth Precision analysis

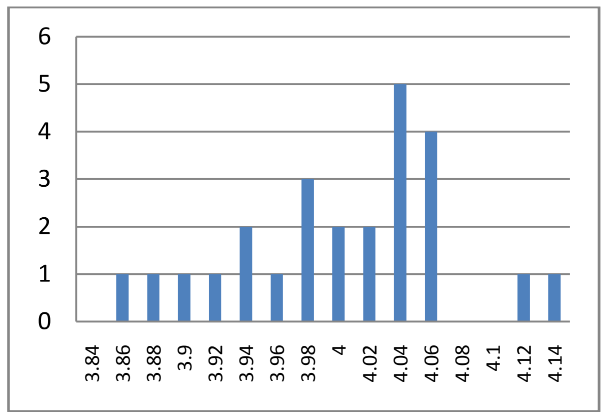
The diametrical data collected from the experiment trials is shown in Table 9.6. Included in the table are the *sample mean* and the *squared deviation* of each diameter. Figure 9.10 is a histogram displaying the spread of the data.

Table 9.6 Diametrical Data

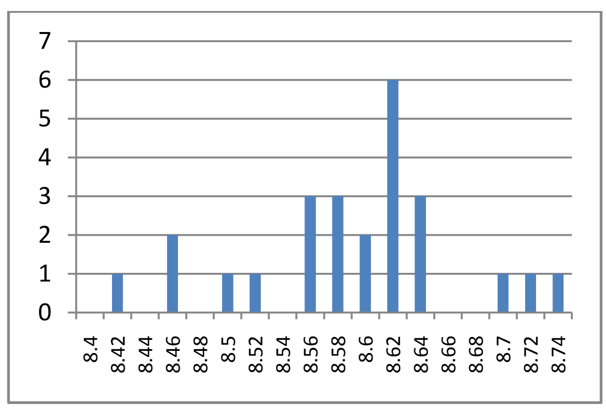
Trial No.	Depth		
	A	B	C
2	2.84	3.95	8.45
3	2.86	4.03	8.62
4	2.8	3.97	8.57
5	2.93	4.03	8.62
6	2.92	4.05	8.64
7	2.72	3.86	8.45
8	2.88	4.05	8.55
13	2.84	4.02	8.52
14	2.79	3.99	8.56
15	2.84	3.91	8.49
16	2.88	3.93	8.61
17	2.86	4.03	8.62
18	2.99	3.97	8.64
19	2.87	4.06	8.63
20	2.81	3.99	8.57
21	2.93	4.04	8.59
22	2.84	3.9	8.57
23	2.85	4.03	8.61
24	2.88	3.98	8.41
25	2.86	3.87	8.55
26	2.86	3.94	8.6
27	2.84	4.01	8.61
28	2.87	4.05	8.68
29	2.98	4.13	8.72
30	2.86	4.12	8.71
Sample Mean	2.864	3.9964	8.5836
Squared Sum	0.196736	0.21946	0.233192



(a) Diameter A Histogram



(b) Diameter B Histogram



(c) Diameter C Histogram

Figure 9.10 Diameter Histogram

Following is the calculation performed in deriving the system precision of it depth elements at the three locations.

Precision calculated from data collected from *Depth A*;

Squared Sum = 0.196736, n = 25

$$= \sqrt{\frac{1}{25-1} \times 0.196736}$$

$$= 0.09054mm$$

Precision calculated from data collected from *Depth B*;

Squared Sum = 0.21946, n = 25

$$= \sqrt{\frac{1}{25-1} \times 0.21946}$$

$$= 0.09563mm$$

Precision calculated from data collected from *Depth C*;

Squared Sum = 0.233192, n = 25

$$= \sqrt{\frac{1}{25-1} \times 0.233192}$$

$$= 0.09857mm$$

The data collected in the experiment suggest the systems depth precision is =/-0.09054mm at around 3m depth and increases to +/-0.1668mm as the distance between the Drive Unit and the Sensory Module increases.

9.4 Experiment Conclusion

From analysing the data collected during the field testing it can be concluded that the RTIDM system is a very capable instrument making appropriate diametrical measurements. As discussed in chapter 4, the Sensory Module is able to make acceptable diametrical inspection potentially at accuracy of +/-0.055mm and precision of +/-0.0929mm. As seen in the previous section this precision was not seen when tested as a complete system where the precision reduced to +/-0.0991mm to +/-0.1668mm. Unfortunately the accuracy of the diametrical measurements could not be confirmed during the field test but it can be hypothesized that the accuracy will reduce as the distance between the Sensory and Drive Module increases. There is a definite relationship between the Diametrical Precision and the distance between the two Modules. This is an indication inconsistency in the radio communication established between the two X-Bee modules.

There is no sign of drifting in the diametrical or depth measurement over time. The biggest draw-back found in the system is the inconsistency in the Bottom Detection depth between each trial. The precision of the depth monitoring is approximately +/-10mm and against increased as the Sensory Module depth increases. 10mm is quite a large deviation and is definitely an area that requires further developments. As mentioned before, with the implementation of wire extension factor, this precision may increase.

10 Conclusion

The aim of this research is to develop a reformer tube internal diameter measuring system that can replace the laser based system currently employed by Methanex furnace. This was challenged by developing the FTIDM system which uses mechanical means to perform reformer inspection through diametrical growth analysis. The outcome device is very promising resulting with encouraging results, however the research exposed some new areas that require further improvement.

10.1 Comparison

The research performed in the literature review revealed that majority of the devices used for reformer tube inspection used advanced inspection design that may be out of use for some applications. The development of the mechanical inspection device in this research is intended to introduce a new method into the industry providing some contribution towards overcoming the limitations.

In chapter 2, two common form of technologies used for Reformer Tube inspection were reviewed. The laser profilometry system inhibits by the LOTIS technology provides advanced means to perform top of the range inspection results. The manufactures specification states that the design is capable of making over million diametrical measurements at accuracy of +/-0.05mm. It is also revealed that the system is over engineered for some applications, resulting in unnecessary cost. The Photo Profilometry technology revealed similar performance yet some limitation was seen in the working operation environment.

Conclusively, the RTIDM system developed in this research opened a new way for reformer tube inspection. With the cost of such prototype system is under $2000 NZD, the design is a much cost effective instrument compared with its rival devices while capable of making diametrical inspection at competitive precision and accuracy.

As mentioned in the literature review, recent study has revealed that creep damage assessment by the diametrical growth measurement alone is not reliable enough to make conclusion. To this, the RTIDM system must incorporate other sensory technology to create a more powerful inspection device. Otherwise it should only be used as a primary process taken to indicate the need for performing further testing.

10.2 Future Development

This research revealed that the FTIDM system has highly competitive inspection performance against its rival devices. With the inexpensive yet high performance design, with appropriate further development will potentially lead to commercially viable product. Discussed in this final section of the thesis are areas requiring further research.

With the FTIDM intended as a portable system an attempt to further miniaturise the mechanical hardware would be a definite and possible step to improving the system design. As discuss in Chapter 4, the IDMU is designed to be fabricated with milling and turning resulting in typically tolerance of 0.01mm. By redesigning the module to allow for CNC manufacturing, the components are able to be made smaller with complex geometry while keeping the system precision. Other simple improvements can be achieved through making use of printed circuit board (PCB) to miniaturise the electrical circuitries used in the system. Here, it should be noted that further study into the material selection and components interaction should be performed yielding the best interaction between moving components.

A review on the effect of the radio propagation inside a reformer tube should also be conducted. As mentioned in chapter 9, the precision of the IDMU reduces as the distance between the Sensory Module and the Drive Module increases. With no verification of mechanical fault there is an indication that the precision deviation is cause of the radio component. Theoretically 109mm reformer tube will act as an appropriate wave guide media and improve the radio propagation of the 2.4GHz used by the XBee Radio Module. It may be beneficial to invest in a more advanced radio module to improve radio implementation while increasing the system processing rate.

Finally, the PICAXE microcontroller may be unsuitable for the purpose of this research for further improving the RTIDM system. The RTIDM system is current able to make one reformer tube inspection in 2~3minutes. This inspection time is currently limited mainly by the slow clock speed and functionality of the PICAXE Microcontroller. Although this period is very acceptable, comparing the 2~3 inspection time of the Photo Profilometry system (see Chapter 2), it is a fact that can be easily improved. Therefore, a microcontroller with faster processing rate should be explored.

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APPENDIX

Appendix A LabVIEW VI and PICAXE Code

PICAXE Code

- Sensory Module: Radio Transmit Code
- Drive Module: Radio Receive Code
- Motor Control: Motor Driver Code

LabVIEW VI

- State Control
- Motor Control
- Duty Cycle Calculation
- Depth Calculation
- Update Shift Register
- Log Session

Sensory Module: Radio Transmit Code

```
Symbol S1=w0          'define word variable w0 as S1 (Sensor 1)
Symbol S2=w1          'define word variable w1 as S2 (Sensor 2)
Symbol S3=w2          'define word variable w2 as S3 (Sensor 3)
Symbol S4=w3          'define word variable w3 as S4 (Sensor 4)
Symbol U1=b8          'define byte variable b9 as U1 (Ultrasonic 1)
Symbol U2=b9          'define byte variable b10 as U2 (Ultrasonic 2)
Symbol BT1=b10        'define byte variable b11 as BT1 (Button 1)
Symbol BT2=b11        'define byte variable b12 as BT2 (Button 2)
Init:
setfreq m8
'input PortC pin1
'input PortC pin2
high PortC 0

Main:
ReadADC10 6,S1                'Read Encoder 1 via 10bits ADC
ReadADC10 1,S2                'Read Encoder 2
ReadADC10 2,S3                'Read Encoder 3
ReadADC10 3,S4                'Read Encoder 4
ReadADC 7,U1                  'Read Ultrasonic Sensor 1
ReadADC 0,U2                  'Read Ultrasonic Sensor 2
if PortC pin1 = 1 then        'If Stopper Button is High, set BT1=1
        BT1 = 0
else
        BT1=1
Endif
if PortC pin2 = 1 then        'If Stopper Button is High, set BT2=1
        BT2 = 0
else
        BT2=1
Endif
sertxd ("S1 =",#S1," S2 =",#S2," S3 =",#S3," S4 =",#S4," U1 =",#U1," U2 =",#U2," BT1 =",#BT1, "
BT2 =",#BT2,13,10)
goto Main:
```

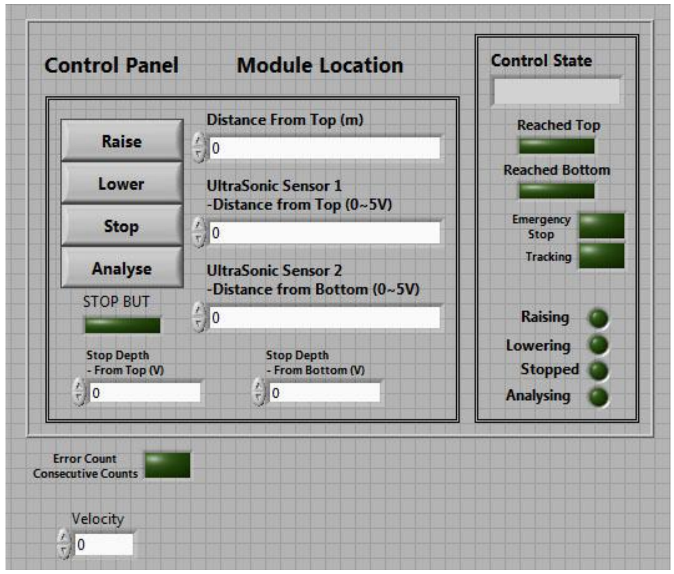
Drive Module: Radio Receive Code

```
Symbol S1=w0        ‘define word variable w0 as S1 (Sensor 1)
Symbol S2=w1        ‘define word variable w1 as S2 (Sensor 2)
Symbol S3=w2        ‘define word variable w2 as S3 (Sensor 3)
Symbol S4=w3        ‘define word variable w3 as S4 (Sensor 4)
Symbol U1=b8        ‘define byte variable b9 as U1 (Ultrasonic 1)
Symbol U2=b9        ‘define byte variable b10 as U2 (Ultrasonic 2)
Symbol BT1=b10      ‘define byte variable b11 as BT1 (Button 1)
Symbol BT2=b11      ‘define byte variable b12 as BT2 (Button 2)

Init:
setfreq m8
'input PortC pin1
'input PortC pin2
high PortC 0

Main:
ReadADC10 6,S1              'Read Encoder 1 via 10bits ADC
ReadADC10 1,S2              'Read Encoder 2
ReadADC10 2,S3              'Read Encoder 3
ReadADC10 3,S4              'Read Encoder 4
ReadADC10 7,U1              'Read Ultrasonic Sensor 1
ReadADC10 0,U2              'Read Ultrasonic Sensor 2

if PortC pin1 = 1 then      'If Stopper Button is High, set BT1=1
        BT1 = 0
else
        BT1=1
Endif

if PortC pin2 = 1 then      'If Stopper Button is High, set BT2=1
        BT2 = 0
else
        BT2=1
Endif

‘sertxd ("S1 =",#S1," S2 =",#S2," S3 =",#S3," S4 =",#S4," U1 =",#U1," U2 =",#U2," BT
=",#BT,13,10)
serout 7,T9600_8,("HEY",b0,b1,b2,b3,b4,b5,b6,b7,b8,b9,b10,b11,BT)
goto Main:
```

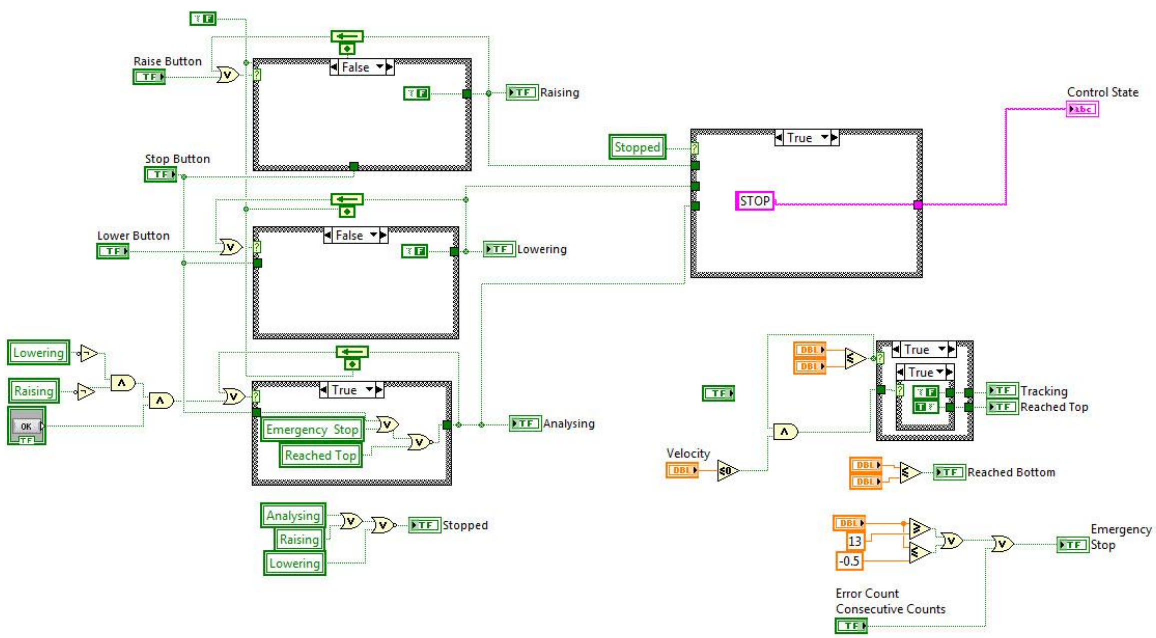
Motor Control: Motor Driver Code

```
Symbol DutyCycle = W0
Symbol Direction = W1
Symbol DC = W2
Symbol Current = W3
Symbol CurrentLimit = B8

Init:
Setfreq M8
DC = 0
CurrentLimit = 2/5*1024

Main:
high 4
serin 2, N4800_8, ("LAB"),Direction,#DutyCycle          'Receive Command from LabView
low 4

ReadADC10 1, Current
if Current >= CurrentLimit then ShutDown

if DC < Dutycycle then
        DC = DC +1
endif

'Motor Start-up Routine
if DC > Dutycycle then
        DC = DutyCycle
endif

if Direction = "B" then Brake
if Direction = "F" then Clockwise
if Direction = "R" then CounterClockwise

Brake:
        High 1          'Brake ON
        Low 2                   'Direction Forwards (NOT IMPORTANT)
        pwmout 3,0,0    'Set PWD
        DC=0                    'STOP Motor
goto Main

Clockwise:
        Low 1                                           'Brake OFF
        High 2                                      'Direction Forwards
        pwmout 3,199,DutyCycle
goto Main

CounterClockwise:
        Low 1                                           'Brake OFF
        Low 2                                       'Direction Reverse
        pwmout 3,199,DutyCycle
goto Main

ShutDown:
pwmout 3,0,0
High 1
```

LabVIEW Code: State Control

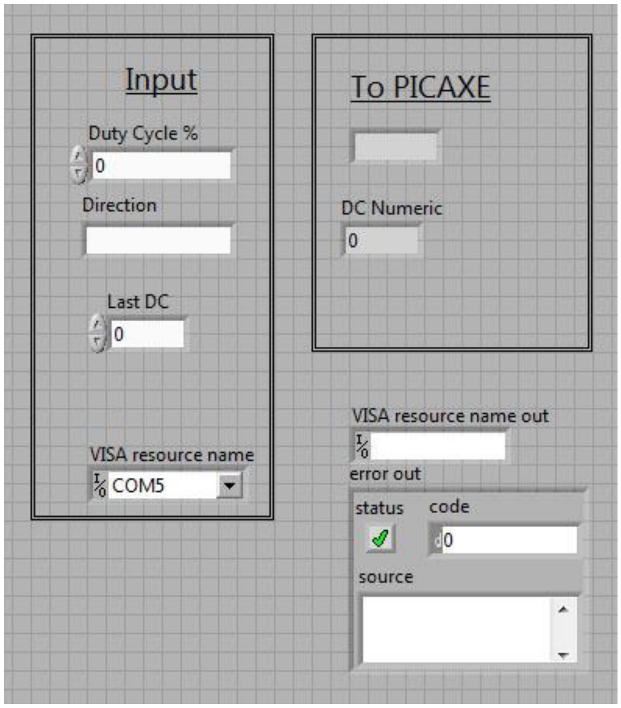


State Control – Front Panel

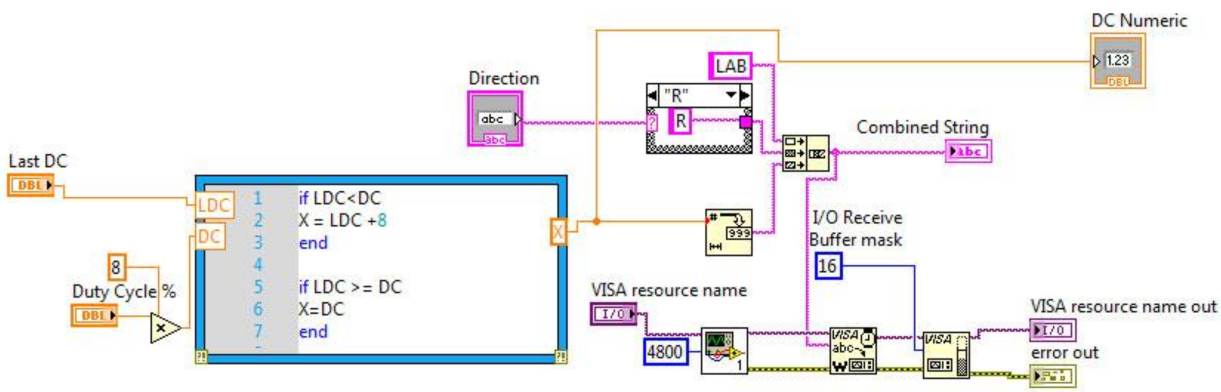


State Control – Block Diagram

LabVIEW Code: Motor Control

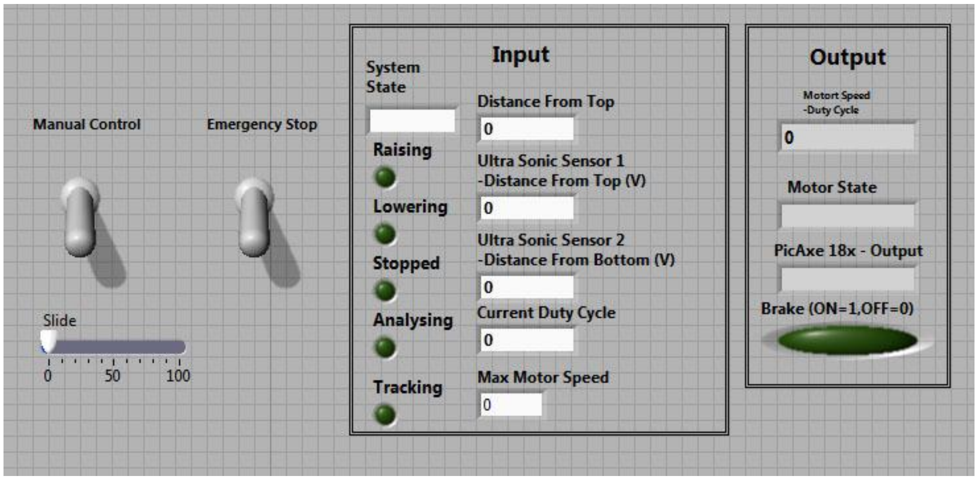


Motor Control – Front Panel

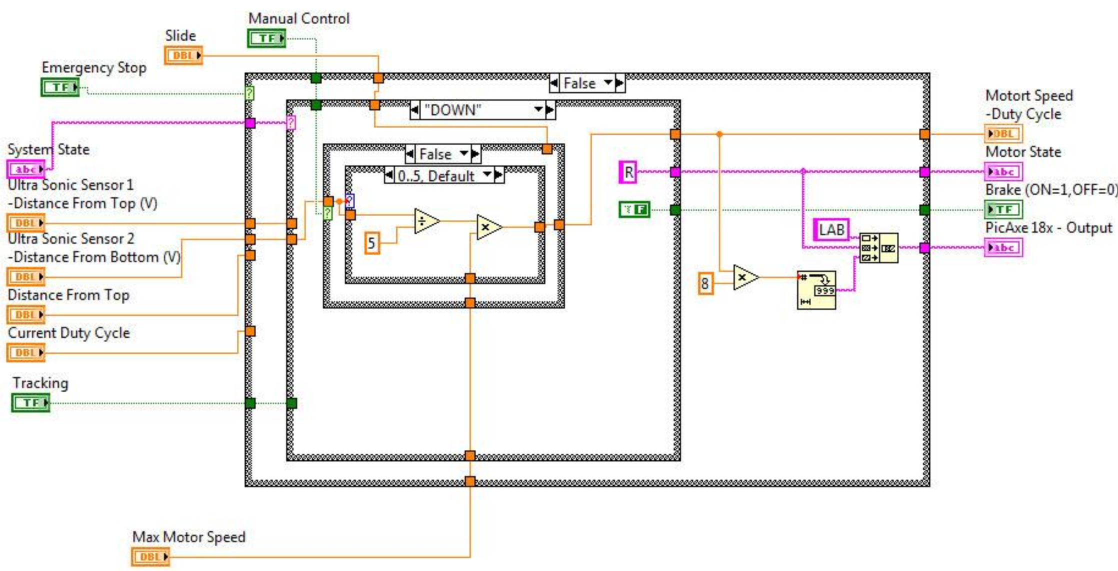


Motor Control – Block Diagram

LabVIEW Code: Duty Cycle Generator

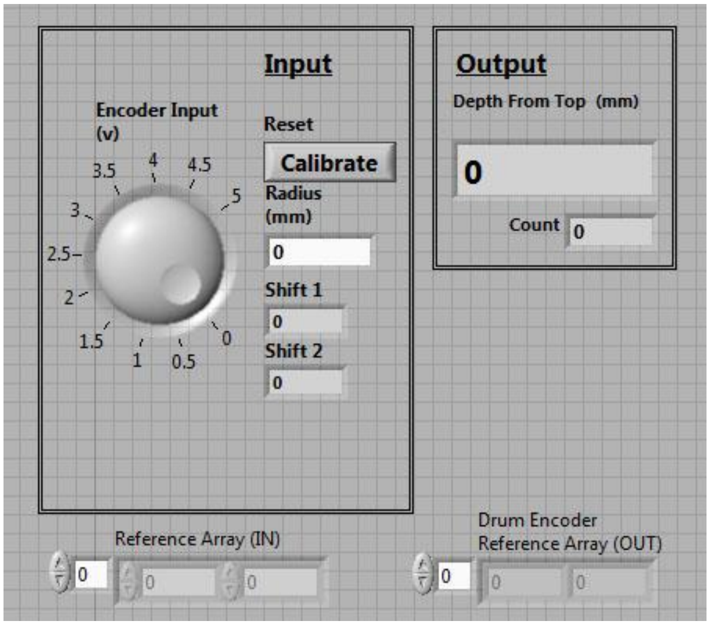


Duty Cycle Generator – Front Panel

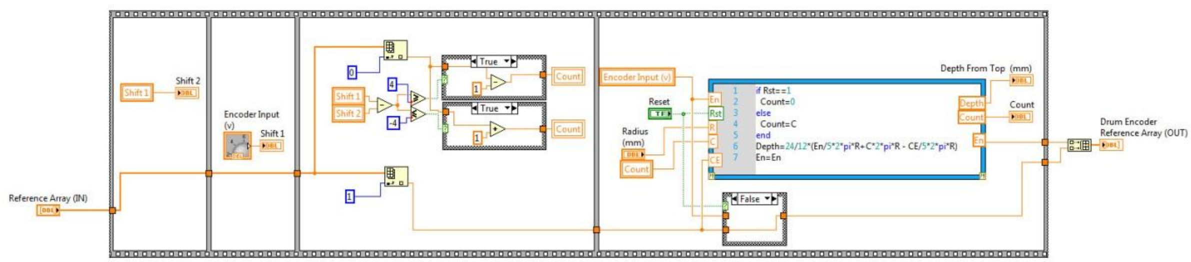


Duty Cycle Generator – Block Diagram

LabVIEW Code: Depth Calculation

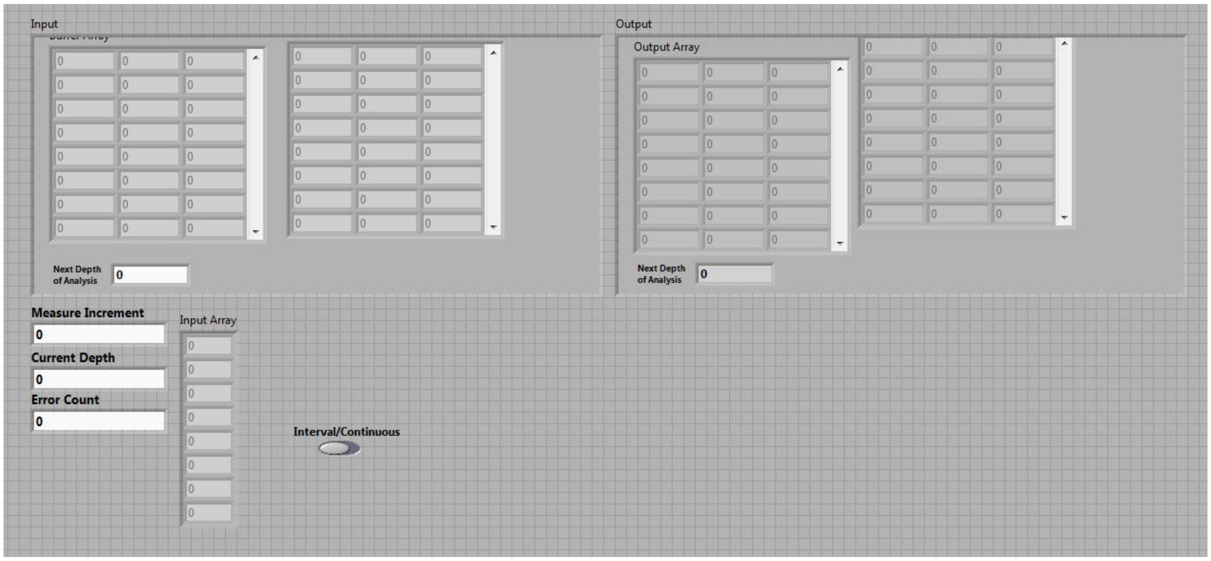


Depth Calculation

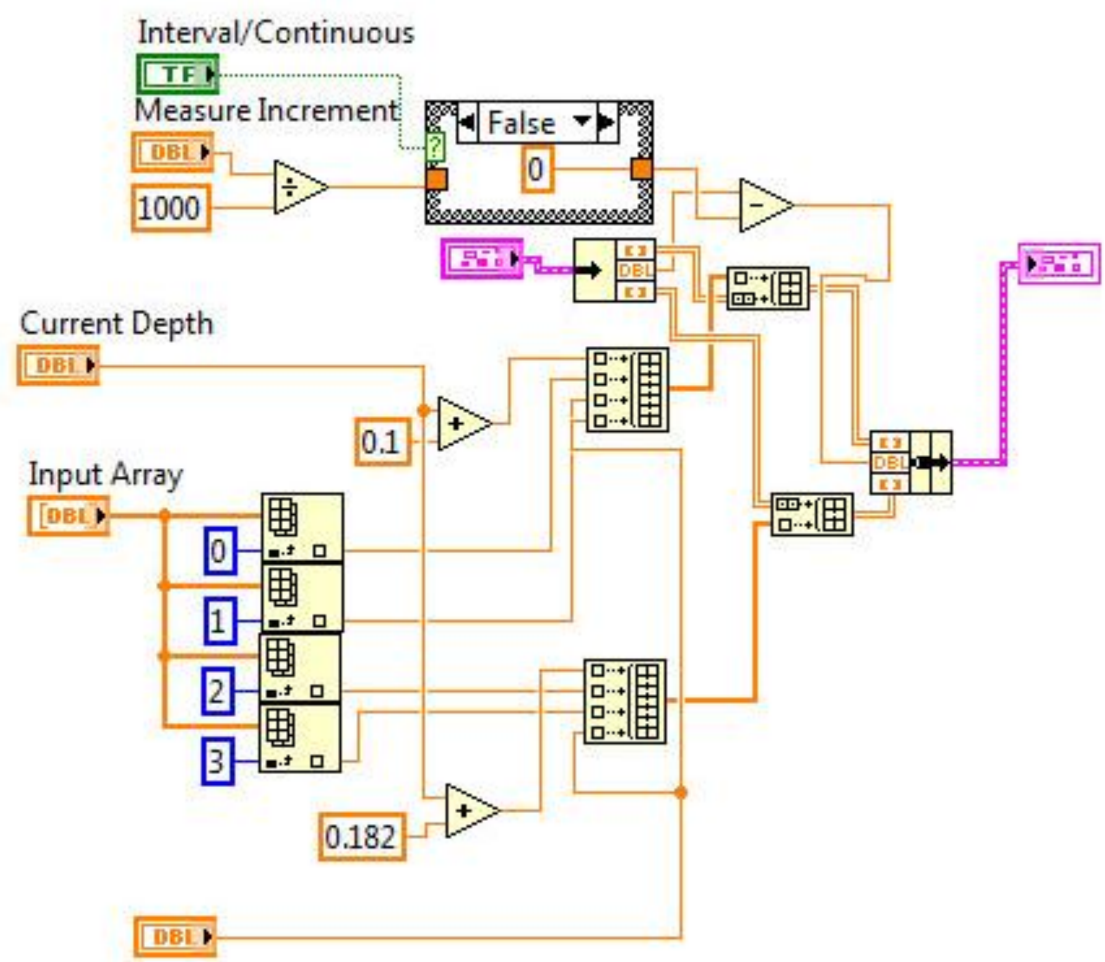


Depth Calculation

LabVIEW Code: Update Shift Register

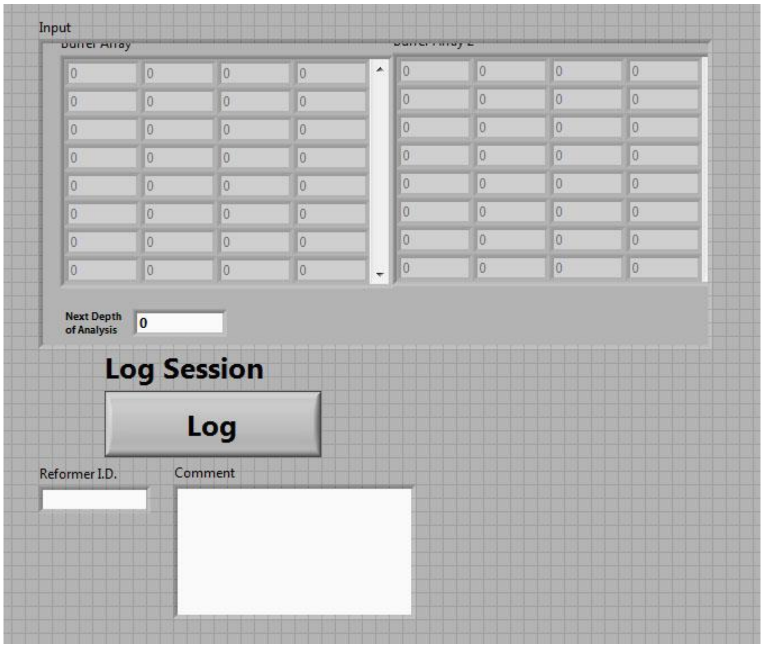


Update Shift Register – Front Panel

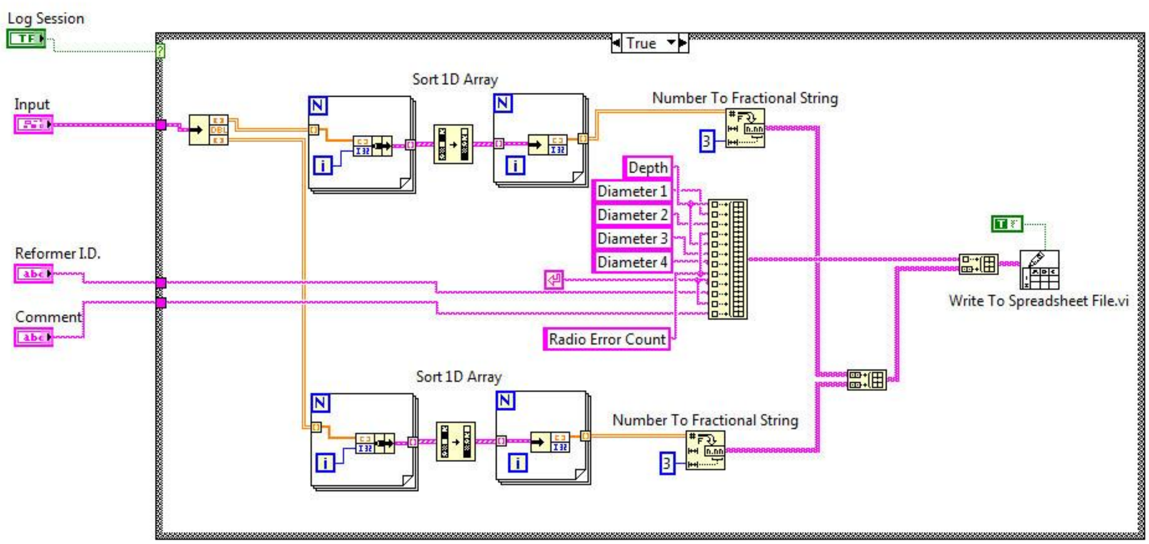


Update Shift Register – Front Panel

LabVIEW Code: Log Session



Log Session – Front Panel



Log Session – Block Diagram

Appendix B Field Testing Raw Data and Plot

Raw Data

- Trial 17 – Raw Data
- Trial 19 – Raw Data

Plot

- Field Testing Raw Data Plot
- Fielding Testing Interpolated Data Plot

Trial 17 - Raw data

Depth (m)	Diameter 1 (mm)	Diameter 2 (mm)	Diameter 3 (mm)	Diameter 4 (mm)
0	109	109.086		
0.01	109	109.086		
0.02	109	109.086		
0.03	108.8964	108.9824		
0.04	109.2068	109.2412		
0.05	109.5717	109.6395		
0.06	109.6499	109.6916		
0.07	109.7281	109.7437		
0.08	109.775	109.7666		
0.09	109.775	109.7456		
0.1	109.775	109.7247		
0.11	109.775	109.7037		
0.12	109.775	109.6826		
0.13	109.775	109.6611		
0.14	109.775	109.6396		
0.15	109.775	109.6181		
0.16	109.775	109.6091		
0.17	109.775	109.6296		
0.18	109.775	109.6501	109.086	109
0.19	109.775	109.6706	109.086	109
0.2	109.775	109.689	109.086	109
0.21	109.775	109.689	109.086	108.9484
0.22	109.775	109.689	109.086	108.9484
0.23	109.775	109.689	109.086	109
0.24	109.775	109.689	109.086	109
0.25	109.775	109.689	109.086	109
0.26	109.775	109.689	109.086	109
0.27	109.775	109.689	109.086	109
0.28	109.775	109.689	109.086	109
0.29	109.775	109.7297	109.086	109
0.3	109.775	109.775	109.086	109.0065
0.31	109.775	109.8203	109.086	109.028
0.32	109.775	109.858	109.086	109.0495
0.33	109.775	109.8284	109.086	109.071
0.34	109.775	109.7987	109.086	109.086
0.35	109.775	109.775	109.086	109.086
0.36	109.775	109.775	109.086	109.086
0.37	109.775	109.775	109.086	109.086
0.38	109.7708	109.775	109.086	109.086
0.39	109.7498	109.775	109.086	109.086
0.4	109.7289	109.775	109.086	109.086
0.41	109.7079	109.775	109.086	109.086
0.42	109.689	109.7775	109.086	109.086
0.43	109.689	109.802	109.0667	109.0667
0.44	109.689	109.8266	109.0452	109.0452
0.45	109.689	109.8512	109.0237	109.0237
0.46	109.689	109.8484	109.0022	109.0022
0.47	109.689	109.8274	109.0204	109.0204
0.48	109.689	109.8065	109.043	109.043
0.49	109.689	109.7855	109.0656	109.0656
0.5	109.678	109.764	109.086	109.086
0.51	109.6559	109.7419	109.086	109.086
0.52	109.6339	109.7199	109.086	109.086
0.53	109.6118	109.6978	109.086	109.086
0.54	109.6276	109.689	109.086	109.086
0.55	109.6685	109.689	109.086	109.086
0.56	109.689	109.689	109.086	109.086
0.57	109.689	109.689	109.086	109.086
0.58	109.689	109.689	109.086	109.086
0.59	109.689	109.689	109.086	109.086
0.6	109.689	109.7136	109.086	109.086
0.61	109.689	109.7627	109.086	109.086
0.62	109.689	109.8119	109.086	109.086
0.63	109.689	109.861	109.086	109.086
0.64	109.689	109.8423	109.086	109.0734
0.65	109.689	109.8236	109.086	109.0524
0.66	109.689	109.8049	109.086	109.0315
0.67	109.689	109.7862	109.086	109.0105
0.68	109.6978	109.775	109.086	109
0.69	109.7199	109.775	109.086	109
0.7	109.7419	109.775	109.086	109
0.71	109.764	109.775	109.086	109
0.72	109.7643	109.775	109.086	109
0.73	109.7428	109.775	109.086	109
0.74	109.7213	109.775	109.086	109
0.75	109.6998	109.775	109.086	109
0.76	109.689	109.775	109.086	109
0.77	109.689	109.775	109.086	109
0.78	109.689	109.775	109.086	109
0.79	109.689	109.775	109.086	109
0.8	109.689	109.7913	109.086	109
0.81	109.689	109.8145	109.086	109

0.82	109.689	109.8378	109.086	109
0.83	109.689	109.861	109.086	109
0.84	109.689	109.861	109.086	109
0.85	109.689	109.861	109.086	109
0.86	109.689	109.861	109.0684	108.9912
0.87	109.689	109.8514	109.0243	108.9691
0.88	109.689	109.8276	108.9802	108.9471
0.89	109.689	109.8037	108.9361	108.925
0.9	109.689	109.7798	108.9031	108.9248
0.91	109.6699	109.775	108.8814	108.9463
0.92	109.646	109.775	108.8596	108.9678
0.93	109.6221	109.775	108.8379	108.9893
0.94	109.5982	109.7654	108.8157	108.9887
0.95	109.5743	109.7177	108.7931	108.9661
0.96	109.5504	109.6699	108.7704	108.9434
0.97	109.5266	109.6221	108.7478	108.9208
0.98	109.517	109.603	108.7573	108.8975
0.99	109.517	109.603	108.7805	108.874
1	109.517	109.603	108.8038	108.8505
1.01	109.517	109.603	108.827	108.827
1.02	109.517	109.603	108.827	108.827
1.03	109.517	109.603	108.827	108.827
1.04	109.517	109.603	108.827	108.827
1.05	109.517	109.5882	108.8367	108.827
1.06	109.517	109.5585	108.8608	108.827
1.07	109.517	109.5289	108.885	108.827
1.08	109.517	109.517	108.9092	108.827
1.09	109.517	109.517	108.914	108.827
1.1	109.517	109.517	108.914	108.827
1.11	109.517	109.517	108.914	108.827
1.12	109.517	109.5367	108.914	108.827
1.13	109.517	109.5612	108.914	108.827
1.14	109.517	109.5858	108.914	108.827
1.15	109.524	109.596	108.914	108.827
1.16	109.5472	109.5728	108.914	108.827
1.17	109.5705	109.5495	108.914	108.827
1.18	109.5937	109.5263	108.914	108.827
1.19	109.603	109.5317	108.914	108.827
1.2	109.603	109.5563	108.914	108.827
1.21	109.603	109.5809	108.914	108.827
1.22	109.603	109.6015	108.914	108.827
1.23	109.603	109.5867	108.914	108.827
1.24	109.603	109.5719	108.914	108.827
1.25	109.603	109.557	108.914	108.827

1.26	109.603	109.5422	108.914	108.827
1.27	109.603	109.5274	108.914	108.827
1.28	109.603	109.517	108.914	108.827
1.29	109.603	109.517	108.914	108.827
1.3	109.603	109.517	108.914	108.8469
1.31	109.603	109.517	108.914	108.8717
1.32	109.603	109.517	108.914	108.8966
1.33	109.603	109.517	108.914	108.914
1.34	109.603	109.517	108.914	108.914
1.35	109.603	109.517	108.914	108.914
1.36	109.603	109.517	108.914	108.914
1.37	109.603	109.517	108.914	108.914
1.38	109.603	109.5198	108.914	108.914
1.39	109.603	109.5475	108.914	108.914
1.4	109.603	109.5753	108.914	108.914
1.41	109.603	109.603	108.914	108.914
1.42	109.603	109.603	108.914	108.914
1.43	109.603	109.603	108.914	108.914
1.44	109.603	109.603	108.914	108.914
1.45	109.603	109.603	108.914	108.914
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1.47	109.603	109.603	108.914	108.914
1.48	109.603	109.603	108.914	108.914
1.49	109.603	109.6182	108.914	108.914
1.5	109.603	109.6435	108.914	108.9035
1.51	109.603	109.6688	108.914	108.8771
1.52	109.603	109.6838	108.914	108.8507
1.53	109.603	109.6577	108.914	108.8299
1.54	109.603	109.6317	108.914	108.8589
1.55	109.603	109.6056	108.914	108.8879
1.56	109.603	109.603	108.914	108.914
1.57	109.603	109.603	108.914	108.914
1.58	109.603	109.603	108.914	108.914
1.59	109.603	109.603	108.914	108.914
1.6	109.603	109.603	108.914	108.914
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1.62	109.603	109.603	108.914	108.914
1.63	109.603	109.603	108.914	108.914
1.64	109.603	109.603	108.914	108.914
1.65	109.603	109.603	108.914	108.914
1.66	109.6007	109.6053	108.914	108.914
1.67	109.5781	109.6279	108.914	108.914
1.68	109.5555	109.6505	108.914	108.914
1.69	109.5328	109.6732	108.914	108.914

1.7	109.5238	109.6822	108.914	108.914
1.71	109.5464	109.6596	108.914	108.914
1.72	109.5691	109.6369	108.914	108.914
1.73	109.5917	109.6143	108.914	108.914
1.74	109.603	109.603	108.914	108.9368
1.75	109.603	109.603	108.914	108.9621
1.76	109.603	109.603	108.914	108.9874
1.77	109.603	109.603	108.914	109
1.78	109.603	109.603	108.914	109
1.79	109.603	109.603	108.914	109
1.8	109.603	109.603	108.914	109
1.81	109.603	109.603	108.914	109
1.82	109.603	109.6169	108.914	109
1.83	109.603	109.6402	108.914	109
1.84	109.603	109.6634	108.9185	109
1.85	109.603	109.6867	108.9638	109
1.86	109.603	109.6675	109.0091	109
1.87	109.603	109.6436	109.0543	109
1.88	109.603	109.6197	109.0724	109
1.89	109.6106	109.6106	109.0272	109
1.9	109.6359	109.6359	108.9819	109
1.91	109.6612	109.6612	108.9366	109
1.92	109.6865	109.6865	108.914	109.0108
1.93	109.6675	109.689	108.914	109.0323
1.94	109.6436	109.689	108.914	109.0538
1.95	109.6197	109.689	108.914	109.0753
1.96	109.61	109.689	108.914	109.086
1.97	109.6332	109.689	108.914	109.086
1.98	109.6565	109.689	108.914	109.086
1.99	109.6797	109.689	108.914	109.086
2	109.689	109.689	108.9279	109.086
2.01	109.689	109.689	108.9512	109.086
2.02	109.689	109.689	108.9744	109.086
2.03	109.689	109.689	108.9977	109.086
2.04	109.689	109.7057	109	109.1078
2.05	109.689	109.7296	109	109.1319
2.06	109.689	109.7535	109	109.1561
2.07	109.689	109.7773	109	109.173
2.08	109.689	109.7999	109	109.173
2.09	109.689	109.8225	109	109.173
2.1	109.689	109.8452	109	109.173
2.11	109.6962	109.861	109.0215	109.1945
2.12	109.7201	109.861	109.0454	109.2184
2.13	109.7439	109.861	109.0693	109.2423

2.14	109.7678	109.861	109.086	109.259
2.15	109.775	109.861	109.086	109.259
2.16	109.775	109.861	109.086	109.259
2.17	109.775	109.861	109.086	109.259
2.18	109.7777	109.861	109.0994	109.2722
2.19	109.8046	109.861	109.1217	109.2943
2.2	109.8314	109.861	109.144	109.3163
2.21	109.8583	109.861	109.1663	109.3384
2.22	109.861	109.8852	109.1897	109.345
2.23	109.861	109.9121	109.2136	109.345
2.24	109.861	109.9389	109.2375	109.345
2.25	109.8792	109.9833	109.259	109.345
2.26	109.9053	110.0351	109.259	109.345
2.27	109.9314	110.0869	109.259	109.345
2.28	109.947	110.1013	109.259	109.345
2.29	109.947	110.0596	109.2662	109.3522
2.3	109.947	110.0179	109.2901	109.3761
2.31	109.947	109.9762	109.3139	109.3999
2.32	109.9536	109.9536	109.3378	109.4238
2.33	109.9757	109.9757	109.345	109.4477
2.34	109.9977	109.9977	109.345	109.4716
2.35	110.0198	110.0198	109.345	109.4955
2.36	110.0427	110.0427	109.3477	109.5143
2.37	110.067	110.067	109.3746	109.4874
2.38	110.0913	110.0913	109.4014	109.4606
2.39	110.1156	110.1156	109.4283	109.4337
2.4	110.1401	110.1622	109.4552	109.4794
2.41	110.1647	110.2114	109.4821	109.5331
2.42	110.1893	110.2605	109.5089	109.5869
2.43	110.2136	110.2804	109.5352	109.6212
2.44	110.2374	110.2566	109.5613	109.6473
2.45	110.2613	110.2327	109.5874	109.6734
2.46	110.2852	110.2088	109.603	109.6974
2.47	110.29	110.2216	109.603	109.7184
2.48	110.29	110.2437	109.603	109.7393
2.49	110.29	110.2657	109.603	109.7603
2.5	110.29	110.2878	109.6096	109.7882
2.51	110.29	110.3342	109.6317	109.8323
2.52	110.29	110.3834	109.6537	109.8764
2.53	110.29	110.4325	109.6758	109.9205
2.54	110.29	110.462	109.7087	109.9568
2.55	110.29	110.462	109.7578	109.9814
2.56	110.29	110.462	109.8069	110.006
2.57	110.29	110.462	109.8561	110.0305

2.58	110.3109	110.4829	109.861	110.0109
2.59	110.3342	110.5062	109.861	109.9863
2.6	110.3574	110.5294	109.861	109.9617
2.61	110.3861	110.5531	109.8706	109.947
2.62	110.4367	110.5784	109.8944	109.947
2.63	110.4873	110.6036	109.9183	109.947
2.64	110.5379	110.6289	109.9422	109.947
2.65	110.548	110.6542	109.9294	109.9821
2.66	110.548	110.6795	109.9073	110.0259
2.67	110.548	110.7048	109.8853	110.0698
2.68	110.5591	110.7089	109.8632	110.1136
2.69	110.5868	110.6812	109.9052	110.118
2.7	110.6146	110.6534	109.9544	110.118
2.71	110.634	110.6477	110.0035	110.118
2.72	110.634	110.6932	110.0427	110.1278
2.73	110.634	110.7387	110.067	110.1524
2.74	110.634	110.7842	110.0913	110.177
2.75	110.6574	110.807	110.1156	110.2015
2.76	110.7041	110.807	110.1389	110.2249
2.77	110.7509	110.807	110.1622	110.2482
2.78	110.7976	110.807	110.1854	110.2714
2.79	110.8242	110.8242	110.1989	110.29
2.8	110.8457	110.8457	110.1736	110.29
2.81	110.8672	110.8672	110.1484	110.29
2.82	110.8887	110.8887	110.1231	110.29
2.83	110.893	110.9102	110.118	110.3102
2.84	110.893	110.9317	110.118	110.3355
2.85	110.893	110.9532	110.118	110.3608
2.86	110.893	110.9747	110.118	110.376
2.87	110.893	110.9622	110.118	110.376
2.88	110.893	110.9412	110.118	110.376
2.89	110.893	110.9203	110.118	110.3692
2.9	110.893	110.8993	110.118	110.3466
2.91	110.893	110.893	110.118	110.3239
2.92	110.893	110.893	110.118	110.3013
2.93	110.893	110.893	110.1296	110.29
2.94	110.893	110.893	110.1529	110.29
2.95	110.8801	110.893	110.1761	110.29
2.96	110.8586	110.893	110.1994	110.29
2.97	110.8371	110.893	110.1868	110.2556
2.98	110.8156	110.893	110.1653	110.2126
2.99	110.807	110.8804	110.1438	110.1696
3	110.807	110.8594	110.1223	110.1266
3.01	110.807	110.8385	110.101	110.1352

3.02	110.807	110.8175	110.0798	110.1567
3.03	110.807	110.807	110.0585	110.1782
3.04	110.807	110.807	110.0373	110.1997
3.05	110.807	110.807	110.033	110.1706
3.06	110.807	110.807	110.033	110.1289
3.07	110.7612	110.7612	110.033	110.0872
3.08	110.72	110.72	110.033	110.0455
3.09	110.72	110.72	110.033	110.033
3.1	110.72	110.72	110.033	110.033
3.11	110.72	110.72	110.033	110.033
3.12	110.7077	110.7077	110.033	110.033
3.13	110.6831	110.6831	110.033	110.0201
3.14	110.6586	110.6586	110.033	109.9986
3.15	110.634	110.634	110.033	109.9771
3.16	110.6094	110.6586	110.033	109.9556
3.17	110.5849	110.6831	110.033	109.9344
3.18	110.5603	110.7077	110.033	109.9134
3.19	110.548	110.72	110.033	109.8925
3.2	110.548	110.72	110.033	109.8715
3.21	110.548	110.72	110.0084	109.861
3.22	110.548	110.72	109.9593	109.861
3.23	110.5271	110.6991	109.9101	109.861
3.24	110.5038	110.6758	109.861	109.861
3.25	110.4806	110.6526	109.861	109.861
3.26	110.462	110.6304	109.861	109.8586
3.27	110.462	110.6125	109.861	109.8347
3.28	110.462	110.5946	109.861	109.8108
3.29	110.462	110.5767	109.861	109.7869
3.3	110.462	110.5588	109.861	109.7873
3.31	110.462	110.548	109.861	109.8119
3.32	110.462	110.548	109.861	109.8364
3.33	110.462	110.548	109.861	109.861
3.34	110.4749	110.548	109.861	109.861
3.35	110.4964	110.548	109.861	109.861
3.36	110.5179	110.548	109.861	109.861
3.37	110.5394	110.548	109.8491	109.861
3.38	110.548	110.5337	109.8252	109.861
3.39	110.548	110.5098	109.8013	109.861
3.4	110.548	110.4859	109.7774	109.861
3.41	110.548	110.462	109.775	109.861
3.42	110.548	110.462	109.775	109.861
3.43	110.548	110.462	109.775	109.861
3.44	110.548	110.462	109.775	109.861
3.45	110.548	110.462	109.775	109.861

3.46	110.548	110.462	109.775	109.861
3.47	110.548	110.462	109.775	109.861
3.48	110.548	110.462	109.775	109.861
3.49	110.548	110.462	109.775	109.8487
3.5	110.548	110.462	109.775	109.818
3.51	110.548	110.462	109.775	109.7873
3.52	110.548	110.462	109.775	109.7879
3.53	110.548	110.4494	109.775	109.8094
3.54	110.548	110.4241	109.775	109.8309
3.55	110.548	110.3988	109.775	109.8524
3.56	110.5456	110.376	109.775	109.861
3.57	110.5217	110.376	109.775	109.861
3.58	110.4978	110.376	109.775	109.861
3.59	110.4739	110.376	109.775	109.861
3.6	110.4736	110.376	109.775	109.861
3.61	110.4969	110.376	109.775	109.861
3.62	110.5201	110.376	109.775	109.861
3.63	110.5434	110.376	109.775	109.861
3.64	110.5258	110.3982	109.775	109.8395
3.65	110.4981	110.4259	109.775	109.8156
3.66	110.4703	110.4537	109.775	109.7917
3.67	110.4843	110.462	109.775	109.775
3.68	110.5161	110.462	109.775	109.775
3.69	110.548	110.462	109.775	109.775
3.7	110.5285	110.4425	109.775	109.775
3.71	110.5089	110.4229	109.775	109.775
3.72	110.4894	110.4034	109.775	109.775
3.73	110.4698	110.3838	109.775	109.775
3.74	110.462	110.376	109.7774	109.775
3.75	110.462	110.376	109.8013	109.775
3.76	110.462	110.376	109.8252	109.775
3.77	110.462	110.376	109.8491	109.775
3.78	110.462	110.376	109.8378	109.7634
3.79	110.462	110.376	109.7913	109.7401
3.8	110.462	110.376	109.7448	109.7169
3.81	110.4659	110.3721	109.6983	109.6936
3.82	110.4855	110.3525	109.578	109.6446
3.83	110.505	110.333	109.4393	109.5891
3.84	110.5245	110.3135	109.3006	109.5336
3.85	110.5441	110.2939	109.3928	109.5393
3.86	110.5108	110.2714	109.5839	109.5711
3.87	110.4643	110.2482	109.775	109.603
3.88	110.4178	110.2249	109.7164	109.6225
3.89	110.3893	110.1798	109.6577	109.6421

3.9	110.5218	109.9375	109.5991	109.6616
3.91	110.6544	109.6952	109.5405	109.6812
3.92	110.7869	109.4528	109.5907	109.7185
3.93	110.8256	109.3188	109.7136	109.7676
3.94	110.4887	109.618	109.8364	109.8168
3.95	110.1517	109.9171	109.9514	109.8698
3.96	110.2021	110.0814	109.9952	109.9577
3.97	110.2956	110.2308	110.0391	110.0457
3.98	110.3891	110.3801	110.0829	110.1336
3.99	110.4826	110.5295	110.0985	110.1845
4	110.5745	110.6539	110.001	110.087
4.01	110.663	110.7203	109.9035	109.9895
4.02	110.7515	110.7867	109.806	109.892
4.03	110.8399	110.8532	109.7085	109.7945
4.04	110.8557	110.8743	109.689	109.7564
4.05	110.7625	110.8275	109.689	109.7332
4.06	110.6692	110.7808	109.689	109.7099
4.07	110.576	110.734	109.689	109.6912
4.08	110.5136	110.6684	109.689	109.7133
4.09	110.4645	110.5947	109.689	109.7353
4.1	110.4153	110.521	109.689	109.7574
4.11	110.376	110.4568	109.689	109.775
4.12	110.376	110.4307	109.689	109.775
4.13	110.376	110.4047	109.689	109.775
4.14	110.376	110.3786	109.689	109.775
4.15	110.376	110.376	109.689	109.775
4.16	110.376	110.376	109.689	109.775
4.17	110.376	110.376	109.689	109.775
4.18	110.376	110.376	109.689	109.775
4.19	110.4021	110.376	109.689	109.775
4.2	110.4281	110.376	109.689	109.775
4.21	110.4542	110.376	109.689	109.775
4.22	110.462	110.376	109.689	109.775
4.23	110.462	110.376	109.689	109.775
4.24	110.462	110.376	109.689	109.775
4.25	110.462	110.376	109.689	109.775
4.26	110.462	110.376	109.689	109.775
4.27	110.462	110.376	109.689	109.775
4.28	110.462	110.376	109.689	109.775
4.29	110.462	110.376	109.6942	109.7802
4.3	110.462	110.376	109.7203	109.8063
4.31	110.462	110.376	109.7463	109.8323
4.32	110.462	110.3858	109.7724	109.8584
4.33	110.462	110.4104	109.775	109.861

4.34	110.462	110.435	109.775	109.861
4.35	110.462	110.4595	109.775	109.861
4.36	110.462	110.462	109.775	109.861
4.37	110.462	110.462	109.775	109.861
4.38	110.462	110.462	109.775	109.861
4.39	110.462	110.462	109.775	109.861
4.4	110.462	110.462	109.775	109.861
4.41	110.462	110.462	109.775	109.861
4.42	110.462	110.462	109.775	109.861
4.43	110.462	110.462	109.775	109.8538
4.44	110.462	110.462	109.775	109.8299
4.45	110.462	110.462	109.775	109.8061
4.46	110.462	110.462	109.775	109.7822
4.47	110.462	110.462	109.775	109.775
4.48	110.462	110.462	109.775	109.775
4.49	110.462	110.462	109.775	109.775
4.5	110.4665	110.462	109.7848	109.7848
4.51	110.4892	110.462	109.8094	109.8094
4.52	110.5118	110.462	109.834	109.834
4.53	110.5344	110.462	109.8585	109.8585
4.54	110.548	110.4711	109.861	109.861
4.55	110.548	110.4937	109.861	109.861
4.56	110.548	110.5163	109.861	109.861
4.57	110.548	110.5389	109.861	109.861
4.58	110.5619	110.548	109.861	109.861
4.59	110.5852	110.548	109.861	109.861
4.6	110.6084	110.548	109.861	109.861
4.61	110.6317	110.548	109.861	109.8808
4.62	110.6136	110.548	109.861	109.9029
4.63	110.591	110.548	109.861	109.9249
4.64	110.5684	110.548	109.861	109.947
4.65	110.548	110.548	109.861	109.947
4.66	110.548	110.548	109.861	109.947
4.67	110.548	110.548	109.861	109.947
4.68	110.548	110.548	109.861	109.947
4.69	110.548	110.548	109.861	109.947
4.7	110.548	110.548	109.861	109.947
4.71	110.548	110.548	109.861	109.947
4.72	110.548	110.5532	109.8701	109.947
4.73	110.548	110.5793	109.8927	109.947
4.74	110.548	110.6053	109.9153	109.947
4.75	110.548	110.6314	109.9379	109.947
4.76	110.548	110.634	109.9331	109.947
4.77	110.548	110.634	109.9098	109.947

4.78	110.548	110.634	109.8866	109.947
4.79	110.548	110.634	109.8633	109.947
4.8	110.548	110.634	109.8814	109.947
4.81	110.548	110.634	109.904	109.947
4.82	110.548	110.634	109.9266	109.947
4.83	110.548	110.6521	109.947	109.9447
4.84	110.548	110.6747	109.947	109.9214
4.85	110.548	110.6974	109.947	109.8982
4.86	110.548	110.72	109.947	109.8749
4.87	110.548	110.6747	109.947	109.8718
4.88	110.548	110.634	109.947	109.8986
4.89	110.548	110.634	109.947	109.9255
4.9	110.548	110.634	109.9522	109.947
4.91	110.548	110.634	109.9783	109.947
4.92	110.5573	110.634	110.0043	109.947
4.93	110.5805	110.634	110.0304	109.947
4.94	110.6038	110.634	110.0109	109.947
4.95	110.627	110.634	109.9863	109.947
4.96	110.634	110.6494	109.9617	109.947
4.97	110.634	110.6715	109.9566	109.9566
4.98	110.634	110.6935	109.9804	109.9804
4.99	110.634	110.7156	110.0043	110.0043
5	110.634	110.7047	110.0282	110.0282
5.01	110.634	110.6856	110.033	110.033
5.02	110.634	110.6665	110.033	110.033
5.03	110.634	110.6474	110.033	110.033
5.04	110.634	110.634	110.033	110.033
5.05	110.634	110.634	110.033	110.033
5.06	110.634	110.634	110.033	110.0307
5.07	110.634	110.634	110.033	110.0074
5.08	110.634	110.6586	110.033	109.9842
5.09	110.634	110.6831	110.033	109.9609
5.1	110.634	110.7077	110.033	109.9563
5.11	110.6479	110.72	110.033	109.9795
5.12	110.6756	110.72	110.033	110.0028
5.13	110.7034	110.72	110.033	110.026
5.14	110.7104	110.72	110.033	110.033
5.15	110.6866	110.72	110.033	110.033
5.16	110.6627	110.72	110.033	110.033
5.17	110.6388	110.72	110.033	110.033
5.18	110.634	110.72	110.033	110.033
5.19	110.634	110.72	110.033	110.033
5.2	110.634	110.72	110.033	110.033
5.21	110.6441	110.72	110.033	110.033

5.22	110.6694	110.72	110.033	110.033
5.23	110.6947	110.72	110.033	110.033
5.24	110.72	110.72	110.033	110.033
5.25	110.72	110.72	110.033	110.033
5.26	110.72	110.72	110.033	110.033
5.27	110.72	110.72	110.033	110.033
5.28	110.7081	110.72	110.033	110.033
5.29	110.6842	110.72	110.0467	110.033
5.3	110.6603	110.72	110.0741	110.033
5.31	110.6364	110.72	110.1015	110.033
5.32	110.6549	110.72	110.118	110.033
5.33	110.6782	110.72	110.118	110.033
5.34	110.7014	110.72	110.118	110.033
5.35	110.72	110.72	110.118	110.033
5.36	110.72	110.72	110.118	110.053
5.37	110.72	110.72	110.118	110.078
5.38	110.72	110.72	110.118	110.103
5.39	110.72	110.72	110.118	110.118
5.4	110.72	110.72	110.118	110.118
5.41	110.72	110.72	110.118	110.118
5.42	110.72	110.72	110.118	110.118
5.43	110.72	110.7366	110.118	110.0937
5.44	110.72	110.7573	110.118	110.0694
5.45	110.72	110.778	110.118	110.0451
5.46	110.72	110.7987	110.118	110.0448
5.47	110.72	110.807	110.118	110.0684
5.48	110.72	110.807	110.118	110.092
5.49	110.72	110.807	110.118	110.1156
5.5	110.72	110.807	110.1389	110.118
5.51	110.749	110.807	110.1622	110.118
5.52	110.778	110.807	110.1854	110.118
5.53	110.807	110.807	110.204	110.118
5.54	110.807	110.807	110.204	110.118
5.55	110.807	110.807	110.204	110.118
5.56	110.807	110.807	110.204	110.118
5.57	110.807	110.807	110.204	110.1296
5.58	110.807	110.807	110.204	110.1529
5.59	110.807	110.807	110.204	110.1761
5.6	110.807	110.807	110.204	110.1994
5.61	110.807	110.807	110.204	110.204
5.62	110.807	110.807	110.204	110.204
5.63	110.807	110.807	110.204	110.204
5.64	110.807	110.8213	110.204	110.204
5.65	110.807	110.8418	110.204	110.204

5.66	110.807	110.8623	110.204	110.204
5.67	110.807	110.8828	110.204	110.204
5.68	110.807	110.893	110.204	110.204
5.69	110.807	110.893	110.204	110.204
5.7	110.807	110.893	110.204	110.204
5.71	110.807	110.893	110.204	110.204
5.72	110.807	110.893	110.204	110.204
5.73	110.807	110.893	110.204	110.204
5.74	110.807	110.893	110.204	110.204
5.75	110.807	110.893	110.217	110.204
5.76	110.807	110.893	110.2431	110.204
5.77	110.807	110.893	110.2692	110.204
5.78	110.807	110.9033	110.29	110.204
5.79	110.807	110.9377	110.29	110.204
5.8	110.807	110.9721	110.29	110.204
5.81	110.807	110.979	110.29	110.204
5.82	110.807	110.979	110.29	110.1897
5.83	110.807	110.979	110.29	110.1692
5.84	110.807	110.979	110.29	110.1487
5.85	110.8274	110.979	110.29	110.1282
5.86	110.85	110.979	110.29	110.1296
5.87	110.8726	110.979	110.29	110.1529
5.88	110.893	110.979	110.29	110.1761
5.89	110.893	110.979	110.29	110.1994
5.9	110.893	110.979	110.29	110.204
5.91	110.893	110.979	110.29	110.204
5.92	110.893	110.979	110.29	110.204
5.93	110.893	110.979	110.2959	110.204
5.94	110.893	110.979	110.3256	110.204
5.95	110.893	110.979	110.3552	110.204
5.96	110.893	110.979	110.376	110.2143
5.97	110.893	110.979	110.376	110.2487
5.98	110.893	110.979	110.376	110.2831
5.99	110.893	110.979	110.376	110.29
6	110.893	110.979	110.376	110.29
6.01	110.893	110.979	110.376	110.29
6.02	110.893	110.979	110.376	110.29
6.03	110.893	110.979	110.376	110.29
6.04	110.893	110.979	110.376	110.29
6.05	110.893	110.979	110.376	110.29
6.06	110.893	110.979	110.3744	110.29
6.07	110.893	110.979	110.3582	110.29
6.08	110.893	110.979	110.3419	110.29
6.09	110.893	110.979	110.3257	110.29

6.1	110.893	110.979	110.3095	110.29
6.11	110.893	110.9946	110.2932	110.29
6.12	110.893	111.0207	110.3199	110.29
6.13	110.893	111.0468	110.3573	110.29
6.14	110.893	111.065	110.376	110.2784
6.15	110.893	111.065	110.376	110.2551
6.16	110.893	111.065	110.376	110.2319
6.17	110.893	111.065	110.376	110.2086
6.18	110.893	111.065	110.376	110.2178
6.19	110.893	111.065	110.376	110.235
6.2	110.893	111.065	110.376	110.2522
6.21	110.893	111.065	110.376	110.2694
6.22	110.893	111.065	110.376	110.2866
6.23	110.893	111.065	110.376	110.29
6.24	110.893	111.065	110.376	110.29
6.25	110.893	111.0531	110.376	110.29
6.26	110.893	111.0292	110.376	110.29
6.27	110.893	111.0053	110.376	110.29
6.28	110.893	110.9814	110.376	110.29
6.29	110.893	111.0005	110.376	110.29
6.3	110.893	111.0244	110.376	110.29
6.31	110.893	111.0483	110.376	110.29
6.32	110.9006	111.065	110.376	110.2972
6.33	110.9259	111.065	110.376	110.3211
6.34	110.9512	111.065	110.376	110.3449
6.35	110.9765	111.065	110.376	110.3688
6.36	110.979	111.065	110.3932	110.376
6.37	110.979	111.065	110.4178	110.376
6.38	110.979	111.065	110.4423	110.376
6.39	110.979	111.065	110.4574	110.376
6.4	110.979	111.065	110.4341	110.376
6.41	110.979	111.065	110.4109	110.376
6.42	110.979	111.065	110.3876	110.376
6.43	110.979	111.065	110.3879	110.3641
6.44	110.979	111.065	110.4118	110.3402
6.45	110.979	111.065	110.4357	110.3163
6.46	110.979	111.065	110.4596	110.2924
6.47	110.979	111.065	110.462	110.3115
6.48	110.979	111.065	110.462	110.3354
6.49	110.979	111.065	110.462	110.3593
6.5	110.979	111.065	110.462	110.376
6.51	110.979	111.065	110.462	110.376
6.52	110.979	111.065	110.462	110.376
6.53	110.979	111.065	110.462	110.376

6.54	110.979	111.065	110.462	110.376
6.55	110.979	111.065	110.462	110.376
6.56	110.979	111.065	110.462	110.376
6.57	110.979	111.065	110.462	110.376
6.58	110.979	111.065	110.462	110.376
6.59	110.979	111.065	110.462	110.376
6.6	110.979	111.065	110.462	110.376
6.61	110.979	111.065	110.462	110.376
6.62	110.979	111.0756	110.462	110.376
6.63	110.979	111.0968	110.462	110.376
6.64	110.979	111.118	110.462	110.376
6.65	110.979	111.1393	110.462	110.376
6.66	110.979	111.1423	110.462	110.376
6.67	110.979	111.1182	110.462	110.376
6.68	110.979	111.094	110.462	110.376
6.69	110.979	111.0698	110.4907	110.3473
6.7	110.979	111.065	110.5265	110.3115
6.71	110.979	111.065	110.54	110.29
6.72	110.979	111.065	110.52	110.29
6.73	110.9945	111.0807	110.5	110.29
6.74	111.0117	111.0981	110.48	110.29
6.75	111.0289	111.1155	110.4639	110.2937
6.76	111.0461	111.1329	110.4826	110.3311
6.77	111.0633	111.1503	110.5013	110.3685
6.78	111.065	111.152	110.52	110.4059
6.79	111.065	111.152	110.5387	110.4433
6.8	111.0622	111.152	110.548	110.441
6.81	111.0345	111.152	110.548	110.3991
6.82	111.0067	111.152	110.548	110.3571
6.83	110.979	111.152	110.548	110.3152
6.84	111.0029	111.152	110.5384	110.3091
6.85	111.0268	111.152	110.5146	110.3569
6.86	111.0507	111.152	110.4907	110.4047
6.87	111.065	111.152	110.4668	110.4524
6.88	111.065	111.152	110.462	110.462
6.89	111.065	111.152	110.462	110.462
6.9	111.065	111.152	110.462	110.462
6.91	111.065	111.152	110.4775	110.462
6.92	111.065	111.152	110.4947	110.462
6.93	111.065	111.152	110.5119	110.462
6.94	111.065	111.1748	110.5291	110.462
6.95	111.065	111.2001	110.5463	110.462
6.96	111.065	111.2254	110.548	110.462
6.97	111.065	111.238	110.548	110.462

6.98	111.065	111.238	110.548	110.4592
6.99	111.065	111.238	110.548	110.4315
7	111.065	111.238	110.548	110.4037
7.01	111.065	111.238	110.548	110.376
7.02	111.065	111.238	110.5241	110.3999
7.03	111.065	111.238	110.5002	110.4238
7.04	111.065	111.238	110.4763	110.4477
7.05	111.065	111.238	110.4866	110.462
7.06	111.065	111.238	110.548	110.462
7.07	111.065	111.238	110.6094	110.462
7.08	111.065	111.238	110.6201	110.462
7.09	111.065	111.238	110.5968	110.462
7.1	111.065	111.238	110.5736	110.462
7.11	111.065	111.238	110.5503	110.462
7.12	111.065	111.2292	110.548	110.4392
7.13	111.065	111.2071	110.548	110.4139
7.14	111.065	111.1851	110.548	110.3886
7.15	111.065	111.163	110.5596	110.3876
7.16	111.065	111.1639	110.5829	110.4109
7.17	111.065	111.1878	110.6061	110.4341
7.18	111.065	111.2117	110.6294	110.4574
7.19	111.065	111.2356	110.634	110.4796
7.2	111.065	111.238	110.634	110.5017
7.21	111.065	111.238	110.634	110.5237
7.22	111.065	111.238	110.634	110.5458
7.23	111.0678	111.2408	110.634	110.548
7.24	111.0959	111.2689	110.634	110.548
7.25	111.1239	111.2969	110.634	110.548
7.26	111.152	111.325	110.634	110.548
7.27	111.1291	111.2795	110.634	110.548
7.28	111.1062	111.2339	110.634	110.548
7.29	111.0833	111.1884	110.634	110.548
7.3	111.07	111.1619	110.6252	110.548
7.31	111.0948	111.2113	110.6031	110.548
7.32	111.1197	111.2607	110.5811	110.548
7.33	111.1445	111.3102	110.559	110.548
7.34	111.152	111.325	110.5719	110.548
7.35	111.152	111.325	110.6197	110.548
7.36	111.152	111.325	110.6674	110.548
7.37	111.152	111.3199	110.7152	110.548
7.38	111.152	111.2943	110.72	110.548
7.39	111.152	111.2687	110.72	110.548
7.4	111.152	111.2431	110.72	110.548
7.41	111.152	111.238	110.72	110.548

7.42	111.152	111.238	110.72	110.548
7.43	111.152	111.238	110.72	110.548
7.44	111.152	111.2554	110.72	110.548
7.45	111.152	111.3134	110.7429	110.548
7.46	111.152	111.3714	110.7658	110.548
7.47	111.152	111.412	110.7887	110.548
7.48	111.152	111.412	110.807	110.548
7.49	111.152	111.412	110.807	110.548
7.5	111.152	111.412	110.807	110.548
7.51	111.152	111.412	110.807	110.548
7.52	111.152	111.412	110.807	110.548
7.53	111.152	111.412	110.807	110.548
7.54	111.152	111.412	110.807	110.548
7.55	111.1616	111.412	110.8121	110.5429
7.56	111.1854	111.412	110.8374	110.5176
7.57	111.2093	111.412	110.8626	110.4924
7.58	111.2332	111.412	110.8879	110.4671
7.59	111.238	111.4319	110.8733	110.4817
7.6	111.238	111.4567	110.8488	110.5062
7.61	111.238	111.4816	110.8242	110.5308
7.62	111.238	111.4903	110.807	110.548
7.63	111.238	111.4613	110.807	110.548
7.64	111.238	111.4323	110.807	110.548
7.65	111.238	111.412	110.813	110.548
7.66	111.238	111.412	110.833	110.548
7.67	111.238	111.412	110.853	110.548
7.68	111.238	111.412	110.873	110.548
7.69	111.238	111.412	110.893	110.548
7.7	111.238	111.412	110.8691	110.548
7.71	111.238	111.412	110.8452	110.548
7.72	111.238	111.4195	110.8213	110.548
7.73	111.238	111.4443	110.8166	110.5576
7.74	111.238	111.4692	110.8404	110.5814
7.75	111.238	111.494	110.8643	110.6053
7.76	111.2568	111.499	110.8882	110.6292
7.77	111.2803	111.499	110.8733	110.6143
7.78	111.3038	111.499	110.8488	110.5898
7.79	111.325	111.499	110.8242	110.5652
7.8	111.325	111.499	110.807	110.5566
7.81	111.325	111.499	110.807	110.5853
7.82	111.325	111.499	110.807	110.6139
7.83	111.325	111.499	110.8217	110.6266
7.84	111.325	111.499	110.8709	110.6021
7.85	111.325	111.499	110.92	110.5775

7.86	111.325	111.499	110.9692	110.5529
7.87	111.325	111.499	110.9593	110.5677
7.88	111.325	111.499	110.9348	110.5922
7.89	111.325	111.499	110.9102	110.6168
7.9	111.325	111.499	110.9004	110.6414
7.91	111.325	111.5262	110.9249	110.6659
7.92	111.325	111.5534	110.9495	110.6905
7.93	111.325	111.5806	110.9741	110.7151
7.94	111.325	111.586	110.979	110.7014
7.95	111.325	111.586	110.979	110.6782
7.96	111.325	111.586	110.979	110.6549
7.97	111.325	111.586	110.979	110.6366
7.98	111.325	111.586	110.979	110.6627
7.99	111.325	111.586	110.979	110.6887
8	111.325	111.586	110.979	110.7148
8.01	111.325	111.586	110.979	110.72
8.02	111.325	111.586	110.979	110.72
8.03	111.325	111.586	110.979	110.72
8.04	111.325	111.586	110.979	110.72
8.05	111.325	111.5884	110.9712	110.72
8.06	111.325	111.6119	110.9451	110.72
8.07	111.325	111.6354	110.9191	110.72
8.08	111.325	111.6589	110.893	110.72
8.09	111.325	111.673	110.9199	110.72
8.1	111.325	111.673	110.9468	110.72
8.11	111.325	111.673	110.9736	110.72
8.12	111.325	111.673	110.9966	110.7378
8.13	111.325	111.673	111.0187	110.7602
8.14	111.325	111.673	111.0407	110.7825
8.15	111.325	111.673	111.0628	110.8048
8.16	111.325	111.673	111.065	110.7858
8.17	111.325	111.673	111.065	110.7623
8.18	111.325	111.673	111.065	110.7388
8.19	111.325	111.673	111.0692	110.72
8.2	111.3301	111.6781	111.0905	110.72
8.21	111.3557	111.7037	111.1117	110.72
8.22	111.3813	111.7293	111.1329	110.72
8.23	111.4069	111.7549	111.152	110.7224
8.24	111.412	111.76	111.152	110.7459
8.25	111.412	111.76	111.152	110.7694
8.26	111.412	111.76	111.152	110.7929
8.27	111.412	111.76	111.1697	110.807
8.28	111.412	111.7383	111.2141	110.807
8.29	111.412	111.7141	111.2585	110.807

8.3	111.412	111.6899	111.3028	110.807
8.31	111.421	111.691	111.325	110.7952
8.32	111.451	111.751	111.325	110.7717
8.33	111.481	111.811	111.325	110.7482
8.34	111.499	111.847	111.325	110.7247
8.35	111.499	111.847	111.3057	110.7393
8.36	111.499	111.847	111.2815	110.7635
8.37	111.499	111.847	111.2573	110.7877
8.38	111.5083	111.8377	111.2329	110.8019
8.39	111.5394	111.8066	111.2076	110.7763
8.4	111.5705	111.7755	111.1824	110.7507
8.41	111.5767	111.76	111.1571	110.7251
8.42	111.5582	111.76	111.1342	110.7024
8.43	111.5397	111.76	111.1118	110.6803
8.44	111.5212	111.76	111.0895	110.6583
8.45	111.5027	111.76	111.0672	110.6362
8.46	111.4802	111.7412	111.0868	110.6555
8.47	111.4567	111.7177	111.1109	110.6794
8.48	111.4332	111.6942	111.1351	110.7033
8.49	111.412	111.6698	111.1341	110.72
8.5	111.412	111.6376	111.0744	110.72
8.51	111.412	111.6053	111.0148	110.72
8.52	111.4229	111.5969	110.9537	110.678
8.53	111.4501	111.6241	110.8906	110.5732
8.54	111.4773	111.6513	110.8274	110.4683
8.55	111.4832	111.6572	110.7642	110.3634
8.56	111.4041	111.5781	110.6739	110.2716
8.57	111.325	111.499	110.5204	110.2101
8.58	111.2459	111.4199	110.3668	110.1487
8.59	111.0746	111.2481	110.3817	110.2004
8.6	110.893	111.066	110.5651	110.3653
8.61	110.7114	110.8839	110.7485	110.5302
8.62	110.5718	110.7416	110.9319	110.6951
8.63	110.8095	110.9581	111.1153	110.86
8.64	111.0473	111.1746	111.152	110.9116
8.65	111.285	111.3911	111.152	110.9348
8.66	111.5031	111.5901	111.152	110.9581
8.67	111.5446	111.6316	111.152	110.979
8.68	111.586	111.673	111.152	110.979
8.69	111.6274	111.7144	111.152	110.979
8.7	111.6689	111.7559	111.1411	110.9898
8.71	111.673	111.76	111.1139	111.0166
8.72	111.673	111.76	111.0868	111.0435
8.73	111.673	111.76	111.0598	111.0598

8.74	111.673	111.76	111.0337	111.0337	9.18	111.7685	111.847	111.3598	111.2212
8.75	111.673	111.76	111.0077	111.0077	9.19	111.7897	111.847	111.3847	111.2706
8.76	111.673	111.76	110.9816	110.9816	9.2	111.8109	111.847	111.4095	111.3201
8.77	111.6655	111.76	110.9994	110.979	9.21	111.8321	111.847	111.412	111.3044
8.78	111.6407	111.76	111.022	110.979	9.22	111.8399	111.8541	111.412	111.2815
8.79	111.6158	111.76	111.0446	110.979	9.23	111.8164	111.8779	111.412	111.2586
8.8	111.591	111.76	111.065	110.979	9.24	111.7929	111.9017	111.4097	111.238
8.81	111.6065	111.76	111.065	110.979	9.25	111.7694	111.9255	111.3868	111.238
8.82	111.6321	111.76	111.065	110.979	9.26	111.79	111.935	111.3639	111.238
8.83	111.6576	111.76	111.065	110.979	9.27	111.84	111.935	111.341	111.238
8.84	111.673	111.7513	111.0671	110.981	9.28	111.89	111.935	111.3319	111.2449
8.85	111.673	111.7296	111.0878	111.0015	9.29	111.9326	111.9374	111.3548	111.2678
8.86	111.673	111.7078	111.1085	111.022	9.3	111.9081	111.9616	111.3777	111.2907
8.87	111.673	111.6861	111.1292	111.0425	9.31	111.8837	111.9858	111.4006	111.3136
8.88	111.673	111.6819	111.1499	111.063	9.32	111.8592	112.0099	111.4014	111.325
8.89	111.673	111.7042	111.152	111.065	9.33	111.8596	112.022	111.3802	111.325
8.9	111.673	111.7265	111.152	111.065	9.34	111.8847	112.022	111.359	111.325
8.91	111.673	111.7488	111.152	111.065	9.35	111.9099	112.022	111.3377	111.325
8.92	111.6851	111.76	111.152	111.0849	9.36	111.935	112.022	111.325	111.3165
8.93	111.7093	111.76	111.152	111.1097	9.37	111.9099	111.9971	111.325	111.2953
8.94	111.7334	111.76	111.152	111.1346	9.38	111.8847	111.9723	111.325	111.2741
8.95	111.7576	111.76	111.152	111.152	9.39	111.8596	111.9474	111.325	111.2529
8.96	111.76	111.7824	111.152	111.152	9.4	111.847	111.95	111.3391	111.238
8.97	111.76	111.8072	111.152	111.152	9.41	111.847	111.98	111.3861	111.238
8.98	111.76	111.8321	111.152	111.152	9.42	111.847	112.01	111.4332	111.238
8.99	111.7501	111.8371	111.1722	111.1722	9.43	111.847	112.004	111.4802	111.238
9	111.7252	111.8122	111.1975	111.1975	9.44	111.847	111.974	111.4841	111.2529
9.01	111.7003	111.7873	111.2228	111.2228	9.45	111.847	111.944	111.4592	111.2778
9.02	111.6755	111.7625	111.238	111.2294	9.46	111.847	111.9546	111.4344	111.3026
9.03	111.6936	111.76	111.238	111.2079	9.47	111.847	111.9827	111.412	111.3202
9.04	111.7165	111.76	111.238	111.1864	9.48	111.847	112.0108	111.412	111.2721
9.05	111.7394	111.76	111.238	111.1649	9.49	111.847	112.022	111.412	111.2241
9.06	111.76	111.7623	111.2469	111.152	9.5	111.847	112.022	111.412	111.176
9.07	111.76	111.7852	111.2692	111.152	9.51	111.847	112.022	111.3996	111.152
9.08	111.76	111.8081	111.2915	111.152	9.52	111.847	112.022	111.3747	111.152
9.09	111.76	111.831	111.3138	111.152	9.53	111.847	112.022	111.3499	111.152
9.1	111.7669	111.847	111.3129	111.1639	9.54	111.847	112.022	111.325	111.152
9.11	111.7898	111.847	111.2888	111.1878	9.55	111.847	112.022	111.325	111.1271
9.12	111.8127	111.847	111.2646	111.2117	9.56	111.847	112.022	111.325	111.1023
9.13	111.8356	111.847	111.2404	111.2356	9.57	111.847	112.0123	111.325	111.0774
9.14	111.8364	111.847	111.2604	111.2159	9.58	111.847	111.9882	111.325	111.08
9.15	111.8152	111.847	111.2852	111.1913	9.59	111.847	111.964	111.325	111.11
9.16	111.794	111.847	111.3101	111.1667	9.6	111.847	111.9398	111.325	111.14
9.17	111.7727	111.847	111.3349	111.1718	9.61	111.847	111.935	111.307	111.152

9.62	111.847	111.935	111.277	111.152
9.63	111.847	111.935	111.247	111.152
9.64	111.847	111.935	111.2186	111.1324
9.65	111.847	111.9282	111.1908	111.1043
9.66	111.847	111.9057	111.1631	111.0762
9.67	111.847	111.8831	111.152	111.065
9.68	111.847	111.8605	111.152	111.065
9.69	111.8361	111.8361	111.152	111.065
9.7	111.8089	111.8089	111.152	111.065
9.71	111.7818	111.7818	111.1378	111.051
9.72	111.7549	111.76	111.1176	111.031
9.73	111.7293	111.76	111.0974	111.011
9.74	111.7037	111.76	111.0771	110.991
9.75	111.6781	111.76	111.065	110.979
9.76	111.6531	111.76	111.065	110.979
9.77	111.6283	111.76	111.065	110.979
9.78	111.6034	111.76	111.065	110.979
9.79	111.586	111.7459	111.0344	110.9637
9.8	111.586	111.6989	110.9962	110.9446
9.81	111.586	111.6518	110.958	110.9255
9.82	111.586	111.6048	110.9198	110.9064
9.83	111.586	111.586	110.8996	110.8996
9.84	111.586	111.586	110.9217	110.9217
9.85	111.586	111.586	110.9437	110.9437
9.86	111.586	111.5886	110.9658	110.9658
9.87	111.586	111.615	110.979	110.9683
9.88	111.586	111.6414	110.979	110.9414
9.89	111.586	111.6677	110.979	110.9145
9.9	111.586	111.661	110.9739	110.8879
9.91	111.586	111.646	110.9486	110.8626
9.92	111.586	111.631	110.9234	110.8374
9.93	111.586	111.616	110.8981	110.8121
9.94	111.586	111.601	110.893	110.807
9.95	111.586	111.586	110.893	110.807
9.96	111.5618	111.586	110.893	110.807
9.97	111.5377	111.586	110.886	110.814
9.98	111.5135	111.586	110.8628	110.8372
9.99	111.499	111.5766	110.8395	110.8605
10	111.499	111.5531	110.8163	110.8837
10.01	111.499	111.5296	110.7921	110.8783
10.02	111.499	111.5061	110.7672	110.8537
10.03	111.499	111.499	110.7424	110.8291
10.04	111.499	111.499	110.7226	110.807

10.05	111.499	111.499	110.749	110.807
10.06	111.499	111.4901	110.7754	110.807
10.07	111.499	111.4678	110.8017	110.807
10.08	111.499	111.4455	110.807	110.795
10.09	111.499	111.4232	110.807	110.78
10.1	111.4872	111.4238	110.807	110.765
10.11	111.4637	111.4473	110.807	110.75
10.12	111.4402	111.4708	110.807	110.735
10.13	111.4167	111.4943	110.807	110.72
10.14	111.4308	111.499	110.807	110.7442
10.15	111.4543	111.499	110.807	110.7683
10.16	111.4778	111.499	110.807	110.7925
10.17	111.499	111.4966	110.807	110.8163
10.18	111.499	111.4724	110.807	110.8395
10.19	111.499	111.4483	110.807	110.8628
10.2	111.499	111.4241	110.807	110.886
10.21	111.499	111.4234	110.807	110.8563
10.22	111.499	111.4463	110.807	110.8039
10.23	111.499	111.4692	110.807	110.7515
10.24	111.499	111.4921	110.807	110.7377
10.25	111.499	111.499	110.807	110.7821
10.26	111.499	111.499	110.807	110.8265
10.27	111.499	111.499	110.807	110.8708
10.28	111.499	111.499	110.8186	110.893
10.29	111.499	111.4932	110.8419	110.893
10.3	111.499	111.4739	110.8651	110.893
10.31	111.499	111.4545	110.8884	110.893
10.32	111.499	111.4352	110.893	110.893
10.33	111.499	111.4159	110.893	110.893
10.34	111.499	111.4294	110.893	110.893
10.35	111.499	111.4512	110.8906	110.8906
10.36	111.499	111.4729	110.8667	110.8667
10.37	111.499	111.4947	110.8428	110.8428
10.38	111.499	111.499	110.8189	110.8189
10.39	111.499	111.499	110.8183	110.8183

10.4	111.499	111.499	110.8409	110.8409
10.41	111.499	111.499	110.8636	110.8636
10.42	111.499	111.499	110.8862	110.8862
10.43	111.499	111.499	110.893	110.893
10.44	111.499	111.499	110.893	110.893
10.45	111.499	111.499	110.893	110.893
10.46	111.499	111.499	110.893	110.893
10.47	111.499	111.499	110.8873	110.8873
10.48	111.499	111.499	110.8682	110.8682
10.49	111.499	111.499	110.849	110.849
10.5	111.499	111.499	110.8299	110.8299
10.51	111.499	111.499	110.8108	110.8108
10.52	111.499	111.499	110.807	110.807
10.53	111.499	111.499	110.807	110.807
10.54	111.499	111.499	110.807	110.807
10.55	111.499	111.499	110.807	110.807
10.56	111.499	111.4934	110.807	110.7792
10.57	111.499	111.4653	110.807	110.7444
10.58	111.499	111.4373	110.807	110.7245
10.59	111.4966	111.412	110.807	110.7395
10.6	111.4731	111.412	110.807	110.7545
10.61	111.4496	111.412	110.807	110.7695
10.62	111.4261	111.412	110.807	110.7845
10.63	111.4219	111.4021	110.807	110.7995
10.64	111.4468	111.3772	110.807	110.7859
10.65	111.4717	111.3523	110.807	110.7437
10.66	111.4965	111.3275	110.807	110.7015
10.67	111.4778	111.325	110.807	110.6593
10.68	111.4543	111.325	110.807	110.6455
10.69	111.4308	111.325	110.807	110.6741
10.7	111.407	111.33	110.807	110.7028
10.71	111.3822	111.3548	110.807	110.7093
10.72	111.3573	111.3797	110.807	110.6824
10.73	111.3325	111.4045	110.807	110.6555
10.74	111.3415	111.3955	110.8014	110.6395

10.75	111.365	111.372	110.7733	110.6673
10.76	111.3885	111.3485	110.7453	110.695
10.77	111.412	111.325	110.7224	110.72
10.78	111.412	111.325	110.7459	110.72
10.79	111.412	111.325	110.7694	110.72
10.8	111.412	111.325	110.7929	110.72
10.81	111.412	111.325	110.7971	110.7102
10.82	111.412	111.325	110.7722	110.6856
10.83	111.412	111.325	110.7473	110.661
10.84	111.412	111.325	110.7225	110.6365
10.85	111.412	111.325	110.7412	110.6549
10.86	111.412	111.325	110.7647	110.6782
10.87	111.412	111.325	110.7882	110.7014
10.88	111.412	111.325	110.807	110.72
10.89	111.4053	111.3317	110.807	110.72
10.9	111.383	111.354	110.807	110.72
10.91	111.3607	111.3763	110.807	110.72
10.92	111.3384	111.3986	110.8233	110.7037
10.93	111.3347	111.412	110.8465	110.6805
10.94	111.3588	111.412	110.8698	110.6572
10.95	111.383	111.412	110.893	110.634
10.96	111.4072	111.412	110.893	110.6561
10.97	111.412	111.412	110.893	110.6781
10.98	111.412	111.412	110.893	110.7002
10.99	111.412	111.412	110.893	110.7221
11	111.412	111.412	110.893	110.7433
11.01	111.412	111.412	110.893	110.7646
11.02	111.412	111.412	110.893	110.7858
11.03	111.412	111.412	110.893	110.807
11.04	111.412	111.412	110.893	110.807
11.05	111.412	111.412	110.893	110.807
11.06	111.412	111.412	110.893	110.807
11.07	111.412	111.412	110.8864	110.807
11.08	111.4369	111.412	110.8643	110.807
11.09	111.4617	111.412	110.8423	110.807

11.1	111.4866	111.412	110.8202	110.807
11.11	111.499	111.412	110.8166	110.7973
11.12	111.499	111.412	110.8404	110.7732
11.13	111.499	111.412	110.8643	110.749
11.14	111.499	111.412	110.8882	110.7248
11.15	111.499	111.412	110.8754	110.72
11.16	111.499	111.412	110.8533	110.72
11.17	111.499	111.412	110.8313	110.72
11.18	111.499	111.412	110.8092	110.72
11.19	111.499	111.412	110.8285	110.72
11.2	111.499	111.412	110.8524	110.72
11.21	111.4907	111.4203	110.8763	110.72
11.22	111.47	111.441	110.893	110.72
11.23	111.4493	111.4617	110.893	110.72
11.24	111.4286	111.4824	110.893	110.72
11.25	111.4166	111.499	110.893	110.72
11.26	111.4395	111.499	110.8684	110.7449
11.27	111.4624	111.499	110.8439	110.7697
11.28	111.4853	111.499	110.8193	110.7946
11.29	111.4888	111.499	110.817	110.817
11.3	111.4632	111.499	110.837	110.837
11.31	111.4376	111.499	110.857	110.857
11.32	111.412	111.499	110.877	110.877
11.33	111.4525	111.499	110.893	110.893
11.34	111.4929	111.499	110.893	110.893
11.35	111.5334	111.499	110.893	110.893
11.36	111.5739	111.499	110.893	110.893
11.37	111.586	111.499	110.893	110.8834
11.38	111.586	111.499	110.893	110.8357
11.39	111.586	111.499	110.9012	110.8152
11.4	111.586	111.499	110.9217	110.8357
11.41	111.586	111.499	110.9421	110.8561
11.42	111.586	111.499	110.9626	110.8766
11.43	111.586	111.499	110.9745	110.8975
11.44	111.586	111.499	110.9518	110.9202

11.45	111.586	111.499	110.9292	110.9428
11.46	111.586	111.499	110.9066	110.9654
11.47	111.586	111.499	110.893	110.9689
11.48	111.6092	111.4758	110.893	110.9436
11.49	111.6382	111.4468	110.893	110.9183
11.5	111.6672	111.4178	110.893	110.893
11.51	111.673	111.4518	110.913	110.893
11.52	111.673	111.5015	110.933	110.893
11.53	111.673	111.5512	110.953	110.893
11.54	111.673	111.586	110.973	110.893
11.55	111.673	111.586	110.979	110.9247
11.56	111.673	111.586	110.979	110.9699
11.57	111.673	111.586	110.979	111.0152
11.58	111.673	111.586	110.979	111.0605
11.59	111.673	111.586	110.979	111.065
11.6	111.673	111.586	110.979	111.065
11.61	111.673	111.586	110.979	111.065
11.62	111.673	111.5643	110.979	111.065
11.63	111.673	111.5401	110.979	111.065
11.64	111.673	111.5159	110.979	111.065
11.65	111.6805	111.5065	110.979	111.065
11.66	111.7053	111.5313	111.0019	111.065
11.67	111.7302	111.5562	111.0306	111.065
11.68	111.755	111.581	111.0593	111.065
11.69	111.76	111.586	111.065	111.0849
11.7	111.76	111.586	111.065	111.1097
11.71	111.76	111.586	111.065	111.1346
11.72	111.76	111.586	111.065	111.1668
11.73	111.76	111.586	111.065	111.2163
11.74	111.76	111.586	111.065	111.2657
11.75	111.76	111.586	111.065	111.3151
11.76	111.7768	111.6028	111.1005	111.3072
11.77	111.8049	111.6309	111.1448	111.2848
11.78	111.833	111.659	111.1892	111.2625
11.79	111.847	111.6858	111.2336	111.2402

11.8	111.847	111.7114	111.238	111.2598
11.81	111.847	111.737	111.238	111.2839
11.82	111.847	111.76	111.238	111.3081
11.83	111.847	111.76	111.2306	111.3175
11.84	111.847	111.76	111.2061	111.2927
11.85	111.847	111.76	111.1815	111.2678
11.86	111.847	111.7829	111.1569	111.243
11.87	111.847	111.8058	111.1939	111.238
11.88	111.847	111.8287	111.2464	111.238
11.89	111.847	111.8522	111.2988	111.238
11.9	111.847	111.8781	111.3138	111.2492
11.91	111.847	111.9039	111.2915	111.2715
11.92	111.847	111.9298	111.2692	111.2938
11.93	111.869	111.913	111.2469	111.3161
11.94	111.8965	111.8855	111.2548	111.3418
11.95	111.924	111.858	111.2829	111.3699
11.96	111.935	111.882	111.311	111.398
11.97	111.935	111.9403	111.3378	111.3992
11.98	111.935	111.9987	111.3634	111.3736
11.99	111.935	112.022	111.389	111.348
12	111.935	112.022	111.412	111.3278
12.01	111.935	112.022	111.412	111.3559
12.02	111.9502	112.0144	111.412	111.3839
12.03	112.0263	111.9766	111.412	111.412
12.04	112.1024	111.9388	111.3891	111.3891
12.05	112.0783	111.9663	111.3662	111.3662
12.06	112.0431	112.0011	111.3433	111.3433
12.07	112.0086	112.022	111.3301	111.325
12.08	111.9752	112.022	111.3557	111.325
12.09	111.9417	112.022	111.3813	111.325
12.1	111.9501	112.0069	111.4069	111.325
12.11	111.969	111.988	111.3903	111.3467
12.12	111.988	111.969	111.3631	111.3739
12.13	112.0069	111.9501	111.3359	111.4011
12.14	112.0416	111.9543	111.3598	111.4294

12.15	112.099	112.033	111.4178	111.4584
12.16	112.0623	112.0697	111.4758	111.4874
12.17	112.0257	112.1063	111.499	111.4836
12.18	112.0475	112.0845	111.499	111.4581
12.19	112.0759	112.0561	111.499	111.4325
12.2	112.1043	112.0277	111.499	111.412
12.21	112.11	112.0463	111.499	111.412
12.22	112.11	112.0766	111.499	111.412
12.23	112.11	112.107	111.499	111.412
12.24	112.11	112.0783	111.499	111.412
12.25	112.11	112.0431	111.499	111.412
12.26	112.11	112.0373	111.499	111.412
12.27	112.11	112.0756	111.499	111.412
12.28	112.1069	112.1038	111.4839	111.412
12.29	112.0754	112.0413	111.465	111.412
12.3	112.044	111.9788	111.446	111.412
12.31	112.0326	111.956	111.4271	111.412
12.32	112.0678	112.026	111.4313	111.4507
12.33	112.103	112.096	111.499	111.5751
12.34	112.11	112.0849	111.499	111.5389
12.35	112.11	112.0534	111.499	111.5026
12.36	112.11	112.022	111.4737	111.499
12.37	112.11	112.0572	111.4457	111.499
12.38	112.11	112.0924	111.4176	111.499
12.39	112.11	112.11	111.436	111.523
12.4	112.11	112.11	111.466	111.553
12.41	112.0965	112.0831	111.496	111.583
12.42	112.0739	112.0382	111.405	111.4298
12.43	112.0513	111.9933	111.3006	111.2562
12.44	112.0288	111.9485	111.2834	111.1972
12.45	112.022	111.9821	111.3969	111.3103
12.46	112.022	112.0494	111.499	111.4151
12.47	112.0275	112.11	111.499	111.4462
12.48	112.0825	112.11	111.499	111.4772
12.49	112.11	112.0974	111.499	111.499

12.5	112.11	112.0723	111.499	111.499
12.51	112.11	112.0471	111.499	111.499
12.52	112.11	112.022	111.4741	111.4741
12.53	112.11	112.022	111.4431	111.4431
12.54	112.11	112.022	111.412	111.412
12.55	112.0423	111.9551	111.4468	111.4468
12.56	112.022	111.9529	111.4816	111.4816
12.57	112.022	111.9785	111.4761	111.499
12.58	112.022	112.0041	111.4303	111.499
12.59	112.022	112.0039	111.412	111.4856
12.6	112.022	111.9436	111.412	111.4633
12.61	112.022	111.8832	111.412	111.441
12.62	112.0111	111.8361	111.412	111.4187
12.63	111.9839	111.8089	111.412	111.412
12.64	111.9568	111.7818	111.412	111.412
12.65	111.9502	111.76	111.4066	111.4066
12.66	112.0263	111.76	111.3522	111.3522
12.67	112.1024	111.76	111.325	111.325
12.68	112.11	111.76	111.325	111.325
12.69	112.11	111.76	111.325	111.325
12.7	112.1328	111.7374	111.325	111.325
12.71	112.1654	111.7052	110.6625	110.6625

12.72	112.198	111.673	110	110
12.73	112.2318	111.673	111.0862	111.0192
12.74	112.2657	111.673	111.412	111.325
12.75	112.286	111.673	111.412	111.325
12.76	112.286	111.673	111.412	111.325
12.77	112.286	111.673	111.412	111.325
12.78			111.412	111.325
12.79			111.412	111.325
12.8			111.412	111.325
12.81			111.412	111.325
12.82			111.412	111.325
12.83			111.2892	111.2098
12.84			110.6753	110.6337
12.85			110.0614	110.0576
12.86			110	110
12.87			110	110
12.88			110.2987	110.2092
12.89			110.7253	110.5081
12.9			111.152	110.807
12.91			110.9528	110.6412
12.92			110.7535	110.4755

Trial 19 Raw data

Depth (m)	Diameter 1 (mm)	Diameter 2 (mm)	Diameter 3 (mm)	Diameter 4 (mm)
0	108.914	108.914		
0.01	108.914	108.914		
0.02	108.914	108.914		
0.03	108.914	108.914		
0.04	108.914	108.914		
0.05	109	109.173		
0.06	109.1723	109.345		
0.07	109.3447	109.517		
0.08	109.517	109.689		
0.09	109.5391	109.6669		
0.1	109.5611	109.6449		
0.11	109.5832	109.6228		
0.12	109.603	109.603		
0.13	109.603	109.603		
0.14	109.603	109.603		
0.15	109.603	109.603		
0.16	109.603	109.6091		
0.17	109.603	109.6296		
0.18	109.603	109.6501	108.827	108.827
0.19	109.603	109.6706	108.827	108.827
0.2	109.603	109.689	108.827	108.827
0.21	109.603	109.689	108.827	108.827
0.22	109.603	109.689	108.827	108.827
0.23	109.603	109.689	108.741	108.827
0.24	109.603	109.689	108.741	108.856
0.25	109.5798	109.6658	108.741	108.885
0.26	109.5565	109.6425	108.741	108.914
0.27	109.5333	109.6193	108.741	108.914
0.28	109.5225	109.603	108.741	108.914
0.29	109.5408	109.603	108.741	108.914
0.3	109.5591	109.603	108.741	108.914
0.31	109.5774	109.603	108.741	108.914
0.32	109.5957	109.603	108.741	108.914
0.33	109.603	109.603	108.741	108.914
0.34	109.603	109.603	108.741	108.914
0.35	109.603	109.603	108.741	108.914
0.36	109.603	109.603	108.741	108.914
0.37	109.603	109.603	108.741	108.914
0.38	109.603	109.603	108.741	108.914
0.39	109.5901	109.6159	108.741	108.914
0.4	109.5686	109.6374	108.741	108.914
0.41	109.5471	109.6589	108.741	108.914
0.42	109.5256	109.6804	108.741	108.914
0.43	109.517	109.6675	108.741	108.914
0.44	109.517	109.6317	108.741	108.914
0.45	109.517	109.6081	108.741	108.914
0.46	109.517	109.6334	108.741	108.914
0.47	109.517	109.6586	108.741	108.914
0.48	109.517	109.6839	108.741	108.914
0.49	109.517	109.689	108.741	108.914
0.5	109.517	109.689	108.741	108.914
0.51	109.517	109.689	108.741	108.914
0.52	109.517	109.689	108.741	108.914
0.53	109.517	109.6686	108.741	108.914
0.54	109.517	109.646	108.741	108.914
0.55	109.517	109.6234	108.741	108.914
0.56	109.517	109.603	108.741	108.914
0.57	109.517	109.603	108.741	108.914
0.58	109.517	109.603	108.741	108.914
0.59	109.517	109.603	108.741	108.914
0.6	109.517	109.603	108.741	108.914
0.61	109.517	109.603	108.7625	108.914
0.62	109.517	109.603	108.7983	108.914
0.63	109.517	109.603	108.8219	108.914
0.64	109.517	109.603	108.7966	108.914
0.65	109.517	109.603	108.7714	108.914
0.66	109.517	109.603	108.7461	108.914
0.67	109.517	109.603	108.741	108.914
0.68	109.517	109.6156	108.741	108.914
0.69	109.517	109.6366	108.741	108.914
0.7	109.517	109.6575	108.741	108.914
0.71	109.517	109.6785	108.741	108.914
0.72	109.517	109.689	108.741	108.914
0.73	109.517	109.689	108.741	108.914
0.74	109.517	109.689	108.741	108.914
0.75	109.517	109.689	108.741	108.914
0.76	109.517	109.6738	108.741	108.914
0.77	109.517	109.6485	108.741	108.914
0.78	109.517	109.6232	108.7591	108.914
0.79	109.517	109.603	108.7817	108.914
0.8	109.517	109.603	108.8044	108.914
0.81	109.517	109.603	108.827	108.914

0.82	109.517	109.603	108.8075	108.8942
0.83	109.517	109.6074	108.7879	108.8745
0.84	109.517	109.6295	108.7684	108.8547
0.85	109.517	109.6515	108.7488	108.8349
0.86	109.517	109.6736	108.7155	108.827
0.87	109.5096	109.6816	108.6731	108.827
0.88	109.4851	109.6571	108.6307	108.827
0.89	109.4605	109.6325	108.5882	108.827
0.9	109.4359	109.6079	108.5558	108.816
0.91	109.431	109.603	108.5335	108.7939
0.92	109.431	109.603	108.5112	108.7719
0.93	109.431	109.603	108.4889	108.7498
0.94	109.4184	109.5904	108.4954	108.741
0.95	109.3931	109.5651	108.5209	108.741
0.96	109.3678	109.5398	108.5465	108.741
0.97	109.3425	109.5145	108.567	108.741
0.98	109.318	109.49	108.567	108.741
0.99	109.2934	109.4654	108.567	108.741
1	109.2688	109.4408	108.567	108.741
1.01	109.259	109.4132	108.5625	108.7365
1.02	109.259	109.3836	108.5402	108.7142
1.03	109.259	109.3539	108.5179	108.6919
1.04	109.2741	109.3751	108.4956	108.6696
1.05	109.2956	109.4181	108.4875	108.654
1.06	109.3171	109.4611	108.5123	108.654
1.07	109.3386	109.5041	108.5372	108.654
1.08	109.345	109.517	108.562	108.654
1.09	109.345	109.517	108.567	108.654
1.1	109.345	109.517	108.567	108.654
1.11	109.345	109.517	108.567	108.654
1.12	109.345	109.517	108.567	108.654
1.13	109.345	109.517	108.567	108.654
1.14	109.345	109.517	108.567	108.654
1.15	109.345	109.517	108.567	108.6515
1.16	109.345	109.517	108.567	108.6267
1.17	109.345	109.517	108.567	108.6018
1.18	109.345	109.517	108.567	108.5769
1.19	109.345	109.5003	108.585	108.585
1.2	109.345	109.4764	108.615	108.615
1.21	109.345	109.4525	108.645	108.645
1.22	109.345	109.4332	108.654	108.654
1.23	109.345	109.4547	108.654	108.654
1.24	109.345	109.4762	108.654	108.654
1.25	109.345	109.4977	108.654	108.654

1.26	109.345	109.517	108.6361	108.654
1.27	109.345	109.517	108.6105	108.654
1.28	109.345	109.517	108.5849	108.654
1.29	109.345	109.517	108.5752	108.654
1.3	109.345	109.5022	108.6023	108.654
1.31	109.345	109.4725	108.6295	108.654
1.32	109.345	109.4429	108.654	108.654
1.33	109.3544	109.431	108.654	108.654
1.34	109.37	109.431	108.654	108.654
1.35	109.3857	109.431	108.654	108.654
1.36	109.4013	109.431	108.654	108.654
1.37	109.4169	109.431	108.654	108.6709
1.38	109.4259	109.4361	108.654	108.6951
1.39	109.3754	109.4866	108.654	108.7193
1.4	109.3554	109.517	108.6518	108.7432
1.41	109.3815	109.517	108.6301	108.7647
1.42	109.4075	109.517	108.6083	108.7862
1.43	109.431	109.517	108.5866	108.8077
1.44	109.431	109.517	108.567	108.8246
1.45	109.431	109.517	108.567	108.8007
1.46	109.431	109.517	108.567	108.7768
1.47	109.431	109.5106	108.567	108.7529
1.48	109.431	109.4891	108.582	108.741
1.49	109.431	109.4676	108.612	108.741
1.5	109.431	109.4461	108.642	108.741
1.51	109.431	109.4453	108.6445	108.741
1.52	109.431	109.4931	108.6287	108.741
1.53	109.431	109.5409	108.6129	108.741
1.54	109.431	109.5887	108.5971	108.741
1.55	109.431	109.5676	108.5812	108.741
1.56	109.431	109.517	108.567	108.741
1.57	109.431	109.4664	108.567	108.741
1.58	109.431	109.431	108.5775	108.741
1.59	109.431	109.431	108.6039	108.741
1.6	109.431	109.431	108.6303	108.741
1.61	109.431	109.431	108.6563	108.741
1.62	109.431	109.431	108.6792	108.741
1.63	109.431	109.431	108.7021	108.741
1.64	109.431	109.431	108.725	108.741
1.65	109.431	109.431	108.728	108.741
1.66	109.431	109.452	108.6845	108.741
1.67	109.431	109.473	108.641	108.741
1.68	109.431	109.4939	108.5975	108.741
1.69	109.431	109.5149	108.5743	108.741

1.7	109.431	109.517	108.5984	108.741
1.71	109.431	109.517	108.6226	108.741
1.72	109.431	109.517	108.6468	108.741
1.73	109.431	109.517	108.654	108.7587
1.74	109.431	109.517	108.654	108.784
1.75	109.431	109.517	108.654	108.8093
1.76	109.431	109.517	108.6468	108.827
1.77	109.431	109.517	108.6226	108.827
1.78	109.431	109.517	108.5984	108.827
1.79	109.431	109.517	108.5743	108.827
1.8	109.431	109.517	108.567	108.827
1.81	109.4457	109.517	108.567	108.827
1.82	109.4703	109.517	108.567	108.827
1.83	109.4949	109.517	108.567	108.827
1.84	109.5147	109.5147	108.567	108.8482
1.85	109.4914	109.4914	108.567	108.8694
1.86	109.4682	109.4682	108.567	108.8907
1.87	109.4449	109.4449	108.567	108.9119
1.88	109.4408	109.431	108.5856	108.8954
1.89	109.4654	109.431	108.6064	108.8746
1.9	109.49	109.431	108.6271	108.8539
1.91	109.5145	109.431	108.6478	108.8332
1.92	109.517	109.4531	108.654	108.8444
1.93	109.517	109.4777	108.654	108.8693
1.94	109.517	109.5023	108.654	108.8941
1.95	109.5266	109.5074	108.654	108.914
1.96	109.5504	109.4836	108.654	108.914
1.97	109.5743	109.4597	108.654	108.914
1.98	109.5982	109.4358	108.654	108.914
1.99	109.5828	109.4715	108.6689	108.914
2	109.5575	109.5221	108.6938	108.914
2.01	109.5322	109.5726	108.7186	108.914
2.02	109.517	109.5934	108.7386	108.914
2.03	109.517	109.5696	108.7151	108.914
2.04	109.517	109.5457	108.6916	108.914
2.05	109.517	109.5218	108.6681	108.914
2.06	109.517	109.5378	108.6837	108.9238
2.07	109.517	109.5639	108.758	108.9484
2.08	109.517	109.59	108.8323	108.973
2.09	109.5396	109.603	108.9066	108.9975
2.1	109.5849	109.603	108.8471	109
2.11	109.6302	109.603	108.7729	109
2.12	109.6754	109.603	108.6986	109
2.13	109.6756	109.6164	108.6637	109.0096

2.14	109.6565	109.6355	108.6878	109.0334
2.15	109.6374	109.6546	108.712	109.0573
2.16	109.6183	109.6737	108.7362	109.0812
2.17	109.6075	109.689	108.741	109.1065
2.18	109.6302	109.689	108.741	109.1321
2.19	109.6528	109.689	108.741	109.1576
2.2	109.6754	109.689	108.7506	109.173
2.21	109.689	109.689	108.7744	109.173
2.22	109.689	109.689	108.7983	109.173
2.23	109.689	109.689	108.8222	109.173
2.24	109.6935	109.6981	108.8689	109.173
2.25	109.7162	109.7433	108.9214	109.173
2.26	109.7388	109.7886	108.9738	109.173
2.27	109.7614	109.8338	109	109.1843
2.28	109.7869	109.8729	109	109.2069
2.29	109.8165	109.9025	109	109.2296
2.3	109.8462	109.9322	109	109.2522
2.31	109.861	109.9363	109.0134	109.259
2.32	109.861	109.9148	109.0325	109.259
2.33	109.861	109.8933	109.0516	109.259
2.34	109.861	109.8718	109.0707	109.259
2.35	109.8764	109.8764	109.086	109.2635
2.36	109.9071	109.9071	109.086	109.2862
2.37	109.9378	109.9378	109.086	109.3088
2.38	109.947	109.947	109.086	109.3314
2.39	109.947	109.947	109.1076	109.345
2.4	109.947	109.947	109.1617	109.345
2.41	109.9568	109.9519	109.2158	109.345
2.42	110.0056	109.9765	109.2545	109.3541
2.43	110.0545	110.0011	109.2318	109.3993
2.44	110.1033	110.0256	109.2092	109.4446
2.45	110.118	110.0495	109.1866	109.4898
2.46	110.118	110.0731	109.1849	109.5289
2.47	110.118	110.0968	109.2145	109.5585
2.48	110.1199	110.1199	109.2442	109.5882
2.49	110.139	110.139	109.2698	109.603
2.5	110.1581	110.1581	109.2913	109.603
2.51	110.1772	110.1772	109.3128	109.603
2.52	110.1964	110.1964	109.3343	109.603
2.53	110.2176	110.2176	109.345	109.6337
2.54	110.2402	110.2402	109.345	109.6951
2.55	110.2628	110.2628	109.345	109.7566
2.56	110.2855	110.2855	109.345	109.775
2.57	110.3115	110.29	109.345	109.775

2.58	110.3384	110.29	109.345	109.775
2.59	110.3653	110.29	109.3548	109.775
2.6	110.376	110.3158	109.404	109.775
2.61	110.376	110.3588	109.4531	109.775
2.62	110.376	110.4018	109.5023	109.775
2.63	110.376	110.4448	109.5337	109.7917
2.64	110.3907	110.462	109.5576	109.8156
2.65	110.4153	110.462	109.5815	109.8395
2.66	110.4399	110.462	109.603	109.8629
2.67	110.462	110.4597	109.603	109.882
2.68	110.462	110.4371	109.603	109.9011
2.69	110.462	110.4145	109.603	109.9202
2.7	110.462	110.3918	109.603	109.9394
2.71	110.4692	110.3903	109.6302	109.974
2.72	110.4931	110.4381	109.6754	110.019
2.73	110.5169	110.4859	109.7207	110.064
2.74	110.5408	110.5337	109.7659	110.109
2.75	110.5638	110.5638	109.7535	110.118
2.76	110.5865	110.5865	109.7266	110.118
2.77	110.6091	110.6091	109.6998	110.118
2.78	110.6317	110.6317	109.7019	110.118
2.79	110.6582	110.6582	109.7234	110.118
2.8	110.6851	110.6851	109.7449	110.118
2.81	110.7119	110.7119	109.7664	110.118
2.82	110.72	110.72	109.8045	110.1327
2.83	110.72	110.72	109.8536	110.1573
2.84	110.72	110.72	109.9028	110.1819
2.85	110.72	110.7247	109.9447	110.204
2.86	110.72	110.7482	109.9221	110.204
2.87	110.72	110.7717	109.8995	110.204
2.88	110.72	110.7952	109.8768	110.204
2.89	110.7324	110.807	109.861	110.204
2.9	110.7573	110.807	109.861	110.204
2.91	110.7821	110.807	109.861	110.204
2.92	110.807	110.807	109.861	110.204
2.93	110.7853	110.7853	109.861	110.1882
2.94	110.7635	110.7635	109.861	110.1655
2.95	110.7418	110.7418	109.861	110.1429
2.96	110.72	110.72	109.861	110.1203
2.97	110.7442	110.72	109.861	110.0941
2.98	110.7683	110.72	109.861	110.0675
2.99	110.7925	110.72	109.861	110.041
3	110.7976	110.7107	109.8438	110.0158
3.01	110.7741	110.6875	109.8192	109.9912

3.02	110.7506	110.6642	109.7947	109.9667
3.03	110.7271	110.641	109.7704	109.947
3.04	110.705	110.634	109.7471	109.947
3.05	110.6835	110.634	109.7239	109.947
3.06	110.662	110.634	109.7006	109.947
3.07	110.6405	110.634	109.6767	109.947
3.08	110.634	110.6163	109.6521	109.947
3.09	110.634	110.591	109.6276	109.947
3.1	110.634	110.5657	109.603	109.947
3.11	110.6262	110.548	109.5815	109.9255
3.12	110.6001	110.548	109.56	109.904
3.13	110.5741	110.548	109.5385	109.8825
3.14	110.548	110.548	109.517	109.861
3.15	110.5248	110.548	109.517	109.861
3.16	110.5015	110.548	109.517	109.861
3.17	110.4783	110.548	109.517	109.861
3.18	110.4556	110.548	109.517	109.861
3.19	110.4341	110.548	109.517	109.861
3.2	110.4126	110.548	109.517	109.861
3.21	110.3911	110.548	109.517	109.861
3.22	110.376	110.555	109.517	109.846
3.23	110.376	110.5782	109.517	109.8245
3.24	110.376	110.6015	109.517	109.803
3.25	110.376	110.6247	109.517	109.7815
3.26	110.3628	110.6208	109.517	109.7573
3.27	110.3407	110.5987	109.517	109.732
3.28	110.3187	110.5767	109.517	109.7067
3.29	110.2966	110.5546	109.517	109.689
3.3	110.29	110.5308	109.517	109.689
3.31	110.29	110.5062	109.517	109.689
3.32	110.29	110.4817	109.517	109.689
3.33	110.29	110.4569	109.517	109.689
3.34	110.29	110.4316	109.517	109.689
3.35	110.29	110.4064	109.517	109.689
3.36	110.29	110.3811	109.517	109.689
3.37	110.29	110.3604	109.517	109.689
3.38	110.29	110.3408	109.517	109.689
3.39	110.29	110.3213	109.517	109.689
3.4	110.29	110.3017	109.517	109.689
3.41	110.3011	110.29	109.517	109.689
3.42	110.3288	110.29	109.517	109.689
3.43	110.3566	110.29	109.517	109.689
3.44	110.376	110.29	109.517	109.689
3.45	110.376	110.29	109.517	109.689

3.46	110.376	110.29	109.517	109.689
3.47	110.376	110.29	109.517	109.689
3.48	110.376	110.3097	109.517	109.6718
3.49	110.376	110.3342	109.517	109.6472
3.5	110.376	110.3588	109.517	109.6227
3.51	110.376	110.3686	109.517	109.603
3.52	110.376	110.3441	109.517	109.603
3.53	110.376	110.3195	109.517	109.603
3.54	110.376	110.2949	109.517	109.603
3.55	110.376	110.2719	109.517	109.603
3.56	110.376	110.2493	109.517	109.603
3.57	110.376	110.2266	109.517	109.603
3.58	110.376	110.204	109.517	109.603
3.59	110.376	110.2286	109.517	109.603
3.6	110.376	110.2531	109.517	109.603
3.61	110.376	110.2777	109.517	109.603
3.62	110.376	110.29	109.517	109.603
3.63	110.376	110.29	109.517	109.603
3.64	110.376	110.29	109.517	109.603
3.65	110.376	110.29	109.517	109.603
3.66	110.376	110.29	109.4973	109.603
3.67	110.376	110.29	109.4728	109.603
3.68	110.376	110.29	109.4482	109.603
3.69	110.3644	110.29	109.431	109.603
3.7	110.3411	110.29	109.431	109.603
3.71	110.3179	110.29	109.431	109.603
3.72	110.2946	110.29	109.431	109.603
3.73	110.29	110.274	109.431	109.5849
3.74	110.29	110.254	109.431	109.5623
3.75	110.29	110.234	109.431	109.5396
3.76	110.29	110.214	109.431	109.517
3.77	110.29	110.204	109.431	109.517
3.78	110.29	110.204	109.431	109.517
3.79	110.29	110.204	109.431	109.517
3.8	110.29	110.204	109.4184	109.5044
3.81	110.29	110.204	109.3931	109.4791
3.82	110.29	110.204	109.3678	109.4538
3.83	110.29	110.204	109.3498	109.4046
3.84	110.29	110.204	109.3976	109.1404
3.85	110.29	110.194	109.4453	108.8763
3.86	110.29	110.174	109.4931	108.6121
3.87	110.29	110.154	109.4355	108.5736
3.88	110.29	110.134	109.2725	108.7609
3.89	110.2557	110.0689	109.1096	108.9482

3.9	110.0839	109.8235	108.9466	109.1355
3.91	109.9122	109.5781	109.0102	109.301
3.92	109.7405	109.3326	109.1304	109.461
3.93	109.768	109.3382	109.2507	109.621
3.94	109.8809	109.4514	109.3709	109.781
3.95	109.9938	109.5645	109.4939	109.9133
3.96	110.1067	109.6777	109.6198	110.018
3.97	110.1649	109.8529	109.7456	110.1226
3.98	110.217	110.035	109.8715	110.2272
3.99	110.2692	110.2172	109.9029	110.2548
4	110.3223	110.3223	109.7926	110.1669
4.01	110.376	110.376	109.6824	110.0789
4.02	110.4298	110.4298	109.5721	109.991
4.03	110.462	110.4721	109.497	109.907
4.04	110.462	110.4974	109.457	109.827
4.05	110.462	110.5227	109.417	109.747
4.06	110.462	110.548	109.377	109.667
4.07	110.3958	110.5039	109.345	109.603
4.08	110.3297	110.4598	109.345	109.603
4.09	110.2635	110.4157	109.345	109.603
4.1	110.204	110.3734	109.345	109.603
4.11	110.204	110.3473	109.345	109.603
4.12	110.204	110.3213	109.345	109.603
4.13	110.204	110.2952	109.345	109.603
4.14	110.204	110.2736	109.345	109.603
4.15	110.204	110.2531	109.345	109.603
4.16	110.204	110.2327	109.345	109.603
4.17	110.204	110.2122	109.345	109.603
4.18	110.204	110.2201	109.345	109.603
4.19	110.204	110.247	109.345	109.603
4.2	110.204	110.2739	109.345	109.603
4.21	110.2148	110.2793	109.3551	109.603
4.22	110.2416	110.2524	109.3804	109.603
4.23	110.2685	110.2255	109.4057	109.603
4.24	110.2856	110.2084	109.431	109.603
4.25	110.2635	110.2305	109.431	109.603
4.26	110.2415	110.2525	109.431	109.603
4.27	110.2194	110.2746	109.431	109.603
4.28	110.2106	110.29	109.431	109.6056
4.29	110.2327	110.29	109.431	109.6317
4.3	110.2547	110.29	109.431	109.6577
4.31	110.2768	110.29	109.431	109.6838
4.32	110.29	110.2789	109.431	109.689
4.33	110.29	110.2512	109.431	109.689

4.34	110.29	110.2234	109.431	109.689
4.35	110.29	110.2089	109.431	109.689
4.36	110.29	110.2251	109.431	109.7051
4.37	110.29	110.2413	109.431	109.732
4.38	110.29	110.2575	109.431	109.7589
4.39	110.29	110.2738	109.431	109.7643
4.4	110.29	110.29	109.431	109.7374
4.41	110.29	110.3514	109.431	109.7105
4.42	110.29	110.376	109.431	109.689
4.43	110.29	110.376	109.431	109.689
4.44	110.29	110.376	109.431	109.689
4.45	110.29	110.376	109.431	109.689
4.46	110.3108	110.3552	109.4376	109.689
4.47	110.3369	110.3291	109.4597	109.689
4.48	110.363	110.303	109.4817	109.689
4.49	110.376	110.3016	109.5038	109.689
4.5	110.376	110.3249	109.517	109.689
4.51	110.376	110.3481	109.517	109.689
4.52	110.376	110.3714	109.517	109.689
4.53	110.376	110.3545	109.517	109.6939
4.54	110.376	110.3276	109.517	109.7101
4.55	110.376	110.3008	109.517	109.7263
4.56	110.376	110.3195	109.517	109.7425
4.57	110.376	110.3686	109.517	109.7588
4.58	110.376	110.4178	109.517	109.775
4.59	110.376	110.4597	109.517	109.775
4.6	110.376	110.4364	109.517	109.775
4.61	110.376	110.4132	109.517	109.775
4.62	110.376	110.3899	109.517	109.775
4.63	110.376	110.376	109.517	109.775
4.64	110.376	110.376	109.517	109.775
4.65	110.376	110.376	109.517	109.775
4.66	110.376	110.376	109.517	109.775
4.67	110.376	110.376	109.517	109.775
4.68	110.376	110.376	109.517	109.775
4.69	110.376	110.376	109.517	109.775
4.7	110.376	110.376	109.517	109.775
4.71	110.376	110.376	109.517	109.775
4.72	110.376	110.376	109.517	109.775
4.73	110.376	110.376	109.517	109.775
4.74	110.376	110.376	109.517	109.7897
4.75	110.376	110.376	109.517	109.8143
4.76	110.376	110.376	109.517	109.8389
4.77	110.376	110.376	109.517	109.861

4.78	110.376	110.3949	109.517	109.861
4.79	110.376	110.4159	109.517	109.861
4.8	110.376	110.4368	109.517	109.861
4.81	110.376	110.4578	109.517	109.861
4.82	110.376	110.4992	109.517	109.861
4.83	110.376	110.5457	109.517	109.861
4.84	110.376	110.5922	109.517	109.861
4.85	110.376	110.6316	109.5313	109.861
4.86	110.376	110.6077	109.5552	109.861
4.87	110.376	110.5838	109.5791	109.861
4.88	110.376	110.5599	109.603	109.861
4.89	110.376	110.5341	109.603	109.861
4.9	110.376	110.5064	109.603	109.861
4.91	110.376	110.4786	109.603	109.861
4.92	110.376	110.462	109.603	109.8491
4.93	110.376	110.462	109.603	109.8252
4.94	110.376	110.462	109.603	109.8013
4.95	110.3815	110.462	109.603	109.7774
4.96	110.3998	110.462	109.6219	109.7939
4.97	110.4181	110.462	109.6429	109.8149
4.98	110.4364	110.462	109.6638	109.8358
4.99	110.4547	110.462	109.6848	109.8568
5	110.462	110.462	109.689	109.861
5.01	110.462	110.462	109.689	109.861
5.02	110.462	110.462	109.689	109.861
5.03	110.462	110.462	109.689	109.861
5.04	110.462	110.4776	109.689	109.861
5.05	110.462	110.4972	109.689	109.861
5.06	110.462	110.5167	109.689	109.861
5.07	110.462	110.5363	109.689	109.861
5.08	110.462	110.5581	109.689	109.861
5.09	110.462	110.5834	109.689	109.861
5.1	110.462	110.6087	109.689	109.861
5.11	110.462	110.634	109.689	109.861
5.12	110.462	110.6053	109.689	109.861
5.13	110.462	110.5767	109.689	109.861
5.14	110.462	110.548	109.689	109.861
5.15	110.462	110.548	109.689	109.861
5.16	110.462	110.548	109.689	109.861
5.17	110.462	110.548	109.689	109.861
5.18	110.462	110.5568	109.689	109.861
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5.2	110.462	110.5919	109.689	109.861
5.21	110.462	110.6094	109.689	109.861

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5.23	110.462	110.6068	109.689	109.861
5.24	110.462	110.5616	109.689	109.861
5.25	110.462	110.548	109.689	109.861
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5.27	110.462	110.548	109.689	109.861
5.28	110.462	110.548	109.689	109.861
5.29	110.462	110.548	109.689	109.861
5.3	110.462	110.548	109.689	109.861
5.31	110.462	110.548	109.689	109.861
5.32	110.4796	110.548	109.689	109.861
5.33	110.5017	110.548	109.7136	109.8856
5.34	110.5237	110.548	109.7381	109.9101
5.35	110.5458	110.548	109.7627	109.9347
5.36	110.548	110.5701	109.775	109.947
5.37	110.548	110.5947	109.775	109.947
5.38	110.548	110.6193	109.775	109.947
5.39	110.548	110.634	109.775	109.947
5.4	110.548	110.634	109.775	109.947
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5.43	110.548	110.634	109.775	109.947
5.44	110.548	110.634	109.775	109.947
5.45	110.548	110.634	109.775	109.947
5.46	110.548	110.634	109.7955	109.9675
5.47	110.548	110.634	109.816	109.988
5.48	110.548	110.634	109.8364	110.0084
5.49	110.548	110.634	109.8569	110.0289
5.5	110.548	110.634	109.8434	110.033
5.51	110.548	110.634	109.8213	110.033
5.52	110.548	110.634	109.7993	110.033
5.53	110.548	110.634	109.7772	110.033
5.54	110.548	110.634	109.775	110.033
5.55	110.548	110.634	109.775	110.033
5.56	110.548	110.634	109.775	110.033
5.57	110.548	110.634	109.7836	110.033
5.58	110.5722	110.634	109.8051	110.033
5.59	110.5991	110.634	109.8266	110.033
5.6	110.6259	110.634	109.8481	110.033
5.61	110.634	110.6522	109.8522	110.033
5.62	110.634	110.6783	109.8301	110.033
5.63	110.634	110.7044	109.8081	110.033
5.64	110.634	110.72	109.786	110.033
5.65	110.634	110.72	109.775	110.033

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5.67	110.634	110.72	109.775	110.033
5.68	110.634	110.72	109.775	110.033
5.69	110.634	110.72	109.8228	110.033
5.7	110.634	110.72	109.8706	110.033
5.71	110.6266	110.72	109.9183	110.033
5.72	110.6021	110.72	109.9372	110.033
5.73	110.5775	110.72	109.9126	110.033
5.74	110.5529	110.72	109.888	110.033
5.75	110.5688	110.72	109.8635	110.033
5.76	110.5949	110.72	109.861	110.0569
5.77	110.621	110.72	109.861	110.0835
5.78	110.634	110.7318	109.861	110.11
5.79	110.634	110.7553	109.861	110.118
5.8	110.634	110.7788	109.861	110.118
5.81	110.634	110.8023	109.861	110.118
5.82	110.634	110.807	109.861	110.118
5.83	110.634	110.807	109.861	110.118
5.84	110.634	110.807	109.861	110.118
5.85	110.634	110.807	109.861	110.118
5.86	110.634	110.807	109.8842	110.118
5.87	110.634	110.807	109.9075	110.118
5.88	110.634	110.807	109.9307	110.118
5.89	110.634	110.807	109.947	110.118
5.9	110.634	110.807	109.947	110.118
5.91	110.634	110.807	109.947	110.118
5.92	110.634	110.807	109.947	110.118
5.93	110.634	110.807	109.947	110.118
5.94	110.634	110.8254	109.947	110.118
5.95	110.634	110.8459	109.947	110.118
5.96	110.634	110.8664	109.947	110.118
5.97	110.634	110.8869	109.947	110.118
5.98	110.6528	110.8742	109.947	110.118
5.99	110.6797	110.8473	109.947	110.118
6	110.7066	110.8204	109.947	110.0986
6.01	110.72	110.8183	109.947	110.0743
6.02	110.72	110.8409	109.947	110.05
6.03	110.72	110.8636	109.947	110.0423
6.04	110.72	110.8862	109.947	110.0734
6.05	110.72	110.9124	109.947	110.1045
6.06	110.72	110.9402	109.947	110.1356
6.07	110.72	110.9679	109.947	110.1667
6.08	110.72	110.9658	109.947	110.1978
6.09	110.72	110.9437	109.947	110.1803

6.1	110.72	110.9217	109.947	110.1506
6.11	110.72	110.8996	109.947	110.121
6.12	110.72	110.893	109.947	110.1364
6.13	110.72	110.893	109.947	110.1569
6.14	110.72	110.893	109.947	110.1774
6.15	110.72	110.893	109.947	110.1979
6.16	110.72	110.9183	109.947	110.204
6.17	110.72	110.9436	109.947	110.204
6.18	110.72	110.9689	109.947	110.204
6.19	110.72	110.9638	109.947	110.1927
6.2	110.72	110.9385	109.947	110.1701
6.21	110.72	110.9132	109.947	110.1474
6.22	110.72	110.893	109.947	110.1248
6.23	110.72	110.893	109.947	110.1374
6.24	110.72	110.893	109.947	110.1652
6.25	110.72	110.893	109.947	110.1929
6.26	110.72	110.893	109.947	110.204
6.27	110.72	110.893	109.947	110.204
6.28	110.72	110.893	109.947	110.204
6.29	110.72	110.893	109.947	110.204
6.3	110.72	110.893	109.9633	110.204
6.31	110.72	110.893	109.9865	110.204
6.32	110.7223	110.8953	110.0098	110.204
6.33	110.7452	110.9179	110.033	110.204
6.34	110.7681	110.9405	110.033	110.1787
6.35	110.791	110.9632	110.033	110.1534
6.36	110.7988	110.979	110.033	110.1281
6.37	110.7717	110.979	110.033	110.1332
6.38	110.7445	110.979	110.033	110.1585
6.39	110.7224	110.9766	110.033	110.1838
6.4	110.7466	110.9527	110.033	110.204
6.41	110.7708	110.9288	110.033	110.204
6.42	110.7949	110.9049	110.033	110.204
6.43	110.807	110.9046	110.033	110.204
6.44	110.807	110.9279	110.033	110.204
6.45	110.807	110.9511	110.033	110.204
6.46	110.807	110.9744	110.033	110.204
6.47	110.807	110.979	110.033	110.204
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6.53	110.807	110.979	110.033	110.204

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6.55	110.807	110.979	110.0675	110.204
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6.57	110.807	110.979	110.1156	110.204
6.58	110.807	110.979	110.092	110.204
6.59	110.807	110.979	110.0684	110.204
6.6	110.807	110.979	110.0448	110.204
6.61	110.807	110.979	110.0445	110.2156
6.62	110.807	110.979	110.0675	110.2389
6.63	110.807	110.979	110.0904	110.2621
6.64	110.807	110.979	110.1134	110.2854
6.65	110.807	110.979	110.1001	110.29
6.66	110.807	110.979	110.0777	110.29
6.67	110.807	110.979	110.0554	110.29
6.68	110.807	110.979	110.033	110.29
6.69	110.807	110.979	110.0588	110.29
6.7	110.807	110.979	110.0845	110.29
6.71	110.807	110.979	110.1103	110.29
6.72	110.807	110.979	110.118	110.29
6.73	110.807	110.979	110.118	110.29
6.74	110.807	110.979	110.118	110.29
6.75	110.807	110.979	110.118	110.29
6.76	110.807	110.979	110.118	110.29
6.77	110.807	110.979	110.118	110.29
6.78	110.807	110.979	110.118	110.29
6.79	110.8233	110.9953	110.118	110.29
6.8	110.8465	111.0185	110.118	110.29
6.81	110.8698	111.0418	110.118	110.29
6.82	110.893	111.065	110.118	110.29
6.83	110.8669	111.065	110.118	110.29
6.84	110.8409	111.065	110.118	110.29
6.85	110.8148	111.065	110.118	110.29
6.86	110.807	111.065	110.118	110.29
6.87	110.807	111.065	110.118	110.29
6.88	110.807	111.065	110.118	110.29
6.89	110.807	111.065	110.118	110.29
6.9	110.8193	111.065	110.118	110.29
6.91	110.85	111.065	110.118	110.29
6.92	110.8807	111.065	110.118	110.29
6.93	110.893	111.065	110.118	110.2972
6.94	110.893	111.065	110.118	110.3211
6.95	110.893	111.065	110.118	110.3449
6.96	110.893	111.065	110.118	110.3688
6.97	110.893	111.065	110.118	110.3597

6.98	110.893	111.065	110.118	110.3365
6.99	110.893	111.065	110.118	110.3132
7	110.893	111.065	110.118	110.29
7.01	110.893	111.065	110.118	110.3161
7.02	110.893	111.065	110.118	110.3421
7.03	110.893	111.065	110.118	110.3682
7.04	110.893	111.065	110.132	110.376
7.05	110.893	111.065	110.152	110.376
7.06	110.893	111.065	110.172	110.376
7.07	110.893	111.065	110.192	110.376
7.08	110.893	111.0795	110.204	110.376
7.09	110.893	111.1085	110.204	110.376
7.1	110.893	111.1375	110.204	110.376
7.11	110.893	111.152	110.1901	110.376
7.12	110.893	111.152	110.1668	110.376
7.13	110.893	111.152	110.1436	110.376
7.14	110.893	111.152	110.1203	110.376
7.15	110.893	111.152	110.1384	110.376
7.16	110.893	111.152	110.161	110.376
7.17	110.893	111.152	110.1836	110.376
7.18	110.893	111.152	110.204	110.376
7.19	110.893	111.152	110.204	110.376
7.2	110.893	111.152	110.204	110.376
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7.24	110.893	111.152	110.204	110.4271
7.25	110.893	111.152	110.204	110.4504
7.26	110.9183	111.152	110.204	110.462
7.27	110.9436	111.152	110.204	110.462
7.28	110.9689	111.152	110.204	110.462
7.29	110.9647	111.152	110.204	110.462
7.3	110.9408	111.152	110.204	110.462
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7.32	110.893	111.152	110.204	110.462
7.33	110.9191	111.152	110.204	110.462
7.34	110.9451	111.152	110.204	110.462
7.35	110.9712	111.152	110.204	110.462
7.36	110.979	111.1697	110.204	110.462
7.37	110.979	111.195	110.204	110.462
7.38	110.979	111.2203	110.204	110.462
7.39	110.979	111.238	110.204	110.462
7.4	110.979	111.238	110.2141	110.4721
7.41	110.979	111.238	110.2394	110.4974
7.42	110.979	111.238	110.2647	110.5227
7.43	110.979	111.238	110.29	110.548
7.44	110.979	111.238	110.29	110.548
7.45	110.979	111.238	110.29	110.548
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7.47	110.979	111.2629	110.29	110.548
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7.49	110.979	111.3043	110.29	110.548
7.5	110.979	111.325	110.29	110.548
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7.6	110.979	111.325	110.376	110.548
7.61	110.979	111.325	110.3969	110.5271
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7.64	110.979	111.3782	110.462	110.462
7.65	110.979	111.4023	110.462	110.462
7.66	110.979	111.412	110.462	110.462
7.67	110.979	111.412	110.462	110.462
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7.69	110.979	111.412	110.462	110.4841
7.7	110.979	111.412	110.462	110.5061
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7.74	110.979	111.412	110.462	110.548
7.75	110.979	111.412	110.462	110.548
7.76	110.9892	111.412	110.462	110.548
7.77	111.0097	111.412	110.462	110.548
7.78	111.0302	111.412	110.462	110.548
7.79	111.0507	111.412	110.462	110.548
7.8	111.065	111.412	110.4668	110.548
7.81	111.065	111.412	110.4907	110.548
7.82	111.065	111.412	110.5146	110.548
7.83	111.065	111.412	110.5384	110.548
7.84	111.065	111.412	110.548	110.548
7.85	111.065	111.412	110.548	110.548

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7.87	111.065	111.412	110.548	110.548
7.88	111.065	111.412	110.548	110.548
7.89	111.065	111.412	110.548	110.548
7.9	111.065	111.4187	110.548	110.5623
7.91	111.065	111.441	110.548	110.5828
7.92	111.065	111.4633	110.548	110.6033
7.93	111.065	111.4856	110.548	110.6238
7.94	111.065	111.499	110.548	110.634
7.95	111.065	111.499	110.548	110.634
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7.97	111.065	111.499	110.548	110.634
7.98	111.065	111.499	110.548	110.6421
7.99	111.065	111.499	110.548	110.6689
8	111.065	111.499	110.548	110.6958
8.01	111.065	111.499	110.5453	110.72
8.02	111.065	111.499	110.5184	110.72
8.03	111.065	111.499	110.4916	110.72
8.04	111.065	111.499	110.4647	110.72
8.05	111.065	111.499	110.462	110.72
8.06	111.0791	111.499	110.462	110.72
8.07	111.1026	111.499	110.462	110.72
8.08	111.1261	111.499	110.4686	110.72
8.09	111.1496	111.499	110.4907	110.72
8.1	111.152	111.499	110.5127	110.72
8.11	111.152	111.499	110.5348	110.72
8.12	111.152	111.499	110.548	110.72
8.13	111.152	111.499	110.548	110.72
8.14	111.152	111.5225	110.548	110.72
8.15	111.152	111.546	110.548	110.72
8.16	111.152	111.5695	110.548	110.72
8.17	111.152	111.586	110.548	110.72
8.18	111.152	111.586	110.548	110.72
8.19	111.152	111.586	110.548	110.72
8.2	111.152	111.586	110.5644	110.72
8.21	111.152	111.6029	110.5849	110.72
8.22	111.152	111.6271	110.6053	110.72
8.23	111.152	111.6513	110.6258	110.72
8.24	111.152	111.673	110.634	110.72
8.25	111.152	111.673	110.634	110.72
8.26	111.152	111.673	110.634	110.72
8.27	111.152	111.673	110.634	110.72
8.28	111.152	111.6871	110.6538	110.7401
8.29	111.152	111.7106	110.6759	110.7624

8.3	111.152	111.7341	110.6979	110.7847
8.31	111.152	111.7576	110.72	110.807
8.32	111.152	111.7824	110.7435	110.807
8.33	111.152	111.8072	110.767	110.807
8.34	111.152	111.8321	110.7905	110.807
8.35	111.152	111.8368	110.807	110.807
8.36	111.152	111.8112	110.807	110.807
8.37	111.152	111.7856	110.807	110.807
8.38	111.152	111.76	110.807	110.807
8.39	111.1766	111.7849	110.7901	110.7901
8.4	111.2011	111.8097	110.7659	110.7659
8.41	111.2257	111.8346	110.7418	110.7418
8.42	111.238	111.8371	110.7175	110.72
8.43	111.238	111.8173	110.693	110.72
8.44	111.238	111.7976	110.6684	110.72
8.45	111.238	111.7778	110.6438	110.72
8.46	111.2352	111.7572	110.634	110.7061
8.47	111.2075	111.7291	110.634	110.6828
8.48	111.1797	111.7011	110.634	110.6596
8.49	111.152	111.673	110.634	110.6363
8.5	111.152	111.673	110.634	110.634
8.51	111.152	111.673	110.634	110.634
8.52	111.152	111.673	110.634	110.634
8.53	111.152	111.6565	110.6138	110.6239
8.54	111.152	111.633	110.5632	110.5986
8.55	111.152	111.6095	110.5126	110.5733
8.56	111.152	111.586	110.462	110.548
8.57	111.152	111.5618	110.2166	110.2289
8.58	111.152	111.5377	109.9711	109.9097
8.59	111.152	111.5135	109.7257	109.5906
8.6	111.0028	111.3493	109.7104	109.5677
8.61	110.6298	110.9749	109.9252	109.8411
8.62	110.2568	110.6006	110.1399	110.1145
8.63	110.1169	110.4517	110.3547	110.3879
8.64	110.3267	110.641	110.5564	110.6424
8.65	110.5364	110.8302	110.6399	110.7259
8.66	110.7462	111.0195	110.7235	110.8095
8.67	110.93	111.1967	110.807	110.893
8.68	111.0535	111.3455	110.807	110.893
8.69	111.1769	111.4944	110.807	110.893
8.7	111.3003	111.6432	110.807	110.893
8.71	111.3433	111.673	110.7905	110.893
8.72	111.3662	111.673	110.767	110.893
8.73	111.3891	111.673	110.7435	110.893

8.74	111.412	111.673	110.72	110.893
8.75	111.4431	111.6419	110.72	110.893
8.76	111.4741	111.6109	110.72	110.893
8.77	111.4945	111.586	110.72	110.893
8.78	111.4722	111.586	110.72	110.893
8.79	111.4499	111.586	110.72	110.893
8.8	111.4276	111.586	110.72	110.893
8.81	111.4191	111.586	110.7285	110.893
8.82	111.4426	111.586	110.7497	110.893
8.83	111.4661	111.586	110.7709	110.893
8.84	111.4896	111.586	110.7921	110.893
8.85	111.499	111.586	110.7995	110.893
8.86	111.499	111.586	110.7747	110.893
8.87	111.499	111.586	110.7498	110.893
8.88	111.499	111.586	110.725	110.893
8.89	111.499	111.586	110.7383	110.9111
8.9	111.499	111.586	110.7612	110.9337
8.91	111.499	111.586	110.7841	110.9564
8.92	111.499	111.586	110.807	110.979
8.93	111.499	111.586	110.807	110.979
8.94	111.499	111.5937	110.807	110.979
8.95	111.499	111.6193	110.807	110.979
8.96	111.499	111.6449	110.807	110.979
8.97	111.499	111.6704	110.807	110.979
8.98	111.5235	111.673	110.807	110.979
8.99	111.5507	111.673	110.814	110.986
9	111.5778	111.673	110.8372	111.0092
9.01	111.586	111.673	110.8605	111.0325
9.02	111.586	111.673	110.8837	111.0557
9.03	111.586	111.673	110.893	111.065
9.04	111.586	111.6803	110.893	111.065
9.05	111.586	111.7044	110.893	111.065
9.06	111.586	111.7286	110.893	111.065
9.07	111.586	111.7528	110.893	111.065
9.08	111.586	111.76	110.893	111.065
9.09	111.586	111.76	110.893	111.065
9.1	111.586	111.76	110.893	111.065
9.11	111.586	111.76	110.893	111.065
9.12	111.586	111.76	110.893	111.065
9.13	111.586	111.76	110.893	111.065
9.14	111.586	111.76	110.893	111.065
9.15	111.5882	111.76	110.893	111.065
9.16	111.6105	111.76	110.9172	111.065
9.17	111.6328	111.76	110.9441	111.065

9.18	111.6552	111.76	110.9709	111.065
9.19	111.673	111.7647	110.979	111.0829
9.2	111.673	111.7882	110.979	111.1085
9.21	111.673	111.8117	110.979	111.1341
9.22	111.673	111.8352	110.979	111.152
9.23	111.673	111.847	110.979	111.152
9.24	111.673	111.847	110.979	111.152
9.25	111.673	111.847	110.979	111.152
9.26	111.673	111.847	110.979	111.152
9.27	111.673	111.8721	110.979	111.152
9.28	111.673	111.8973	110.979	111.152
9.29	111.673	111.9224	110.979	111.152
9.3	111.673	111.935	110.979	111.152
9.31	111.673	111.935	110.979	111.152
9.32	111.673	111.935	110.979	111.152
9.33	111.673	111.935	110.9812	111.152
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9.37	111.673	111.935	111.065	111.152
9.38	111.673	111.935	111.065	111.152
9.39	111.673	111.935	111.065	111.152
9.4	111.673	111.935	111.065	111.152
9.41	111.673	111.9297	111.065	111.152
9.42	111.673	111.903	111.065	111.152
9.43	111.673	111.8763	111.065	111.152
9.44	111.673	111.8497	111.065	111.152
9.45	111.673	111.8734	111.065	111.152
9.46	111.673	111.9027	111.065	111.152
9.47	111.673	111.9321	111.065	111.152
9.48	111.673	111.935	111.065	111.152
9.49	111.673	111.935	111.065	111.152
9.5	111.673	111.935	111.065	111.152
9.51	111.673	111.935	111.065	111.152
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9.53	111.673	111.935	111.0355	111.1222
9.54	111.673	111.935	111.0109	111.0973
9.55	111.673	111.935	110.9864	111.0725
9.56	111.673	111.935	110.979	111.065
9.57	111.673	111.935	110.979	111.065
9.58	111.673	111.935	110.979	111.065
9.59	111.673	111.9295	110.979	111.065
9.6	111.673	111.902	110.979	111.065
9.61	111.673	111.8745	110.979	111.065

9.62	111.673	111.847	110.979	111.065
9.63	111.6368	111.847	110.9532	111.0392
9.64	111.6005	111.847	110.9245	111.0105
9.65	111.586	111.8361	110.8959	110.9819
9.66	111.586	111.818	110.893	110.979
9.67	111.586	111.7999	110.893	110.979
9.68	111.586	111.7818	110.893	110.979
9.69	111.586	111.7636	110.893	110.979
9.7	111.5635	111.7375	110.8709	110.9569
9.71	111.5355	111.7095	110.8463	110.9323
9.72	111.5074	111.6814	110.8217	110.9077
9.73	111.499	111.673	110.7987	110.893
9.74	111.499	111.673	110.778	110.893
9.75	111.499	111.673	110.7573	110.893
9.76	111.499	111.673	110.7366	110.893
9.77	111.499	111.6501	110.72	110.893
9.78	111.499	111.6272	110.72	110.893
9.79	111.499	111.6043	110.72	110.893
9.8	111.494	111.586	110.72	110.893
9.81	111.4692	111.586	110.6842	110.8572
9.82	111.4443	111.586	110.6483	110.8213
9.83	111.4195	111.586	110.634	110.807
9.84	111.412	111.57	110.634	110.807
9.85	111.412	111.5471	110.634	110.807
9.86	111.412	111.5242	110.634	110.807
9.87	111.412	111.5013	110.634	110.807
9.88	111.412	111.499	110.634	110.807
9.89	111.412	111.499	110.634	110.807
9.9	111.412	111.499	110.634	110.807
9.91	111.3919	111.4789	110.6177	110.807
9.92	111.3696	111.4566	110.5945	110.807
9.93	111.3473	111.4343	110.5712	110.807
9.94	111.325	111.412	110.548	110.807
9.95	111.325	111.412	110.548	110.7841
9.96	111.325	111.412	110.548	110.7612
9.97	111.325	111.412	110.548	110.7383
9.98	111.325	111.412	110.548	110.72
9.99	111.325	111.412	110.548	110.72
10	111.325	111.412	110.548	110.72
10.01	111.325	111.412	110.548	110.72
10.02	111.325	111.412	110.548	110.7042
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10.04	111.325	111.412	110.548	110.6589

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10.07	111.325	111.3556	110.548	110.634
10.08	111.325	111.3321	110.548	110.634
10.09	111.3081	111.325	110.5282	110.634
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10.37	111.325	111.325	110.548	110.7024
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10.99	111.238	111.325	110.548	110.548
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11.07	111.238	111.325	110.548	110.5606
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11.75	111.6271	111.5401	110.8826	111.1206
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11.84	111.76	111.673	110.9047	111.152
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11.86	111.76	111.673	110.9202	111.152
11.87	111.76	111.673	110.9428	111.152
11.88	111.76	111.673	110.9654	111.152
11.89	111.76	111.673	110.979	111.1647
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11.91	111.76	111.7227	110.979	111.2284
11.92	111.76	111.7476	110.9957	111.238
11.93	111.76	111.76	111.0196	111.238
11.94	111.76	111.76	111.0435	111.238
11.95	111.76	111.76	111.065	111.238
11.96	111.7679	111.7679	111.065	111.238
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11.99	111.847	111.847	111.065	111.238
12	111.8221	111.8721	111.065	111.238
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12.03	111.76	111.935	111.065	111.238
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12.05	111.76	111.935	111.065	111.238
12.06	111.76	111.935	111.065	111.238
12.07	111.7455	111.9203	111.065	111.238
12.08	111.7165	111.891	111.065	111.238
12.09	111.6875	111.8617	111.065	111.238
12.1	111.6854	111.847	111.065	111.238
12.11	111.7103	111.847	111.0786	111.2516
12.12	111.7351	111.847	111.1058	111.2788
12.13	111.76	111.847	111.133	111.306
12.14	111.76	111.847	111.152	111.325

12.15	111.76	111.847	111.152	111.325
12.16	111.7619	111.849	111.152	111.325
12.17	111.7813	111.8685	111.152	111.325
12.18	111.8006	111.8881	111.152	111.325
12.19	111.8199	111.9076	111.152	111.325
12.2	111.8393	111.9272	111.152	111.325
12.21	111.8673	111.935	111.152	111.3141
12.22	111.9012	111.935	111.152	111.2924
12.23	111.935	111.935	111.152	111.2706
12.24	111.9118	111.9118	111.152	111.2489
12.25	111.8887	111.8887	111.152	111.2525
12.26	111.8655	111.8655	111.152	111.2815
12.27	111.847	111.854	111.152	111.3105
12.28	111.847	111.8892	111.152	111.325
12.29	111.847	111.9244	111.152	111.325
12.3	111.847	111.9184	111.152	111.325
12.31	111.847	111.8946	111.152	111.325
12.32	111.847	111.8708	111.152	111.325
12.33	111.847	111.847	111.152	111.325
12.34	111.847	111.847	111.152	111.325
12.35	111.847	111.847	111.152	111.325
12.36	111.847	111.847	111.152	111.325
12.37	111.847	111.8684	111.152	111.325
12.38	111.847	111.8922	111.152	111.325
12.39	111.847	111.916	111.152	111.325
12.4	111.847	111.935	111.152	111.325
12.41	111.847	111.935	111.152	111.325
12.42	111.847	111.935	111.152	111.3021
12.43	111.847	111.923	111.152	111.2792
12.44	111.847	111.883	111.152	111.2563
12.45	111.8494	111.8494	111.152	111.238
12.46	111.8732	111.8732	111.152	111.238
12.47	111.8969	111.8969	111.152	111.238
12.48	111.9207	111.9207	111.152	111.2545
12.49	111.935	111.935	111.152	111.278

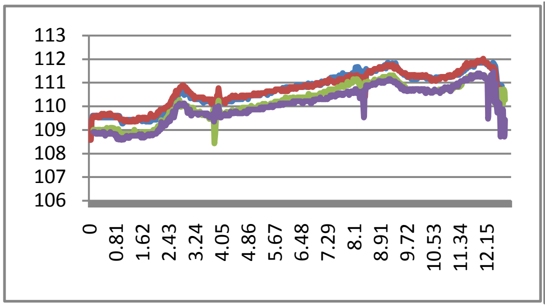
12.5	111.935	111.935	111.152	111.3015
12.51	111.935	111.935	111.152	111.325
12.52	111.8933	111.8933	111.1239	111.2969
12.53	111.847	111.847	111.0959	111.2689
12.54	111.8148	111.8796	111.0678	111.2408
12.55	111.7826	111.9122	111.065	111.238
12.56	111.7684	111.9265	111.065	111.238
12.57	111.7965	111.8981	111.065	111.238
12.58	111.8245	111.8697	111.065	111.238
12.59	111.847	111.847	111.065	111.238
12.6	111.847	111.847	111.065	111.238
12.61	111.847	111.847	111.065	111.2144
12.62	111.8391	111.8391	111.065	111.1358
12.63	111.7995	111.7995	111.065	111.065
12.64	111.76	111.76	111.065	111.065
12.65	111.76	111.76	111.065	111.065
12.66	111.76	111.76	111.065	111.065
12.67	111.7751	111.7449	111.0789	111.0512
12.68	111.794	111.726	111.1137	111.0168
12.69	111.813	111.707	111.1485	110.9824
12.7	111.8319	111.6881	111.152	110.979
12.71	111.847	111.673	111.152	110.979
12.72	111.847	111.673	111.1839	110.979
12.73	111.847	111.673	111.2157	110.979
12.74	111.847	111.673	111.1795	110.904
12.75	111.847	111.673	110.9847	110.654
12.76	111.847	111.673	110.7899	110.404
12.77	111.847	111.673	110.6801	110.2499
12.78	111.8139	111.6399	110.9104	110.4796
12.79	111.7724	111.5984	111.1407	110.7093
12.8	111.7106	111.5366	111.3093	110.8852
12.81	111.6401	111.4661	111.2306	110.8461
12.82	111.5695	111.3955	111.152	110.807
12.83	111.499	111.325	111.0734	110.6502
12.84	111.2677	111.0943	110.9947	110.4934

12.85	111.0823	110.9372	110.8741	110.3874
12.86	110.943	110.8537	110.743	110.2941
12.87	110.8036	110.7701	110.612	110.2009
12.88	110.72	110.7309	110.4809	110.1076
12.89	110.72	110.7581	110.3462	110.0404
12.9	110.72	110.7852	110.197	110.0773
12.91	110.72	110.8166	110.0479	110.1143
12.92	110.72	110.8643	110.0999	110.118
12.93	110.72	110.9068	110.1743	110.118
12.94	110.72	110.9412	110.1753	110.118
12.95	110.72	110.9756	110.1276	110.118
12.96	110.6627	111.0077	110.0529	110.118
12.97	110.599	111.0395	109.9714	110.118
12.98	110.5361	111.071	109.9307	110.118
12.99	110.4768	111.101	109.9075	110.118
13	110.4175	111.131	109.8842	110.118
13.01	110.3473	111.1663	109.861	110.118
13.02	110.2518	111.2141	109.9183	110.118
13.03	110.1625	111.252	109.8638	110.1043
13.04	110.0796	111.2801	109.6973	110.0769
13.05	109.9967	111.3082	109.5309	110.0495
13.06	109.775	111.499	109.4417	110.033
13.07	109.775	111.499	109.4686	110.033
13.08	109.775	111.499	109.4955	110.033
13.09			109.5361	110.0424
13.1			109.6317	110.0897
13.11			109.7388	110.0991
13.12			109.8632	110.0519
13.13			109.9876	110.0047
13.14			109.7817	109.9823
13.15			109.5391	109.9627
13.16			109.3902	109.9507
13.17			109.616	109.9689
13.18			109.8419	109.9872
13.19			109.8765	109.9912

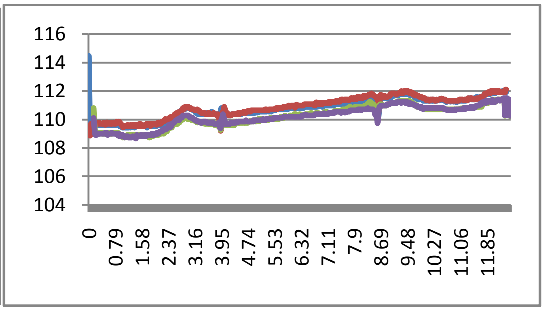
13.2			109.4648	109.9617
13.21			109.3785	109.9555
13.22			109.6175	109.9726

13.23			109.8566	109.9897

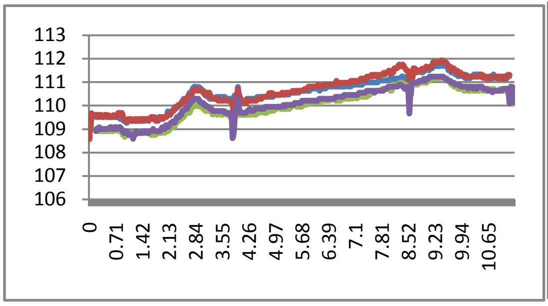
Raw Data Plot



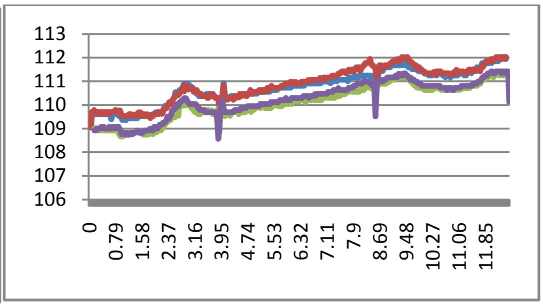
Trial 1



Trial 2



Trial 3



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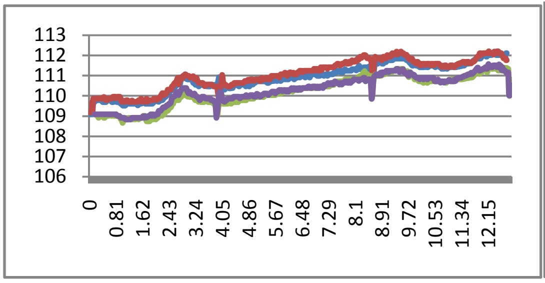

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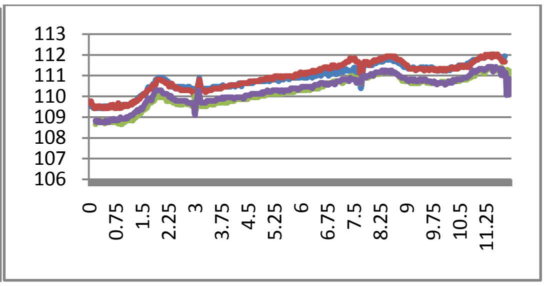

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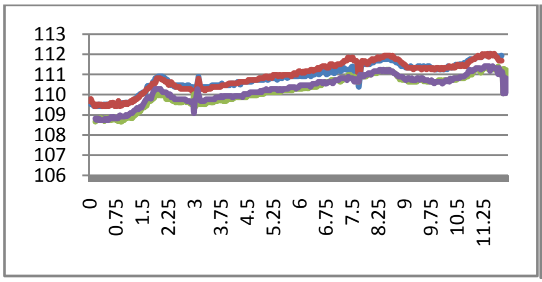
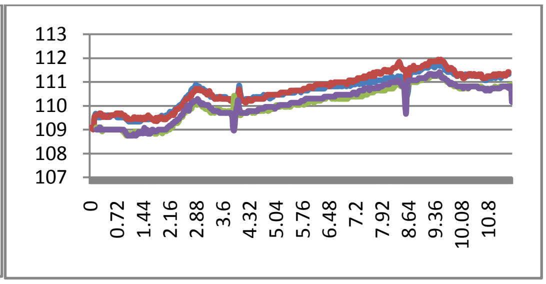
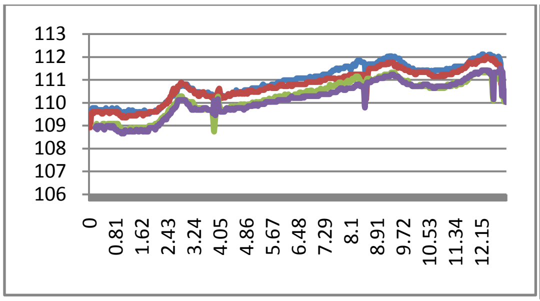


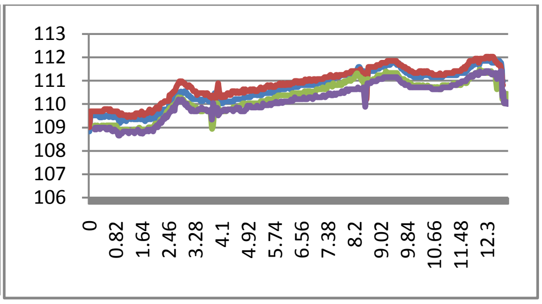
Trial 7



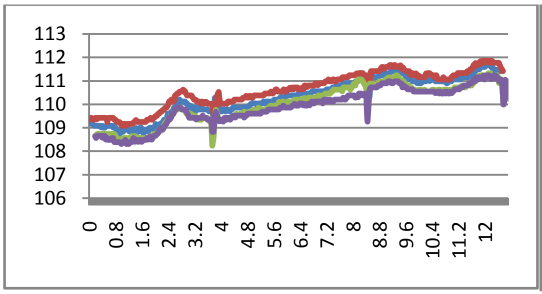
Trial 8



Trial 13



Trial 14



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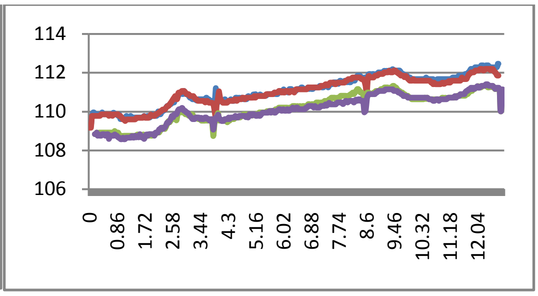
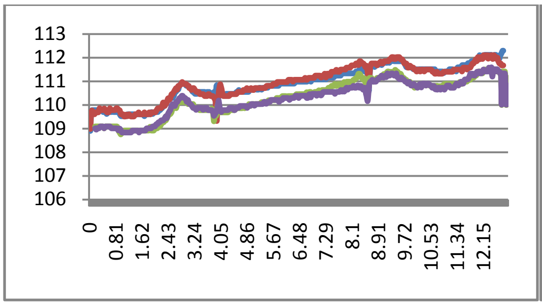
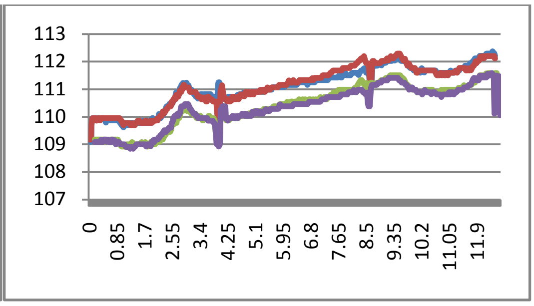


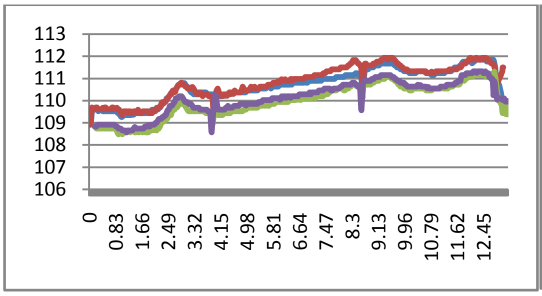
Trial 16



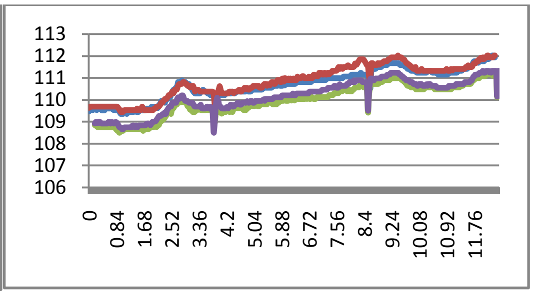
Trial 17



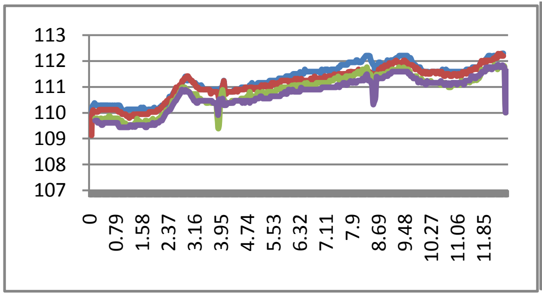
Trial 18



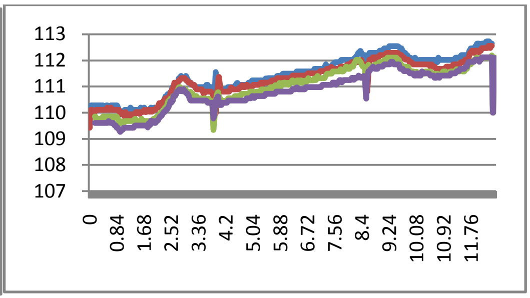
Trial 19



Trial 20



Trial 21



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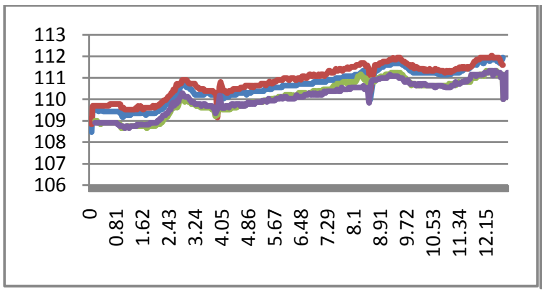
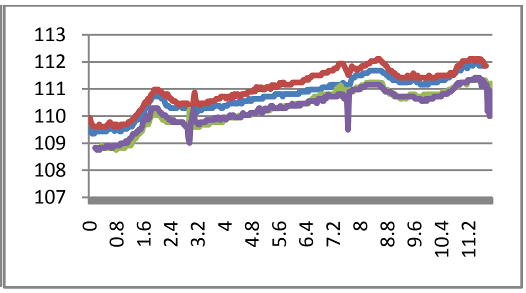
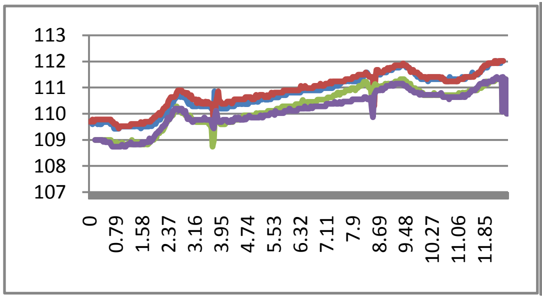


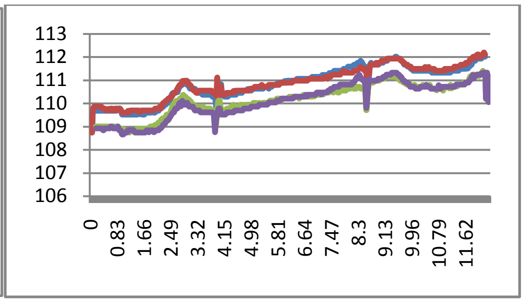
Trial 23



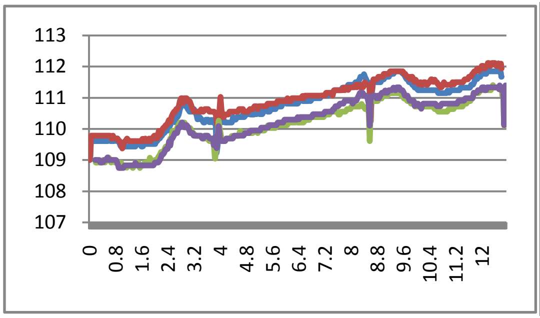
Trial 24



Trial 25



Trial 26



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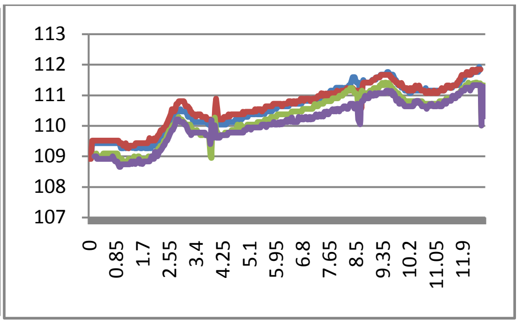

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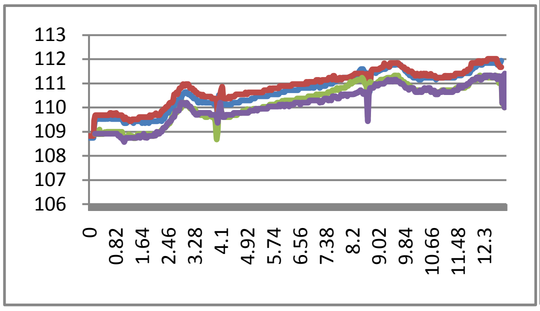

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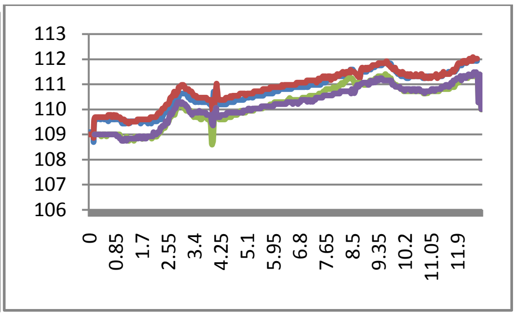
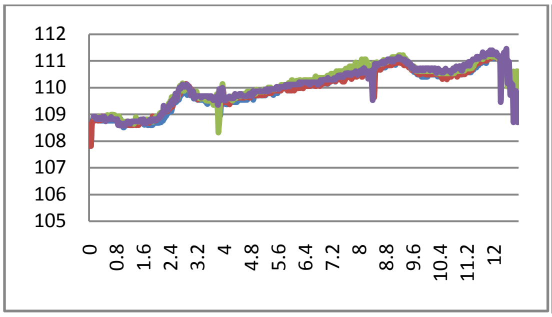
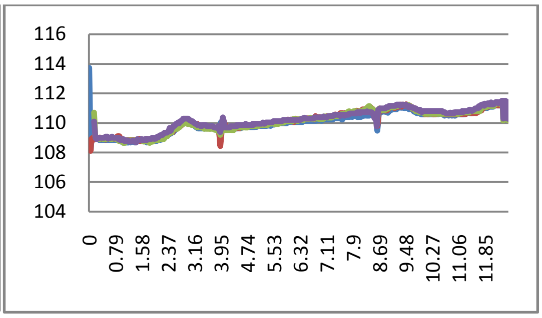


Trial 30

Interpolated Data Plot



Trial 1



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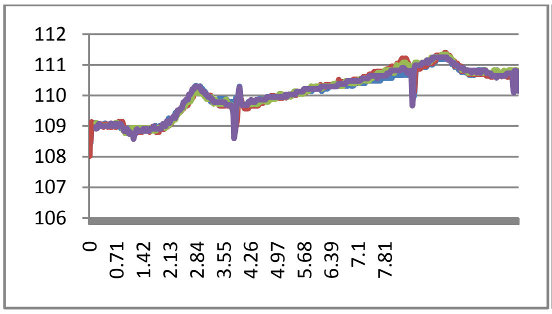

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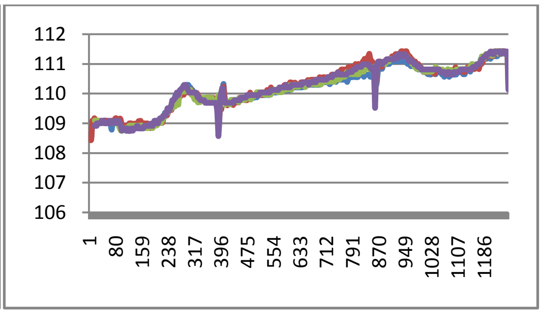
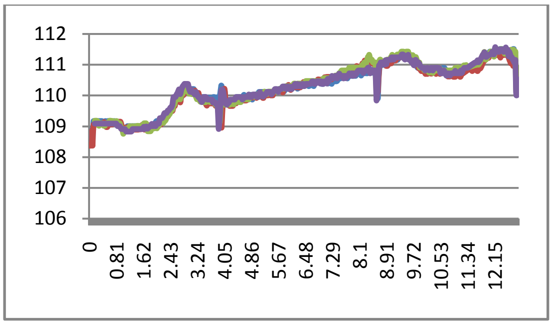


Trial 4



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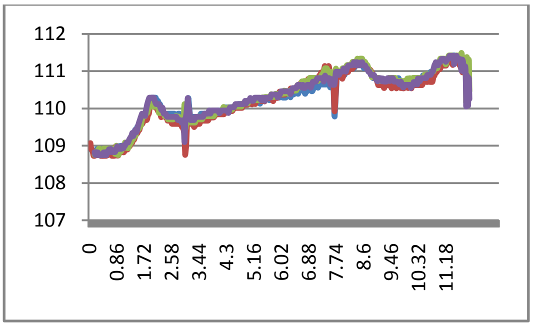
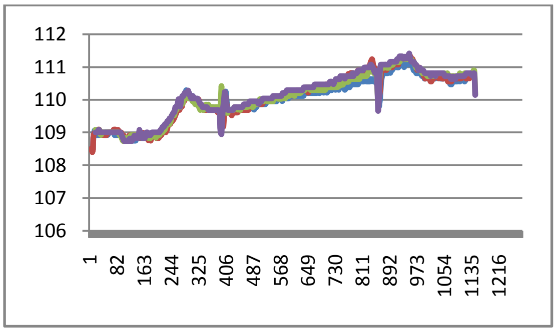
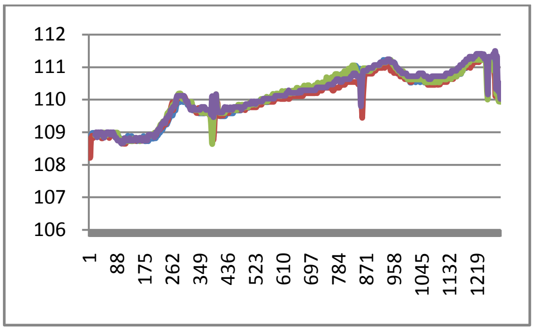


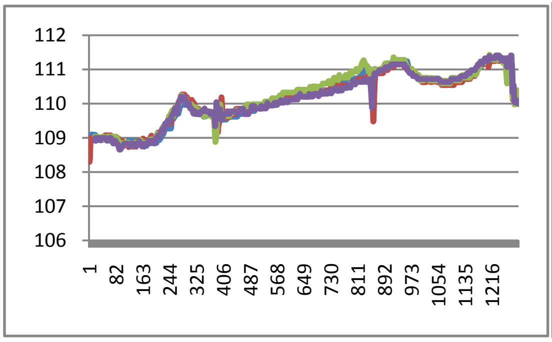
Trial 6



Trial 7



Trial 8



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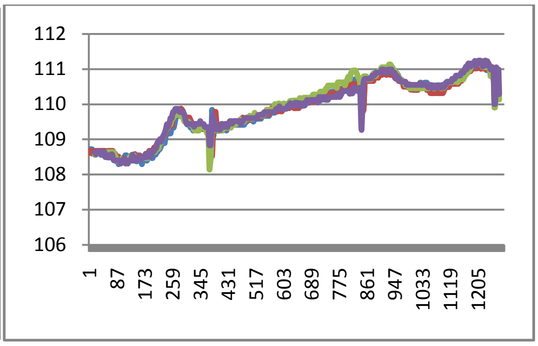
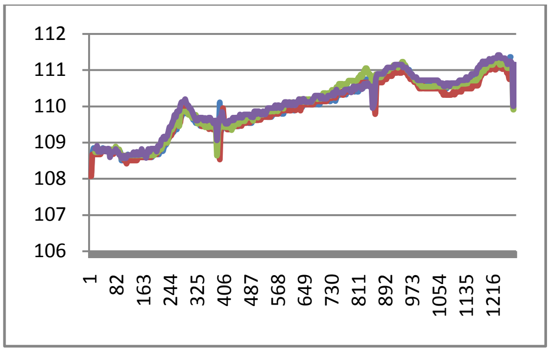


Trial 14



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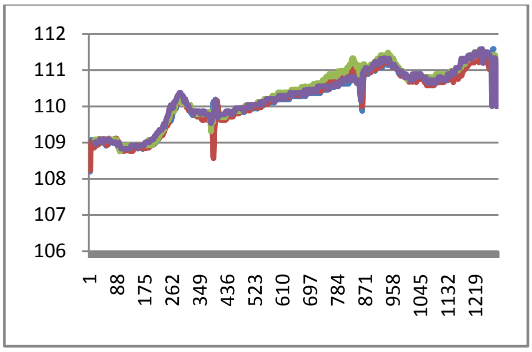

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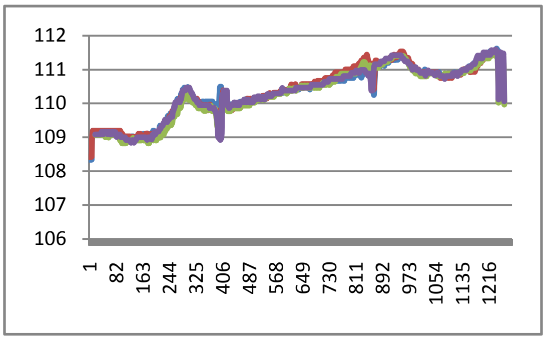
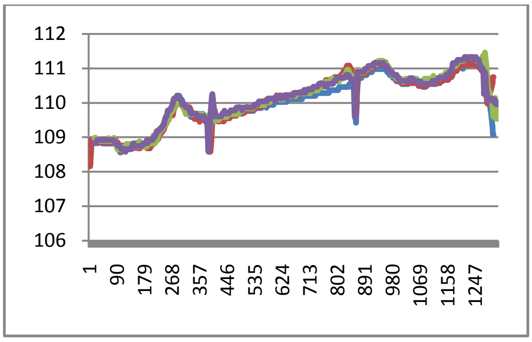
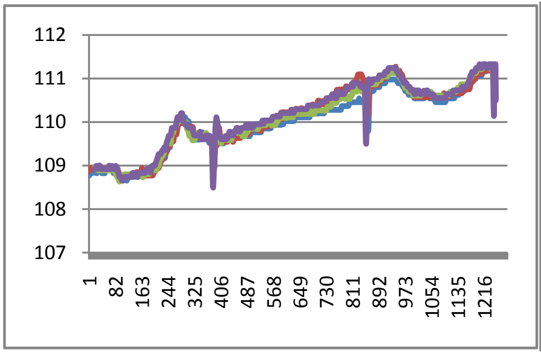


Trial 17



Trial 18



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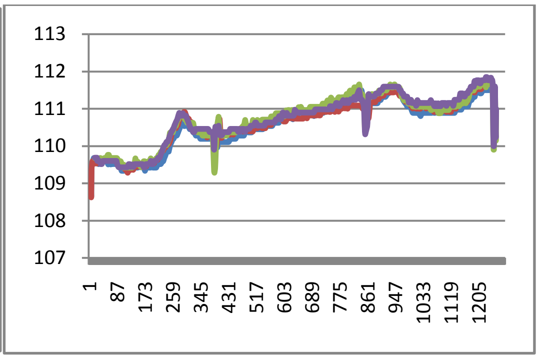

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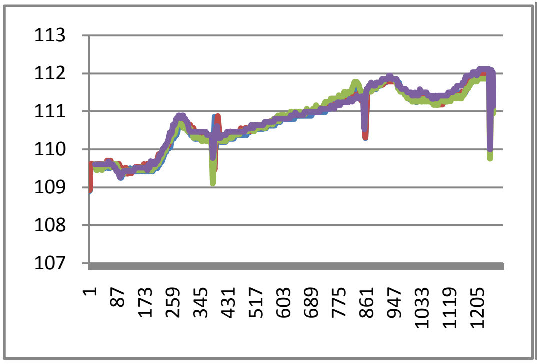

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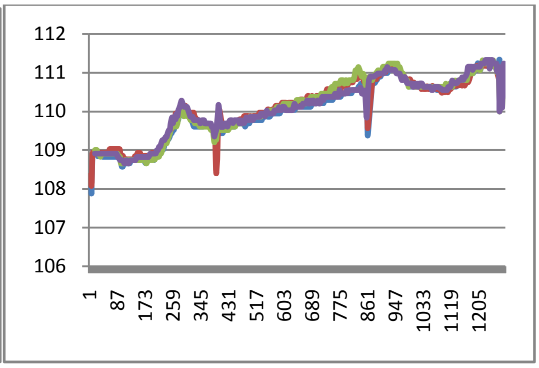

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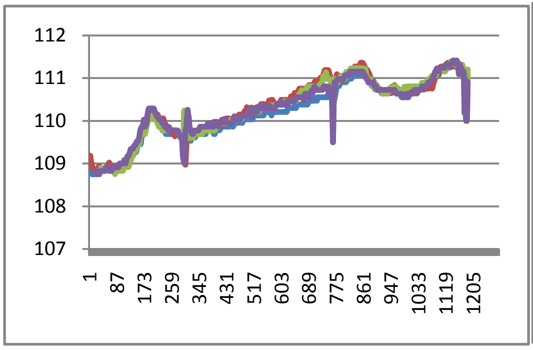

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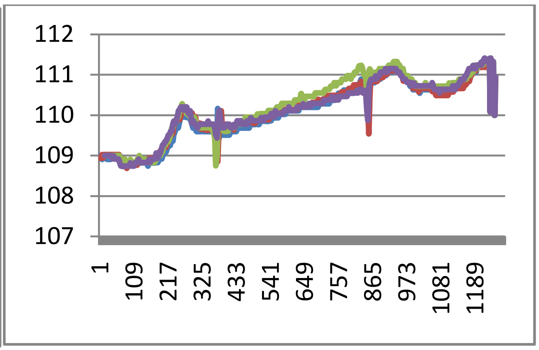
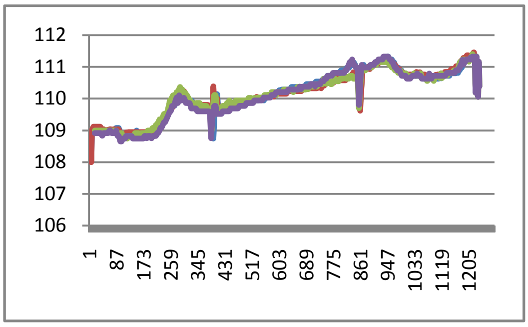
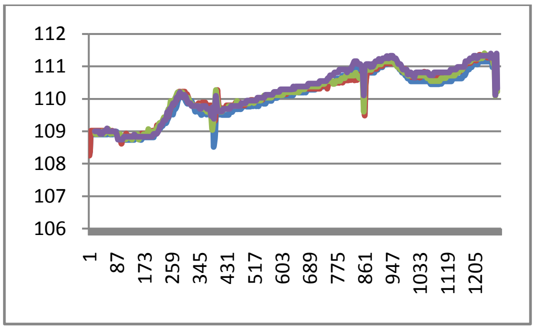


Trial 24



Trial 25



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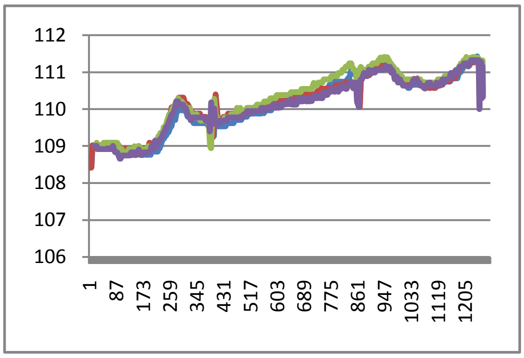
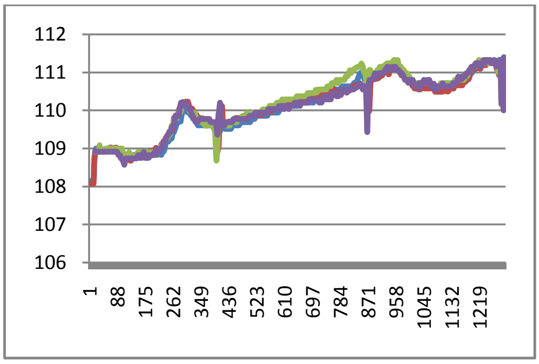
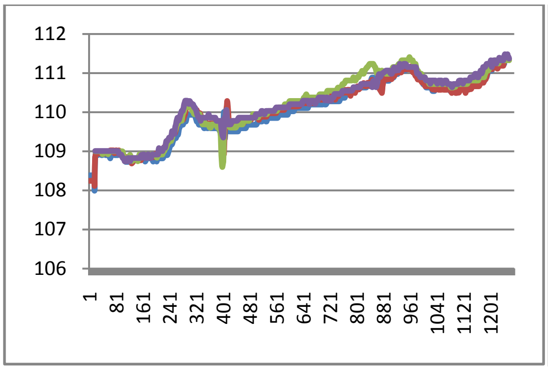
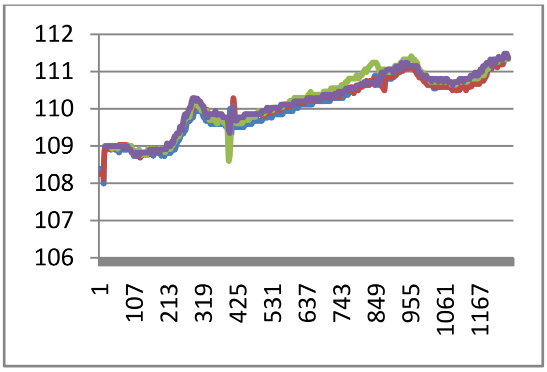




Trial 27

Trial 28



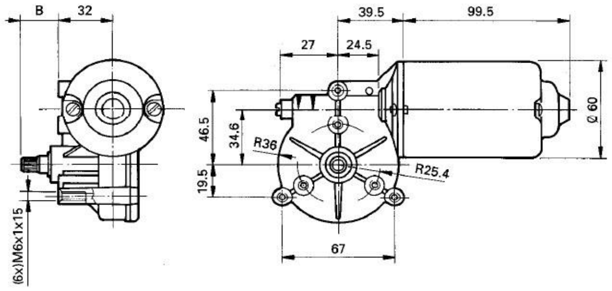


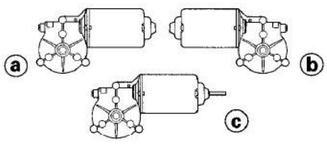
Trial 29 ***Trial 30***

Appendix C Datasheet

- DOGA Geared DC Motor
- 3A, 55V H-Bridge - LMD18200T
- PICAXE210 – XBee Module
- LV-MaxSonar-EZ4
- MAE3: Absolute Magnetic Kit Encoder
- MA3: Miniature Absolute Magnetic Shaft Encoder
- Reformer Tube Internal Diameter Measuring System User Manual

DOGA Mod. 111

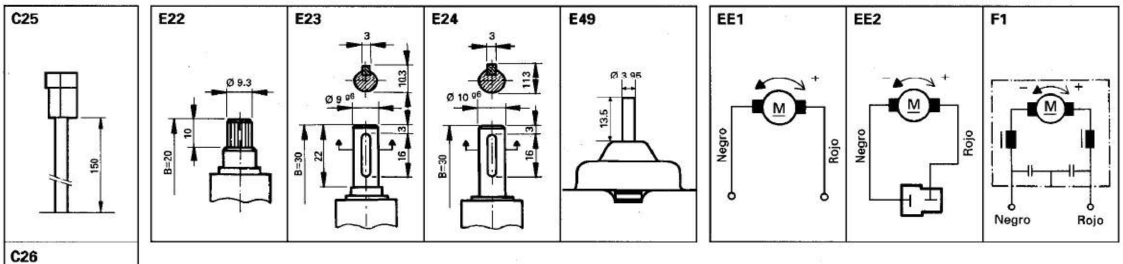


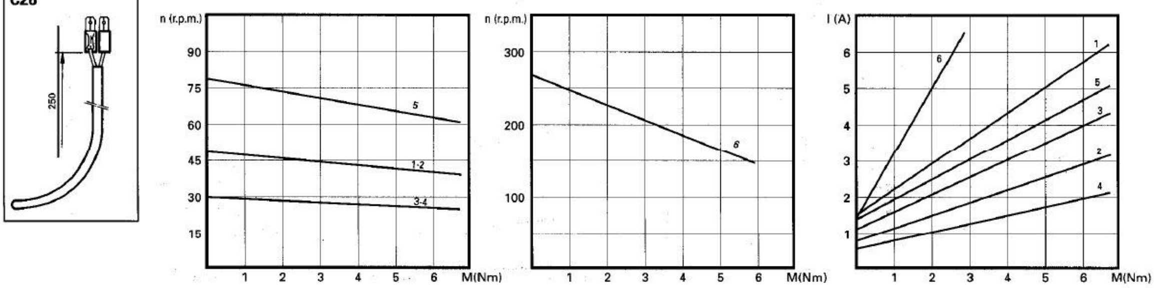


P = 1,25 kg aprox.
Est = IP 53
i = 62:1

REF.	Tensión nominal / Nominal voltage / Tension nominale / Nennspannung U (V)	Par nominal / Nominal torque / Couple nominal / Nenndrehmoment Mn (N.m)	Velocidad nominal / Nominal speed / Vitesse nominale / Nenndrehzahl n (R.P.M.)	Potencia absorbida / Input power / Puissance absorbée / Aufnahmeleistung P_1(U.I) (W)	Potencia nominal / Nominal power / Puissance nominale / Vollastleistung P_2(n.Mn) (W)	Corriente nominal / Nominal current / Courant nominal / Nennstrom I (A)	Par de arranque / Starting torque / Couple de démarrage / Anzugsmoment Ma (N.m)	Corriente de Arranque / Starting current / Courant de démarrage / Anlaufstrom Ia (A)	Eje / Shaft / Arbre / Welle	Curva / Curve / Courbe / Kurve	Conexiones / Connections / Connexions / Anschlußart	Esq. eléct. / Wiring diag. / Sch. élect. / Schaltbild	a b c
111.3711.20.00	12					5		25	E22	1			
111.3711.30.00	24	5	40	60	20	2.5		13		2			
111.3761.20.00	12					5		25		1			
111.3761.30.00	24					2.5		13		2			a
111.3763.20.00	12	6	25	48	16	4		15	E23	3			
111.3763.30.00	24					2	25	8		4	C25	EE2	
111.4761.20.00	12					5		25		1			b
111.4761.30.00	24	5	40	60	20	2.5		13		2			
111.9023.30.00	24								E24				
111.9031.30.00	24	3	70	72	22	3		17		5			
111.9039.30.00 (*)	24	1.5	240	96	38	4	14	23	E23	6	C26	EE1	a
111.9040.30.00 (*)	24											F1	
111.9041.30.00 (**)	24	5	40	60	20	2.5	25	13	E24	2	C25	EE2	c
111.9092.30.00	24	1.5	240	96	38	4	14	23	E23/E49	6			

(*) i = 49:4 (**) Rueda de bronce – Bronze worm wheel – Roue de vis sans fin en bronze – Bronze-Schneckenrad





National Semiconductor

December 1999

LMD18200
3A, 55V H-Bridge

General Description

The LMD18200 is a 3A H-Bridge designed for motion control applications. The device is built using a multi-technology process which combines bipolar and CMOS control circuitry with DMOS power devices on the same monolithic structure. Ideal for driving DC and stepper motors; the LMD18200 accommodates peak output currents up to 6A. An innovative circuit which facilitates low-loss sensing of the output current has been implemented.

Features

- Delivers up to 3A continuous output
- Operates at supply voltages up to 55V
- Low R_{DS}(ON) typically 0.3Ω per switch
- TTL and CMOS compatible inputs
- No “shoot-through” current
- Thermal warning flag output at 145˚C
- Thermal shutdown (outputs off) at 170˚C
- Internal clamp diodes
- Shorted load protection
- Internal charge pump with external bootstrap capability

Applications

- DC and stepper motor drives
- Position and velocity servomechanisms
- Factory automation robots
- Numerically controlled machinery
- Computer printers and plotters

Functional Diagram

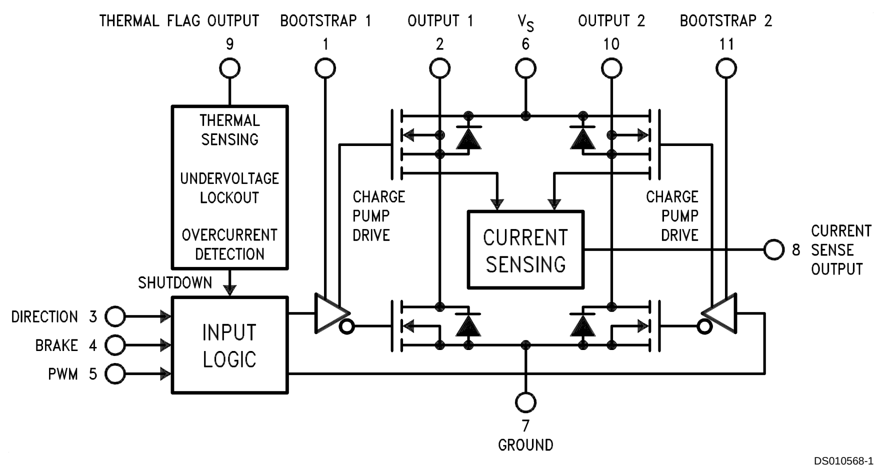
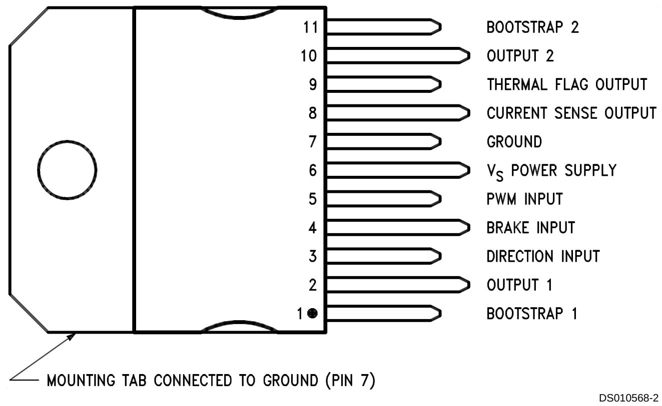
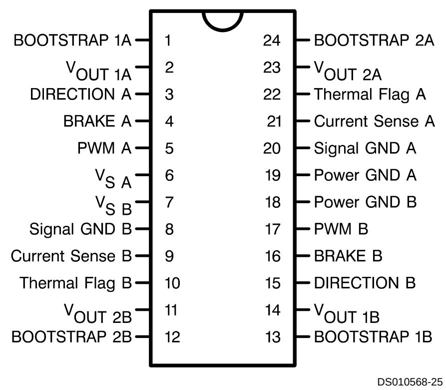


FIGURE 1. Functional Block Diagram of LMD18200

Connection Diagrams and Ordering Information



11-Lead TO-220 Package
Top View
Order Number LMD18200T
See NS Package TA11B



24-Lead Dual-in-Line Package
Top View
Order Number LMD18200-2D-QV
5962-9232501VXA
LMD18200-2D/883
5962-9232501MXA
See NS Package DA24B

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Total Supply Voltage (V_S, Pin 6)	60V
Voltage at Pins 3, 4, 5, 8 and 9	12V
Voltage at Bootstrap Pins	
(Pins 1 and 11)	V_{OUT} +16V
Peak Output Current (200 ms)	6A
Continuous Output Current (Note 2)	3A
Power Dissipation (Note 3)	25W
Power Dissipation (T_A = 25˚C, Free Air)	3W
Junction Temperature, $T_{J(max)}$	150˚C
ESD Susceptibility (Note 4)	1500V
Storage Temperature, T_{STG}	−40˚C to +150˚C
Lead Temperature (Soldering, 10 sec.)	300˚C

Operating Ratings (Note 1)

Junction Temperature, T_J	−40˚C to +125˚C
V_S Supply Voltage	+12V to +55V

Electrical Characteristics (Note 5)

The following specifications apply for V_S = 42V, unless otherwise specified. **Boldface** limits apply over the entire operating temperature range, −40˚C ≤ T_J ≤ +125˚C, all other limits are for T_A = T_J = 25˚C.

Symbol	Parameter	Conditions	Typ	Limit	Units
R_{DS}(ON)	Switch ON Resistance	Output Current = 3A (Note 6)	0.33	0.4/**0.6**	Ω (max)
R_{DS}(ON)	Switch ON Resistance	Output Current = 6A (Note 6)	0.33	0.4/**0.6**	Ω (max)
V_{CLAMP}	Clamp Diode Forward Drop	Clamp Current = 3A (Note 6)	1.2	1.5	V (max)
V_{IL}	Logic Low Input Voltage	Pins 3, 4, 5		**−0.1**	V (min)
				0.8	V (max)
I_{IL}	Logic Low Input Current	V_{IN} = −0.1V, Pins = 3, 4, 5		**−10**	µA (max)
V_{IH}	Logic High Input Voltage	Pins 3, 4, 5		**2**	V (min)
				12	V (max)
I_{IH}	Logic High Input Current	V_{IN} = 12V, Pins = 3, 4, 5		**10**	µA (max)
	Current Sense Output	I_{OUT} = 1A (Note 8)	377	325/**300**	µA (min)
				425/**450**	µA (max)
	Current Sense Linearity	1A ≤ I_{OUT} ≤ 3A (Note 7)	±6	±9	%
	Undervoltage Lockout	Outputs turn OFF		9	V (min)
				11	V (max)
T_{JW}	Warning Flag Temperature	Pin 9 ≤ 0.8V, I_L = 2 mA	145		˚C
V_F(ON)	Flag Output Saturation Voltage	T_J = T_{JW}, I_L = 2 mA	0.15		V
I_F(OFF)	Flag Output Leakage	V_F = 12V	0.2	10	µA (max)
T_{JSD}	Shutdown Temperature	Outputs Turn OFF	170		˚C
I_S	Quiescent Supply Current	All Logic Inputs Low	13	25	mA (max)
t_{Don}	Output Turn-On Delay Time	Sourcing Outputs, I_{OUT} = 3A	300		ns
		Sinking Outputs, I_{OUT} = 3A	300		ns
t_{on}	Output Turn-On Switching Time	Bootstrap Capacitor = 10 nF			
		Sourcing Outputs, I_{OUT} = 3A	100		ns
		Sinking Outputs, I_{OUT} = 3A	80		ns
t_{Doff}	Output Turn-Off Delay Times	Sourcing Outputs, I_{OUT} = 3A	200		ns
		Sinking Outputs, I_{OUT} = 3A	200		ns
t_{off}	Output Turn-Off Switching Times	Bootstrap Capacitor = 10 nF			
		Sourcing Outputs, I_{OUT} = 3A	75		ns
		Sinking Outputs, I_{OUT} = 3A	70		ns
t_{pw}	Minimum Input Pulse Width	Pins 3, 4 and 5	1		µs
t_{cpr}	Charge Pump Rise Time	No Bootstrap Capacitor	20		µs

Electrical Characteristics Notes

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. DC and AC electrical specifications do not apply when operating the device beyond its rated operating conditions.

Note 2: See Application Information for details regarding current limiting.

Note 3: The maximum power dissipation must be derated at elevated temperatures and is a function of $T_{J(max)}$, θ_{JA}, and T_A. The maximum allowable power dissipation at any temperature is $P_{D(max)} = (T_{J(max)} - T_A)/\theta_{JA}$, or the number given in the Absolute Ratings, whichever is lower. The typical thermal resistance from junction to case (θ_{JC}) is 1.0˚C/W and from junction to ambient (θ_{JA}) is 30˚C/W. For guaranteed operation $T_{J(max)}$ = 125˚C.

Note 4: Human-body model, 100 pF discharged through a 1.5 kΩ resistor. Except Bootstrap pins (pins 1 and 11) which are protected to 1000V of ESD.

Note 5: All limits are 100% production tested at 25˚C. Temperature extreme limits are guaranteed via correlation using accepted SQC (Statistical Quality Control) methods. All limits are used to calculate AOQL, (Average Outgoing Quality Level).

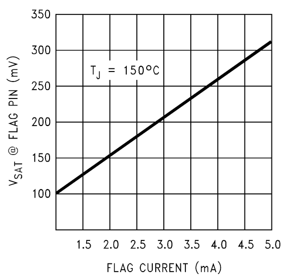
Note 6: Output currents are pulsed (t_W < 2 ms, Duty Cycle < 5%).

Note 7: Regulation is calculated relative to the current sense output value with a 1A load.

Note 8: Selections for tighter tolerance are available. Contact factory.

Typical Performance Characteristics

V_{SAT} vs Flag Current



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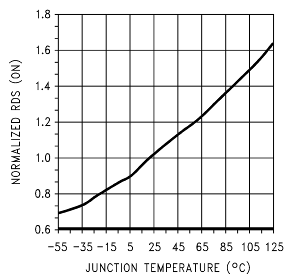
R_{DS}(ON) vs Temperature



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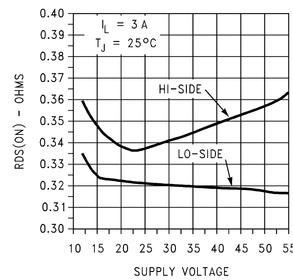
R_{DS}(ON) vs Supply Voltage



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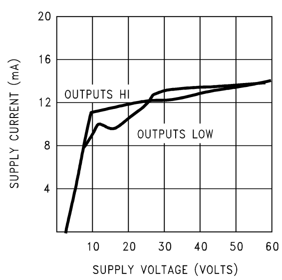
Supply Current vs Supply Voltage



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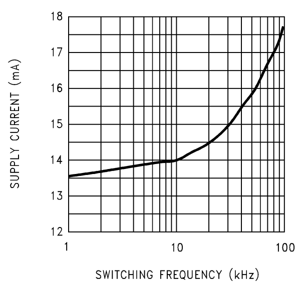
Supply Current vs Frequency (V_S = 42V)



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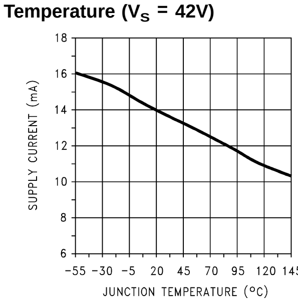
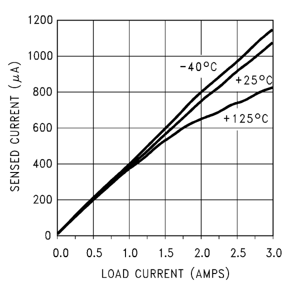
Supply Current vs Temperature (V_S = 42V)



DS010568-21

Current Sense Output vs Load Current



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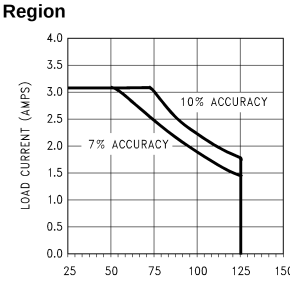
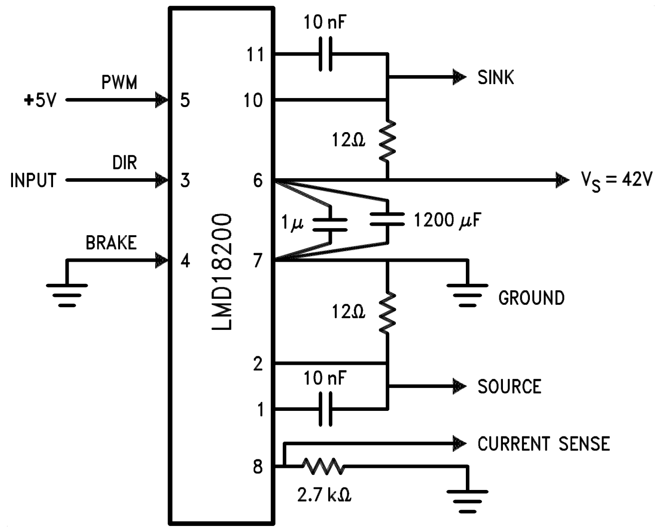
Current Sense Operating Region



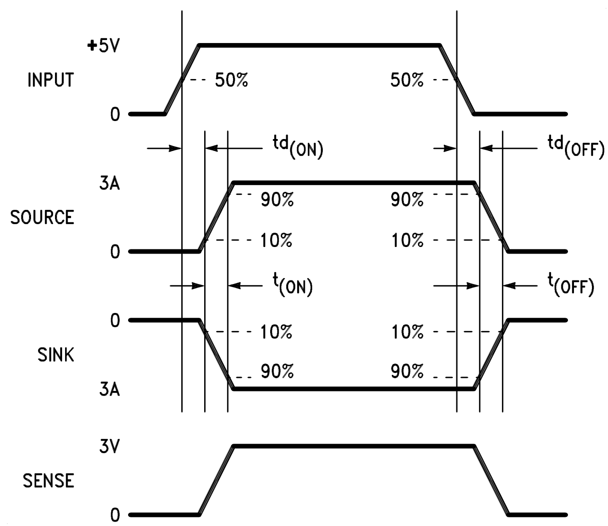
DS010568-23

Test Circuit



DS010568-8

Switching Time Definitions



DS010568-9

Pinout Description (See Connection Diagram)

Pin 1, BOOTSTRAP 1 Input: Bootstrap capacitor pin for half H-bridge number 1. The recommended capacitor (10 nF) is connected between pins 1 and 2.

Pin 2, OUTPUT 1: Half H-bridge number 1 output.

Pin 3, DIRECTION Input: See *Table 1.* This input controls the direction of current flow between OUTPUT 1 and OUTPUT 2 (pins 2 and 10) and, therefore, the direction of rotation of a motor load.

Pin 4, BRAKE Input: See *Table 1.* This input is used to brake a motor by effectively shorting its terminals. When braking is desired, this input is taken to a logic high level and it is also necessary to apply logic high to PWM input, pin 5. The drivers that short the motor are determined by the logic level at the DIRECTION input (Pin 3): with Pin 3 logic high, both current sourcing output transistors are ON; with Pin 3 logic low, both current sinking output transistors are ON. All output transistors can be turned OFF by applying a logic high to Pin 4 and a logic low to PWM input Pin 5; in this case only a small bias current (approximately −1.5 mA) exists at each output pin.

Pin 5, PWM Input: See *Table 1.* How this input (and DIRECTION input, Pin 3) is used is determined by the format of the PWM Signal.

Pinout Description

(See Connection Diagram) (Continued)

Pin 6, V_S Power Supply

Pin 7, GROUND Connection: This pin is the ground return, and is internally connected to the mounting tab.

Pin 8, CURRENT SENSE Output: This pin provides the sourcing current sensing output signal, which is typically 377 µA/A.

Pin 9, THERMAL FLAG Output: This pin provides the thermal warning flag output signal. Pin 9 becomes active-low at 145˚C (junction temperature). However the chip will not shut itself down until 170˚C is reached at the junction.

Pin 10, OUTPUT 2: Half H-bridge number 2 output.

Pin 11, BOOTSTRAP 2 Input: Bootstrap capacitor pin for Half H-bridge number 2. The recommended capacitor (10 nF) is connected between pins 10 and 11.

TABLE 1. Logic Truth Table

PWM	Dir	Brake	Active Output Drivers
H	H	L	Source 1, Sink 2
H	L	L	Sink 1, Source 2
L	X	L	Source 1, Source 2
H	H	H	Source 1, Source 2
H	L	H	Sink 1, Sink 2
L	X	H	NONE

Application Information

TYPES OF PWM SIGNALS

The LMD18200 readily interfaces with different forms of PWM signals. Use of the part with two of the more popular forms of PWM is described in the following paragraphs.

Simple, locked anti-phase PWM consists of a single, variable duty-cycle signal in which is encoded both direction and amplitude information (see *Figure 2*). A 50% duty-cycle PWM signal represents zero drive, since the net value of voltage (integrated over one period) delivered to the load is zero. For the LMD18200, the PWM signal drives the direction input (pin 3) and the PWM input (pin 5) is tied to logic high.

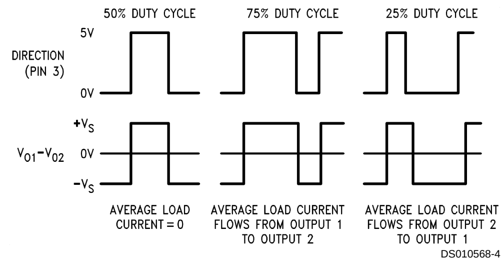


FIGURE 2. Locked Anti-Phase PWM Control

Sign/magnitude PWM consists of separate direction (sign) and amplitude (magnitude) signals (see *Figure 3*). The (absolute) magnitude signal is duty-cycle modulated, and the absence of a pulse signal (a continuous logic low level) represents zero drive. Current delivered to the load is proportional to pulse width. For the LMD18200, the DIRECTION input (pin 3) is driven by the sign signal and the PWM input (pin 5) is driven by the magnitude signal.

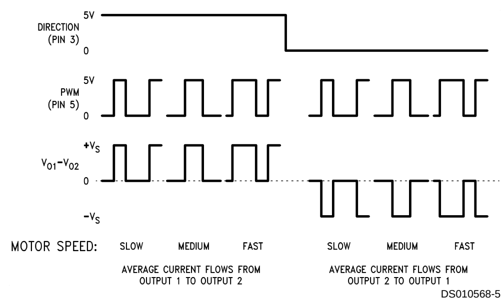


FIGURE 3. Sign/Magnitude PWM Control

SIGNAL TRANSITION REQUIREMENTS

To ensure proper internal logic performance, it is good practice to avoid aligning the falling and rising edges of input signals. A delay of at least 1 µsec should be incorporated between transitions of the Direction, Brake, and/or PWM input signals. A conservative approach is be sure there is at least 500ns delay between the end of the first transition and the beginning of the second transition. See *Figure 4*.

Application Information (Continued)

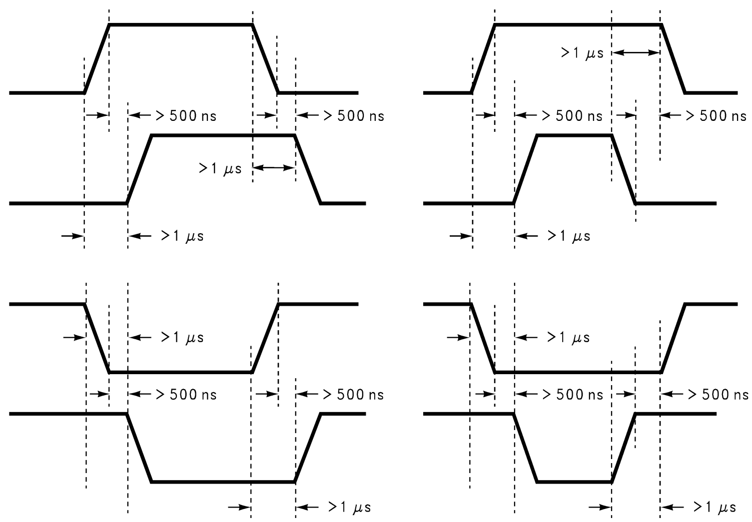


FIGURE 4. Transitions in Brake, Direction, or PWM Must Be Separated By At Least 1 µsec

USING THE CURRENT SENSE OUTPUT

The CURRENT SENSE output (pin 8) has a sensitivity of 377 µA per ampere of output current. For optimal accuracy and linearity of this signal, the value of voltage generating resistor between pin 8 and ground should be chosen to limit the maximum voltage developed at pin 8 to 5V, or less. The maximum voltage compliance is 12V.

It should be noted that the recirculating currents (free wheeling currents) are ignored by the current sense circuitry. Therefore, only the currents in the upper sourcing outputs are sensed.

USING THE THERMAL WARNING FLAG

The THERMAL FLAG output (pin 9) is an open collector transistor. This permits a wired OR connection of thermal warning flag outputs from multiple LMD18200's, and allows the user to set the logic high level of the output signal swing to match system requirements. This output typically drives the interrupt input of a system controller. The interrupt service routine would then be designed to take appropriate steps, such as reducing load currents or initiating an orderly system shutdown. The maximum voltage compliance on the flag pin is 12V.

SUPPLY BYPASSING

During switching transitions the levels of fast current changes experienced may cause troublesome voltage transients across system stray inductance.

It is normally necessary to bypass the supply rail with a high quality capacitor(s) connected as close as possible to the V_S Power Supply (Pin 6) and GROUND (Pin 7). A 1 µF high-frequency ceramic capacitor is recommended. Care should be taken to limit the transients on the supply pin below the Absolute Maximum Rating of the device. When operating the chip at supply voltages above 40V a voltage suppressor (transorb) such as P6KE62A is recommended from supply to ground. Typically the ceramic capacitor can be eliminated in the presence of the voltage suppressor. Note that when driving high load currents a greater amount of supply bypass capacitance (in general at least 100 µF per Amp of load current) is required to absorb the recirculating currents of the inductive loads.

CURRENT LIMITING

Current limiting protection circuitry has been incorporated into the design of the LMD18200. With any power device it is important to consider the effects of the substantial surge currents through the device that may occur as a result of shorted loads. The protection circuitry monitors this increase in current (the threshold is set to approximately 10 Amps) and shuts off the power device as quickly as possible in the event of an overload condition. In a typical motor driving application the most common overload faults are caused by shorted motor windings and locked rotors. Under these conditions the inductance of the motor (as well as any series inductance in the V_{CC} supply line) serves to reduce the magnitude of a current surge to a safe level for the LMD18200. Once the device is shut down, the control circuitry will periodically try to turn the power device back on. This feature allows the immediate return to normal operation in the event that the fault condition has been removed. While the fault remains however, the device will cycle in and out of thermal shutdown. This can create voltage transients on the V_{CC} supply line and therefore proper supply bypassing techniques are required.

The most severe condition for any power device is a direct, hard-wired ("screwdriver") long term short from an output to ground. This condition can generate a surge of current through the power device on the order of 15 Amps and require the die and package to dissipate up to 500 Watts of power for the short time required for the protection circuitry to shut off the power device. This energy can be destructive, particularly at higher operating voltages (>30V) so some precautions are in order. Proper heat sink design is essential and it is normally necessary to heat sink the V_{CC} supply pin (pin 6) with 1 square inch of copper on the PCB.

Application Information (Continued)

INTERNAL CHARGE PUMP AND USE OF BOOTSTRAP CAPACITORS

To turn on the high-side (sourcing) DMOS power devices, the gate of each device must be driven approximately 8V more positive than the supply voltage. To achieve this an internal charge pump is used to provide the gate drive voltage. As shown in *Figure 5*, an internal capacitor is alternately switched to ground and charged to about 14V, then switched to V supply thereby providing a gate drive voltage greater than V supply. This switching action is controlled by a continuously running internal 300 kHz oscillator. The rise time of this drive voltage is typically 20 µs which is suitable for operating frequencies up to 1 kHz.

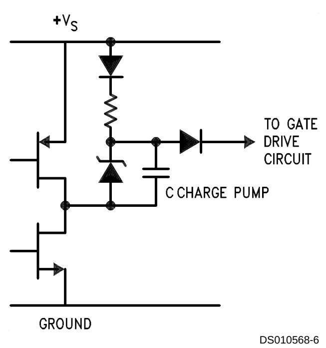


FIGURE 5. Internal Charge Pump Circuitry

For higher switching frequencies, the LMD18200 provides for the use of external bootstrap capacitors. The bootstrap principle is in essence a second charge pump whereby a large value capacitor is used which has enough energy to quickly charge the parasitic gate input capacitance of the power device resulting in much faster rise times. The switching action is accomplished by the power switches themselves *Figure 6*. External 10 nF capacitors, connected from the outputs to the bootstrap pins of each high-side switch provide typically less than 100 ns rise times allowing switching frequencies up to 500 kHz.

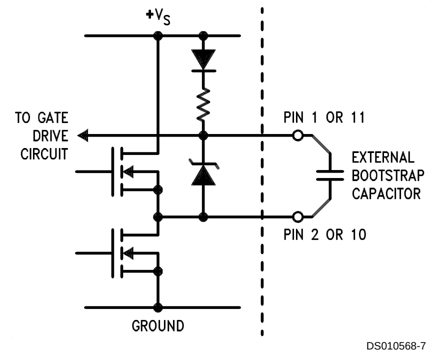


FIGURE 6. Bootstrap Circuitry

INTERNAL PROTECTION DIODES

A major consideration when switching current through inductive loads is protection of the switching power devices from the large voltage transients that occur. Each of the four switches in the LMD18200 have a built-in protection diode to clamp transient voltages exceeding the positive supply or ground to a safe diode voltage drop across the switch.

The reverse recovery characteristics of these diodes, once the transient has subsided, is important. These diodes must come out of conduction quickly and the power switches must be able to conduct the additional reverse recovery current of the diodes. The reverse recovery time of the diodes protecting the sourcing power devices is typically only 70 ns with a reverse recovery current of 1A when tested with a full 6A of forward current through the diode. For the sinking devices the recovery time is typically 100 ns with 4A of reverse current under the same conditions.

Typical Applications

FIXED OFF-TIME CONTROL

This circuit controls the current through the motor by applying an average voltage equal to zero to the motor terminals for a fixed period of time, whenever the current through the motor exceeds the commanded current. This action causes the motor current to vary slightly about an externally controlled average level. The duration of the Off-period is adjusted by the resistor and capacitor combination of the LM555. In this circuit the Sign/Magnitude mode of operation is implemented (see Types of PWM Signals).

Typical Applications (Continued)

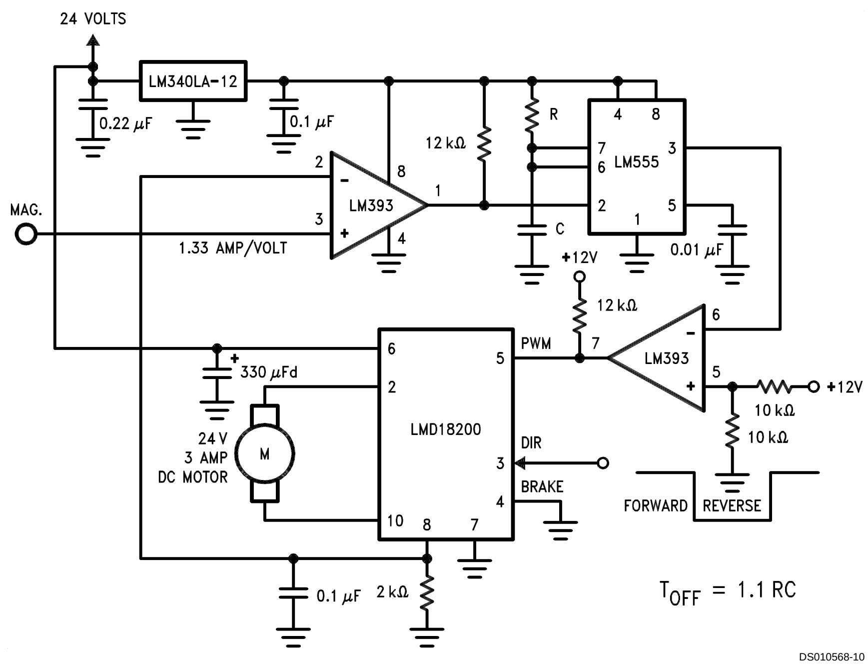


FIGURE 7. Fixed Off-Time Control

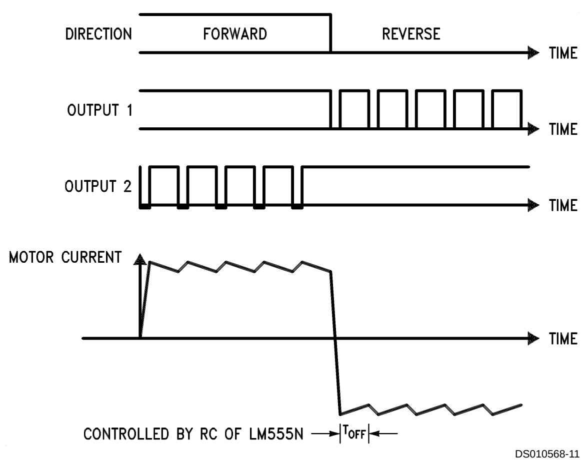


FIGURE 8. Switching Waveforms

TORQUE REGULATION

Locked Anti-Phase Control of a brushed DC motor. Current sense output of the LMD18200 provides load sensing. The LM3525A is a general purpose PWM controller. The relationship of peak motor current to adjustment voltage is shown in *Figure 10*.

Typical Applications (Continued)

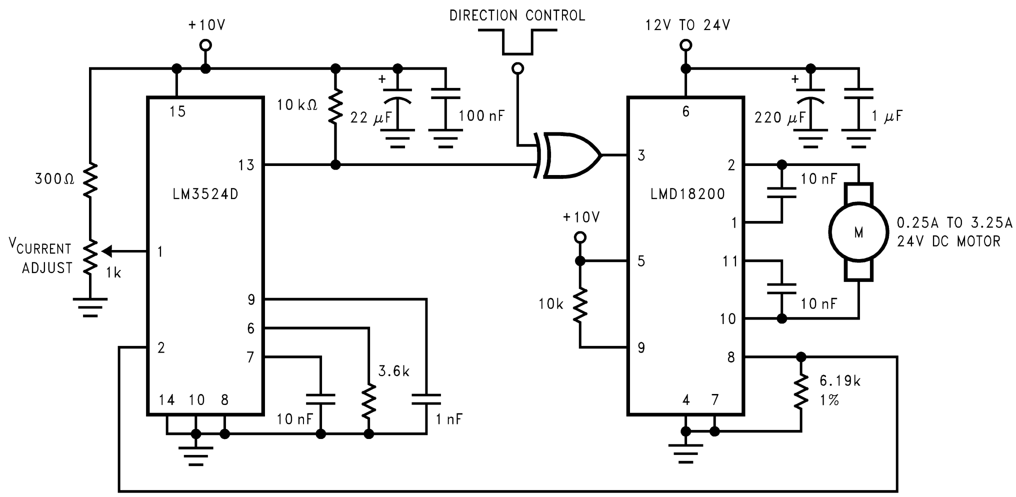


FIGURE 9. Locked Anti-Phase Control Regulates Torque

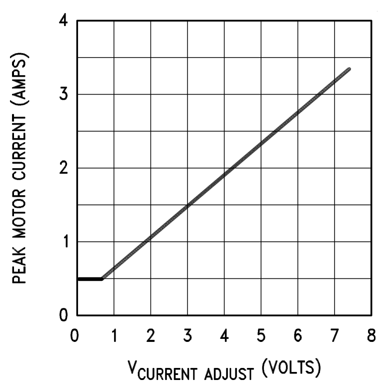


FIGURE 10. Peak Motor Current vs Adjustment Voltage

VELOCITY REGULATION

Utilizes tachometer output from the motor to sense motor speed for a locked anti-phase control loop. The relationship of motor speed to the speed adjustment control voltage is shown in *Figure 12.*

Typical Applications (Continued)

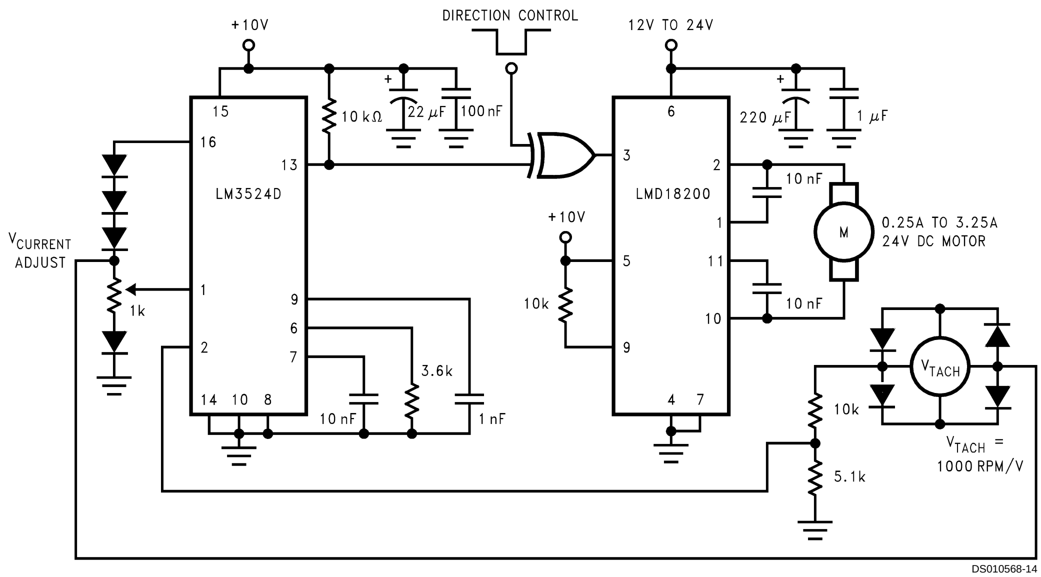


FIGURE 11. Regulate Velocity with Tachometer Feedback

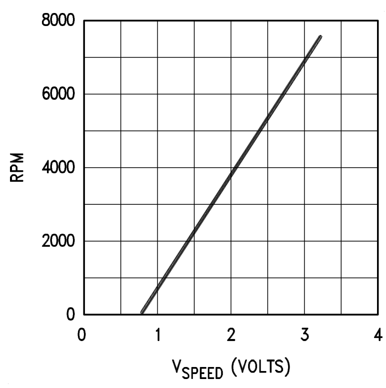
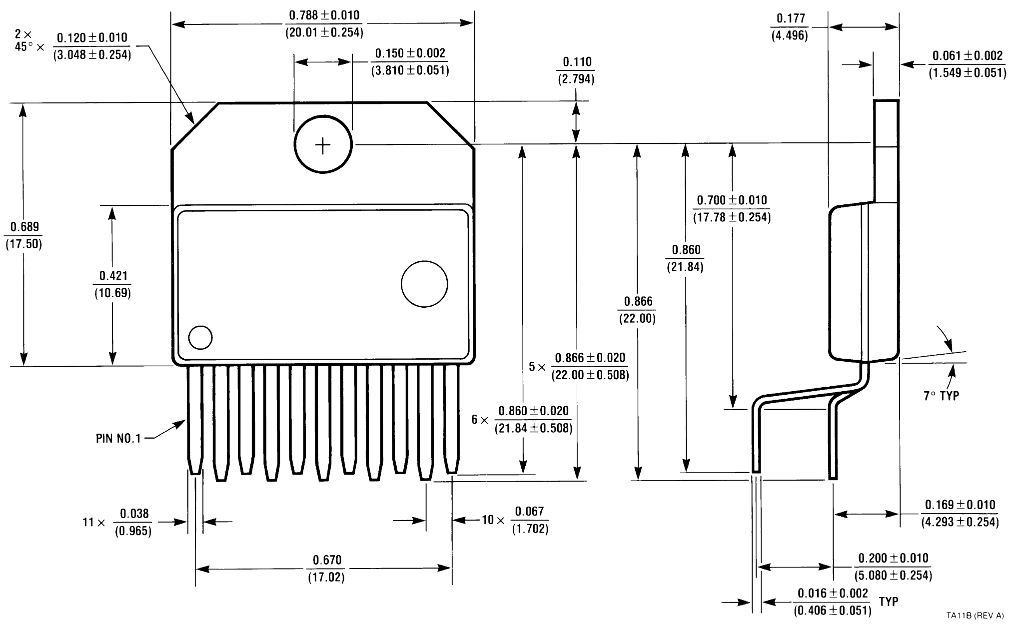


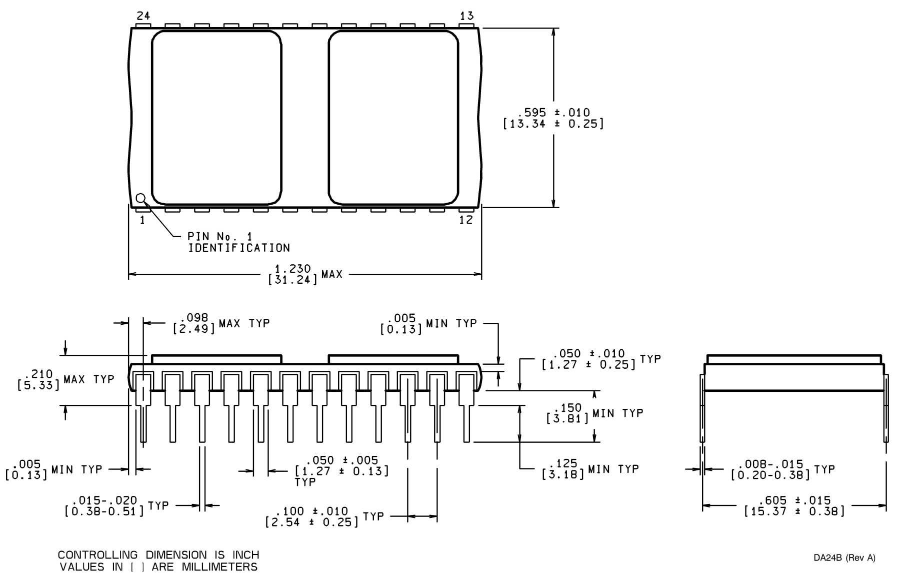
FIGURE 12. Motor Speed vs Control Voltage

Physical Dimensions inches (millimeters) unless otherwise noted



11-Lead TO-220 Power Package (T)
Order Number LMD18200T
NS Package Number TA11B

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



24-Lead Dual-in-Line Package
Order Number LMD18200-2D-QV
5962-9232501VXA
LMD18200-2D/883
5962-9232501MXA
NS Package Number DA24B

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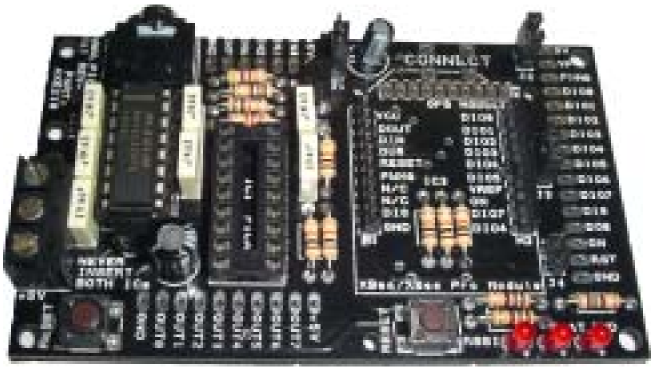
Fax: 81-3-5639-7507

PICAXE CONNECT (AXE210)

Description:



The AXE210 Connect board has been designed as a experimental project board for users wishing to learn how to interface a PICAXE chip to the Maxstream XBee module or a LocSense GPS module.

Use with XBee Wireless Modem

When considering a wireless PICAXE application most users will compare the 2.4GHz XBee modem units with the slightly lower-cost 433MHz RF modules.

Whilst the 433 modules are low cost and may be suitable for some very simple PICAXE applications, the XBee modules offer considerable advantages. The primary advantage is that the XBee modules are 'bi-directional'. Most budget 433 systems only transmit in one direction, so the transmitter has no idea whether the receiver is actually getting the data! The XBee modules transmit and receive in both directions, so you can easily test (at both ends) if the system is working correctly.

The second advantage is that of unique addressing. Each XBee unit has a unique serial number. This means two (or more) units can be set up to exclusively talk to each other, ignoring all signals from other modules. This is not easily achieved with 433 modules.

The third advantage is that the XBee module has in build 'data-packet' building and error-checking to ensure reliable data transmission.

Finally the XBee protocol allows for a number of 'channels'. By setting different units on different channels additional interference can be avoided.

Typical wireless networks could include

PC to remote PICAXE	e.g. remote control of robot/equipment
remote PICAXE to PC	e.g. data collection from a greenhouse
multiple remote PICAXEs to PC	e.g. a security system
remote PICAXE to remote PICAXE	e.g. different sensor modules of a weather station

The Maxstream XBee module is available from
www.techsupplies.co.uk XBE001

Use with a GPS module

The AXE210 Connect board can also be used to interface to the LocSense LS-40EB-3V or LS-41EB-3V GPS module, to provide a PICAXE to GPS project/experimentation board. It is not possible to use both XBee and GPS modules at the same time.

The LocSense LS-40EB-3V (or LS-41EB-3V) GPS module is available from
www.techsupplies.co.uk GPS001
Farnell 856-8316

An external active antenna for the module is also available (apply 3.3V to Ext Ant pin)
www.techsupplies.co.uk GPS002
Farnell 856-8359

It is recommended that 3 nylon support posts are also purchased, part GPS003.

Principles of Operation

The PICAXE ‘AXE210 Connect Board’ has been designed to support:
two XBee modes of use:

- as a computer to XBee wireless modem interface (MAX3232 chip inserted)
- as a PICAXE to XBee wireless modem interface (PICAXE chip inserted)

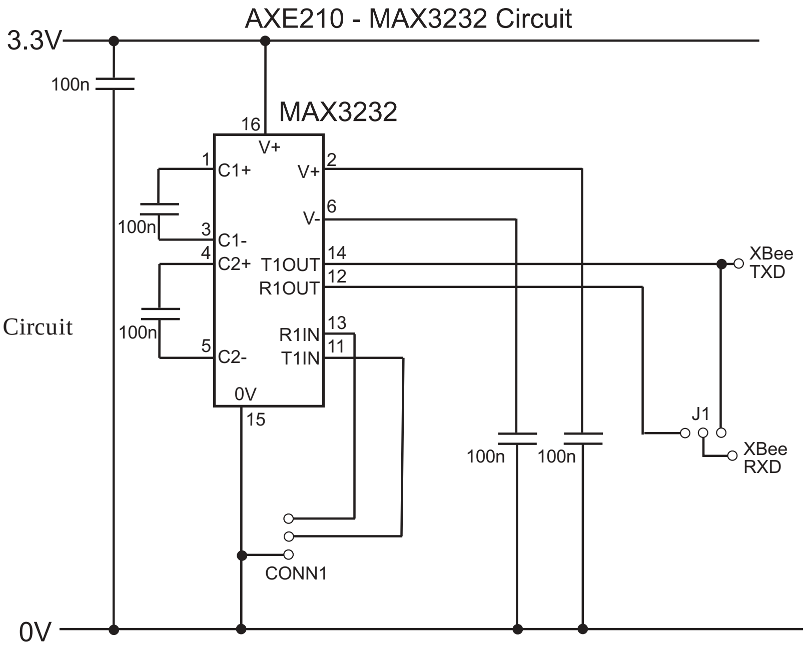
or two GPS modes of use:

- as a computer to GPS interface (MAX3232 chip inserted)
- as a PICAXE to GPS interface (PICAXE chip inserted)

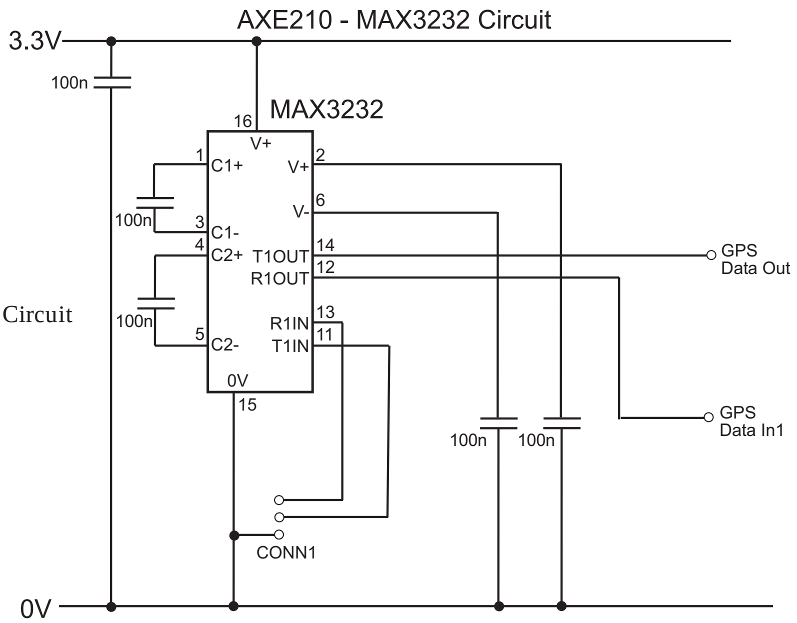
Important Note:
When used as a PICAXE interface a PICAXE chip is inserted in the 18 pin socket.
When used as a computer interface a MAX3232CPE chip is inserted in the 16 pin socket.
Never insert both the PICAXE chip and MAX3232 chip at the same time!

Circuit Diagrams (MAX3232 chip inserted)

XBee Circuit

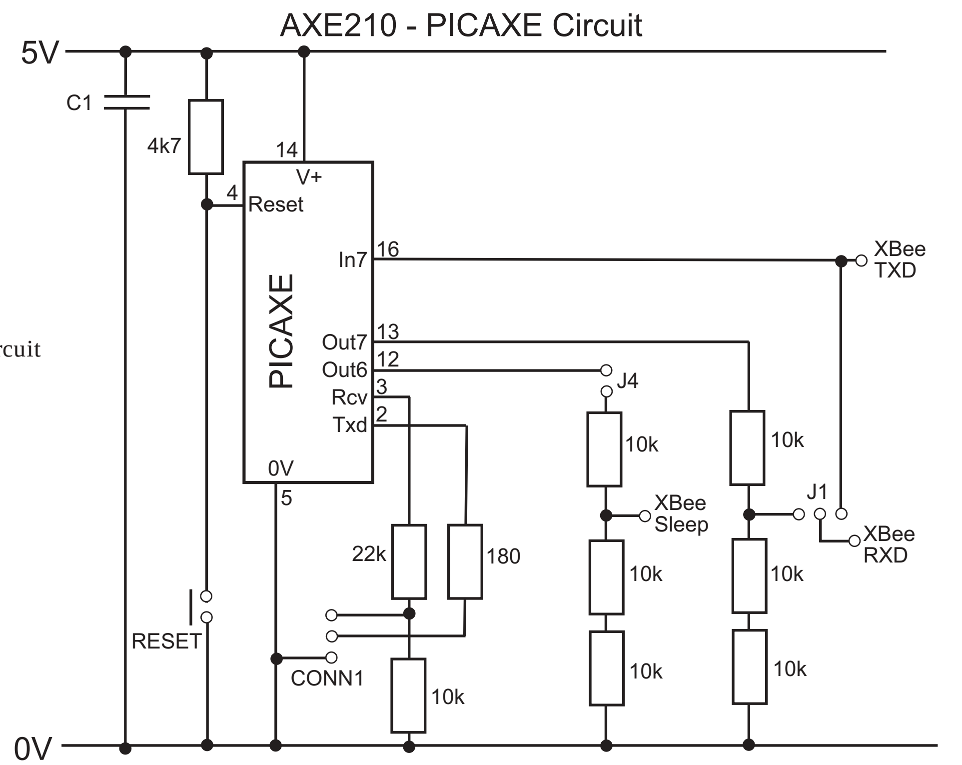


GPS Circuit

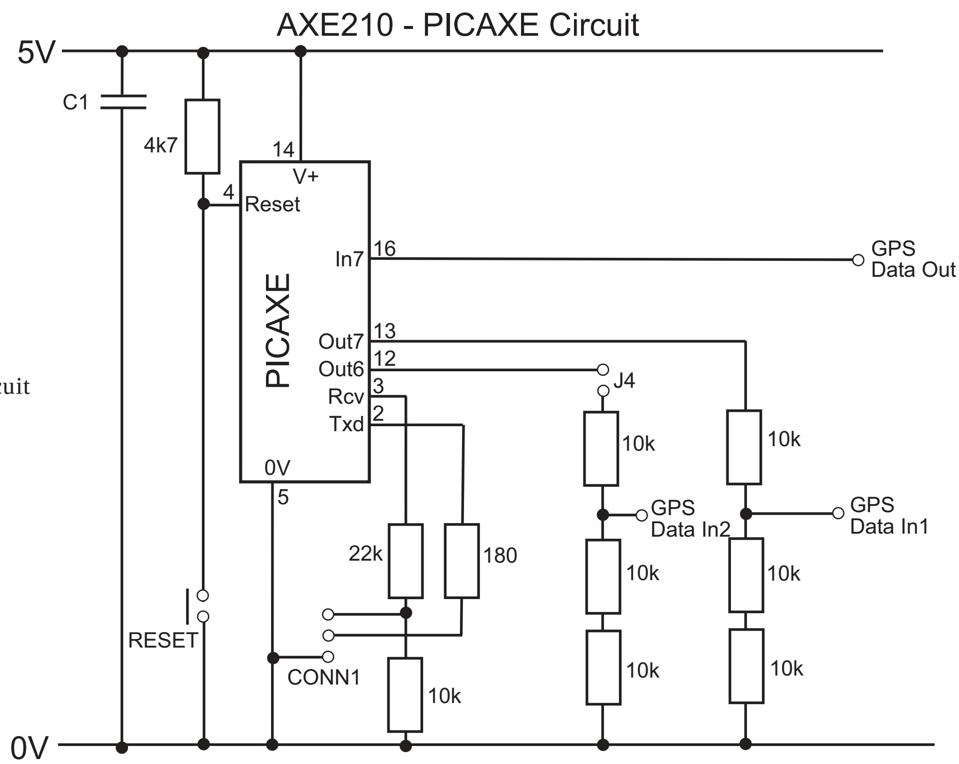


Circuit Diagrams (PICAXE chip inserted)

XBee Circuit



GPS Circuit



Power Supply

For experimentation work the AXE210 is designed to work from a regulated 9V or 5V DC supply. It can also be used with batteries (4.5V from 3xAA cell).

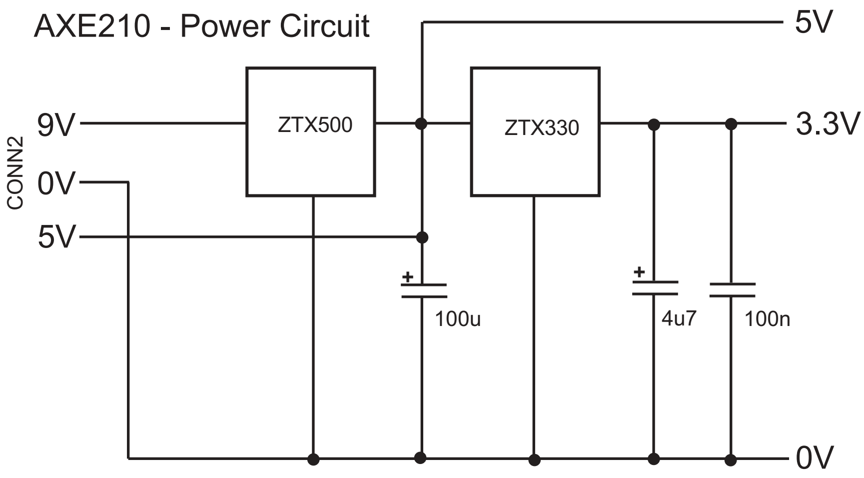
The ground (0V) connection is via the centre terminal of connector CONN2. A 9V regulated DC supply can be connected to the top terminal. Alternately a regulated 5V DC supply (or 4.5V battery pack) can be connected to the bottom terminal.

For ease of use whilst experimenting, the AXE210 contains both a 5V and 3.3V regulator. The PICAXE chip (and therefore also its output pins) operate at 5V. The XBee/GPS module operates at 3.3V. Therefore when connecting a PICAXE output pin to the module it is necessary to use a voltage divider circuit to step down the 5V PICAXE output to 3.3V (see circuit diagrams). Connecting 5V directly to the module will cause damage to the module.

The regulators are convenient for experimentation. However when powered by batteries, the 5V and 3.3V regulators are fairly inefficient and so will draw a few mA of standby current. This is not ideal for long term battery powered installations and so in this situtaion it is recommended that the end user considers using a permanent 3.3V supply and modifying the board to remove these regulators.

Connection of a higher voltage (e.g. a 9V PP3 battery) to the 5V input, or accidentally reversing the power supply connections, will damage the ICs and modules. These will then require replacing.

Note that the voltage regulators are rated to 200mA. This is suitable for the XBee or GPS modules. The MaxStream 'XBee Pro' module can draw currents greater than 200mA and so the regulator will need upgrading for use with this unit.



Serial Cable Connection

The Connect board has a 'stereo' type socket for connection of the PICAXE serial cable, part AXE026. This cable is used for PICAXE downloads when a PICAXE chip is connected, or direct computer communication with the XBee/GPS module when the MAX323 chip is fitted.
If you only have access to a USB port you will also require the USB adapter, part USB010.

LED indicators

The AXE210 board has three LED indicators.

XBEE Module

RSSI connects to the XBee RSSI (pin 6)
STATUS connects to the XBee ON/Sleep pin (pin 13)
IND connects via Jumper 3 to either XBee Associate (pin 15) or Transmit (pin 11)

RSSI indicates the XBee received signal strength
STATUS indicates whether the XBee module is active/sleeping
IND indicates whether the XBee module has associated with another module (Associate) or is transmitting data (Transmit).

GPS Module

RSSI connects to the GPS 1PPS pin (pin 6)
STATUS connects to the GPS PIO pin (pin 5)
IND not used

RSSI indicates the GPS status
STATUS indicates the UTC second (see GPS datasheet)

Jumper Function (XBee Module only)

The AXE210 board has 4 jumpers, labelled J1 to J4.
These jumpers should not be fitted or used with the GPS module.

The operation of each jumper when used with the XBee module is shown below.
The default position of each jumper is shown in **bold ***.

J1
Open - (not used)
Top * - Normal use
Bottom - Loopback test (XBee DOUT connected to DIN)

J2
Open - XBee Vref not connected
Fitted * - XBee Vref connected to 3.3V

J3
Open - IND. LED not connected
Top - IND. LED connected to XBee Transmit (DIO4)
Bottom * - IND. LED connected to XBee Associate (DIO5)

J4
Open * - PICAXE output 6 not connected
Fitted - PICAXE output 6 connected to XBee sleep pin (DI8)

Assembly instructions:

The AXE210 Connect board is a high quality plated through PCB and is therefore relatively straight forward to assemble. However a number of the electronic components are polarised, so please ensure these components are fitted the correct way around before soldering (see table below). Soldering experience is assumed.

Tools required (not supplied):

- Soldering iron and solder
- Side Cutters
- Small pair of pliers

Contents:

• PCB	1	AXE210 Connect PCB	
• IC1	1	18 pin IC socket	
• IC2	1	16 pin IC socket	
• R1	1	4k7 resistor (yellow violet red gold)	
• R2-5	4	180 resistor (brown grey brown gold)	
• R6-12	7	10k resistor (brown black orange gold)	
• R13	1	22k resistor (red red orange gold)	
• C7-8	7	100nF (104) polyester capacitor	
• C1	1	100uF electrolytic capacitor	*** + marked on PCB
• C9	1	4.7uF electrolytic capacitor	*** + marked on PCB
• LED1-3	3	3mm LED	*** flat marked on PCB
• RG1	1	ZTX500 5V regulator	*** curved side marked on PCB
• RG2	1	ZTX330 3V regulator	*** curved side marked on PCB
• S1-2	2	miniature push switch	
• CONN1	1	3.5mm stereo socket	
• CONN2	1	3 pin screw terminal block	
• J1-4	1	10 pin header (snap into 2x3 and 2x2)	
• J1-4	4	jumper links	
• H1,2	2	10 pin connector	
• BAT1	1	battery clip	
• BAT1	1	4.5V (3xAA) battery box	
• IC2	1	MAX3232CPE	*** pin 1 faces up

(*** denotes components which must be soldered the correct way around. See notes above).

Important Information for GPS Use:

The following extra information about assembly is important for GPS module users:

- Resistors R10, R11, R12 are not fitted.
- Headers J1, J2, J3, J4 are not fitted.
- Sockets H1 and H2 are not used. Instead solder one socket in the H3 position.
- The reset switch SW2 is soldered in the top position (over the word 'CONNECT') - if placed in the normal lower position it will be under the GPS module and so not accessible.
- The LEDS must be soldered at right angles to the PCB (see photo overleaf) to avoid contact with the GPS module.
- It is recommended that the GPS module is supported by three plastic support posts (available separately as part GPS003). However due to supply difficulties it has been necessary to substitute support posts that require a 2.5mm hole on the AXE210 PCB (the holes are currently drilled to 2mm). Therefore it is necessary for the user to carefully drill out the 3 support holes on the PCB to 2.5mm before using the support posts provided in kit GPS003.

Assembly Instructions:

1. Solder the resistors in position.
   Do not insert resistors R10-R12 if using the GPS module.
2. Solder the two IC sockets and push switch S1 in position.
3. XBee - solder switch S2 in position.
   GPS - solder switch over the word CONNECT (not in position S2)
4. Solder the capacitors and LEDs in position.
   If using the GPS module the LEDs should be inserted at right angles to the PCB.
4. Solder the RG1 (ZTX500) and RG2 (ZTX330) regulators in position.
5. Solder the CONN1 and CONN2 connectors in place. Ensure the stereo socket ‘clicks’ into position flat on the PCB prior to soldering.
6. XBee - Solder the headers H1, H2 and jumpers J1-4 in position.
   GPS - Solder the header H3 in position

Assembled board (XBee):

Assembled board (GPS):

XBee / PICAXE Connections

The PICAXE input pins are connected to solder pads at the top of the board.
The PICAXE output pins are connected to solder pads at the bottom of the board.
The XBee pins are connected to solder pads on the right hand side of the board.

PICAXE to XBee Connection

When a PICAXE chip is inserted in the 18pin socket the following connections are made:

PICAXE output7 is connected to the XBee transmit pin (via jumper J1).
PICAXE output6 is connected to the XBee sleep pin (via jumper J4)
PICAXE input7 is connected to the XBee receive pin.

Therefore data to be transmitted by the XBee module can be output via the PICAXE command serout e.g.

```
serout 7,T2400,(“Data”)
```

Data received by the XBee module can be processed by the PICAXE command serin e.g.

```
serin 7,T2400, b1
```

When configured for external pin activated sleep, the XBee module can be put to sleep / woken from sleep by the PICAXE commands high and low e.g.

```
high 6 / low 6
```

Note that hardware controlled sleep needs to be configured by the XBee Wizard – the default condition is no hardware sleep control. Jumper 4 must also be fitted.

Remember - never insert both the PICAXE chip and MAX3232 chip at the same time.

Computer to XBee Connection

When a MAX3232 chip is inserted in the 16pin socket the XBee module is connected (via the download cable) directly to the computer serial port. Therefore data can be transmitted from/received by the computer. The XBee module can also be configured via use of the XBee Wizard or configuration commands (see XBee datasheet XBE001.pdf and tutorial AXE210_XBEE.pdf for more details).

If your laptop computer does not have a conventional 9 pin serial port you will require the USB adapter (part USB010 – cost around £5).

For further information about using the XBee module with the PICAXE chip please see the separate XBee tutorial datasheet (datasheet AXE210_XBEE.pdf available from the datasheets section at www.picaxe.co.uk)

Remember -
never insert both the PICAXE chip and MAX3232 chip
at the same time.

GPS / PICAXE Connections

The PICAXE input pins are connected to solder pads at the top of the board.
The PICAXE output pins are connected to solder pads at the bottom of the board.
The GPS pins are connected to solder pads on the right hand side of the board.

Computer to GPS Connection

When a MAX3232 chip is inserted in the 16pin socket the GPS module is connected (via the download cable) directly to the computer serial port. Therefore data can be transmitted from/received by the computer. The GPS module can also be configured via use of the GPS Wizard or configuration commands (see GPS datasheet GPS001.pdf for more details).

If your laptop computer does not have a conventional 9 pin serial port you will require the USB adapter (part USB010 – cost around £5).

PICAXE to GPS Connection

When a PICAXE chip is inserted in the 18pin socket the following connections are made:

GPS Pin		AXE210 Function	AXE210 Solder Pad
1	Data Out	PICAXE Input 7	IN7
2	Data In	PICAXE Output 7	OUT7
3	Vcc	+3.3V	3V
4	GND	Ground	GND
5	PIO	Status LED	ON
6	1PPS	RSSI LED	PWM0
7	Reset	Reset Switch	RST
8	Data In 2	(optional) Output 6*	DI8
9	VBAT	-	DIO1
10	Ant Pwr	(link to 3V for active ant.)	DIO0

*Data In 2 to PICAXE connection is enabled by soldering a wire link in the J4 position and adding resistors R10, R11, R12 (all 10k) to the board.

For further information about using the GPS module with the PICAXE chip please see the separate GPS tutorial datasheet (datasheet AXE210_GPS.pdf, available from the datasheets section at www.picaxe.co.uk)

Please remember:
Never insert both the PICAXE chip and MAX3232 chip at the same time.

When using an ‘active’ antenna (eg GPS002) it is necessary to connect GPS ‘Ant Pwr’ to 3.3V (ie connect pads DIO0 & 3V together)

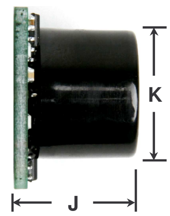
The GPS Module requires a clear view of the sky to operate (i.e. will not operate correctly in a building).

The GPS module may require 5 minutes or more after original power-up to locate the satellite signal (see GPS datasheet).

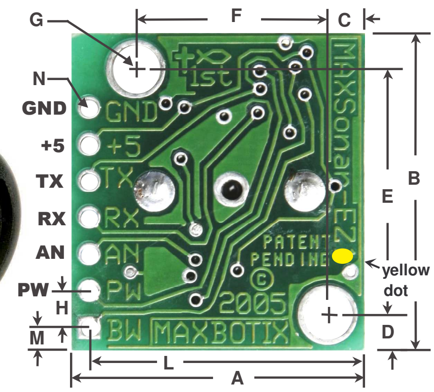
LV-MaxSonar®-EZ4™ High Performance Sonar Range Finder

RoHS COMPLIANT

With 2.5V - 5.5V power the LV-MaxSonar®-EZ4™ provides very short to long-range detection and ranging, in an incredibly small package. The LV-MaxSonar®-EZ4™ detects objects from 0-inches to 254-inches (6.45-meters) and provides sonar range information from 6-inches out to 254-inches with 1-inch resolution. Objects from 0-inches to 6-inches range as 6-inches. The interface output formats included are pulse width output, analog voltage output, and serial digital output.



approximately actual size



A	0.785"	19.9 mm		H	0.100"	2.54 mm
B	0.870"	22.1 mm		J	0.645"	16.4 mm
C	0.100"	2.54 mm		K	0.610"	15.5 mm
D	0.100"	2.54 mm		L	0.735"	18.7 mm
E	0.670"	17.0 mm		M	0.065"	1.7 mm
F	0.510"	12.6 mm		N	0.038" dia.	1.0 mm dia.
G	0.124" dia.	3.1 mm dia.		weight, 4.3 grams		

values are nominal

Features

- Continuously variable gain for beam control and side lobe suppression
- Object detection includes zero range objects
- 2.5V to 5.5V supply with 2mA typical current draw
- Readings can occur up to every 50mS, (20-Hz rate)
- Free run operation can continually measure and output range information
- Triggered operation provides the range reading as desired
- All interfaces are active simultaneously
  - Serial, 0 to Vcc
    - 9600Baud, 81N
  - Analog, (Vcc/512) / inch
  - Pulse width, (147uS/inch)
- Learns ringdown pattern when commanded to start ranging
- Designed for protected indoor environments
- Sensor operates at 42KHz
- High output square wave sensor drive (double Vcc)

Benefits

- Very low cost sonar ranger
- Reliable and stable range data
- Sensor dead zone virtually gone
- Lowest power ranger
- Quality beam characteristics
- Mounting holes provided on the circuit board
- Very low power ranger, excellent for multiple sensor or battery based systems
- Can be triggered externally or internally
- Sensor reports the range reading directly, frees up user processor
- Fast measurement cycle
- User can choose any of the three sensor outputs

Beam Characteristics

Many applications require a narrower beam or lower sensitivity than the LV-MaxSonar®-EZ1™. Consequently, MaxBotix® Inc., is offering, the EZ2™, EZ3™, & EZ4™ with progressively narrower beam angles allowing the sensor to match the application. Sample results for the LV-MaxSonar®-EZ4™ measured beam patterns are shown below on a 12-inch grid. The detection pattern is shown for;

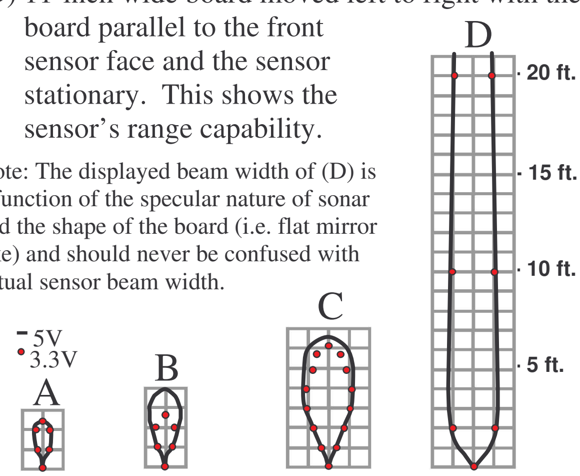
(A) 0.25-inch diameter dowel, note the narrow beam for close small objects,

(B) 1-inch diameter dowel, note the long narrow detection pattern,

(C) 3.25-inch diameter rod, note the long controlled detection pattern,

(D) 11-inch wide board moved left to right with the board parallel to the front sensor face and the sensor stationary. This shows the sensor's range capability.

Note: The displayed beam width of (D) is a function of the specular nature of sonar and the shape of the board (i.e. flat mirror like) and should never be confused with actual sensor beam width.



beam characteristics are approximate

8757 East Chimney Spring Drive, Tucson AZ, 85747 USA
4613 County Road 8, Brainerd, MN 56401 USA
Email: info@maxbotix.com Web: www.maxbotix.com

LV-MaxSonar®-EZ4™ Pin Out

GND – Return for the DC power supply. GND (& Vcc) must be ripple and noise free for best operation.

+5V – Vcc – Operates on 2.5V - 5.5V. Recommended current capability of 3mA for 5V, and 2mA for 3V.

TX – When the *BW is open or held low, the TX output delivers asynchronous serial with an RS232 format, except voltages are 0-Vcc. The output is an ASCII capital “R”, followed by three ASCII character digits representing the range in inches up to a maximum of 255, followed by a carriage return (ASCII 13). The baud rate is 9600, 8 bits, no parity, with one stop bit. Although the voltage of 0-Vcc is outside the RS232 standard, most RS232 devices have sufficient margin to read 0-Vcc serial data. If standard voltage level RS232 is desired, invert, and connect an RS232 converter such as a MAX232. When BW pin is held high the TX output sends a single pulse, suitable for low noise chaining. (no serial data).

RX – This pin is internally pulled high. The EZ4™ will continually measure range and output if RX data is left unconnected or held high. If held low the EZ4™ will stop ranging. Bring high for 20uS or more to command a range reading.

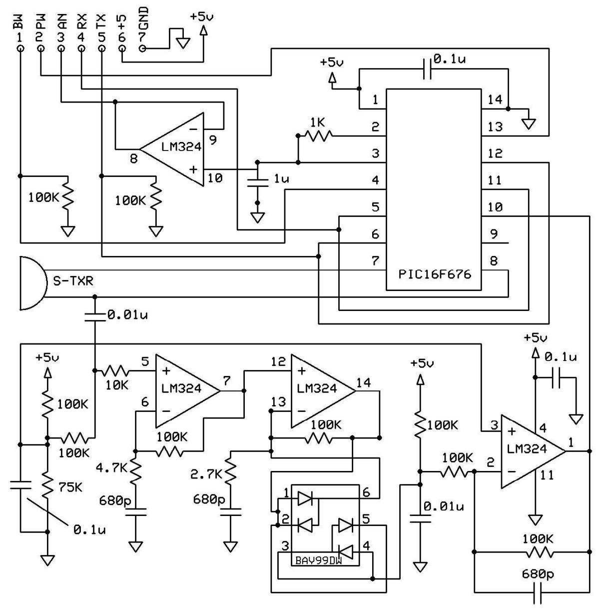
AN – Outputs analog voltage with a scaling factor of (Vcc/512) per inch. A supply of 5V yields ~9.8mV/in. and 3.3V yields ~6.4mV/in. The output is buffered and corresponds to the most recent range data.

PW – This pin outputs a pulse width representation of range. The distance can be calculated using the scale factor of 147uS per inch.

BW – *Leave open or hold low for serial output on the TX output. When BW pin is held high the TX output sends a pulse (instead of serial data), suitable for low noise chaining.

LV-MaxSonar®-EZ4™ Circuit

The LV-MaxSonar®-EZ4™ sensor functions using active components consisting of an LM324, a diode array, a PIC16F676, together with a variety of passive components.



LV-MaxSonar®-EZ4™ Timing Description

250mS after power-up, the LV-MaxSonar®-EZ4™ is ready to accept the RX command. If the RX pin is left open or held high, the sensor will first run a calibration cycle (49mS), and then it will take a range reading (49mS). Therefore, the first reading will take ~100mS. Subsequent readings will take 49mS. The LV-MaxSonar®-EZ4™ checks the RX pin at the end of every cycle. Range data can be acquired once every 49mS.

Each 49mS period starts by the RX being high or open, after which the LV-MaxSonar®-EZ4™ sends thirteen 42KHz waves, after which the pulse width pin (PW) is set high. When a target is detected the PW pin is pulled low. The PW pin is high for up to 37.5mS if no target is detected. The remainder of the 49mS time (less 4.7mS) is spent adjusting the analog voltage to the correct level. When a long distance is measured immediately after a short distance reading, the analog voltage may not reach the exact level within one read cycle. During the last 4.7mS, the serial data is sent. The LV-MaxSonar®-EZ4™ timing is factory calibrated to one percent at five volts, and in use is better than two percent. In addition, operation at 3.3V typically causes the objects range, to be reported, one to two percent further than actual.

LV-MaxSonar®-EZ4™ General Power-Up Instruction

Each time after the LV-MaxSonar®-EZ4™ is powered up, it will calibrate during its first read cycle. The sensor uses this stored information to range a close object. It is important that objects not be close to the sensor during this calibration cycle. The best sensitivity is obtained when it is clear for fourteen inches, but good results are common when clear for at least seven inches. If an object is too close during the calibration cycle, the sensor may then ignore objects at that distance.

The LV-MaxSonar®-EZ4™ does not use the calibration data to temperature compensate for range, but instead to compensate for the sensor ringdown pattern. If the temperature, humidity, or applied voltage changes during operation, the sensor may require recalibration to reacquire the ringdown pattern. Unless recalibrated, if the temperature increases, the sensor is more likely to have false close readings. If the temperature decreases, the sensor is more likely to have reduced up close sensitivity. To recalibrate the LV-MaxSonar®-EZ4™, cycle power, then command a read cycle.

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LV-EZ4™ • v3.0c • 01/2007 • patent pending

RoHS COMPLIANT

Description

The **MAE3** is an absolute magnetic kit encoder that provides shaft position information over 360 ° of rotation with no stops or gaps. This magnetic encoder is designed to easily mount to, and dismount from, an existing shaft to provide digital feedback information. The **MAE3** is available with an analog or a pulse width modulated (PWM) digital output.

Analog output provides an analog voltage that is proportional to the absolute shaft position. Analog output is only available in 10-bit resolution.

PWM output provides a pulse width duty cycle that is proportional to the absolute shaft position. PWM output is available in 10-bit and 12-bit resolutions. While the accuracy is the same for both encoders the 12-bit version provides higher resolution.

The **MAE3** consists of three components: base, push-on magnetic hub, and encoder body. The base will accommodate 0.750", 1.280" and 1.812" mounting bolt circles. No tools are needed for the push-on, collet gripping hub. The hub mounts to a standard shaft in seconds and provides a simple and reliable means of securing the magnet to the shaft.

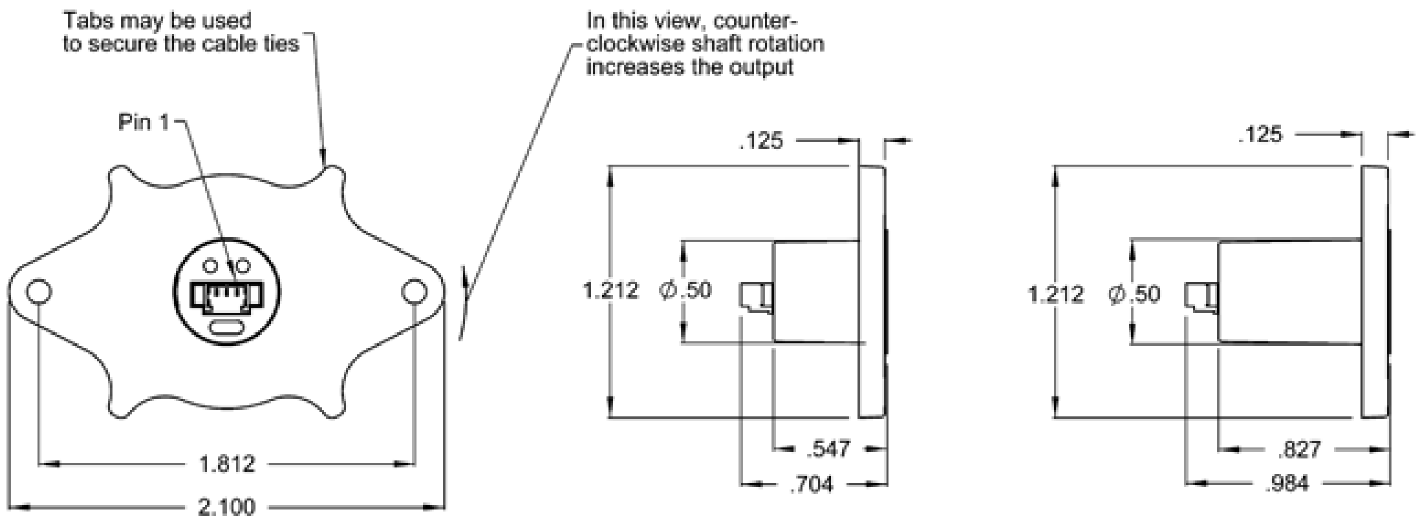
Two 4-40 pan head screws secure the base and encoder body to any flat surface. If desired, the encoder can be powered up and rotated by hand to any desired absolute position before the screws are tightened.

Connecting to the **MAE3** is simple. The 3-pin, high retention, snap-in 1.25mm pitch polarized connector provides for +5V, output, and ground.

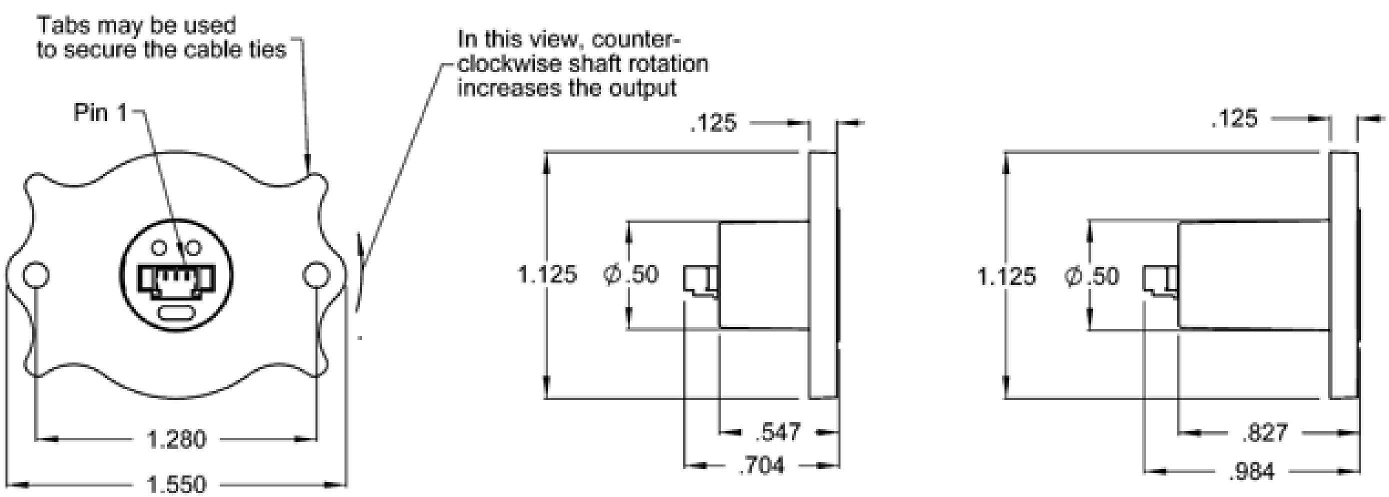
Features

- Quick, simple assembly and disassembly
- -40C to +125C operating temperature
- Accepts .010" axial shaft play
- Mounts to 0.750", 1.280" and 1.812" bolt circles
- Fits shaft diameters from .125" to .250" or 2mm to 6mm
- 10-bit Analog output - 2.6 kHz sampling rate
- 10-bit PWM output - 1024 positions per revolution, 1 kHz
- 12-bit PWM output - 4096 positions per revolution, 250 Hz

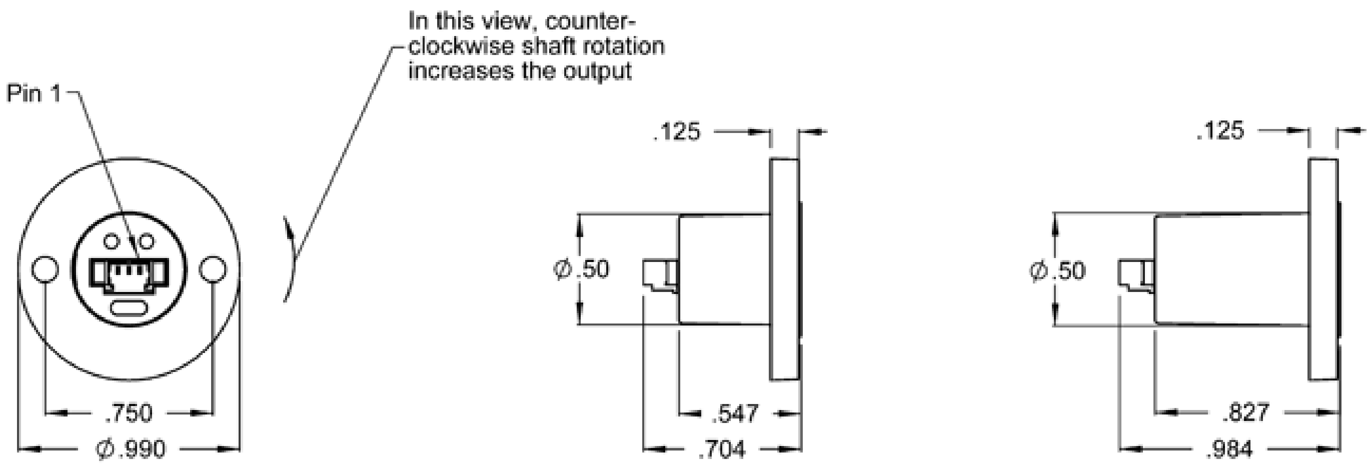
Size 18 Bolt Circle



Size 12 Bolt Circle



Size 7 Bolt Circle



Mechanical

Parameter	Value	Units
Moment of Inertia	8.49 x 10^-7	oz-in-s²
Mounting Screw Size (pan head)	4-40 x 1/4"	-
Required Shaft Length **Size 220 Shaft Length**-option **Size 500 Shaft Length**-option	 0.220 (+0.04 / -0.02) 0.500 (+0.04 / -0.02)	 in. in.
Base to Mounting Surface Torque	4 - 6	in.-lbs.
Shaft diameter tolerance, relative to nominal	-0.0001 to -0.0006	in.

Absolute Maximum Ratings

Parameter	Max. Value	Units
Vibration (5Hz to 2kHz)	20	G
Shaft Axial Play	±0.025	in.
Shaft Eccentricity Plus Radial Play	0.004	in.
Acceleration	250,000	rad/sec²

Note that radial play translates directly to position inaccuracy.

Electrical

Parameter	Min.	Typ.	Max.	Units

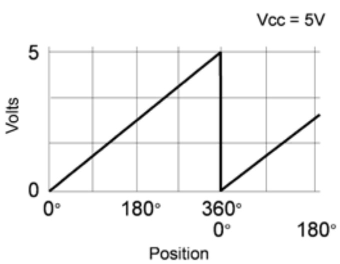
RoHS COMPLIANT

Power Supply	4.5	5.0	5.5	Volts
Supply Current	-	16	20	mA
Power-up Time	-	-	50	mS

Environmental

Parameter	Value
Operating Temperature	-40C to +125C
Storage Temperature	-55C to +125C
ESD	± 2 kV max.
Humidity Non-condensing	5% to 85%

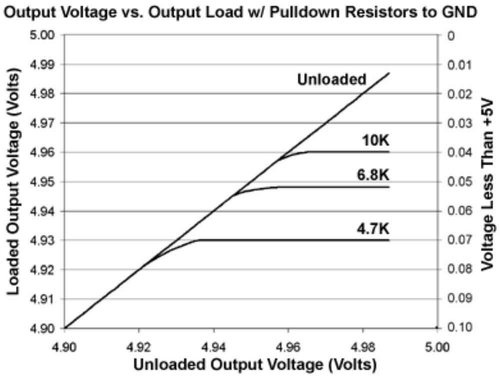
Analog Output Operation

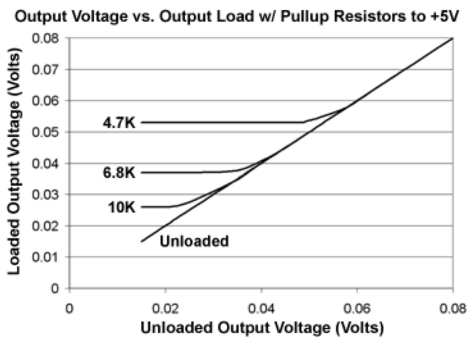


Analog output is only available in 10-bit resolution. The analog output voltage is ratiometric to the power supply voltage and will typically swing within 15 millivolts of the power supply rails with no output load. This non-linearity near the rails increases with increasing output loads. For this reason, the output load impedance should be $\geq 4.7k\Omega$ and less than 100pF. The graphs below show the typical output levels for various output loads when powered by a 5V supply.

Parameter	Min.	Typ.	Max.	Units
Position Sampling Rate	2.35	2.61	2.87	kHz
Propagation Delay	-	-	384	?S
Analog Output Voltage Maximum	-	4.987	-	Volts*
Analog Output Voltage Minimum	-	0.015	-	Volts*
Output Short Circuit Sink Current	-	32	50	mA**
Output Short Circuit Source Current	-	36	66	mA**
Output Noise	160	220	490	μ Vrms**
Output Transition Noise	-	0.06	-	Degrees RMS***

* With no output load. See graphs below.
** Continuous short to +5V or ground will not damage the **MAE3**.
*** Transition noise is defined as the jitter in the transition between two adjacent position steps.





PWM Output Operation

The magnetic sensor chip in the **MAE3** has an on-chip RC oscillator which is factory trimmed to 5% accuracy at room temperature (10% over full temperature range). This tolerance influences the sampling rate and the pulse width of the PWM output. If only the PWM pulse width t on is used to measure the angle, the resulting value also has this timing tolerance. However, this tolerance can be cancelled by measuring both t on and t off and calculating the angle from the duty cycle. Accuracy including non-linearity is within 0.5 deg. at 25C, but may increase to 0.9 deg. at high temperatures.

Parameter	Min.	Typ.	Max.	Units
PWM Frequency (-40C to 125C)				
10-bit	0.877	0.975	1.072	kHz
12-bit	220	244	268	Hz
Minimum Pulse Width				
10-bit	0.95	1.00	1.05	?S
12-bit	0.95	1.00	1.05	?S
Maximum Pulse Width				
10-bit	974	1025	1076	?S
12-bit	3892	4097	4302	?S
Internal Sampling Rate				
10-bit	9.38	10.42	11.46	kHz
12-bit	2.35	2.61	2.87	kHz

Parameter	Min.	Typ.	Max.	Units
Propagation Delay				
10-bit	-	-	48	?S
12-bit	-	-	384	?S
High Level Output Voltage (VOH: @4mA Source)	Vcc -0.5	-	-	V*
Low Level Output Voltage (VOL: @4mA Sink)	-	-	0.4	V*

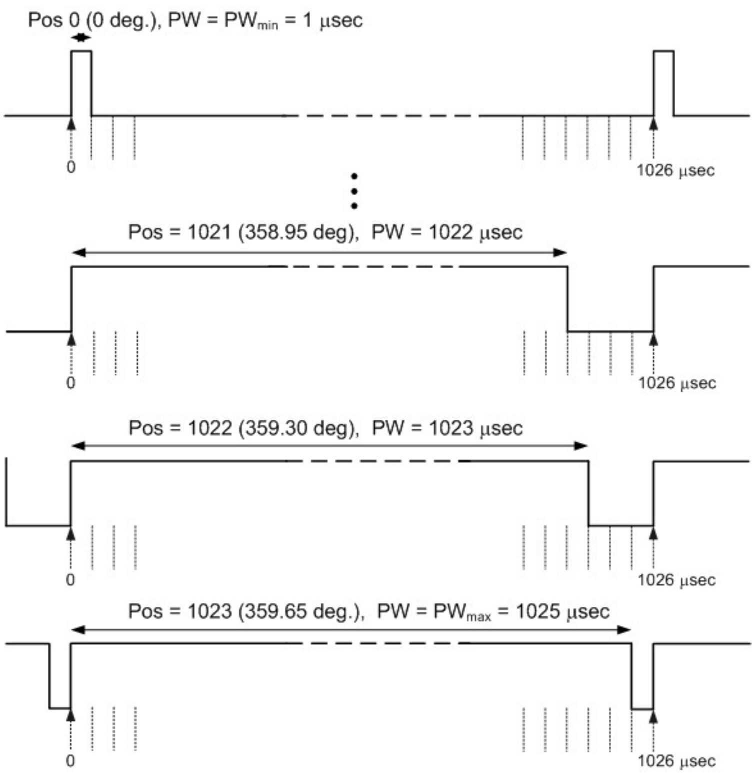
* Continuous short to +5V or ground will not damage the **MAE3**.

10-bit PWM:

x = ((t on * 1026) / (t on+ t off)) -1

If x <= 1022, then Position = x

If x = 1024 then Position = 1023

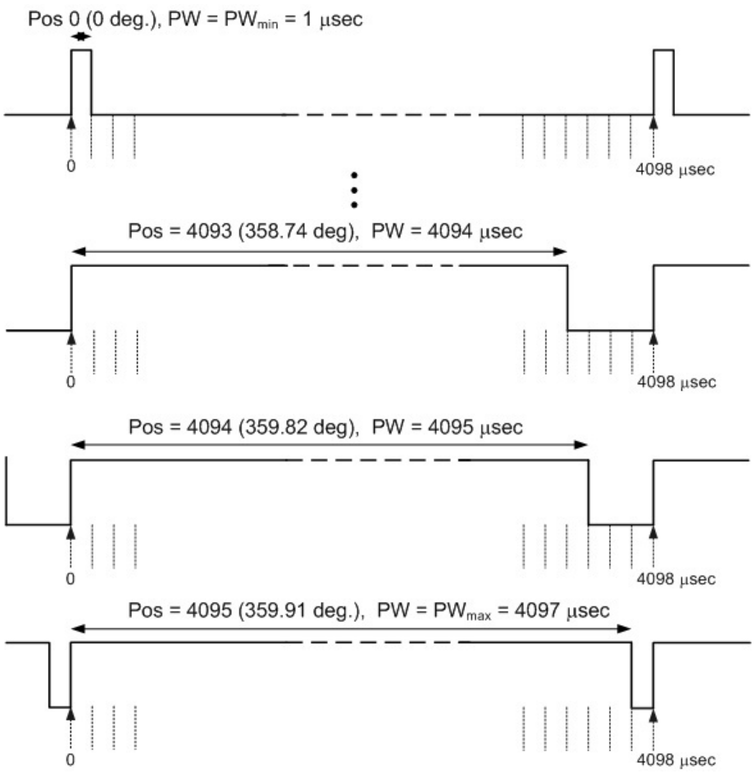


12-bit PWM:

$x = ((t_{on} * 4098) / (t_{on} + t_{off})) - 1$

If x <= 4094, then Position = x

If x = 4096 then Position = 4095



Pin-outs

Analog Output (MAE3-A):

Pin	Name	Description
1	5	+5VDC power
2	A	Analog output
3	G	Ground

PWM Output (MAE3-P10, MAE3-P12):

Pin	Name	Description
1	5	+5VDC power
2	A	PWM output

Pin	Name	Description
3	G	Ground

Accessories

Screws

Part #:	SCREW-440-250-PH
Description:	4-40 x 1/4" Pan head screw
Quantity Required for Mounting	2 per encoder

RoHS COMPLIANT

Ordering Information

MAE3 - [ ] - [ ] - [ ] - [ ] - [ ]

Interface	Bore	Shaft Length	Bolt Circle	Packaging
A10 = *10-Bit Analog*	079 = *2mm*	220 = *0.220"*	7 = *0.750"*	B = *Encoder components packaged in bulk.*
P10 = *10-Bit PWM*	091 = *2.3mm*	500 = *0.500"*	12 = *1.280"*	1 = *Each encoder packaged individually*
P12 = *12-Bit PWM*	098 = *2.5mm*		18 = *1.812"*	
	118 = *3mm*			
	125 = *1/8"*			
	156 = *5/32"*			
	157 = *4mm*			
	188 = *3/16"*			
	197 = *5mm*			
	236 = *6mm*			
	250 = *1/4"*			

Notes

- Cables and connectors are not included and must be ordered separately.
- US Digital warrants its products against defects in materials and workmanship for two years. See complete warranty for details.

Pricing

Quantity	Price
1	$43.50
10	$32.85
50	$20.13
100	$16.40

- Add 17% per unit for **Interface** of 12-Bit PWM
- Add $3.00 per unit for **Packaging** of Each encoder packaged individually

RoHS COMPLIANT

Description

The **MA3** is a miniature rotary absolute shaft encoder that reports the shaft position over 360° with no stops or gaps. The **MA3** is available with an analog or a pulse width modulated (PWM) digital output.

Analog output provides an analog voltage that is proportional to the absolute shaft position. Analog output is only available in 10-bit resolution.

PWM output provides a pulse width duty cycle that is proportional to the absolute shaft position. PWM output is available in 10-bit and 12-bit resolutions. While the accuracy is the same for both encoders, the 12-bit version provides higher resolution.

Three shaft torque versions are available. The standard torque version has a sleeve bushing lubricated with a viscous motion control gel to provide torque and feel that is ideal for front panel human interface applications.

The no torque added option has a sleeve bushing and a low viscosity lubricant (that does not intentionally add torque) for low RPM applications where a small amount of torque is acceptable.

The ball bearing version uses miniature precision ball bearings that are suitable for high speed and ultra low torque applications. The shaft diameter for ball bearing version option is 1/8" rather than 1/4".

Connecting to the **MA3** is simple. The 3-pin high retention snap-in 1.25mm pitch polarized connector provides for +5V, output, and ground.

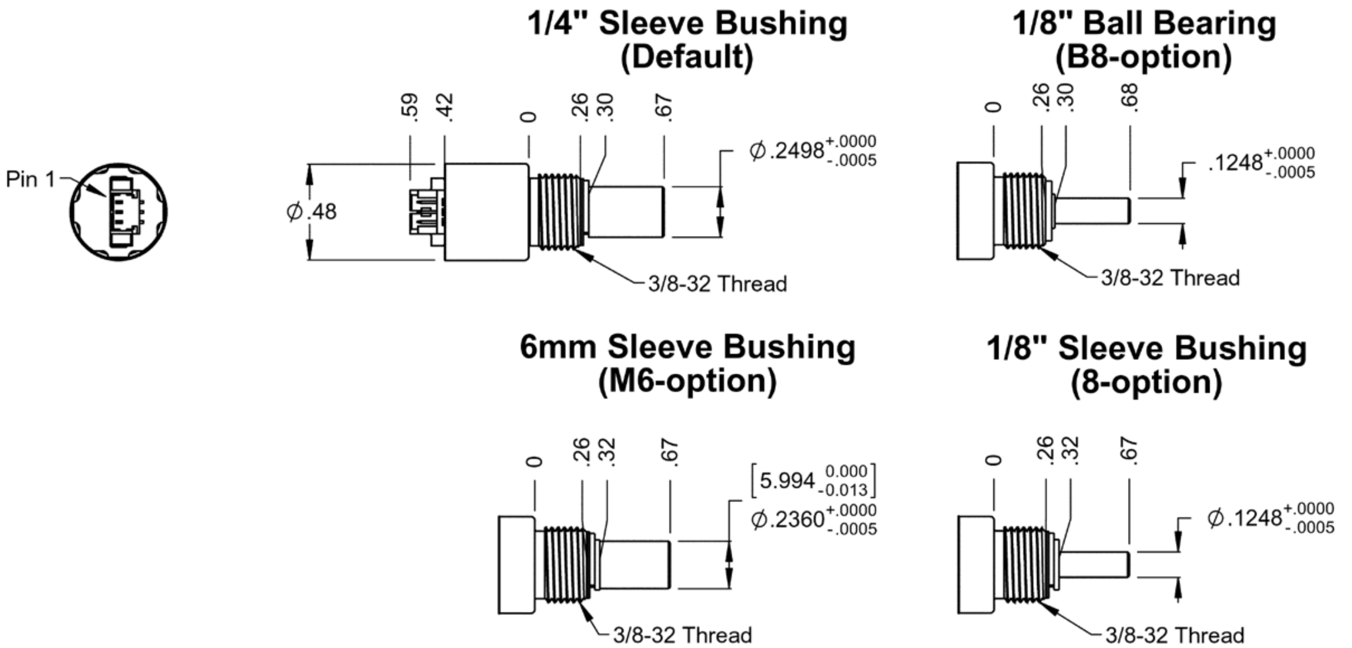
Features

- Patent pending
- Miniature size (0.48" diameter)
- Non-contacting magnetic single chip sensing technology
- -40C to 125C. operating temperature range
- 10-bit Analog output - 2.6 kHz sampling rate
- 10-bit PWM output - 1024 positions per revolution, 1 kHz
- 12-bit PWM output - 4096 positions per revolution, 250 Hz

Order Using #MA3 starting at $36.00 per unit

Configure online at
usdigital.com/products/ma3

Mechanical Drawing



Mechanical

Specification	Sleeve Bushing	Ball Bearing
Moment of Inertia	4.1 x 10^-6 oz-in-s²	4.1 x 10^-6 oz-in-s²
Angular Accuracy	<0.5 deg. @ 25C	<0.5 deg. @ 25C
Angular Accuracy Over Temperature	<0.9 deg. @ -40 to 125C	<0.9 deg. @ -40 to 125C
Shaft Speed	100 RPM max. continuous	15,000 RPM max. continuous
Acceleration	10,000 rad/sec²	250,000 rad/sec²
Vibration	20G. 5Hz to 2kHz	20G. 5Hz to 2kHz
Shaft Torque	0.5 ± 0.2 in. oz. (D - torque option) 0.3 in. oz. max. (N - torque option)	0.05 in. oz. max.
Shaft Loading	2 lbs. max. dynamic* 20 lbs. max. static	1 lb. max.
Bearing Life	-	(40/P)³ = life in millions of revs. where P = radial load in pounds
Weight	0.46 oz.	0.37 oz.
Shaft Runout	0.0015 T.I.R. max.	0.0015 T.I.R. max.

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* When a pulley, gear, or friction wheel drives the shaft, the Ball Bearing option is recommended instead of the Sleeve Bushing.

Environmental

Parameter	Dimension
Operating Temperature	-40C to +125C
Storage Temperature	-55C to +125C
ESD	2 kV minimum
Humidity Non-condensing	5% to 85%

Mounting

Parameter	Dimension
Hole Diameter	0.375" +0.005 / -0.0
Panel Thickness	0.125" max.
Panel Nut Max. Torque	20 in.-lbs.

Materials

Parameter	Dimension
Shaft	Stainless
Bushing	Brass

Magnetic Field Crosstalk

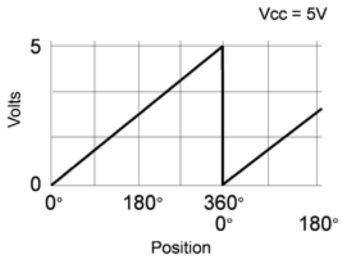
The MA3 absolute encoder contains a small internal magnet, mounted on the end of the shaft that generates a weak magnetic field extending outside the housing of each encoder. If two MA3 units are to be installed closer than 1 inch apart (measured between the center of both shafts), a magnetic shield, such as a small steel plate should be installed in between to prevent one encoder from causing small changes in reported position through magnetic field cross-talk.

Electrical

Parameter	Min.	Typ.	Max.	Units
Power Supply	4.5	5.0	5.5	Volts
Supply Current	-	16	20	mA

Parameter	Min.	Typ.	Max.	Units
Power-up Time	-	-	50	mS

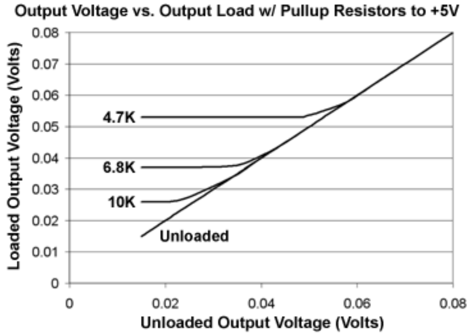
Analog Output Operation

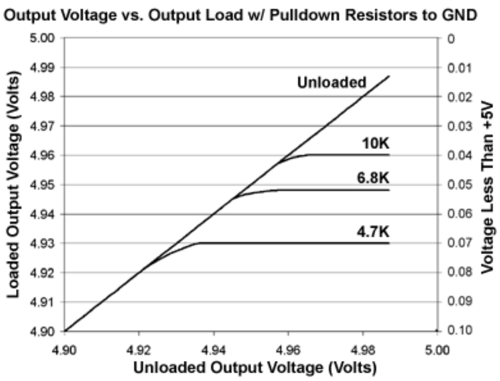


Analog output is only available in 10-bit resolution. The analog output voltage is ratiometric to the power supply voltage and will typically swing within 15 millivolts of the power supply rails with no output load. This non-linearity near the rails increases with increasing output loads. For this reason, the output load impedance should be $\geq$ 4.7kΩ and less than 100pF. The graphs below show the typical output levels for various output loads when powered by a 5V supply.

Parameter	Min.	Typ.	Max.	Units
Position Sampling Rate	2.35	2.61	2.87	kHz
Propagation Delay	-	-	384	?S
Analog Output Voltage Maximum	-	4.987	-	Volts*
Analog Output Voltage Minimum	-	0.015	-	Volts*
Output Short Circuit Sink Current	-	32	50	mA**
Output Short Circuit Source Current	-	36	66	mA**
Output Noise	160	220	490	Vrms**
Output Transition Noise	-	0.06	-	Degrees RMS***

* With no output load. See graphs below.
** Continuous short to +5V or ground will not damage the MA3.
*** Transition noise is defined as the jitter in the transition between two adjacent position steps.





PWM Output Operation

The magnetic sensor chip in the MA3 has an on-chip RC oscillator which is factory trimmed to 5% accuracy at room temperature (10% over full temperature range). This tolerance influences the sampling rate and the pulse width of the PWM output. If only the PWM pulse width t on is used to measure the angle, the resulting value also has this timing tolerance. However, this tolerance can be cancelled by measuring both ton and toff and calculating the angle from the duty cycle. Angular accuracy including non-linearity is within 0.5 deg. at 25C, but may increase to 0.9 deg. at high temperatures.

Parameter	Min.	Typ.	Max.	Units
PWM Frequency (-40C to 125C)	0.878	0.976	1.074	kHz
10-bit	220	244	268	Hz
12-bit				
Minimum Pulse Width	0.95	1.00	1.05	?S
10-bit	0.95	1.00	1.05	?S
12-bit				
Maximum Pulse Width	973	1024	1075	?S
10-bit	3891	4096	4301	?S
12-bit				

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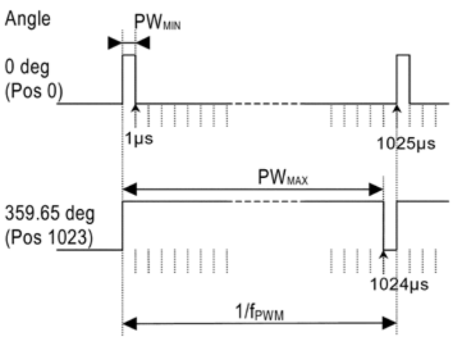
Parameter	Min.	Typ.	Max.	Units
Internal Sampling Rate	9.38	10.42	11.46	kHz
10-bit	2.35	2.61	2.87	kHz
12-bit				
Propagation	-	-	48	?S
10-bit	-	-	384	?S
12-bit				
High Level Output Voltage (V OH: @4mA Source)	Vcc -0.5	-	-	V*
Low Level Output Voltage (V OL: @4mA Sink)	-	-	0.4	V*

* Continuous short to +5V or ground will not damage the MA3.

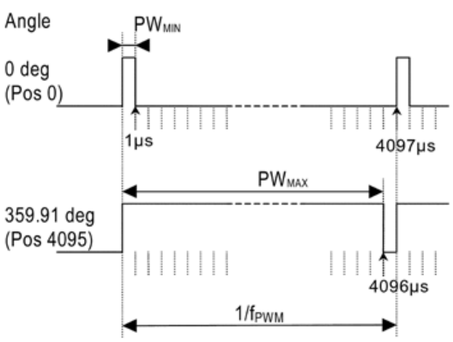
10-bit PWM:

Position = ((t on * 1025) / (t on+ t off)) -1



12-bit PWM:

Position = ((t on * 4097) / (t on+ t off)) -1



Pin-outs

Order Using #MA3 starting at $36.00 per unit

Configure online at
usdigital.com/products/ma3

Analog Output (MA3-A):

Pin	Name	Description
1	5	+5VDC power
2	A	Analog output
3	G	Ground

PWM Output (MA3-P10, MA3-P12):

Pin	Name	Description
1	5	+5VDC power
2	A	PWM output
3	G	Ground

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Ordering Information

MA3 - [ ] - [ ] - [ ]

Interface	Shaft	Torque
A10 = *10-Bit Analog*	125 = *1/8" dia. sleeve bushing (standard torque)*	D = *Default*
P10 = *10-Bit PWM*	236 = *6mm dia. sleeve bushing (standard torque)*	B = *1/8" dia. ball bearing*
P12 = *12-Bit PWM*	250 = *1/4"*	N = *Replaces standard torque with no torque added*

Rules

- Torque must be something other than B when Shaft is 125

Notes

- Cables and connectors are not included and must be ordered separately.
- US Digital warrants its products against defects in materials and workmanship for two years. See complete warranty for details.

Pricing

Quantity	Price
1	$36.00
10	$31.54
50	$27.78
100	$23.89

- Add 17% per unit for **Interface** of 12-Bit PWM
- Add $1.00 per unit for **Shaft** of 6mm dia. sleeve bushing (standard torque)
- Add $5.80 per unit for **Torque** of 1/8" dia. ball bearing

Order Using #MA3 starting at $36.00 per unit

Configure online at
usdigital.com/products/ma3

Reformer Tube Internal Diameter Measuring System

User Manual:

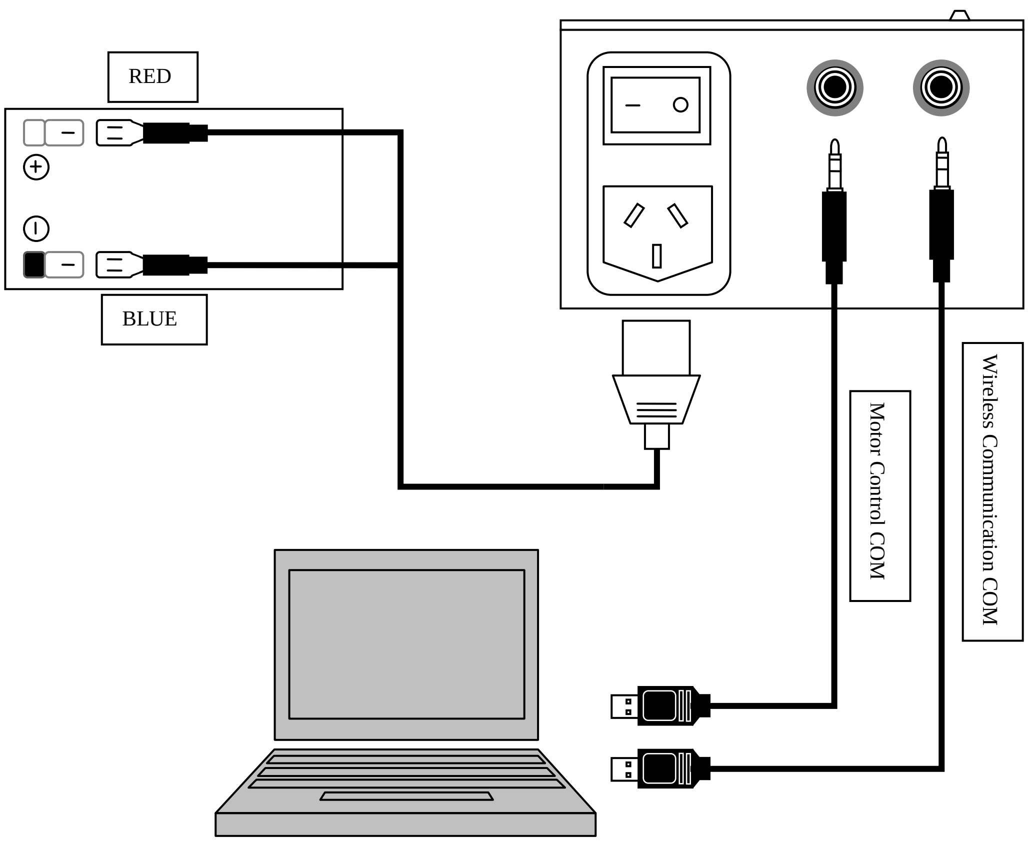
Contents

Getting Started:

Step 1: Connection

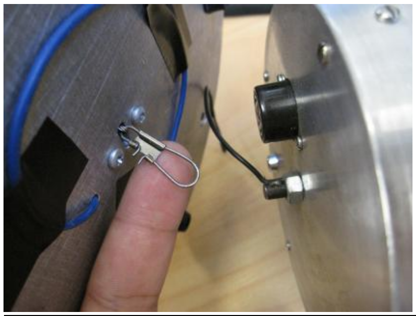
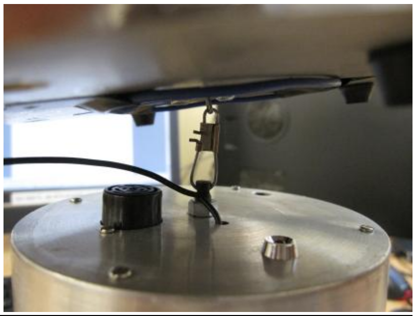
These connections are required in allowing the device to communicate with the Operating Program. In using the system the following three connections must be made:

Motor Control Cable	The Motor Control cable allows commands generated by the Operator Software to be transferred to the system Micro Controller.
Data Cable	The Data cable transfers data received from the sensory module to the Operator Software via USB port.
12V Power Supply	The system requires 12V~15.5V supply voltage to operate.



The USB-Stereo cable can be acquired from the PICAXE official website (AXE027). A USB Driver must be installed onto the computer to be used which can also can be downloaded from the PicAxe website.

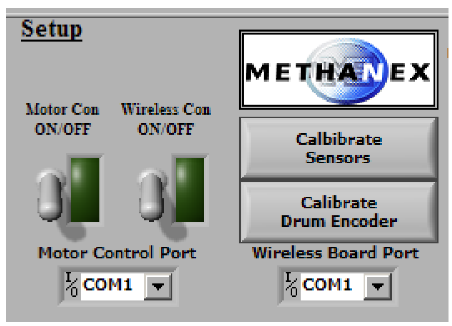
Step 2: Setting up the System on Reformer

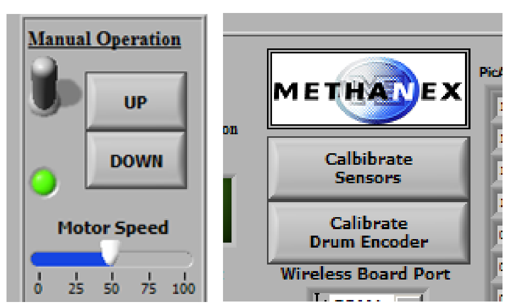
1) Hook the sensory unit to the hook attached to the wire extending out of the base of the Motor Module then Turn on the Sensory module by flicking the red power button. The Red LED will start flashing.


2) Insert the sensory module into the reformer tube (For smaller tubes the encoder shafts maybe required to be retracted by applying pressure with fingers to assist this process.) and firmly rest the device on the tube. Be sure to place the device so that the wire extends near the center of the Tube without making contact with the internal walls.

3) Turn on the Device via power button near the power cable. Wait till the middle Green LED on, indicating that the radio communication has been successfully made between the two modules.



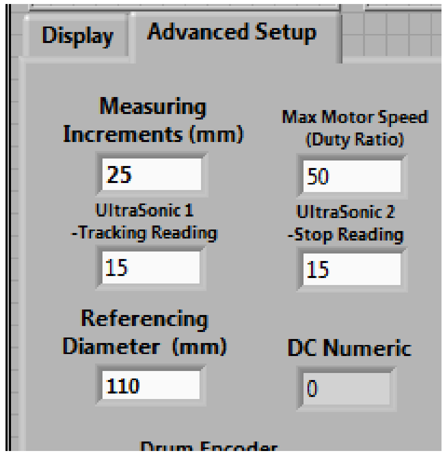
4) In the "Setup" Menu, choose the appropriate USB ports on the interface pull-down box for "Motor Control Port" and "Wireless Board Pert" and turn on the Toggle switch. (It should be noted that the COM number may vary between computers and selected USB ports.)



5) Using the Manual Motor Control buttons, raise the sensory module to the top of the tube if necessary and press the Drum Encoder Calibrate and the Calibrate Sensor buttons.

6) Now the system has been setup ready for analysis.

Step 3: Setting up to match the Reformer



In setting up the system to match the reformer tube the Sensors Module must be calibrated to the diameter of the opening of the reformer tube. To do this, the reformer tube diameter must be inputted into the "Referencing Diameter (mm)" in the "Advanced Setup" menu and the "Calibrate Sensors" button must be press. The diameter must be inputted in millimeters (11.5cm = 115mm). If the diameter is not known, simply measure the opening of the reformer tube with a measuring caliper.

Operating the System:

Typical Reformer Analysis Cycle

Below demonstrates a typical analysis cycle in analyzing the full length of the reformer tube. If only a segment of the tube is of interest then the procedure taken may differ to the following steps.

After going through the setup preparation and calibrating the device:

1. Press **Lower to Bottom**

This will automatically lower the sensory module to the bottom of the Reformer tube. The DC Motor should slowly start rotating to unwind the wire, lowering the sensory module. The location of the module will be indicated on the User Interface both numerically and visually on the graph as a Yellow Line.

As the module reaches the bottom of the tube the motor will slow down (tracking mode) and will eventually come to a steady stop around 20cm from the bottom.

2. Press **Start Recording**

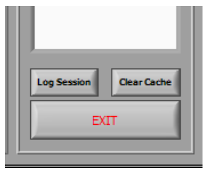
From the instant this button is pressed, the software will start logging the data into its memory. If the Interval Button is pressed the program will only log the data while the module is traveling up the tube at intervals of 20mm. This is recommended it will result in a tidier data collection.

3. Press **Raise to Top**

This will automatically raise the sensory module from the current location to the top of the tube. The motor will start rotating, winding the Module up the tube. During its way up the collected data will be temporary plotted on the graph. Speed of the motor is directly relative to the speed of the module traveling through the tube. To this it is best to run the motor at lower speed for better data collection.

Within 1meter from the top of the tube the motor will slow down to Tracking Speed (set at Advanced Setup) and eventually come to a halt.

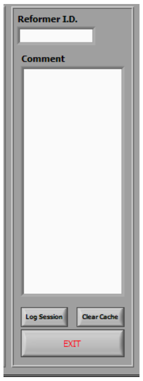
4. Press **Log Session**



If the data plotted on the graph seems adequate, press the Log Data button to save the collect data input to computer. The data will be saved in a text (*.txt) format.

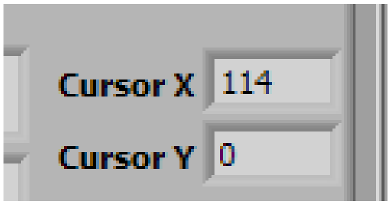
Convenient Function:

Notes and Reformer ID



On the Interface there is an area allocated to drop down notes/comments and Reformer ID. This is often required during each run to note dates, condition and other valuable information. These texts will automatically be saved into the Text file when the Log Data button is pressed.

Cursor

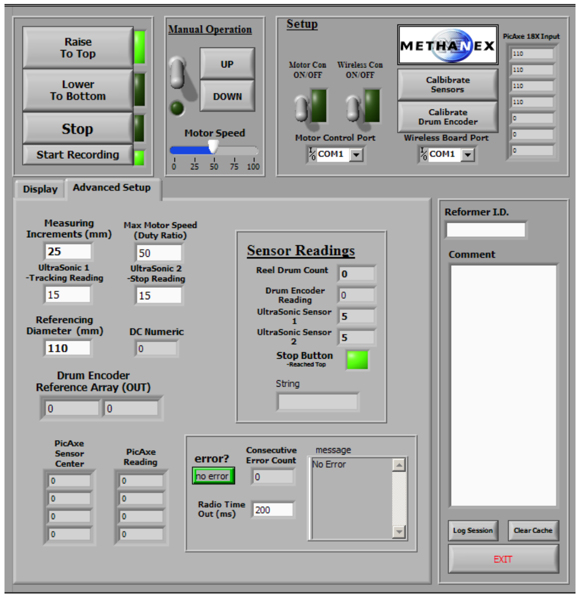


On the User Interface Plot is a cursor function available to cursor through the data to get instant diametric measurements.

Manual Operation Mode

The DC motor can also be manually operated by using the Manual Operation Mode. The Up/Down button is used to control the motor direction and the motor speed can be adjusted using the scroll bar. During this the ultrasonic sensors are still active and it will stop the motor if the module is to be too close to the bottom of the tube.

Advanced Setting:



Advanced setting interface can be display by clicking the Advanced Setting tab. From here the user is able to make changes to the system characteristics to match their application or fine tuning.

Measuring Step	Change the measuring interval that the system will collect data during Recording Data.
Ultrasonic 1 Tracing Reading	Set the distance at which the device will go into tracking mode at the top of the tube.
Max Motor Speed	Set the maximum motor speed during session.
Ultrasonic Sensor 2 Stop Reading	Set the distance at which the motor will stop at the bottom of the Tube. Note: with hardware limits, the reading must be greater then 15

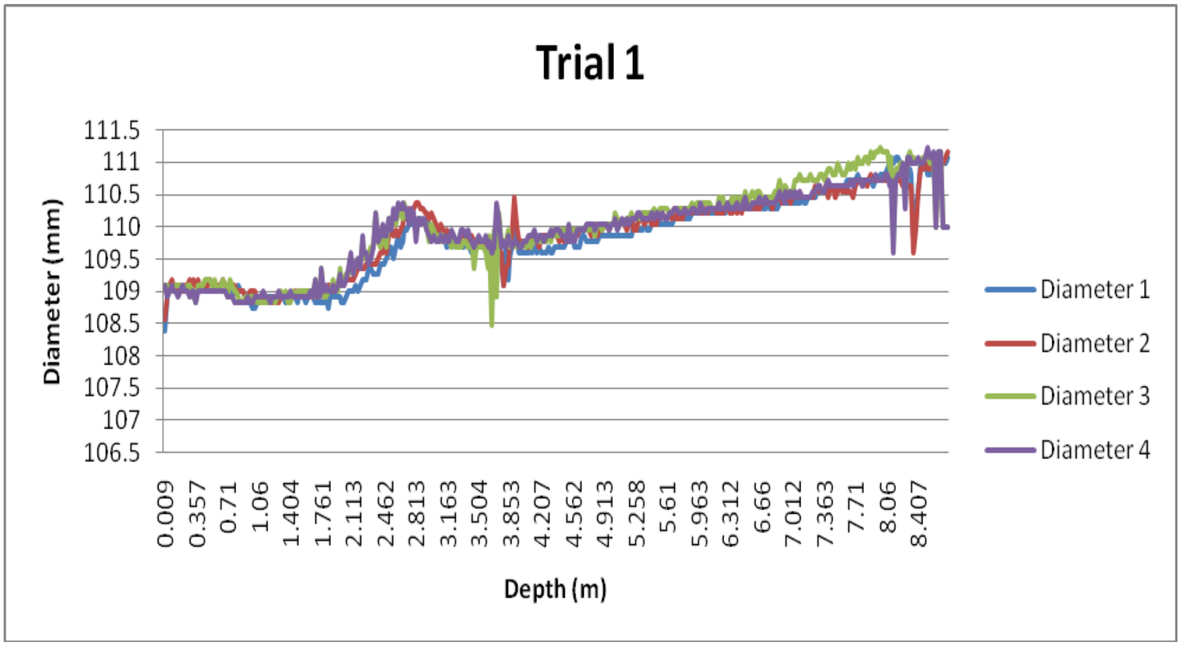
Plotting Recorded Data:

The generated Text file can be directly opened in Microsoft Excel for further analysis. A Macro program is also available to generate Excel plots and assist performing simple analysis.

Sample Output Test File.

Depth	0.009	0.038	0.055	0.085	0.110	0.135	0.162	0.186	0.213	0.236	0.262
	0.286	0.304	0.335	0.357	0.375	0.410	0.435	0.461	0.487	0.499	0.537
	0.552	0.587	0.611	0.635	0.662	0.682	0.710	0.737	0.760	0.785	0.808
	0.837	0.855	0.883	0.907	0.937	0.958	0.983	1.008	1.038	1.060	1.088
	1.109	1.133	1.155	1.181	1.212	1.233	1.262	1.286	1.307	1.326	1.359
	1.388	1.404	1.419	1.459	1.486	1.511	1.529	1.549	1.579	1.609	1.638
	1.662	1.687	1.706	1.732	1.761	1.778	1.812	1.833	1.861	1.882	1.909
Diameter 1		108.393	108.914	109.086	109.086	109.086	109.086	109.086	109.086	109.086	109.000
	109.000	109.000	109.000	108.914	109.000	109.000	109.000	109.000	109.000	109.000	109.000
	109.000	109.000	109.000	109.000	109.000	109.000	109.000	109.000	109.000		
Diameter 2		108.567	108.914	109.086	109.173	109.086	109.000	109.000	109.000	109.000	109.086
	109.086	109.173	109.086	109.173	109.086	109.173	109.000	109.086	109.000	109.086	109.173
	109.086	109.086	109.086	109.086	109.086	109.173	109.086	109.086	109.086		
Diameter 3		109.086	109.086	109.000	109.086	109.000	109.086	109.086	109.086	109.086	109.000
	109.086	109.086	109.000	109.000	108.827	109.086	109.086	109.086	109.173	109.173	109.173
	109.086	109.173	109.086	109.000	109.086	109.173	109.086	108.914	109.173		
Diameter 4		109.086	108.914	109.000	109.086	109.000	109.000	108.914	109.000	109.086	109.000
	109.000	108.914	109.000	109.000	108.827	109.000	109.000	109.000	109.000	109.000	109.000
	109.000	109.000	109.000	109.000	109.000	109.000	109.000	108.914	108.914		
Trial 1											
Comment											

Sample Plot:



Trial 1
Diameter (mm)
111.5
111
110.5
110
109.5
109
108.5
108
107.5
107
106.5
0.009
0.357
0.71
1.06
1.404
1.761
2.113
2.462
2.813
3.163
3.504
3.853
4.207
4.562
4.913
5.258
5.61
5.963
6.312
6.66
7.012
7.363
7.71
8.06
8.407
Depth (m)
Diameter 1
Diameter 2
Diameter 3
Diameter 4