Norris Sucker Rod Project

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Introduction

Mission Statement

Our mission is to use the knowledge and expertise of our members to provide quality service and innovative solutions to the people and businesses of Oklahoma. We aim to help our clients to achieve their goals and to exceed their expectations. We value work that is done right over work that is done quickly, and seek to add value to our client's businesses through quality work.

Problem statement

API specification 11B requires that sucker rods are tested for Total Indicator Reading sometimes referred to as "Total Indicator of Run out" or TIR. Norris has designed and installed equipment on several of the CNC rod end threading machines to check TIR. At present they do not perform inspection on all rods. Norris desires to expand this operation to check TIR on all rods or perform 100% inspection. The proposed system will cut down on cycle time, as well as allow for less user interference with the operators.

Statement of Work

Background: API specification 11B requires that sucker rods are tested for Total Indicator Reading (TIR). Norris Sucker Rods has designed and installed equipment on several of the CNC rod end threading machines to check TIR. At present, they do not perform inspection on all rods, but they do desire to expand operations to check TIR on 100% of the rods. After the rods are inspected and TIR measured, random samples are sent to a third party for "verification". In the past Norris has not had some problems with their readings matching up with the third party's readings. As of late this has not been as big of an issue, but Norris still wants a complete remake of their current process. We will be designing a new mounting system that will have much less user interference. Doing this will allow for 100% inspection of all rods produced, and will not interfere with the operators.

Scope: The objective of this project is to develop a new process for measuring total indicator reading on sucker rods for Norris Sucker Rods. The new process will be integrated into the production process and will inspect all rods (15,000 per day maximum) as they are produced. The total cost must be less than $60,000. After the measuring process has been completed, a statistical analysis of rod failures will be done to identify likely causes of TIR failures. As well, attention will be given to the best way to address non-conforming rods.

Deliverables: 1) Completed design/prototype
2) Layout/location of inspection equipment
3) Process for reworking non-conforming rods
4) Calibration process to ensure alignment

Period: Fall and Spring Semesters (8/2012 – 5/2013)

Location: Norris Sucker Rods – Tulsa, OK
Oklahoma State University – Stillwater, OK

Applicable Standards: API Spec 11B

Acceptance Criteria: The design must meet the basic requirements as outlined in the scope of the project of reliability, durability, cost, and accuracy.

Work Breakdown Structure

See Appendix A for Work Breakdown Structure.

Tasks List

Oversight

- Weekly progress reports submitted to Norris, Win Adams, and Dr. Weckler
- Ensure open communication between parties

Research, Technology, and Information

- Understand requirements set forth by API Spec 11B
- Research methods/technologies used to measure TIR
- Research technologies that are applicable to our situation
- Visit Norris and determine possible locations to integrate measuring system
- Gather information (measurements, specs, layout) needed for design

Design

- Develop designs based upon location, measuring device, etc.
- Perform engineering analyses on designs (fatigue, yield, cost, etc)
- Produce drawings of design(s) and the parts included
- Put finalized design(s) in a report to be presented to Norris at end of Fall semester

Approval

- Meet with Norris and submit design(s) for approval
- Make any modifications and resubmit for approval

Fabrication

- Submit approved drawings to have parts fabricated

Integration

- Assemble measuring devices into mounting system
- Integrate assembled system into Norris' production process (at specified location)
    - Use existing power
    - Use existing PLCs
    - Use existing marking system for failed rods
- Calibrate system

Testing

- Perform functionality tests
- Perform tests for accuracy, repeatability, and durability

Data Collection and Statistical Analysis

- Log data from measuring system
- Perform statistical analysis on collected data as well as on data from Q.C.
- Identify likely areas that cause TIR failures

Customer Satisfaction

- Submit all deliverables to Norris
- Work with Norris to ensure their requirements are met and that they are satisfied

Investigation

Industry Analysis

Our research showed that no sucker rod manufacturer currently inspects 100% of their rods. Norris will be the first to inspect all rods with the implementation of the new measuring system. Not only will this allow them to better market their product, it will also serve as an additional quality check. This would be beneficial since Norris offers their "Zero Defects Guarantee".

Technical Analysis

Technical specifications for the measurement of end straightness are defined in API Spec 11B.

From API Spec 11B:

> **A.6.2 End Straightness**
> **A.6.2.1 Sucker Rods and Pony Rods**
> End straightness shall be measured by supporting the rod body at a distance of 6.00 in. (152.4 mm) from the rod pin shoulder. The rest of the rod shall be supported at a maximum of 6.00 ft (1.83 m) with centers in the same plane. The amount of TIR bend is measured via a dial indicator, laser or other comparable measuring device. The amount of bend shall be measured at the machined surface of the pin shoulder OD. The maximum allowable TIR values for all rod sizes 5/8 in. to 11/8 in. (15.88 mm to 28.58 mm) is 0.130 in. (3.30 mm).

The method used by Norris, as well any companies that perform inspections on sucker rods, must conform to the guidelines set forth by API. As a result, most methods are similar in that they involve rotating the rod 360° on adequately spaced supports while measuring the total indicator run out using an approved measuring device or system.

While the methods of measuring end straightness may be similar, the measurement devices vary. These devices range from simple dial indicators to sophisticated optical measuring systems. The current device used by Norris is an optical micrometer system from Keyence. This type of device can provide the accuracy and repeatability (0.12mil and 0.008mil, respectively) needed while being integrated into the production process without slowing the rate of production. However, the environment these devices are subjected to at Norris make this type of system less than ideal. Therefore, other technologies were pursued. Linear Variable Differential Transformers (LVDT) operate much like a dial indicator but output a digital signal rather than a dial reading. LVDTs come in many setups and can be used in industrial applications.

Such factors as durability and reliability must also be taken into consideration. The design must be able to withstand a maximum of 15,000 rods per day. The measuring system must be reliable and provide accurate and repeatable results, and a simple calibration procedure should be implemented to ensure that the system is operating correctly. Consideration should be given to these aspects in order to help minimize the maintenance costs and requirements.

Patent Searches

To aid in obtaining an idea of what technologies exist that could be used to measure total indicator run out, a patent search was used. From a patent search using Google Patents for "total indicator runout", the following patents were found that were of some interest:

US7197837 — **Gauge assembly for measuring diameter and total indicated runout**
Honda Motor Co. Issued: 4/3/2007
Device used to measure diameter and TIR on camshafts.
www.google.com/patents/US7197837

US 2002/0077770 — **Method and system for identifying and evaluating runout limits of rotational components**
Kaminski and Wilson Filed: 12/20/2000
Method used to measure runout on rotating components, turbines.
www.google.com/patents/US20020077770

US6757636 — **Computerized electronic runout**
Alstom Technology Ltd. Issued: 6/29/2004
Method/Device to measure runout using magnetic field sensing
www.google.com/patents/US6757636

While these patents do not pertain to the measurement of end straightness for sucker rods, the information contained does provide insight on ways to go about measuring runout. No exact matches for the measurement of total indicator on sucker rods were found.

Fall Design Concepts

Our first design concept consisted of placing the LVDT's inside of the CNC machine that is used to cut the threads on the sucker rods. Having the LVDT's placed here would be ideal because measuring TIR would be one process. This would cut down on the time, as well as the user interference. The problem we encountered was that there would be no way to conform to API specifications if the LVDT was inside the CNC. API specifications state that the bracings must be at certain points along the rod. The distance from the front of the loading tube to the exit end of the chuck is approximately 40 inches; therefore there would be no way to incorporate a mounting system inside the CNC that conformed to API specifications. From here we decided the next best option would be to use the current mounting system since it already conforms to API specifications. We plan on building a bracket off of the current mount that holds the LVDT. The current system uses a pneumatic cylinder to push the rod into place to measure the TIR. To make the system less bulky and more user friendly, we have decided to place a roller in the middle of system that will roll the rod into place. An inductive proximity sensor will be used as a limit switch to stop the roller once the rod is in its correct place. This will trigger the actuator to lift the LVDT up until it is touching the shoulder of the rod. The rod will then be rotated 360 degrees and checked for TIR. Once one side of the rod has been measured for TIR, the same process will be done to the other side. From here the rod will either be passed and sent on, or failed and put into the scrap pile. Appendix B shows a CAD drawing of what the set up will look like. Appendix C contains the design layout for the set up.

Fall Presentation / Approval of Design Concept

At the end of the fall semester, the team met with Norris to present the final design concept and discuss how to proceed going forward. After the presentation, Norris approved the design concept and gave the go ahead to produce a prototype.

Fabrication

After receiving the approval from Norris to produce a prototype, all drawings were sent to Dr. Paul Weckler for initial approval. After his initial approval, the drawings were forwarded to Wayne Kiner, manager of the fabrication shop, to get final approval of the drawings and to start the fabrication process. After all pieces were fabricated, the team inspected all parts for correctness. The team coordinated with the shop to correct any issues and address the need for any modifications. Appendix I contains the CAD drawings for the fabricated parts.

Assembly

After all the parts were fabricated and inspected, the team began assembly the pieces. All fasteners, spacers, etc. were purchased and the assemblies were completed. The team conducted general checks for fit and functionality to ensure proper integration of the measuring components.

Instead of the original idea of permanently mounting the system in the lab or at Norris, the team designed and produced a rolling table that would allow the system to movable. All assemblies were then mounted to this table.

Integration

A crucial part of this project was to correctly integrate the key components of the measuring system. The first step was to setup and calibrate the LVDT. Setup was accomplished by using the LDX-3A signal conditioner. This signal conditioner supplies the correct voltage for the LVDT, as well as, it allows the output voltage to be manipulated to suit the application. Since we knew we were going to use an Arduino microprocessor and it was only capable of measuring 0 - 5 volts dc, we were able to adjust the LVDT output to match. Using the LDX-3A, the voltage was corrected using the gain and offset functions. The output voltage was first corrected for a range of 5 volts (+/- 2.5 volts), then offset to 0 – 5 volts. Once the output voltage was corrected, the next step was to calibrate the LVDT to ensure it met our requirements for accuracy and linearity. Two standards were used to calibrate the LVDT: ASTM F2537-06(2011) and USBR 1008-89. These standards are contained in Appendix F. The two standards use the same procedure to calibrate, but they provide different acceptance criteria that the team found useful. The micrometer method was used which involves mounting the LVDT into a fixture and displaced by a micrometer. The micrometer reading and LVDT output (voltage read by multimeter) are recorded for each reference length. The procedure is then repeated to provide a second set of data. The data was entered into the form from the USBR standard. The values from the LVDT are compared to those of the micrometer to check for accuracy. The LVDT values from the two trials are also compared to check for linearity. Percent errors for measurement and voltage were calculated and checked against the USBR acceptable values. From Table 1 in the USBR standard, our values of 0.05, 0.245, and 0.00 for 50, 75, and 100% of TLR were less than the maximum set by the standard of 0.1, 0.25, and 2.00, respectively. Also, a linear regression with equation and R^2-value was created from the data. The R^2-value of

0.9999 was deemed acceptable by the ASTM standard which required an R^2-value greater than 0.95. The completed USBR form and calibration curve can be found in Appendix F as well.

After the LVDT was calibrated in was integrated into the system. An Arduino microprocessor was used to handle the processing of the LVDT output into useful data. The code for the Arduino is in Appendix D. The program takes the LVDT output and converts it into a linear measurement. It then calculates TIR based upon these measurements and will signal a pass or fail condition. Besides calculating TIR, the Arduino works in conjunction with the Allen Bradley PLC to advance through the stages of the program such as stopping the actuation of the cylinder to stop the LVDT at the middle of its stroke.

As previously mentioned, an Allen Bradley PLC was integrated to help automate the system. The PLC was programmed using RS500 ladder logic, and a copy of the program can be found in Appendix D.

The pneumatic system used to raise and lower the LVDT into place was the next to be integrated. First, the pneumatic cylinder was threaded into the base plate of the TIR station. Next, a solenoid valve from Parker was used to handle actuating the cylinder. Since, the cylinder had such a small internal volume, flow control valves were used to help control extension and retraction speeds. A muffler with a built-in needle valve was later added to provide even better control of cylinder speeds. A pressure regulator with filter was added to aid in minimizing the effects of fluctuating pressure while eliminating contaminants from the system. Lastly, all components were plumbed together.

A proximity sensor was used to signal the system to start by sensing when the rod was in position. More information about the proximity sensor is in the discussion section.

Lastly, solid state relays were used for actuating the solenoid valve (one for each direction) as well as to turn on the ac motor driving the rod rotator system.

Testing

After all of the components were integrated, the system was tested for functionality. First, this was done for each subsystem i.e. pneumatic actuation, communication between LVDT/Arduino/PLC, relays, etc. After each subsystem was checked, the whole system was tested for functionality. Some minor modifications/adjustments were needed, but the system was brought up to a fully functional status.

The next step was to perform a measurement system analysis. As per the request of Norris, a gage repeatability and reproducibility (R&R) study was performed using the ANOVA (analysis of variance) method. In order to use this type of study, specific guidelines for collecting data had to be followed. The guidelines called for 3 appraisers (operators), 10 parts, and 3 trials for each part per appraiser. Norris sent 8 (4 – 5/8" and 4 – 1") pony rods to be used for testing purposes. The rods were numbered 1 to 8, and the ends were labeled "A" or "B". Each member of the group took turns "operating" the system. The first 10 sides (1A to 6B, 3B excluded due to damage on shoulder) were measured three times by each member. The data was recorded and entered into spreadsheet specifically designed for gage R&R. The spreadsheet had previously been verified for accuracy using the Ford verification data that serves as the standard for verifying such spreadsheets/software. The table below shows the report generated from the test data. From the report, it could be seen that the gage performance was acceptable. The collected data can be found in Appendix G.

Anova Report	**Standard Deviation (σ)**	**% Total Variation**	**% Contribution**
Repeatability (EV)	26.2031	4.3%	0.2%
Reproducibility (AV)	0.0000	0.0%	0.0%
Appraiser by Part (INT)	5.1288	0.8%	0.0%
GRR	26.2031	4.3%	0.2%
Part-to-Part (PV)	603.7851	99.9%	99.8%
		Gage system O.K	
Note:			
Tolerance = 0.00			Total variation (TV) = 604
Number of distinct data categories (ndc) =	32		
		Gage discrimination acceptable	

This table taken directly from gage R&R spreadsheet.

Financial Analysis

Final Budget

Part	Quantity	Cost/Part ($)	Total Cost($)
Parker Solenoid Valve	1	98.95	98.95
Solid State Relay	3	31.86	95.58
Flow Control Valve	2	23.49	46.98
Pneumatic Quick Connect Fittings	10	2.35	23.50
1/4" Nylon Hose	1	20.95	20.95
Flow Regulator	1	64.20	64.20
Spring actuated LVDT	1	525.00	525.00
AC powered signal conditioning	1	515.00	515.00
DC power supply for inductive sensor	1	165.00	165.00
Inductive proximity sensor	1	84.00	84.00
Microprocessor	1	29.95	29.95
Pneumatic actuator	1	25.00	25.00
Sub Total for One Side			**$1,694.11**
Total with 10% MISC			**$1,863.52**
Total for Both Sides			**$3,727.04**

Cost Comparison

The estimated cost of the full Keyence system per station is $13,000. Our budget estimates the cost of our system to be $3,727. This represents an approximate saving of $9,300 per station.

Project Schedule

Appendix H has the Gantt chart for this projects schedule. All deadlines were met.

Recommendations / Discussion

Currently Norris uses a pneumatic cylinder to push the rods from side to side in order to get the rods into place. The cylinder sticks out the backside and is very intrusive for the operator. We recommend implementing a system that will be less intrusive. The system will be inside the work area and will pick the rods up instead of pushing them. Appendix B shows the design. In consists of two pieces of square tubing working as a sleeve. A pneumatic cylinder will actuate the sleeve upwards once the rod is in place, drive rollers mounted directly to a bidirectional motor will then engage and move the rods from side to side.

During the design process, we decided to use pneumatics to lift the LVDT into place. For something this small, we needed a very small cylinder. With this small of a cylinder, we were working with a very small volume. This made stopping the cylinder in the correct spot somewhat difficult. We recommend looking into using an electric actuator instead of the pneumatic. It will be easier to get set in the correct position and will also ensure the sensor does not creep upwards.

Another recommendation is to use an automated stop system to accurately position the rods shoulder over the LVDT. Currently the only thing being used is a hard stop. We also recommend implementing a way to track the rods. By being able to track the rods, you could run a data analysis and potentially identify where the T.I.R. failure is occurring.

Conclusion

Our main focus is to implement a system that will be able to check TIR for 100% of the rods leaving Norris. The system must be more users friendly for the operators, as well as more efficient. The current shadow system is unreliable and is causing discrepancies between Norris and the third party inspectors. The system we are designing will be much smaller, and will therefore be much easier to maneuver around, making the system more user friendly for the operators. As well, our design will provide a significant cost benefit.

References

Sucker Rod Image on title page: http://www.norrisrods.com/images/body_pic_suckerrods1.jpg

Norris Logo on title page: http://www.ipaa.org/meetings/images/NorrisSuckerRods.JPG

Specification for Sucker rods, Polished Rods and Liners, Couplings, Sinker Bars, Polished Rod Clamps, Stuffing Boxes, and Pumping Tees. API Specification 11B, 27th edition. May 2010

Appendix A – Work Breakdown

WBS 1.0 Current System Remake

Redesign of current system used for checking TIR.

WBS 1.1 – Project Oversight

Work with Norris to ensure successful completion of the project on time and on budget. Submit progress reports to the customer when a step has been completed. Get required information from Norris. Task is complete when information is received and progress report defining the schedule is sent out.

WBS 1.2 – Requirements

New design will have to conform to API specifications. 100% of rods being sent out must be checked. Third party readings must match the readings coming out of Norris. Task is complete when all requirements are approved.

WBS 1.3 – System Redesign

Redesign current system used to check TIR at Norris based on the requirements outlined in WBS 1.2. Task is complete once the new system is in place and has been approved by the appropriate authority.

WBS 2.0 Documentation and Technology

Research available technology's and patents that could be used in the design process. Produce drawings for mounting system.

WBS 2.1 Research

Research patents and other technologies that could be used to determine TIR. Task is complete when an acceptable technology is found that does not conflict with patents.

WBS 2.2 Technology

Once technology has been selected, decide on how to integrate the technology into the current system. Task is complete when all specifications have been gathered and technology is integrated into the design.

WBS 2.3 Drawings

Produce drawings for mounting system. Task is complete once drawings have been approved and sent out for fabrication.

WBS 3.0 Approval

Review design with customer to ensure standards are met.

WBS 3.1 Review design

Work will be complete when the engineering has been approved and drawings have been released.

WBS 4.0 Fabricate Mounting System

Fabricate all approved pieces. Task will be complete once table and mounting brackets are complete.

WBS 4.1 Materials

Gather materials needed to fabricate system. Task is complete once all materials have been received and verified.

WBS 4.2 Fabricate System

Work with shop to get part machined for mounting system. Task is complete once all parts have been fabricated and inspected.

WBS 4.3 Install System

Work with the shop on a location to install system. Task is completed once system is installed and ready for system integration.

WBS 5.0 Integration of Sensor System

Integrate sensors into mounting system. Work is complete once system is fully functional.

WBS 5.1 Install Sensors

Install new sensors into current system. Task is complete once all sensors have been installed.

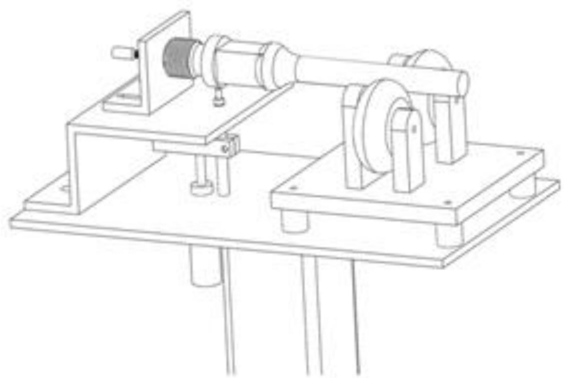
WBS 5.2 Support System

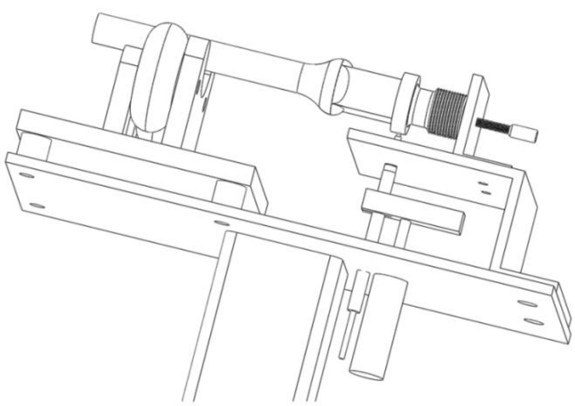
Integrate sensors into existing PLC. Task in complete once sensors have been integrated.

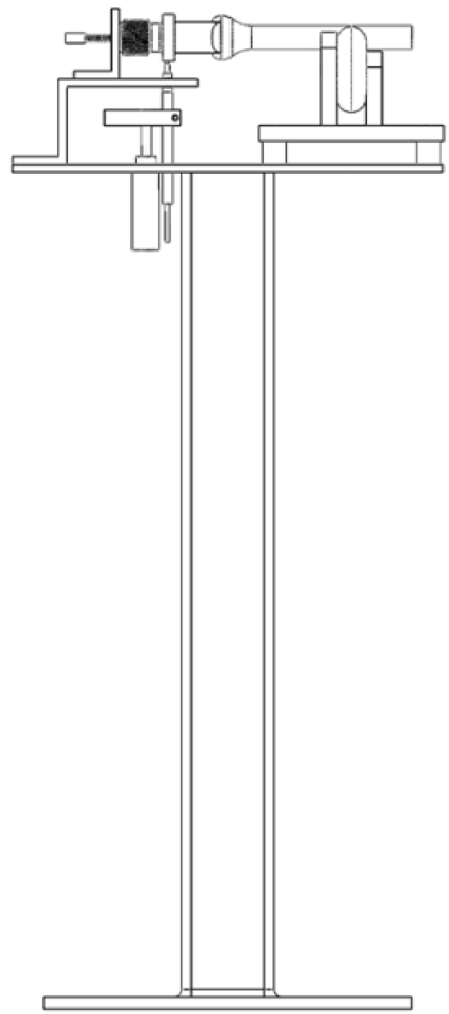
WBS 5.3 Functional Check

Conduct checks on all systems to ensure they are working properly. Task is complete once all systems have been checked and are working correctly.

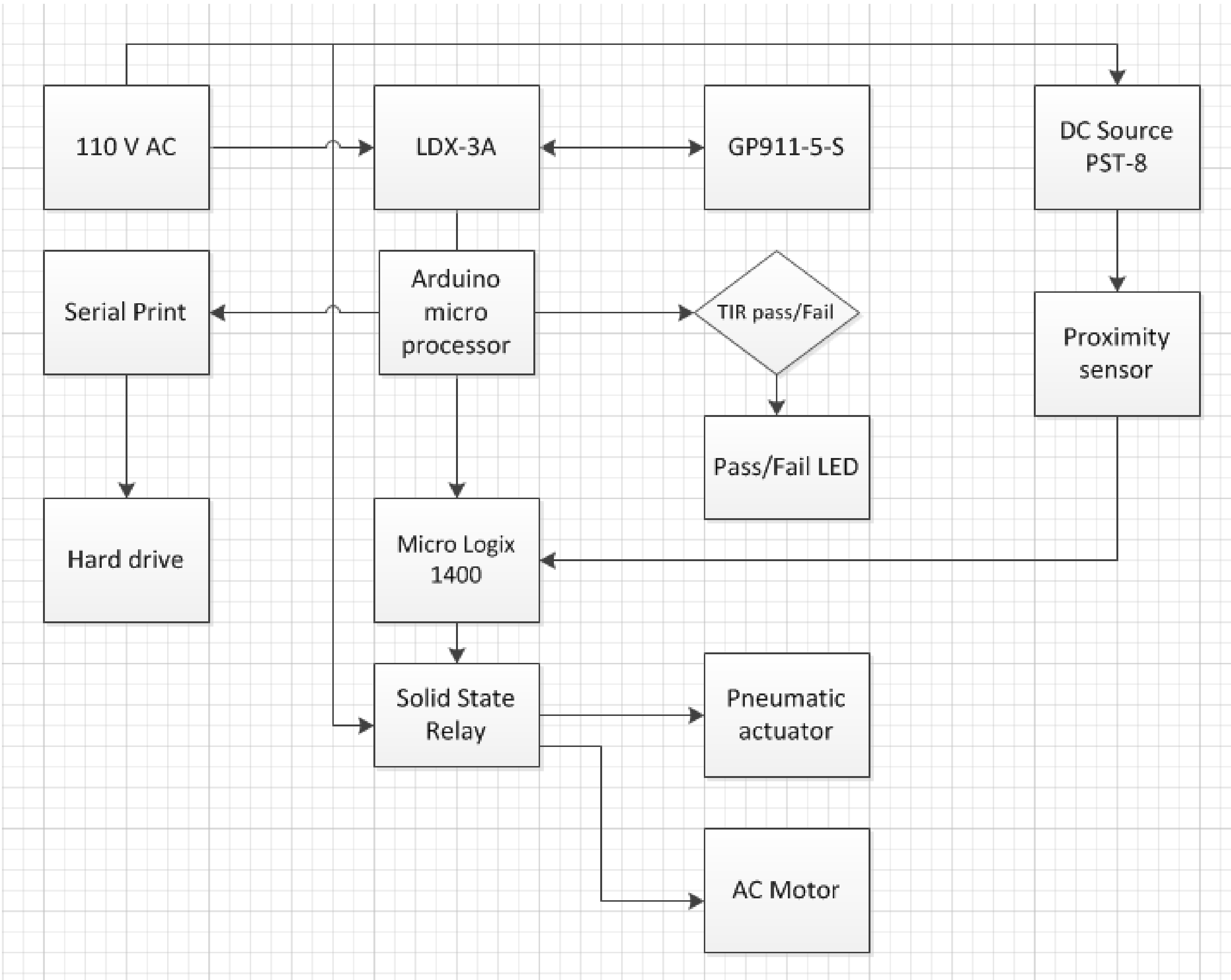
Appendix B – Proposed Design







Appendix C – Design Layout



Appendix D – Coding

Arduino Code

```
//Norris Sucker Rods T.I.R. Team
//This code controls the LVDT functions

int lvdtPin = A0;          //LVDT connected to analog pin 0
int Value;                 //variable to store lvdt value read
int HighVal;               //variable to store high value
int LowVal;                //variable to store low value
int ActuatorStartPin = 2;  //sets actuator start pin to 2
int ActuatorStopPin = 3;   //sets actuator stop pin to 3
int RotatorStartPin = 4;   //sets rotator start pin to 4
int RotatorStopPin = 5;    //sets rotator stop pin to 5
int PassPin = 6;           //sets pass pin to 6
int FailPin = 7;           //setps fail pin to 7
int RejectPin = 8;         //sets reject pin to 8
int ValActStart;           //stores value for actuator start pin
int ValRotStart;           //stores value for rotator start pin
int ValRotStop;            //stores value for rotator stop pin
int ValFailPin;            //stores value of fail pin

void setup()
{
 digitalWrite(ActuatorStartPin,LOW);   //This sections turns all pins off
 digitalWrite(ActuatorStopPin,LOW);
 digitalWrite(RotatorStartPin,LOW);
 digitalWrite(RotatorStopPin,LOW);
 digitalWrite(PassPin,LOW);
 digitalWrite(FailPin,LOW);
 digitalWrite(RejectPin,LOW);
 digitalWrite(9, LOW);
 digitalWrite(10, LOW);

 pinMode(ActuatorStartPin, INPUT);   //This section configures pin modes
 pinMode(ActuatorStopPin, OUTPUT);
 pinMode(RotatorStartPin, INPUT);
 pinMode(RotatorStopPin, INPUT);
 pinMode(PassPin, OUTPUT);
 pinMode(FailPin, OUTPUT);
 pinMode(RejectPin, OUTPUT);
 pinMode(9, OUTPUT);
 pinMode(10, OUTPUT);

 Serial.begin(9600);
}
```

Arduino Code Cont'd

```
void loop()
{
 ValActStart = digitalRead(2);
 ValRotStart = digitalRead(4);
 ValRotStop = digitalRead(5);

 digitalWrite(PassPin,LOW); //Ensures processor controlled pins are turned off
 digitalWrite(FailPin,LOW);
 digitalWrite(RejectPin,LOW);
 digitalWrite(9, LOW);
 digitalWrite(10, LOW);
 digitalWrite(11, LOW);

 HighVal = -2000;   //sets initial high value to lowest
 LowVal = 2000;     //sets initial low value to highest

  if (ValActStart == HIGH){       //actuator is lifting lvdt
   setLVDT();}

  if (ValRotStart == HIGH) {      //motor is rotating rods
   for (int i=0;i<200;i++){      //5ms delay * 200 iterations = 1 second (~full revolution at 82.5 RPM)
    MeasureTIR();}
    digitalWrite(9, HIGH);
    delay(1000);
    CheckTIR();
    delay(2000);
}

 if (ValRotStop == HIGH) {       //actuator is retracting lvdt and motor stops
  Retract();
  delay(1000); }

}
void setLVDT()      //positions lvdt at mid stroke
{
 Value = analogRead(lvdtPin);  //reads lvdt
 //This reading is converted into displacement x 1000 for resolution i.e. 200 = 0.2 inch
 float Displacement = ((Value * .44 / 1024)-.22) *10000;

 if (Displacement >= -1000 && Displacement <= 500){
  digitalWrite(3, HIGH);
  delay(100);
  Serial.print(Displacement);}
 else if (Displacement >= 1500){
```

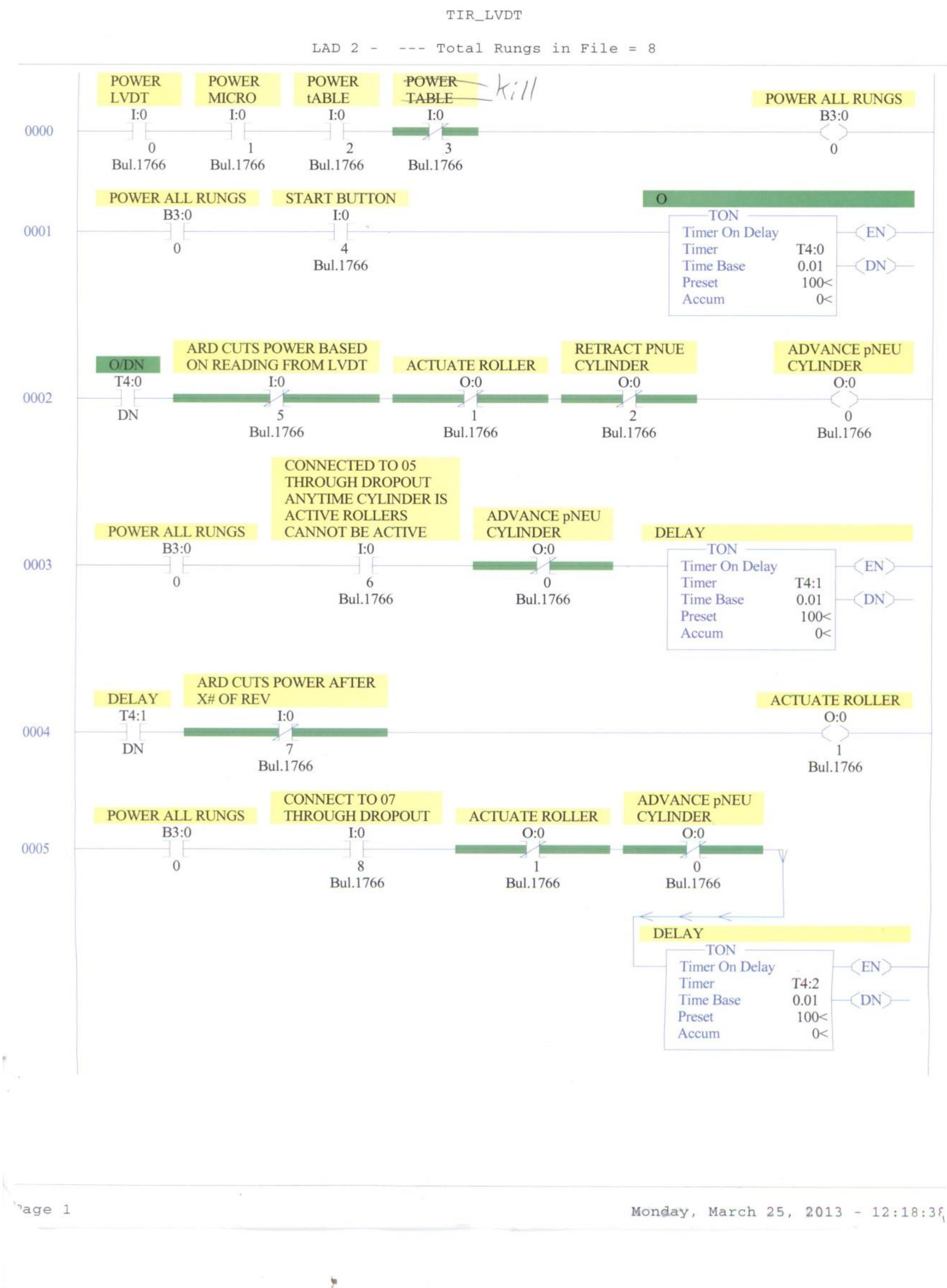
Arduino Code Cont'd

```
   digitalWrite(12, HIGH);
   digitalWrite(11, HIGH);
   delay(2000);}
}

void MeasureTIR()  //reads lvdt and performs tir calculation
{
  Value = analogRead(lvdtPin);  //reads lvdt
  //This reading is converted into displacement x 1000 for resolution i.e. 200 = 0.2 inch
  float Displacement1 = ((Value * .44 / 1024)-.22) *10000;

  if (Displacement1 > HighVal){        //Compares Value to High
    HighVal = Displacement1;}          //sets High to new Value
  else if (Displacement1 < LowVal){    //Compares Value to Low
    LowVal = Displacement1;}           //sets low to new value

  Serial.print("LowVal = "); Serial.print(LowVal);
  Serial.print("HighVal = "); Serial.print(HighVal);


  delay(5);
}

void CheckTIR()
{
  float tir = HighVal - LowVal;
  if (tir > 1350) {           //Check to API Spec
    digitalWrite(FailPin, HIGH);    //Signals failure
    delay(2000);}
  else if (tir <= 1300){      //Check to API Spec
    digitalWrite(PassPin, HIGH);    //Signals pass
    delay(2000);}
    Serial.print("tir = ");Serial.print(tir);
}
void Retract()
{
  ValFailPin = digitalRead(FailPin);     //Checks to see if rod failed
  digitalWrite(3,LOW);    //turns off stop pin for next cycle

  Value = analogRead(lvdtPin);  //reads lvdt
  //This reading is converted into displacement x 1000 for resolution i.e. 200 = 0.2 inch
  float Displacement2 = ((Value * .44 / 1024)-.22) *10000;

  if (ValFailPin == HIGH){             //If rod fails, signal PLC to reject
    digitalWrite(RejectPin, HIGH);}
```

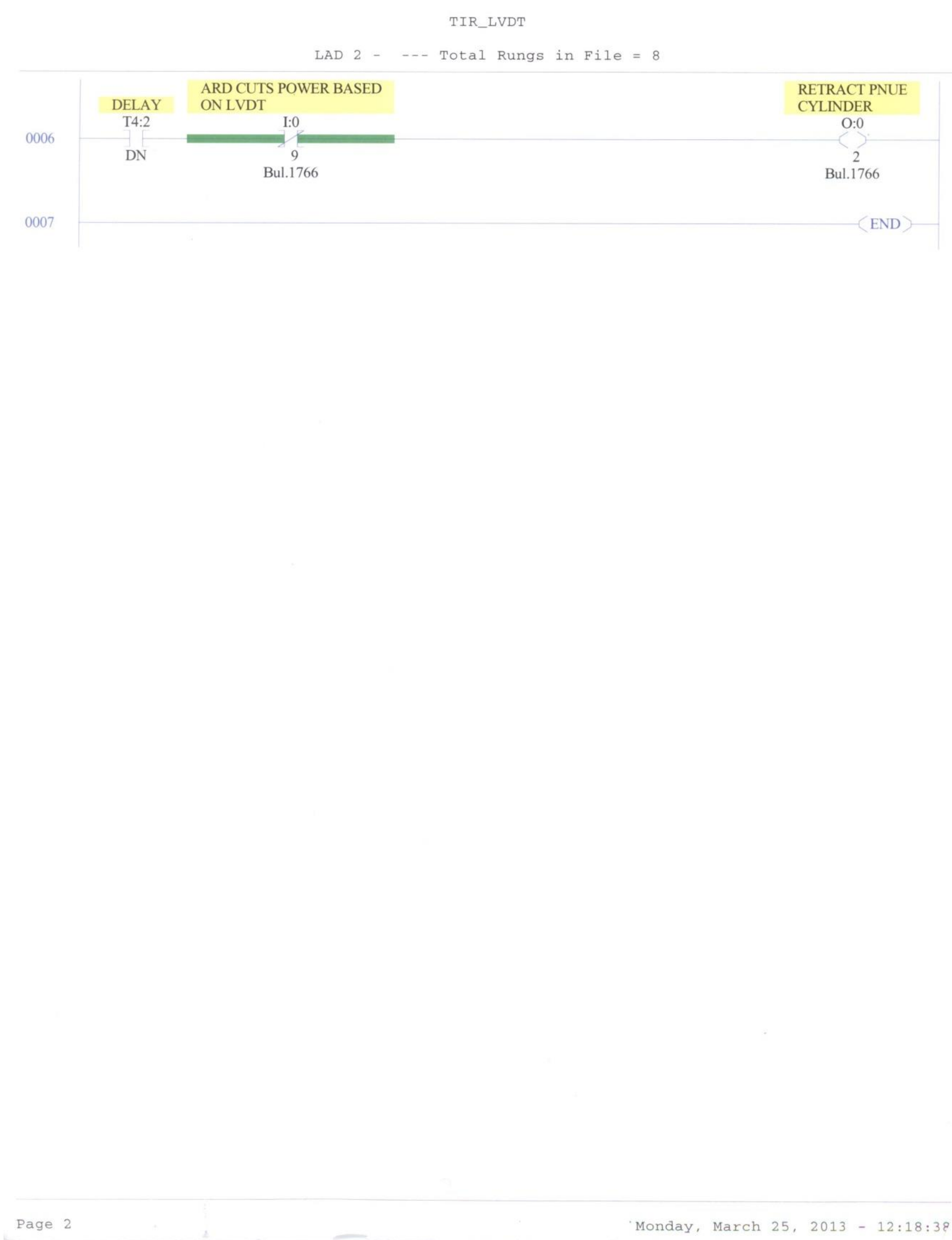
Arduino Code Cont'd

```
  else if (Displacement2 < -1850)
   {
    digitalWrite(10, HIGH);
    delay(2000);
   }
}
```

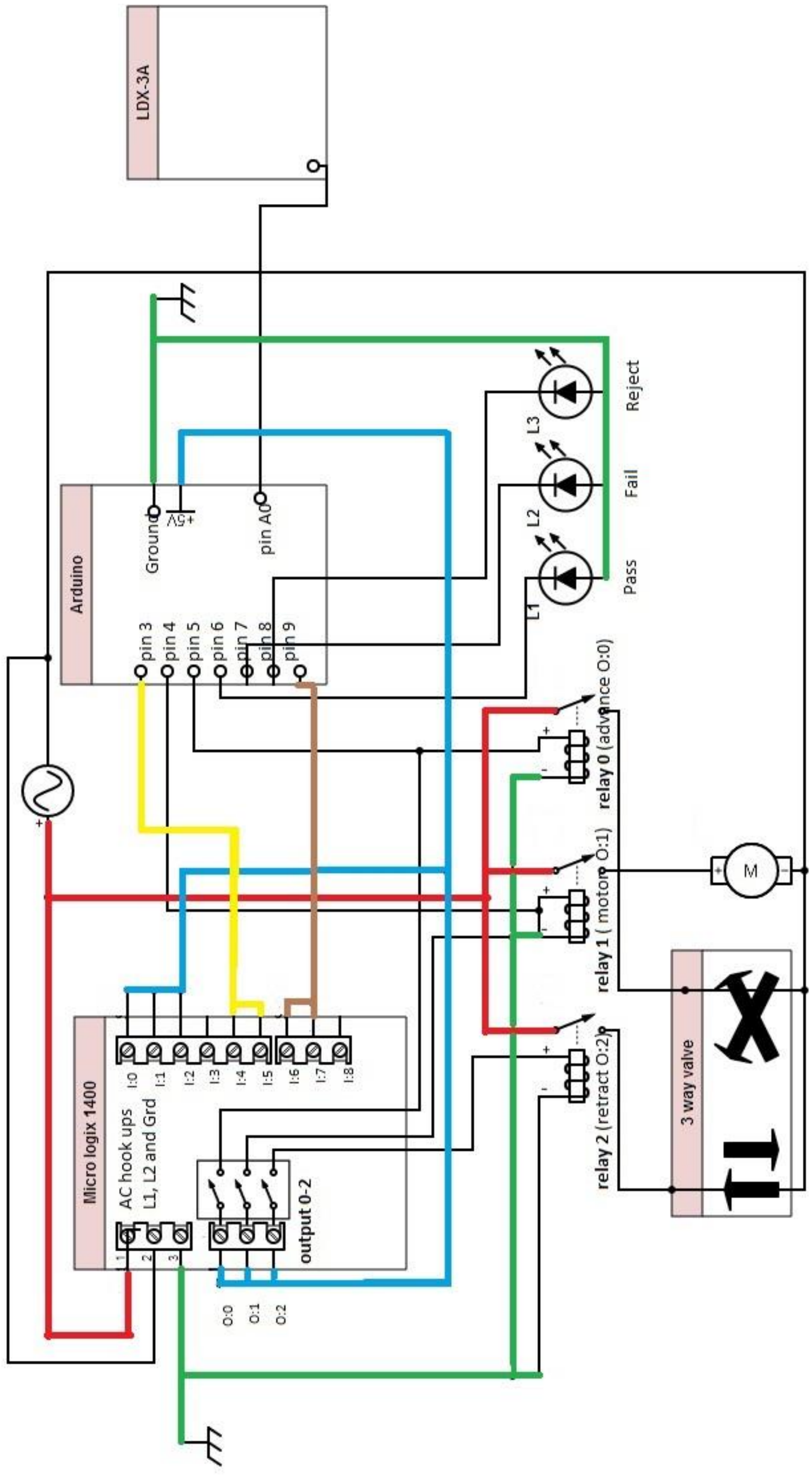
Ladder Logic PLC Code



Ladder Logic PLC Code Cont'd



Appendix E – Wiring Diagram



Appendix F – Calibration

ASTM Calibration

Designation: F2537 – 06 (Reapproved 2011)

Standard Practice for Calibration of Linear Displacement Sensor Systems Used to Measure Micromotion[1]

This standard is issued under the fixed designation F2537; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers the procedures for calibration of linear displacement sensors and their corresponding power supply, signal conditioner, and data acquisition systems (linear displacement sensor systems) for use in measuring micromotion. It covers any sensor used to measure displacement that gives an electrical voltage output that is linearly proportional to displacement. This includes, but is not limited to, linear variable differential transformers (LVDTs) and differential variable reluctance transducers (DVRTs).

1.2 This calibration procedure is used to determine the relationship between output of the linear displacement sensor system and displacement. This relationship is used to convert readings from the linear displacement sensor system into engineering units.

1.3 This calibration procedure is also used to determine the error of the linear displacement sensor system over the range of its use.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Terminology

2.1 *Definitions:*

2.1.1 *calibrated range, n*—distance over which the linear displacement sensor system is calibrated.

2.1.2 *calibration certificate, n*—certification that the sensor meets indicated specifications for its particular grade or model and whose accuracy is traceable to the National Institute of Standards and Technology or another international standard.

2.1.3 *core, n*—central rod that moves in and out of the sensor.

NOTE 1—It is preferable that the sensors prevent the core from exiting the sensor housing.

2.1.4 *data acquisition system, n*—system generally consisting of a terminal block, data acquisition card, and computer that acquire electrical signals and allows them to be captured by a computer.

2.1.5 *differential variable reluctance transducer (DVRT), n*—a linear displacement sensor made of a sensor housing and a core. The sensor housing contains a primary coil and a secondary coil. Core position is detected by measuring the coils' differential reluctance.

2.1.6 *linear displacement sensor, n*—an electrical sensor that converts linear displacement to electrical output.

2.1.7 *linear displacement sensor system, n*—a system consisting of a linear displacement sensor, power supply, signal conditioner, and data acquisition system.

2.1.8 *linear variable differential transformer (LVDT), n*—a linear displacement sensor made of a sensor housing and a core. The sensor housing contains a primary coil and two secondary coils. When an ac excitation signal is applied to the primary coil, voltages are induced in the secondary coils. The magnetic core provides the magnetic flux path linking the primary and secondary coils. Since the two voltages are of opposite polarity, the secondary coils are connected in series opposing in the center, or null position. When the core is displaced from the null position, an electromagnetic imbalance occurs. This imbalance generates a differential ac output voltage across the secondary coils, which is linearly proportional to the direction and magnitude of the displacement. When the core is moved from the null position, the induced voltage in the secondary coil, toward which the core is moved, increases while the induced voltage in the opposite secondary coil decreases.

2.1.9 *null position, n*—the core position within the sensor housing where the sensor voltage output is zero (some sensors do not have a null position).

2.1.10 *offset correction, n*—removal of any offset in a sensor's output so that at zero displacement, zero voltage is recorded.

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[1] This practice is under the jurisdiction of ASTM Committee F04 on Medical and Surgical Materials and Devices and is the direct responsibility of Subcommittee F04.15 on Material Test Methods.

Current edition approved June 1, 2011. Published June 2011. Originally approved in 2006. Last previous edition approved in 2006 as F2537 – 06. DOI: 10.1520/F2537-06R11.

2.1.11 *percent error, n*—the difference between a measurement of a reference standard and the actual length of the reference standard divided by the actual length of the reference standard and the result converted to a percent.

2.1.12 *power supply, n*—a regulated voltage source with output equal to that required by the sensor for proper operation.

2.1.13 *sensor housing, n*—central hole in a linear displacement sensor that senses movement of the core within it.

2.1.14 *signal conditioner, n*—electronic equipment that acts to convert the raw electrical output from the linear displacement sensor into a more useful signal by amplification and filtering.

3. Summary of Practice

3.1 A linear displacement sensor is mounted in a calibration fixture such that it can be subjected to a precise, known displacement.

3.2 Displacement is applied in steps over the full range of the linear displacement sensor and electrical readings (for example, voltages) are collected using the linear displacement sensor system.

3.3 Each voltage reading is taken as the average of 100 readings over 0.1 s, decreasing the error of the reading. The error in the readings is recorded as the standard deviation in the readings. This error should be constant and independent of displacement. It should be noted that the error in the readings is a summation of errors in each of the linear displacement sensor system components.

3.4 The calibration factor (S) is calculated as the slope of the voltage versus displacement curve using linear regression.

3.5 Linearity of the sensor is assessed.

3.6 The percent error is determined for each calibration point collected. This percent error is evaluated together with the tolerance of the micrometer head calibration.

4. Significance and Use

4.1 Linear displacement sensor systems play an important role in orthopedic applications to measure micromotion during simulated use of joint prostheses.

4.2 Linear displacement sensor systems must be calibrated for use in the laboratory to ensure reliable conversions of the system's electrical output to engineering units.

4.3 Linear displacement sensor systems should be calibrated before initial use, at least annually thereafter, after any change in the electronic configuration that employs the sensor, after any significant change in test conditions using the sensor that differ from conditions during the last calibration, and after any physical action on the sensor that might affect its response.

4.4 Verification of sensor performance in accordance with calibration should be performed on a per use basis both before and after testing. Such verification can be done with a less accurate standard than that used for calibration, and may be done with only a few points.

4.5 Linear displacement sensor systems generally have a working range within which voltage output is linearly proportional to displacement of the sensor. This procedure is applicable to the linear range of the sensor. Recommended practice is to use the linear displacement sensor system only within its linear working range.

5. Apparatus and Equipment

5.1 *Linear Displacement Sensor.*

5.2 *Power Supply,* with output equal to that required by the sensor.

5.3 *Signal Conditioner, Data Acquisition System, and Related Cables and Fittings.*

5.4 *Test Method—Micrometer Fixture Calibration:*

5.4.1 *Calibration Fixture,* a fixture that provides a means for fixing both a micrometer head and the linear displacement sensor along a parallel displacement axis, and is capable of applying displacement to the linear displacement sensor throughout its linear range. The alignment tolerance of the calibration fixture must be measured.

5.4.2 *Micrometer Head,* a precision instrument with known error (that is, tolerance). The spindle of the micrometer must be non-rotating and spring-loaded. The micrometer head shall be calibrated annually by the manufacturer or other qualified personnel.

6. Hazards

6.1 *Safety Hazards:*

6.1.1 This practice involves electrical equipment. Verify that all electrical wiring is connected properly and that the power supply and signal conditioner are grounded properly to prevent electrical shock to the operator. Take necessary precautions to avoid exposure to power signals.

6.2 *Safety Precautions:*

6.2.1 Examine the sensor housing for burrs or sharp edges, or both. Remove any protrusions that might cause harm.

6.2.2 The sensor can be permanently damaged if incorrectly handled. Consult the manufacturer's guidelines for handling.

6.2.3 The sensor can be permanently damaged if incorrectly connected to the power supply, or if connected to a power supply with the wrong excitation level. Consult the manufacturer's guidelines for use.

6.2.4 Follow all manufacturer's recommendations with regard to safety.

6.3 *Technical Precautions:*

6.3.1 If using a linear displacement sensor that permits the core to leave the sensor housing, do not interchange cores with other linear displacement sensor housings.

6.3.2 Replace the sensor if it, or any component of it, shows any signs of dents, bending, or other defects that may affect its performance.

6.3.3 Store all system components in dry, protective locations when not in use.

6.3.4 Do not exceed the allowable input voltage of the sensor as specified by the manufacturer.

6.3.5 Do not connect a voltage source to the output leads of the sensor.

6.3.6 Do not over-tighten the sensor within the calibration fixture.

6.3.7 The behavior of some sensors may be affected by metallic holders; this must be considered during use of the sensor.

7. Calibration and Standardization

7.1 Verify that the calibration fixture, micrometer, power supply, signal conditioner, and data acquisition system are all in good working order, and of sufficient precision and bias.

7.2 Verify that all components have been individually calibrated and are within their respective calibration cycles.

8. Procedure

8.1 Perform the calibration in an environment as close to that in which the sensor will be used as possible. All necessary equipment should be in the environment in which they are to be used for calibration for at least 1 h prior to calibration to stabilize temperature effects. Ambient temperature should be quantified and recorded. Ambient temperature during the calibration procedure should be maintained within ±2°C of the initial temperature.

8.2 Verify that the power supply is adjusted to supply the recommended voltage to the sensor.

8.3 With equipment turned off, connect all power supply, signal conditioning, and data acquisition equipment exactly as it will be used in service. Follow the manufacturer's suggested order of connecting equipment, if prescribed. Allow all electronics to warm up for at least 15 min before beginning calibration.

8.4 Verify that the sensor is working properly by changing its displacement position and watching the signal change accordingly on the chart.

8.5 Note the model number and serial number of the linear displacement sensor to be calibrated.

8.6 Note the calibration protocol to be followed.

8.7 Confirm that the micrometer head, data acquisition system, linear displacement sensor, and signal conditioner have been calibrated and are within their calibration cycles.

8.8 If any calibration is not up to date, have the proper calibration performed before calibrating the sensor within the current system.

8.9 Note the tolerance of the micrometer head calibration.

8.10 Record the name of the calibrator, date of calibration, all equipment used (model and serial numbers, if possible), calibration units, input voltage supplied, and input limits and resolution of the data acquisition system.

8.11 *Test Method—Micrometer Fixture Calibration:*

8.11.1 Secure the sensor into the mounting fixture.

8.11.2 Secure the mounting fixture into the calibration fixture.

8.11.3 Secure the micrometer head into the calibration fixture.

8.11.4 Define the zero position of the sensor. This is the position of the first calibration point and it is located at one end of the linear range of motion of the sensor. This position is found by positioning the sensor at its null position (where the voltage output of the sensor is zero) and then rotating the micrometer head in one direction until the sensor has traveled to the end of its rated linear range in that direction (that is, a distance of ½ of its total rated linear range).

8.11.5 Record the sensor system readout as Sensor Reading 1 in a table corresponding to zero displacement. Also include the error in the position reading (that is, the tolerance of the micrometer head and the combined largest error associated with the quantified misalignment of sensor and micrometer head).

8.11.6 Sample the voltage data from the sensor at a fast sampling rate for a finite time. (See Note 2.) Record the average and standard deviation of the sample in the table. It is recommended that a software program be written or used to efficiently perform these tasks.

NOTE 2—At least 1000 Hz for 0.1 s is recommended.

8.11.7 Move the micrometer to a predetermined displacement from the zero position. Move the micrometer in *only* one direction, as there may be significant backlash in the micrometer that will result in unquantified errors in displacement measurements.

8.11.8 Repeat steps 8.11.5 and 8.11.6 for the new position.

8.11.9 Repeat steps 8.11.7 and 8.11.8 for uniform intervals throughout the linear range of the sensor. At least 10 calibration points should be included.

8.11.10 Rotate the micrometer head in reverse order and record readings in the table throughout the linear range of the sensor.

8.11.11 To obtain reproducibility data, repeat these steps for a minimum of two times using the same calibration positions.

8.11.12 Calculate the calibration factor, linearity, error bounds of each data point, displacement error, and percent error as described in Section 9.

9. Calculations

9.1 *Calibration Factor*—The calibration factor (S) is calculated as the slope of the voltage versus displacement curve using linear regression.

9.2 *Linearity*—Linearity of the sensor can be assessed by calculating the coefficient of determination (R^2) of a line fit through the data points using linear regression.

9.3 *Percent Error*—The percent error is calculated for each point collected. First, the difference between the displacement value of the point calculated from the calibration equation and the actual measurement of the displacement at the point collected is calculated. The percent error of each point is 100× the resulting difference/the calibrated range.

10. Acceptability Criteria

10.1 In order for the sensor to be used, it must be calibrated within the following criteria:

10.1.1 The R^2 value must be greater than 0.95.

10.1.2 The standard deviation of the voltage measurement of any given calibration point must not be greater than 0.010 V/V full scale.

10.1.3 The percent errors at each calibration point calculated in 9.3 must be evaluated together with the tolerance of the micrometer head calibration used as the reference standard, against the error requirements for the specific application of the measurement system and be deemed acceptable.

11. Calibration Certificate

11.1 The calibration certificate should include the following:

11.1.1 Type of sensor being calibrated (linear displacement sensor).

11.1.2 Make of the sensor.

11.1.3 Model of the sensor.

11.1.4 Serial number of the sensor.

11.1.5 Date of calibration.

11.1.6 Name of calibrator.

11.1.7 Voltage excitation if applicable.

11.1.8 Input limits and resolution of data acquisition system used.

11.1.9 Acceptability criteria.

11.1.10 PASS/FAIL.

11.1.11 List of all equipment used in the calibration (make, model, serial number, calibration status).

11.1.12 Reference to the calibration protocol followed.

11.1.13 Calibration data (data points and error bounds, average and standard deviation for voltage measurements).

11.1.14 Plot of the calibration data.

11.1.15 Calibration equation and R^2 value.

11.1.16 Ambient temperature as recorded per 8.1.

11.1.17 Tolerance of the micrometer head calibration.

12. Keywords

12.1 calibration; displacement; instrumentation; measurement; micromotion; sensor; transducer

APPENDIX

(Nonmandatory Information)

X1. RATIONALE

X1.1 Calibration of linear displacement sensor systems is a critical practice that should always be performed prior to use of such a system for measurement of displacement. This step is even more critical when the value of the displacement to be measured is on the micron scale.

X1.2 This practice provides a guideline for ensuring proper calibration of such a system. This practice will ensure that product performance dependent on micromotion between orthopedic components and other medical devices will be properly evaluated.

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

USBR 1008-89

PROCEDURE FOR

CALIBRATING LINEAR VARIABLE DIFFERENTIAL TRANSFORMERS

INTRODUCTION

This procedure is under the jurisdiction of the Geotechnical Services Branch, code D-3760, Research and Laboratory Services Division, Denver Office, Denver, Colorado. The procedure is issued under the fixed designation USBR 1008. The number immediately following the designation indicates the year of acceptance or the year of last revision.

1. Scope

1.1 This designation outlines the procedure for calibrating LVDTs (linear variable differential transformers).
1.2 Method A outlines the calibration procedure using precision gauge blocks; method B outlines the calibration procedure incorporating a micrometer fixture.

2. Applicable Documents

2.1 *USBR Procedure*:
USBR 1000 Standards for Linear Measurement Devices
USBR 3900 Standard Definitions of Terms and Symbols Relating to Soil Mechanics
2.2. *Federal Specification*:
GGG-G-15C Gage Blocks and Accessories

3. Summary of Method

3.1 Readings from an LVDT and from either the precision gauge blocks (method A) or the micrometer fixture (method B) are compared to determine the linearity and repeatability of the LVDT. The results are used to determine the acceptability of the LVDT for laboratory use.

4. Significance and Use

4.1 LVDTs must be calibrated for use in the laboratory to ensure reliable linear measurements.
4.2 Calibrate LVDTs before initial use and at least annually thereafter.

5. Terminology (see fig. 1)

5.1 Definitions are in accordance with USBR 3900.
5.2 Terms not included in USBR 3900 specific to this designation are:
5.2.1 *Null Position*.–The LVDT core position within the LVDT body that voltage output is zero.
5.2.2 *TLR* (total linear range).–Total distance that may be traveled by the LVDT core in moving from the position of maximum voltage output at one end of the body—through the null position—to the position of maximum voltage output at the opposite end of the body.
5.2.3 *Full-Scale Displacement*.–Total distance traveled by the core in moving from the null position to one end of the total linear range; i.e., one-half of the total linear range.
5.2.4 *Range*.–Total distance traveled by the core expressed in terms of percent plus or minus full-scale displacement.
5.2.5 *Repeatability*.–The degree of LVDT measurement variation for successive measurements of the same reference standard.
5.2.6 *Linearity*.–The variation of LVDT measurements from a straight line. The measurements are obtained using a series of reference standards applied over the total linear range of the LVDT.
5.2.7 *Percent Error*.–The ratio (expressed as a percent) of (1) the difference between an LVDT measurement of a reference standard and the actual length of the reference standard to (2) the total linear range of the LVDT. Percent error also may be determined over a fraction of the total linear range.
5.2.8 *Voltage Error*.–The difference in LVDT voltage output for successive measurements of the same reference standard.

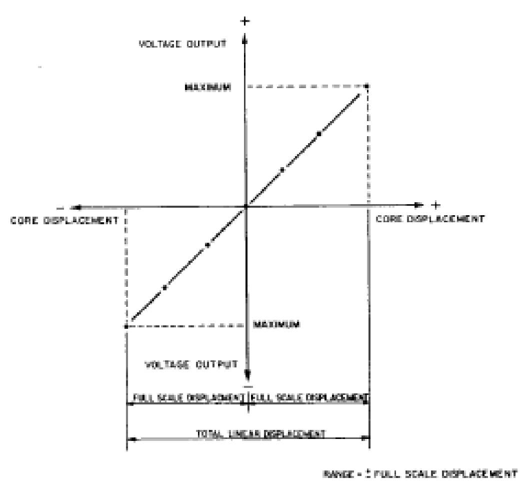

Figure 1. – Terminology of the LVDT.

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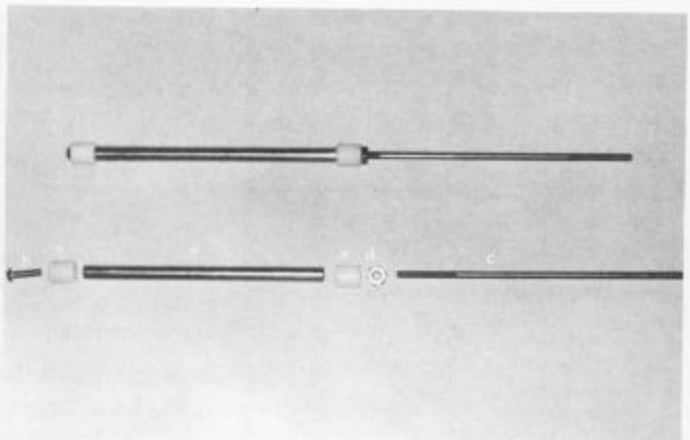
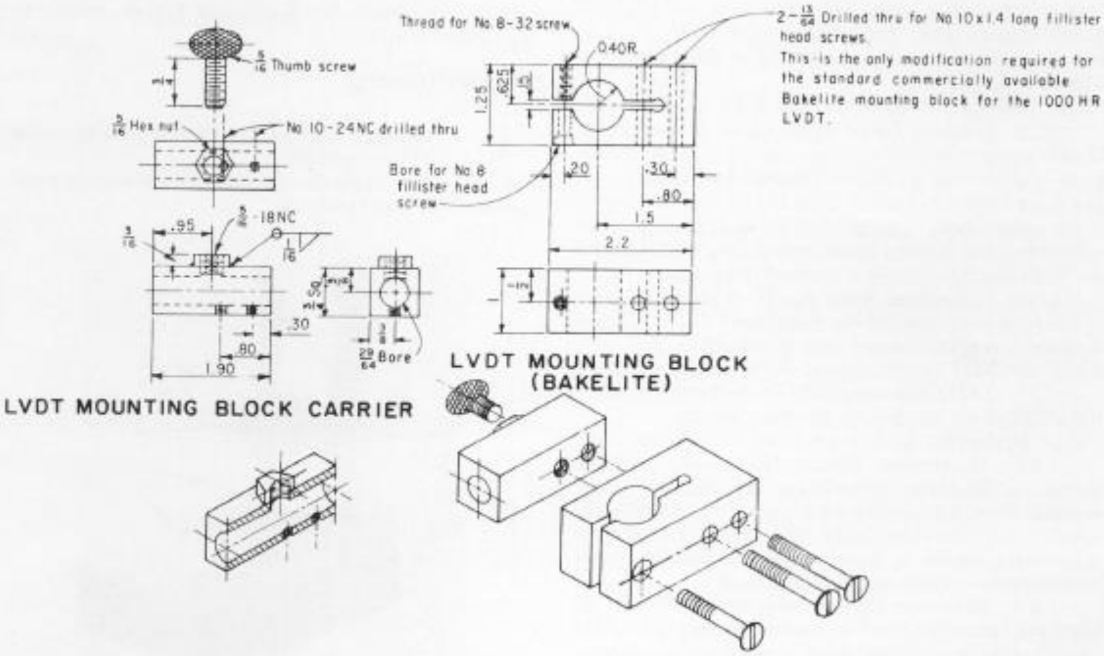


(a) LVDT core/core extension rod assembly. a) teflon guide, b) No. 6-40 UNF threaded screw, c) LVDT core extension rod, d) lock nut, and e) LVDT core.



(b) Schematic of LVDT mounting block.

Figure 2. - LVDT mounting block and rod assembly.

6. Apparatus

6.1 *General Apparatus*:

6.1.1 *LVDT*.–An electrical transducer which converts linear displacement to electrical output. An LVDT (linear variable differential transformer) consists of a stationary LVDT body and a movable LVDT core. The LVDT core is threaded on both ends so the LVDT core extension rods can be attached.

6.1.2 *Signal Conditioner and Readout Equipment*.–A signal conditioner provides excitation voltage for the LVDT, as well as appropriate electronic circuitry to make the output of the transducer (LVDT) compatible with readout equipment. Readout equipment accepts output from the signal conditioner and converts it into a visual display of transducer displacement.

6.1.3 *LVDT Core Extension Rod* (fig. 2a).–A nonmagnetic rod (preferably brass), threaded on both ends. The diameter of the rod and threads must be compatible with the diameter of the hole in the LVDT core. The rod should be threaded a minimum of 1 inch (25 mm) at each end with an approximate total length of 2-1/2 inches (65 mm).

6.1.4 *LVDT Teflon Guides* (fig. 2a).–Two LVDT Teflon guides are required and can be purchased from the LVDT manufacturer. The purpose of the Teflon guides is to minimize transverse movement of the LVDT core within the LVDT body.

6.2 *Method A—Precision Gauge Block Calibration*:

6.2.1 *Precision Gauge Blocks*.–A set of steel gauge blocks (inch-pound and/or metric), usually rectangular, that meet requirements of Federal Specifications GGG-G-15C and those requirements identified in USBR 1000 for precision gauge blocks. A gauge block set should contain sizes (or combination of sizes) necessary to satisfactorily perform the calibration procedures as outlined in paragraph 10.

6.2.2 *Comparator Stand* (fig. 3).–A stand consisting of a base of warp-free stability and ground to a guaranteed flatness; a support column; and an adjustable arm onto which the LVDT mounting block can be securely attached.

6.2.3 *LVDT Mounting Block*.–A device used to attach the LVDT to the comparator stand (see fig. 2b).

6.3 *Method B—Micrometer Fixture Calibration*:

6.3.1 *Micrometer Fixture* (fig. 4).–A precision instrument for linear measurement capable of obtaining readings over the total linear range of the LVDT. The spindle must be nonrotating and spring loaded. The micrometer fixture is to be calibrated annually by the manufacturer or other qualified personnel.

6.3.2 *Electronic Digital Micrometer* (fig. 4).–An electronic micrometer used to convert displacement of the spindle of the micrometer fixture to visual numeric display.

7. Precautions

7.1 *Safety Precautions*:

7.1.1 The LVDT body should be examined for burrs and/or sharp edges.

7.1.2 Verify all electrical wiring is connected properly, and that the signal conditioner (if used) is grounded properly to prevent electrical shock to the operator.

7.2 *Technical Precautions*:

7.2.1 The LVDT core and body are a matched set as purchased from the manufacturer; for best performance, do not interchange cores with other LVDT bodies.

7.2.2 Replace the core and body if either shows any sign of dents, bending, or other defects which may affect performance of the device.

7.2.3 The LVDT core and body should be stored in a suitable box or case when not in use.

7.2.4 Do not exceed the input voltage of the LVDT as specified by the manufacturer.

8. Calibration and Standardization

8.1 *Method A*.–Verify that gauge blocks used for obtaining LVDT comparison readings are currently calibrated in accordance with USBR 1000. If the gauge block calibration is not current, the calibration procedure should be performed before using the gauge blocks.

8.2 *Method B*.–Verify that the micrometer fixture has been currently calibrated by the manufacturer or other qualified personnel. If the calibration is not current, the calibration should be performed before using the micrometer fixture.

9. Conditioning

9.1 Perform this calibration in an environment as close to 68 °F (20 °C) as possible.

9.2 Turn on all electronic equipment and allow to warm up for 30 minutes before use.

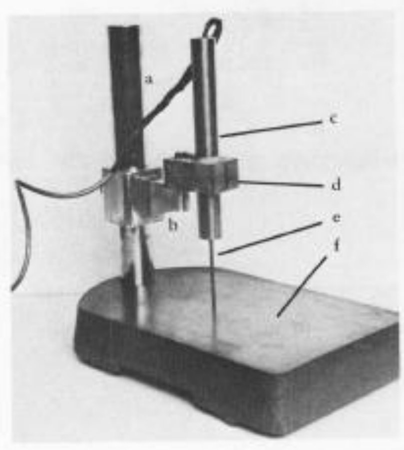


Figure 3. - LVDT Comparator stand and LVDT mounting block (method A). a) support column, b) adjustable arm, c) LVDT body, d) LVDT mounting block, e) LVDT core extension rod, and f) base.

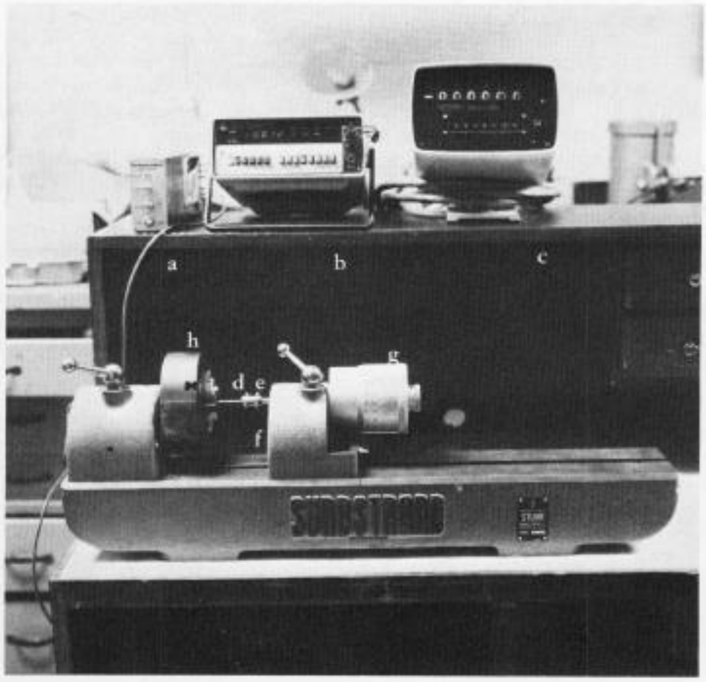


Figure 4. - LVDT Calibration assembly—micrometer fixture (method B). a) signal conditioner, b) readout equipment, c) electronic digital micrometer, d) LVDT core extension rod, e) spindle, f) micrometer head carrier, g) micrometer head, and h) chuck.

9.3 The LVDT, calibration gauge blocks, micrometer fixture, and comparator stand should be in the environment in which they are to be calibrated for at least 24 hours prior to calibration.

10. Procedure

10.1 All data are to be recorded on the "Linear Variable Differential Transformer Calibration" form as shown on figure 5.

10.2 Record type and serial number of the LVDT to be calibrated; if it has no serial number, record the model number and any other identifying markings.

10.3 Record the total linear range of the LVDT.

10.4 Record the type and serial number of the reference standard used.

10.5 Attach the cable from the LVDT to the signal conditioner; and attach the cable from the signal conditioner output to the readout equipment. Plug in the readout equipment to a power source and allow a minimum 30-minute warmup.

10.6 Slide an LVDT Teflon guide onto each end of the LVDT core as shown on figure 2a.

10.7 Attach the LVDT core extension rod to the end of the LVDT core by screwing the LVDT core extension rod into the threaded LVDT core.

10.8 *Method A—Precision Gauge Block Calibration*:

10.8.1 *Null Position of LVDT*:

10.8.1.1 Attach the LVDT mounting block to the adjustable arm of the comparator stand as shown on figure 3.

10.8.1.2 Slide the LVDT core and core extension rod assembly into the LVDT body.

10.8.1.3 Place the LVDT body into the LVDT mounting block and tighten the appropriate screw on the mounting block. (DO NOT overtighten the screw on the mounting block; this can deform the LVDT body.)

10.8.1.4 Apply voltage to the LVDT. Ensure that the line voltage is compatible with the power requirements of the signal conditioner. Refer to the manufacturer's operating instructions for voltage requirements.

10.8.1.5 Place a gauge block (or series of blocks) which has a height equal to one-half the total linear range of the LVDT under the LVDT core extension rod; i.e. for an LVDT having a 2-inch (50.8-mm) total linear range, a 1-inch (25.4-mm) gauge block is used.

10.8.1.6 Using the adjustable arm, adjust the LVDT body up or down on the comparator stand support column as necessary so the output of the readout equipment is approximately equal to 0 volt.

10.8.1.7 Secure the adjustable arm on the support column of the comparator stand in the position described in subparagraph 10.8.1.6, by tightening the screw of the adjustable arm.

10.8.1.8 Use the ZERO adjustment on the signal conditioner to obtain a reading of exactly 0.000 volt. This is the null position of the LVDT.

NOTE 1.–Adjustment of the signal conditioner may vary slightly depending on the type of signal conditioner used. Refer to the manufacturer's operating instructions for adjustment of the specific signal conditioner used.

10.8.2 *Signal Conditioner Span Setting* (LVDT factor determination):

10.8.2.1 Remove the gauge block (or series of blocks) from beneath the LVDT core extension rod.

10.8.2.2 Place a gauge block (or series of blocks) which has a height equal to the total linear range of the LVDT (as recorded in subpar. 10.3) under the core extension rod; i.e., for an LVDT with a 2-inch (50.8-mm) total linear range, a 2-inch gauge block is used.

10.8.2.3 Adjust the signal conditioner, using the GAIN control screw, so that the output of the LVDT is equal to ±10.000 volts d.c. (Polarity depends on the wiring of the LVDT.)

NOTE 2.–For convenience, subparagraph 10.8.2.3 specifies a setting of ±10.000 volts d.c. for the LVDT output at full-scale displacement. Other values of output at full LVDT displacement may be used, if desired.

10.8.2.4 Remove the gauge block (or series of gauge blocks) from beneath the core extension rod and replace it with a gauge block (or series of gauge blocks) having a height equal to one-half the total linear range of the LVDT. The readout should indicate 0.000 volt; if it does not, reset by adjusting the ZERO adjustment.

10.8.2.5 Repeat subparagraphs 10.8.2.2 through 10.8.2.4 until values of 0.000 and ±10.000 (see note 2) volts are obtained.

10.8.2.6 Record the value of LVDT output at full-scale displacement ±10.000 volts (see note 2) as "LVDT output 1" as shown on figure 5.

10.8.2.7 Remove the gauge block (or series of gauge blocks) from beneath the LVDT core extension rod and allow the LVDT core extension rod to rest on the comparator stand base.

10.8.2.8 Record the LVDT output obtained as "LVDT output 2" as shown on figure 5.

10.8.2.9 Calculate and record the LVDT output change and the "LVDT factor" as shown on figure 5.

10.8.3 *Linearity of the LVDT*:

10.8.3.1 Select appropriate displacement increments (gauge blocks) to displace the LVDT core through its total linear range. It is recommended that the gauge blocks be selected such that a minimum of four readings—equally spaced throughout the LVDT total linear range—are used.

10.8.3.2 Raise the LVDT core extension rod, and place the appropriate gauge block(s) on the comparator stand base beneath the LVDT core extension rod.

10.8.3.3 Record the gauge block(s) height in column 1 and the corresponding output of the LVDT readout equipment in column 2 as shown on figure 5.

10.8.3.4 Continue to displace the LVDT core at the selected increments until it has been displaced through its total linear range.

10.8.3.5 Record the gauge block(s) height and the corresponding output of the LVDT readout equipment at each displacement increment as shown on figure 5.

10.8.3.6 Calculate and record values of percent of TLR and percent error for each displacement increment as shown on figure 5.

10.8.3.7 Check the linearity of the LVDT in accordance with provisions in subparagraph 12.1.

10.8.4 *Repeatability of the LVDT*:

10.8.4.1 Remove the gauge block(s) from beneath the LVDT core extension rod.

10.8.4.2 Repeat subparagraphs 10.8.3.2 through 10.8.3.5 using the same displacement increments (gauge blocks) selected in subparagraph 10.8.3.1.

10.8.4.3 Calculate and record the voltage error at each corresponding displacement increment as shown on figure 5.

10.8.4.4 Check repeatability of the LVDT in accordance with provisions in subparagraph 12.2.

10.9 *Method B—Micrometer Fixture Calibration*:

10.9.1 Secure the LVDT body into the chuck of the micrometer fixture as shown on figure 4. (DO NOT overtighten the chuck around the LVDT body.)

10.9.2 Slide the LVDT core with the Teflon guides and core extension rod assembly into the LVDT body.

10.9.3 Attach the LVDT core extension rod to the spindle of the micrometer head carrier using an appropriate attachment assembly as shown on figure 4.

10.9.4 Apply voltage to the LVDT. Ensure that the line voltage is compatible with the power requirements of the signal conditioner. Refer to the manufacturer's operating instructions for voltage requirements.

10.9.5 Ensure that the signal conditioner has had a minimum 30-minute warmup time.

10.9.6 *Null Position of LVDT*:

10.9.6.1 Turn the GAIN control of the signal conditioner (see note 1) to the minimum gain setting.

10.9.6.2 Adjust the ZERO control of the signal conditioner to achieve an output of zero volt.

10.9.6.3 Turn GAIN control to approximately the midpoint position.

10.9.6.4 Remove the LVDT core by sliding the micrometer head carrier along the bed of the micrometer fixture until the output is approximately 0 volt. Tighten the micrometer head carrier to the bed of the micrometer fixture.

10.9.6.5 Rotate the micrometer head to achieve a reading of exactly 0.000 volt. This is the null position of the LVDT.

10.9.7 *Signal Conditioner Span Setting* (LVDT factor determination):

10.9.7.1 Reset the electronic digital micrometer to read 0.000.

10.9.7.2 Rotate the micrometer head until the LVDT core has been displaced a distance equal to one-half the total linear range of the LVDT; i.e. for an LVDT having a 2-inch (50.8-mm) total linear range, the digital micrometer should read ±1.000 inch (25.4 mm). Record the value of LVDT output achieved as "LVDT output 1."

10.9.7.3 Adjust the signal conditioner, using the GAIN control screw, so the output of the LVDT readout equipment is equal to ±10.000 volts d.c. (see note 2). Polarity depends on the wiring of the LVDT.

10.9.7.4 Rotate the micrometer head in the opposite direction until the electronic digital micrometer reads 0.000 volt. The readout equipment should indicate 0.000 volt; if it does not, reset by adjusting the ZERO adjustment.

10.9.7.5 Repeat subparagraphs 10.9.7.2 through 10.9.7.4 until values of 0.000 and ±10.000 volts (see note 2) are obtained.

10.9.7.6 Rotate the micrometer head until the electronic digital micrometer indicates the LVDT has been displaced a distance equal to one-half the total linear range of the LVDT. (This is to be equal displacement but opposite direction as that achieved in subpar. 10.9.7.2.)

10.9.7.7 Record the LVDT output obtained as "LVDT output 2."

10.9.7.8 Calculate and record the LVDT output change and the "LVDT factor."

10.9.8 *Linearity of the LVDT*:

10.9.8.1 Select appropriate displacement increments to displace the LVDT core through its total linear range. It is recommended that the displacement increments be selected such that a minimum of four readings—equally spaced throughout the LVDT range—are used.

10.9.8.2 Rotate the micrometer head until the electronic digital micrometer output corresponds to the desired displacement increment.

10.9.8.3 Read and record the digital micrometer output and corresponding LVDT output voltage.

10.9.8.4 Continue to displace the LVDT by rotating the micrometer head to the selected increments until the LVDT core has been displaced through its total linear range.

10.9.8.5 Record the LVDT displacement as indicated by the digital micrometer and the corresponding voltage output at each displacement increment.

10.9.8.6 Calculate and record values of percent of TLR and percent error for each displacement increment.

10.9.8.7 Check the linearity of the LVDT in accordance with provisions of subparagraph 12.1.

10.9.9 *Repeatability of the LVDT*:

10.9.9.1 Rotate the micrometer head until the digital micrometer reads 0.000 volt.

10.9.9.2 Repeat subparagraphs 10.9.8.2 through 10.9.8.5 using the same displacement increments selected in subparagraph 10.9.8.1.

10.9.9.3 Calculate and record the voltage error at each corresponding displacement increment as shown on figure 5.

10.9.9.4 Check repeatability of the LVDT in accordance with provisions in subparagraph 12.2.

11. Calculations

11.1 Calculations are as shown on the "Linear Variable Differential Transformer Calibration" form. (fig. 5).

12. Interpretation of Results

12.1 *Linearity*.–Table 1 is to be used for evaluation of LVDT linearity.

12.1.2 If percent error, at the listed percent of total linear range, exceeds the amount listed in table 1 the LVDT should be rejected.

12.2 Repeatability.–The voltage error should not exceed ±0.05 volt at any displacement. If the voltage error (col. 8, fig. 5) exceeds ±0.05 volt, the LVDT should be rejected.

13. Report

13.1 The report is to consist of a completed and checked "Linear Variable Differential Transformer Calibration" form (fig. 5).

13.2 All calculations are to show a checkmark.

14. Background Reference

"Handbook of Measurement and Control," *Handbook HB-76*, copyright 1976 by Schaevitz Engineering, Pennsauken, NJ, Library of Congress Catalog No. 76-24971.

Table 1. – LVDT percent error tolerances.

Total linear range		Range, plus or minus		Allowable percent error over indicated percent of total linear range, %		
in	mm	in	mm	50	75	100
0.10	2.5	0.050	1.25	0.10	0.25	2.00
0.20	5	0.100	2.5	.10	.25	2.00
0.40	10	0.200	5.0	.10	.25	2.00
0.60	15	0.300	7.5	.10	.25	2.00
0.80	20	0.400	10	.15	.25	2.00
1.00	25	0.500	12.5	.15	.25	2.00
2.00	50	1.000	25	.25	.25	2.00
4.00	100	2.000	50	.25	.25	2.00
6.00	150	3.000	75	.15	.25	2.00
8.00	200	4.000	100	.15	.25	2.00
10.00	250	5.000	125	.15	.25	2.00
20.00	500	10.000	250	.15	.25	2.00

7-2347 (5-86) Bureau of Reclamation	**LINEAR VARIABLE DIFFERENTIAL TRANSFORMER CALIBRATION**	Designation USBR 1008-89

LVDT TYPE HR 1000 MANUFACTURER Example SERIAL NO. 15

REFERENCE STANDARD USED: ☒ GAUGE BLOCKS SERIAL NO. GB112
☐ MICROMETER FIXTURE SERIAL NO. ____

CALIBRATION PERFORMED BY ____ DATE ____

CALIBRATION CHECKED BY ____ DATE ____

LVDT FACTOR DETERMINATION

(a) LVDT TOTAL LINEAR RANGE (TLR) 2.000 ☒ in ☐ mm
(b) LVDT OUTPUT 1 10.000 V
(c) LVDT OUTPUT 2 -9.978 V
(d) LVDT OUTPUT CHANGE (b) - (c) 19.978 V
(e) LVDT FACTOR (a)/(d) 0.100 ☒ in/V ☐ mm/V

LINEARITY

TRIAL NO.	REFERENCE STANDARD LENGTH ☒ in ☐ mm (1)	PERCENT OF TLR (%)	LVDT OUTPUT (VOLTS) (2)	CHANGE IN LVDT OUTPUT (3) = (2) - (c) (VOLTS) (3)	LVDT MEASUREMENT (4) = (3) x (e) ☒ in ☐ mm (4)	PERCENT ERROR (5) = [(1) - (4)]/(a) x 100 (5)
1	0	0	-9.978	0	0	0
2	0.250	12.5	-7.480	2.498	0.2498	0.010
3	0.500	25	-4.982	4.996	0.4996	0.020
4	0.750	37.5	-2.483	7.495	0.7495	0.025
5	1.000	50	0.000	9.978	0.9978	0.110
6	1.250	62.5	2.525	12.503	1.2503	-0.015
7	1.500	75	5.037	15.015	1.5015	-0.075
8	1.750	87.5	7.533	17.511	1.7511	-0.055
9	2.000	100	10.000	19.978	1.9978	0.110

REPEATABILITY

TRIAL NO.	REFERENCE STANDARD LENGTH ☒ in ☐ mm (6)	PERCENT OF TLR (%)	LVDT OUTPUT (VOLTS) (7)	VOLTAGE ERROR (8) = (7) - (2) (VOLTS) (8)
1	0	0	-9.976	0.002
2	0.250	12.5	-7.519	-0.039
3	0.500	25	-5.003	-0.021
4	0.750	37.5	-2.522	0.039
5	1.000	50	0.000	0.000
6	1.250	62.5	2.532	0.007
7	1.500	75	5.040	0.003
8	1.750	87.5	7.531	-0.002
9	2.000	100	10.000	0.000

LINEARITY ☒ ACCEPT ☐ REJECT

REPEATABILITY ☒ ACCEPT ☐ REJECT

REMARKS ____

GPO 850-945

Figure 5. - Linear variable differential transformer calibration — example.

Calibration Data

LINEAR VARIABLE DIFFERENTIAL TRANSFORMER CALIBRATION

LVDT TYPE GP911-5-S MANUFACTURER OMEGA SERIAL NO.

REFERENCE STANDARD USED: ☐ GAUGE BLOCKS SERIAL NO.
☒ MICROMETER FIXTURE SERIAL NO.

CALIBRATION PERFORMED BY D.O.W. Engineering DATE 4/12/2013

CALIBRATION CHECKED BY DATE

LVDT FACTOR DETERMINATION

(a) LVDT TOTAL LINEAR RANGE (TLR)	0.440	☒ in ☐ mm
(b) LVDT OUTPUT 1	5.02	V
(c) LVDT OUTPUT 2	0.011	V
(d) LVDT OUTPUT CHANGE (b) - (c)	5.009	V
(e) LVDT FACTOR (a)/(d)	0.0878419	☒ in/V ☐ mm/V

LINEARITY

TRIAL NO.	REFERENCE STANDARD LENGTH ☒ in ☐ mm (1)	PERCENT OF TLR (%)	LVDT OUTPUT (VOLTS) (2)	CHANGE IN LVDT OUTPUT (3) = (2) - (c) (VOLTS) (3)	LVDT MEASUREMENT (4) = (3) x (e) ☒ in ☐ mm (4)	PERCENT ERROR $(5) = \frac{(1) - (4)}{(a)} \times 100$ (5)
1	0.000	0	0.011	0	0	0.000%
2	0.055	12.5	0.605	0.594	0.0521781	0.641%
3	0.110	25	1.242	1.231	0.1081334	0.424%
4	0.165	37.5	1.876	1.865	0.1638251	0.267%
5	0.220	50	2.518	2.507	0.2202196	-0.050%
6	0.275	62.5	3.152	3.141	0.2759114	-0.207%
7	0.330	75	3.78	3.769	0.3310761	-0.245%
8	0.385	87.5	4.42	4.409	0.3872949	-0.522%
9	0.440	100	5.02	5.009	0.44	0.000%

REPEATABILITY

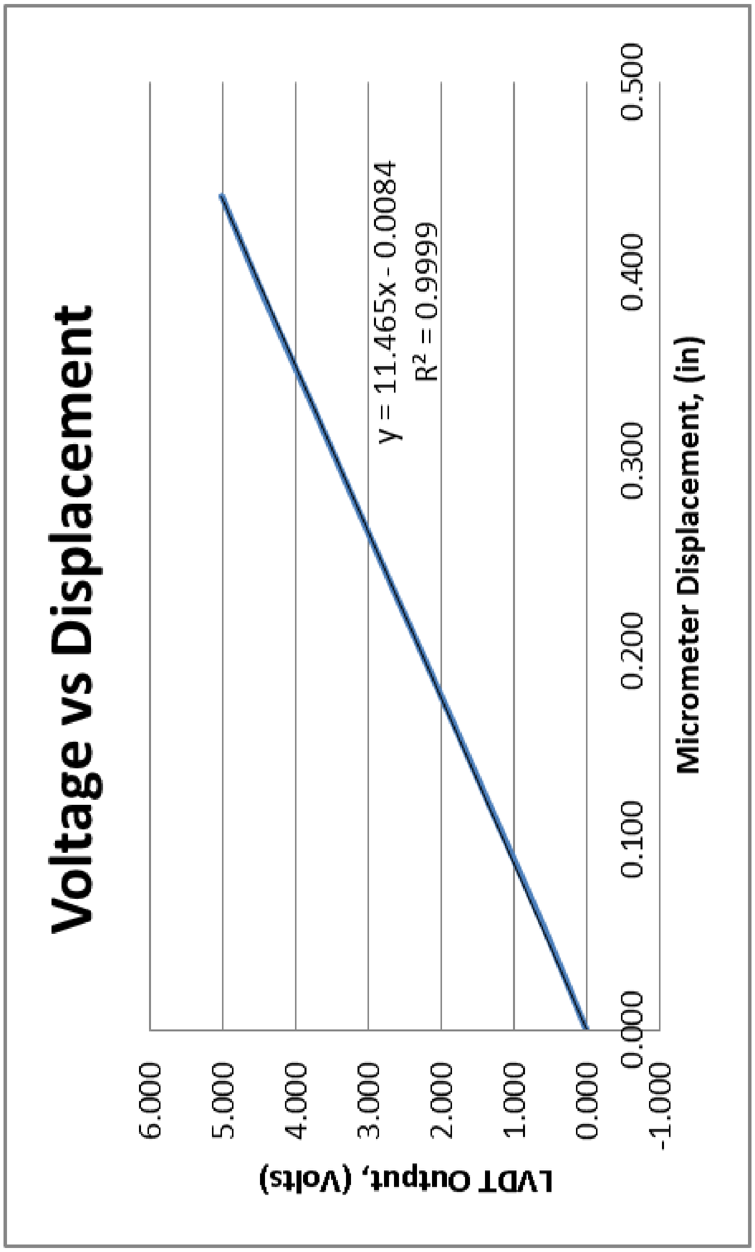
TRIAL NO.	REFERENCE STANDARD LENGTH ☒ in ☐ mm (6)	PERCENT OF TLR (%)	LVDT OUTPUT (VOLTS) (7)	VOLTAGE ERROR (8) = (7) - (2) (VOLTS) (8)
1	0.000	0	0.011	0
2	0.055	12.5	0.608	0.003
3	0.110	25	1.242	0
4	0.165	37.5	1.877	0.001
5	0.220	50	2.512	-0.006
6	0.275	62.5	3.15	-0.002
7	0.330	75	3.79	0.01
8	0.385	87.5	4.41	-0.01
9	0.440	100	5.02	0

LINEARITY ☒ ACCEPT ☐ REJECT

REPEATABILITY ☒ ACCEPT ☐ REJECT

REMARKS

Calibration Curve



Appendix G – Test Data

GAGE REPEATABILITY AND REPRODUCIBILITY DATA SHEET
ANOVA METHOD

Customer Name:	Norris		
Part No: -	Gage Name: -	Appraiser: DOW	
Characteristic: -	Gage Number: -	RRN: -	
Specification: -	Gage Type: LVDT		
Tol. Span: -	Trials: 3	Parts: 10	Appraisers: 3	Date Performed: 4/16/2013

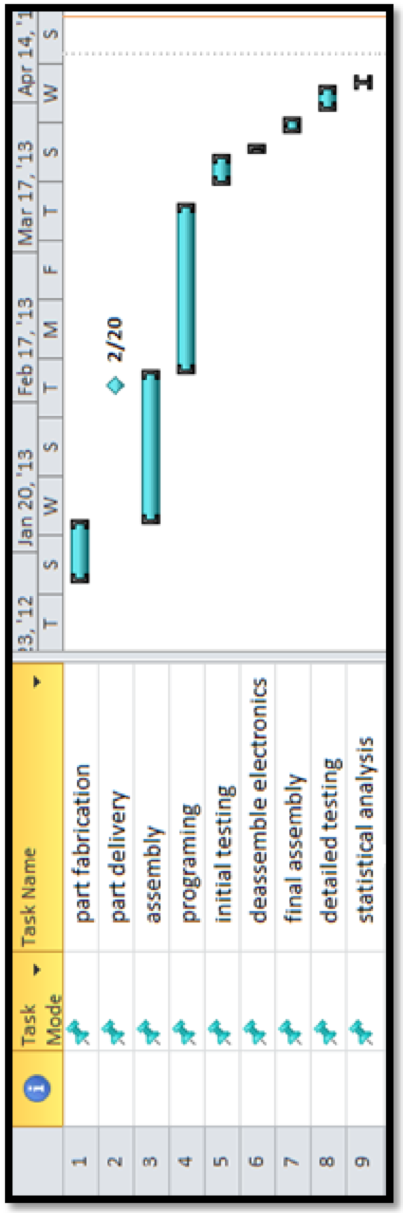
APPRAISER/ TRIAL #		PART 1	2	3	4	5	6	7	8	9	10	AVERAGE	
1. A	1	855.00	945.00	657.00	1465.00	730.00	1314.00	361.00	2436.00	1051.00	700.00		1051.400
2.	2	804.00	971.00	639.00	1542.00	733.00	1352.00	305.00	2491.00	1061.00	691.00		1058.900
3.	3	860.00	911.00	645.00	1460.00	716.00	1395.00	365.00	2478.00	1082.00	682.00		1059.400
4.	AVE	839.67	942.33	647.00	1489.00	726.33	1353.67	343.67	2468.33	1064.67	691.00	X_a=	1056.567
5.	R	56.00	60.00	18.00	82.00	17.00	81.00	60.00	55.00	31.00	18.00	r_a=	47.800
6. B	1	778.00	928.00	691.00	1503.00	734.00	1339.00	333.00	2479.00	1091.00	721.00		1059.700
7.	2	786.00	922.00	639.00	1529.00	714.00	1332.00	299.00	2439.00	1077.00	678.00		1041.500
8.	3	795.00	924.00	613.00	1525.00	705.00	1342.00	304.00	2461.00	1099.00	726.00		1049.400
9.	AVE	786.33	924.67	647.67	1519.00	717.67	1337.67	312.00	2459.67	1089.00	708.33	X_b=	1050.200
10.	R	17.00	6.00	78.00	26.00	29.00	10.00	34.00	40.00	22.00	48.00	r_b=	31.000
11. C	1	812.00	950.00	606.00	1571.00	744.00	1390.00	357.00	2439.00	1107.00	661.00		1063.700
12.	2	786.00	953.00	627.00	1546.00	721.00	1314.00	296.00	2440.00	1069.00	675.00		1042.700
13.	3	812.00	979.00	640.00	1495.00	744.00	1353.00	330.00	2470.00	1129.00	721.00		1067.300
14.	AVE	803.33	960.67	624.33	1537.33	736.33	1352.33	327.67	2449.67	1101.67	685.67	X_c=	1057.900
15.	R	26.00	29.00	34.00	76.00	23.00	76.00	61.00	31.00	60.00	60.00	r_c=	47.600
16. PART												X=	1054.889
AVERAGE		809.78	942.56	639.67	1515.11	726.78	1347.89	327.78	2459.22	1085.11	695.00	R_p=	2131.444

Anova Table

Source	DF	SS	MS	F	Sig
Appraiser	2	1016.0222	508.0111	0.81	
Parts	9	29535247.7778	3281694.1975	5243.16	*
Appraiser-by-Part	18	16001.0889	888.9494	1.42	
Equipment	60	37554.0000	625.9000		
Total	89	29589818.8889			

* Significant at α = 0.05 level

Appendix H – Gantt Chart



Appendix I– CAD Drawings

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Drawings start on next page.

NORRIS
A DOVER COMPANY

Measuring Total Indicator Runout

Andrew Dickey, Justin O'Neal, and

Daniel Whittlesey

D.O.W. engineering solutions

D.O.W. engineering solutions

Meet the Team

Danny Justin Andrew

Norris Sucker Rods

- Headquartered in Tulsa, OK.
- World's leading manufacturer of sucker rods
- Began in 1882 with wooden sucker rod production
- Produced first metal rod
- 6.4 million feet of rod produced each month

Sucker Rod

- Steel rod, 25’- 30’in length
- Used in the oil and gas industry
- Joins surface and downhole components
- Sizes from 5/8” – 1 1/8”
- Various grades

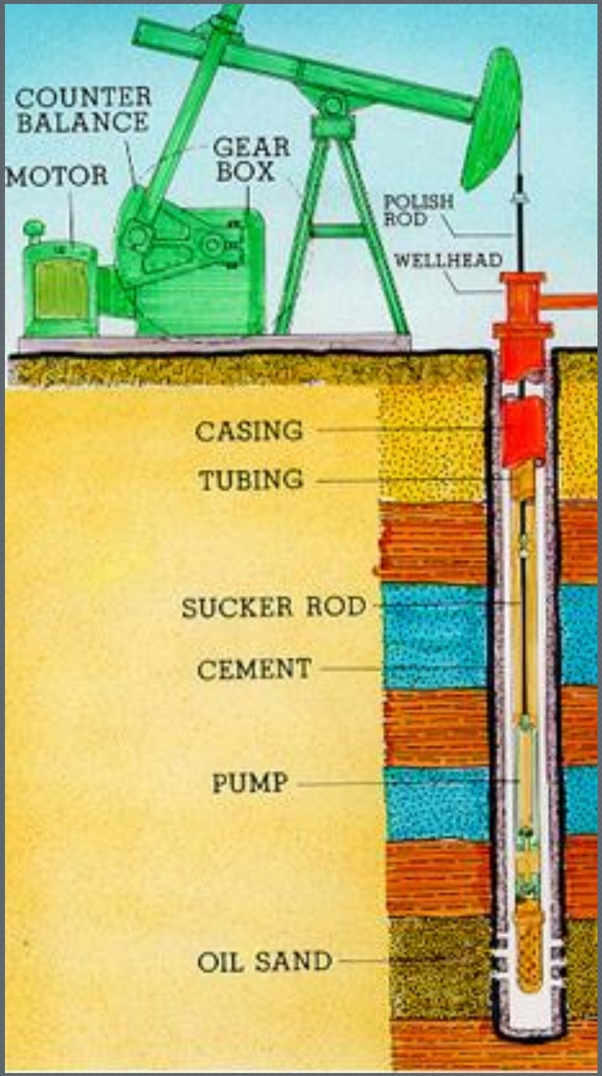


Image Source: http://sjvgeology.org/oil/pumpjack.jpg

Total Indicator Runout

- TIR is difference between the maximum and minimum readings of a dial indicator, or similar device, monitoring a face or cylindrical surface during one complete revolution of the monitored surface.
- For sucker rods, TIR tolerances are governed by the American Petroleum Institute (API).
- The tolerances are outlined in API Spec 11B.

Problem Statement

- Develop a new system of checking for total indicator run out (TIR). System will be more user friendly and also be able to handle 15,000 rods per day. Proposed system will cut down on cycle time while meeting API specification.

Currently:

- Norris has equipment installed to check TIR
- Only 10% of rods produced are checked for TIR
- Discrepancy with third party
- User interference

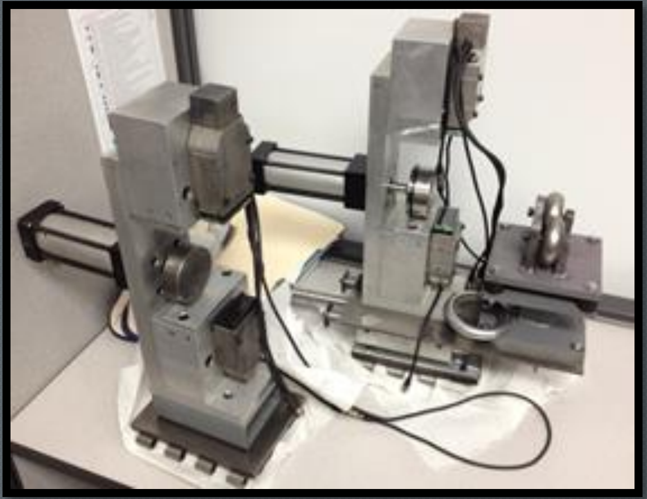
API Specification 11B

- **A.6.2 End Straightness**
  - **A.6.2.1 Sucker Rods and Pony Rods**

    End straightness shall be measured by supporting the rod body at a distance of 6.00 in. (152.4 mm) from the rod pin shoulder. The rest of the rod shall be supported at a maximum of 6.00 ft (1.83 m) with centers in the same plane. The amount of TIR bend is measured via a dial indicator, laser or other comparable measuring device. The amount of bend shall be measured at the machined surface of the pin shoulder OD. The maximum allowable TIR values for all rod sizes 5/8 in. to 11/8 in. (15.88 mm to 28.58 mm) is 0.130 in. (3.30 mm).

Current System

- Keyence shadow system
- Pneumatic cylinders to push rods
- East / West systems
  - East has spindle system to adjust for tolerance in rod length



Disadvantages:

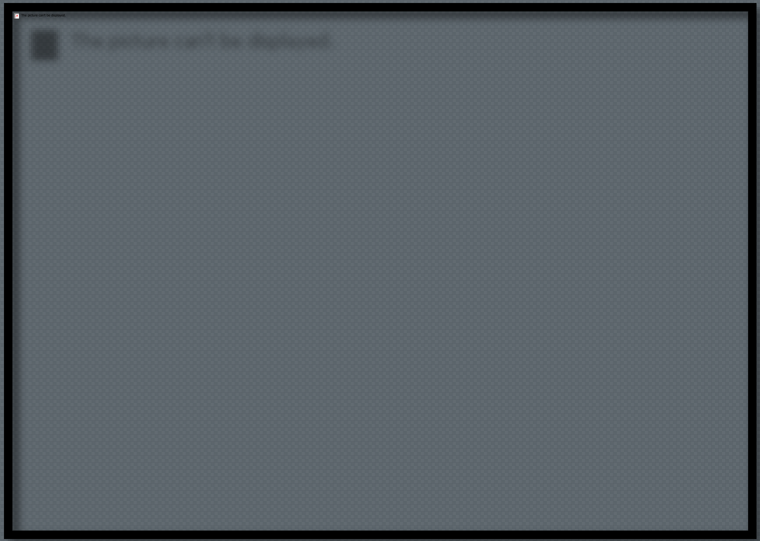
Bulky

Susceptible to user interference

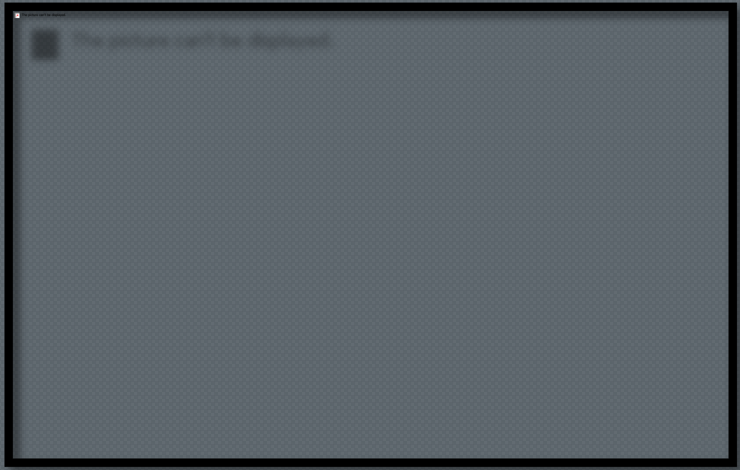
Expensive

Video

Proposed Design



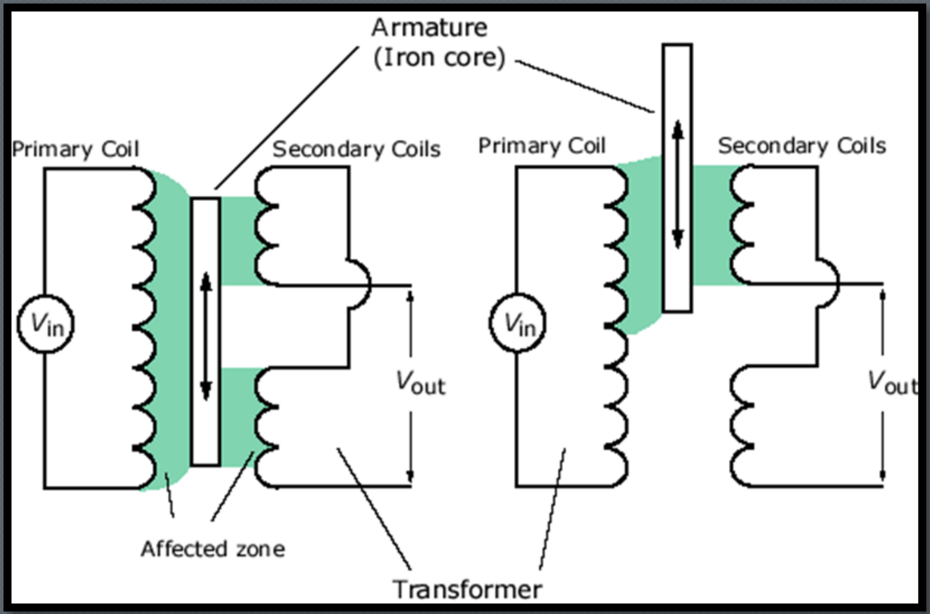
- Linear Variable Displacement Transformer (LVDT)
- Pneumatic cylinder to lift LVDT into place



- Proximity sensor stop system
- Roller system to move rods

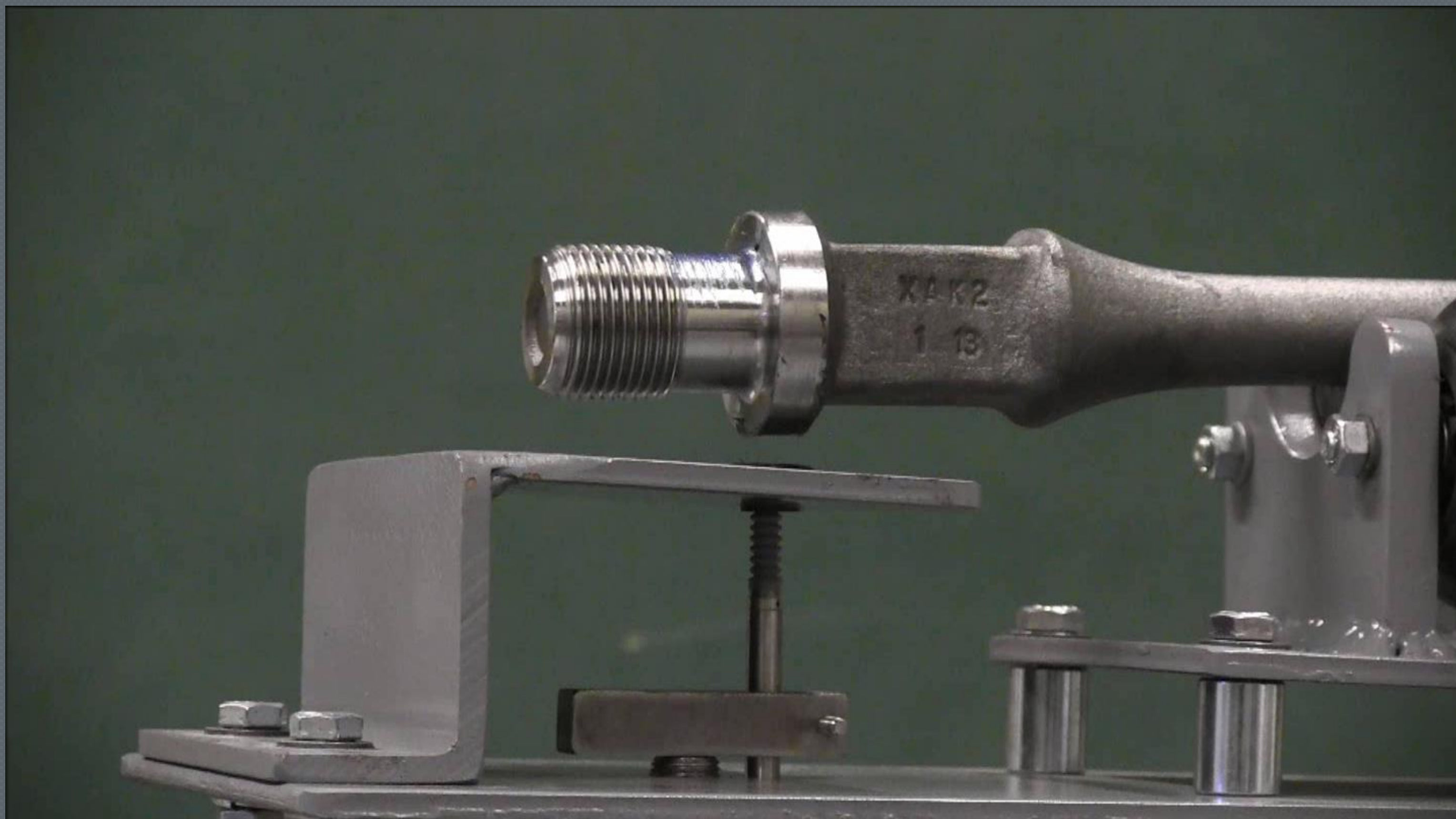
Linear Variable Differential Transformer (LVDT)

- Proven technology
- Compact
- Ideal for harsh industrial environments
  - IP65 Environmental Rating
- Stainless steel body

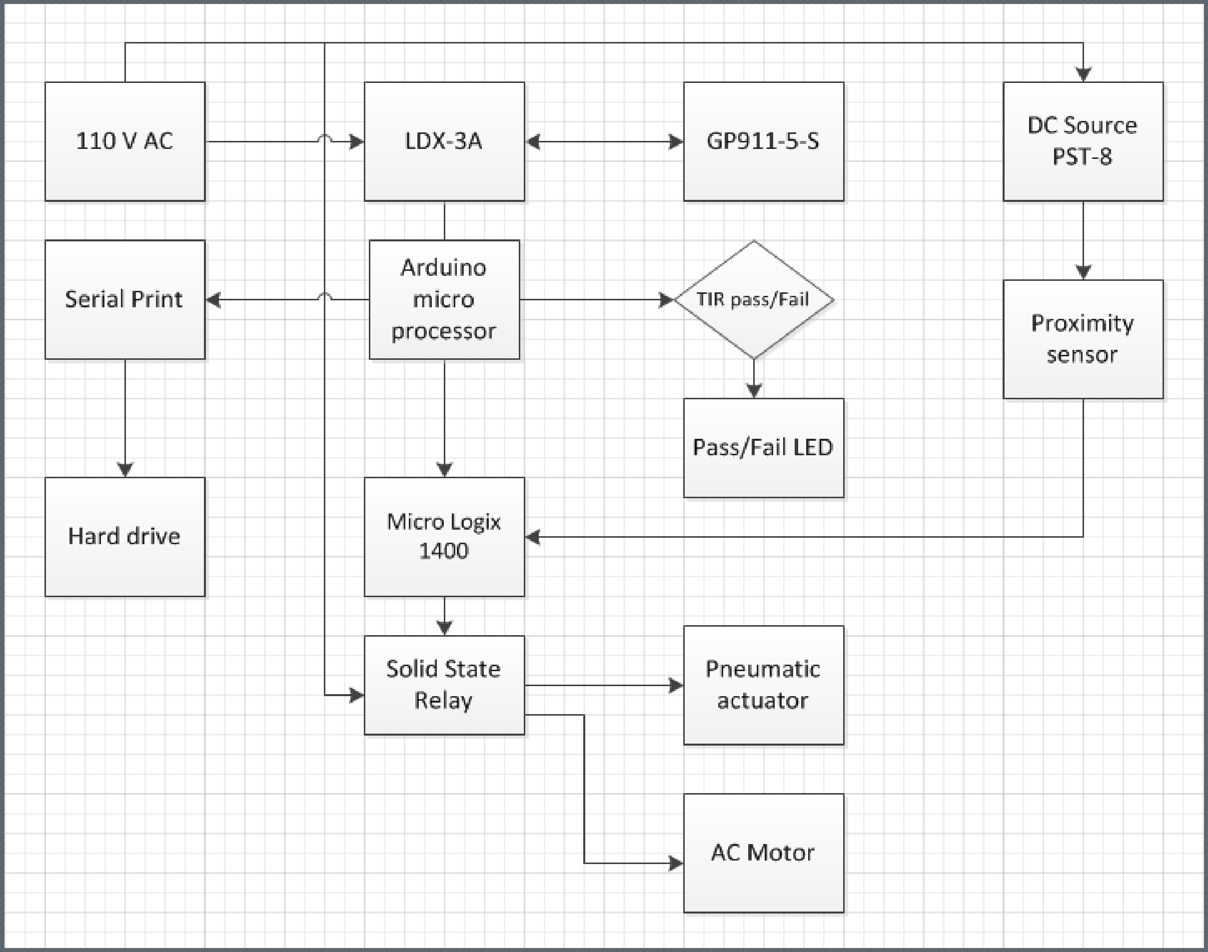


Source: http://www.efunda.com/designstandards/sensors/lvdt/images/lvdt_how.gif

Video



Design layout

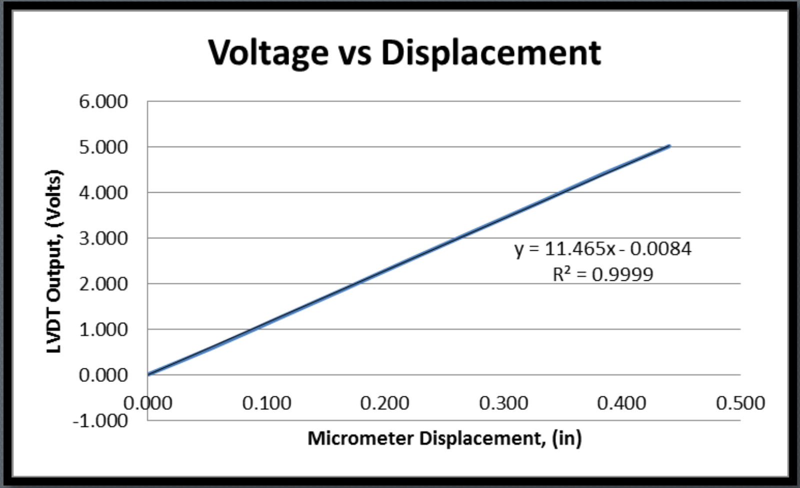


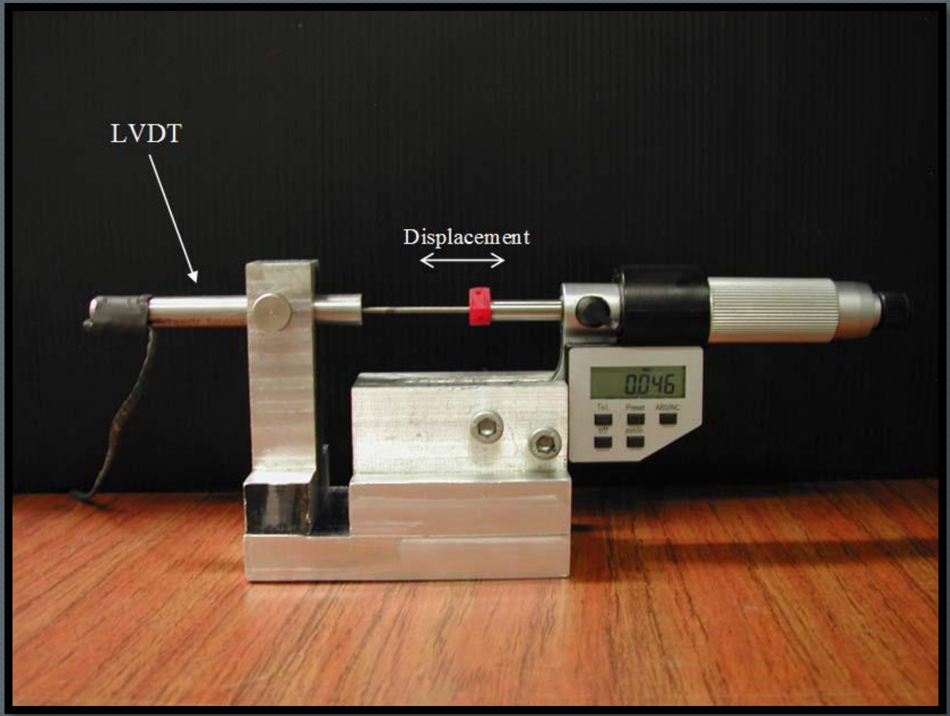
Calibration

- ASTM F2537-06(2011)
- USBR 1008-89

- Micrometer Method

- Generated calibration curve with R^2 – values





Source:
https://nees.org/data/get/facility/RPI/TrainingAndCertification/OnSiteProcedures/LVDT%20Calibration%20Procedure.pdf

Testing

- Performed measurement system analysis (MSA) by conducting a gage R&R (repeatability and reproducibility) study
- ANOVA (analysis of variance) technique
- Followed guidelines for MSA:

  Using supplied rods (4 – 5/8" and 4 – 1" rods):
  - 3 appraisers
  - 3 trials
  - 10 parts

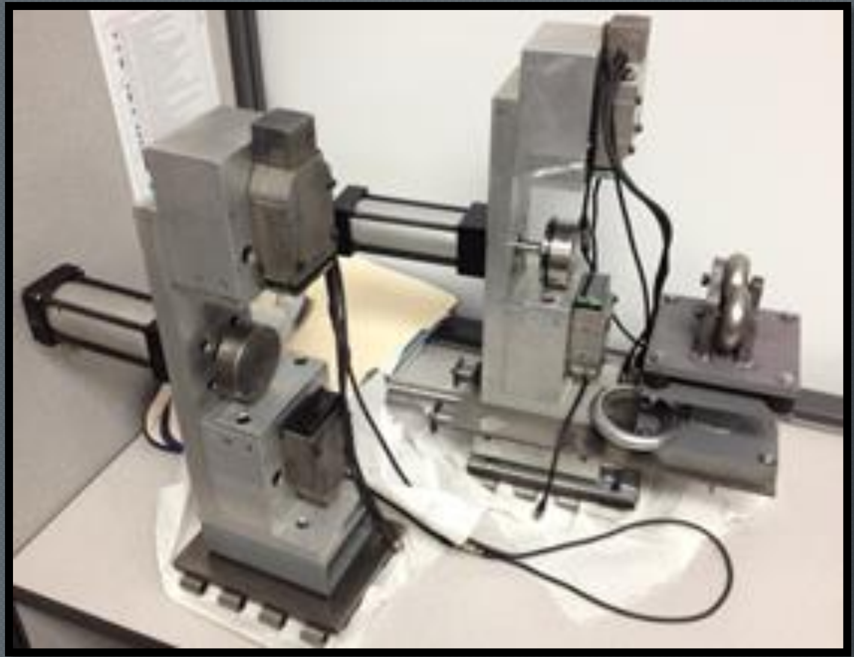
Testing / Data Analysis

Anova Report	Standard Deviation (σ)	% Total Variation	% Contribution
Repeatability (EV)	26.2031	4.3%	0.2%
Reproducibility (AV)	0.0000	0.0%	0.0%
Appraiser by Part (INT)	5.1288	0.8%	0.0%
GRR	26.2031	4.3%	0.2%
Part-to-Part (PV)	603.7851	99.9%	99.8%
		Gage system O.K	
Note:			
Tolerance = 0.00			Total variation (TV) = 604
Number of distinct data categories (ndc) =		32	
		Gage discrimination acceptable	

Verified using Ford Verification data.

Cost Analysis – Current System

- Keyence system
- LS-7501
  - Two sensors one controller
  - $13,000



Cost Analysis – Proposed System

Part	Quantity	Cost/Part ($)	Total Cost($)
Parker Solenoid Valve	1	98.95	98.95
Solid State Relay	3	31.86	95.58
Flow Control Valve	2	23.49	46.98
Pneumatic Quick Connect Fittings	10	2.35	23.50
1/4" Nylon Hose	1	20.95	20.95
Flow Regulator	1	64.20	64.20
Spring actuated LVDT	1	525.00	525.00
AC powered signal conditioning	1	515.00	515.00
DC power supply for inductive sensor	1	165.00	165.00
Inductive proximity sensor	1	84.00	84.00
Microprocessor	1	29.95	29.95
Pneumatic actuator	1	25.00	25.00
Sub Total for One Side			**$1,694.11**
Total with 10% MISC			**$1,863.52**
Total for Both Sides			**$3,727.04**

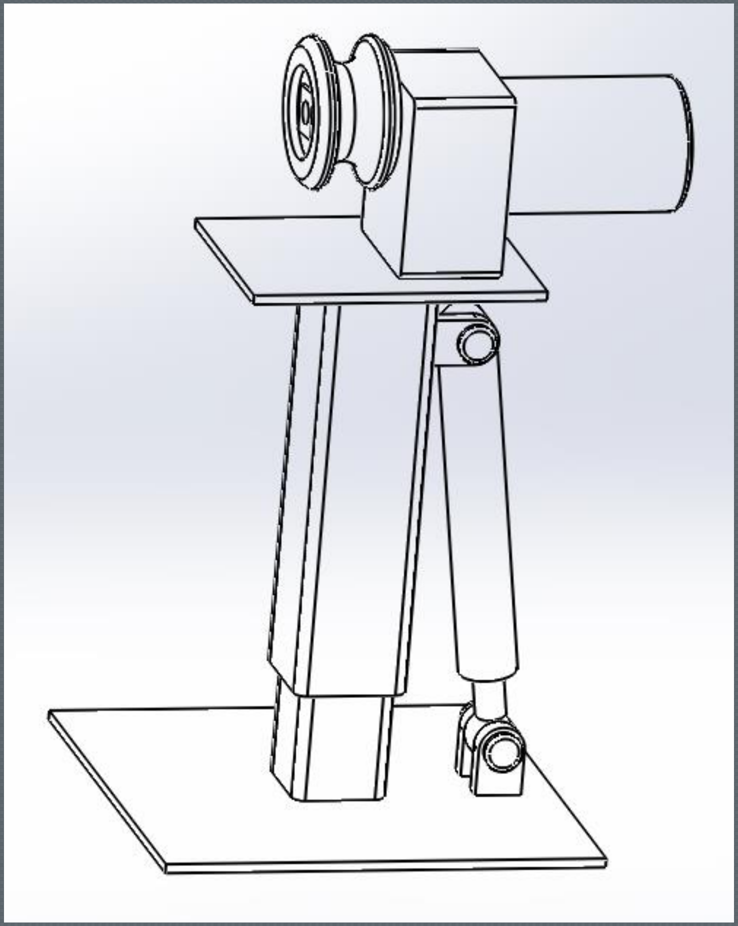
Savings of $9,272.96 per station

Recommendations

- Current system uses pneumatic cylinder to push rods
  - Proposed system lifts rods up and uses rollers to move rods from side to side
- Automated stop system to accurately position shoulder over sensor
- Implement system to track rods

Rod Mover Design

- Pneumatic cylinder to actuate stand
- Motor mounted to drive roller
- Two bi-directional motors



Conclusion

- Proposed System
  - Less user interference
  - Reduced cycle time
  - "Drop-in" measurement system design
  - Cost less
  - Some modifications needed to existing system
- Current System
  - Operational on two stations
  - Cost is much higher
  - Bulky

Special Thanks

- Entire Norris Team
- Dr. Weckler
- Wayne Kiner
- Mike Veldman

Questions?

Norris Sucker Rod Project

Andrew Dickey, Justin O'Neal, and Daniel Whittlesey

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Introduction

Mission Statement

Our mission is to use the knowledge and expertise of our members to provide quality service and innovative solutions to the people and businesses of Oklahoma. We aim to help our clients to achieve their goals and to exceed their expectations. We value work that is done right over work that is done quickly, and seek to add value to our client's businesses through quality work.

Problem statement

API specification 11B requires that sucker rods are tested for Total Indicator Reading sometimes referred to as "Total Indicator of Run out" or TIR. Norris has designed and installed equipment on several of the CNC rod end threading machines to check TIR. At present they do not perform inspection on all rods. Norris desires to expand this operation to check TIR on all rods or perform 100% inspection.

Statement of Work

Background: API specification 11B requires that sucker rods are tested for Total Indicator Reading (TIR). Norris Sucker Rods has designed and installed equipment on several of the CNC rod end threading machines to check TIR. At present, they do not perform inspection on all rods, but they do desire to expand operations to check TIR on 100% of the rods. After the rods are inspected and TIR measured, random samples are sent to a third party for "verification". In the past Norris has not had some problems with their readings matching up with the third party's readings. As of late this has not been as big of an issue, but Norris still wants a complete remake of their current process. We will be designing a new mounting system that will have much less user interference. Doing this will allow for 100% inspection of all rods produced, and will not interfere with the operators.

Scope: The objective of this project is to develop a new process for measuring total indicator reading on sucker rods for Norris Sucker Rods. The new process will be integrated into the production process and will inspect all rods (15,000 per day maximum) as they are produced. The total cost must be less than $60,000. After the measuring process has been completed, a statistical analysis of rod failures will be done to identify likely causes of TIR failures. As well, attention will be given to the best way to address non-conforming rods.

Deliverables: 1) Completed design/prototype
2) Layout/location of inspection equipment
3) Process for reworking non-conforming rods
4) Calibration process to ensure alignment with third party

Period: Fall and Spring Semesters (8/2012 – 5/2013)

Location: Norris Sucker Rods – Tulsa, OK
Oklahoma State University – Stillwater, OK

Applicable Standards: API Spec 11B

Acceptance Criteria: TBD. Further discussion with Norris is needed to determine exact acceptance criteria. However, the design must meet the basic requirements as outlined in the scope of the project of reliability, durability, cost, and accuracy.

Work Breakdown Structure

See Appendix A for Work Breakdown Structure.

Tasks List

Oversight

- Weekly progress reports submitted to Norris, Win Adams, and Dr. Weckler
- Ensure open communication between parties

Research, Technology, and Information

- Understand requirements set forth by API Spec 11B
- Research methods/technologies used to measure TIR
- Research technologies that are applicable to our situation
- Visit Norris and determine possible locations to integrate measuring system
- Gather information (measurements, specs, layout) needed for design

Design

- Develop designs based upon location, measuring device, etc.
- Perform engineering analyses on designs (fatigue, yield, cost, etc)
- Produce drawings of design(s) and the parts included
- Put finalized design(s) in a report to be presented to Norris at end of Fall semester

Approval

- Meet with Norris and submit design(s) for approval
- Make any modifications and resubmit for approval

Fabrication

- Submit approved drawings to have parts fabricated
- Produce a calibration rod

Integration

- Assemble measuring devices into mounting system
- Integrate assembled system into Norris' production process (at specified location)
    - Use existing power
    - Use existing PLCs (if needed)
    - Use existing marking system for failed rods
- Calibrate system

Testing

- Perform functionality tests
- Perform tests for accuracy, repeatability, and durability

Data Collection and Statistical Analysis

- Log data from measuring system
- Perform statistical analysis on collected data as well as on data from Q.C.
- Identify likely areas that cause TIR failures

Customer Satisfaction

- Submit all deliverables to Norris
- Work with Norris to ensure their requirements are met and that they are satisfied

Investigation

Industry Analysis

Our research showed that no sucker rod manufacturer currently inspects 100% of their rods. Norris will be the first to inspect all rods with the implementation of the new measuring system. Not only will this allow them to better market their product, it will also serve as an additional quality check. This would be beneficial since Norris offers their "Zero Defects Guarantee".

Technical Analysis

Technical specifications for the measurement of end straightness are defined in API Spec 11B.

From API Spec 11B:

> **A.6.2 End Straightness**
> **A.6.2.1 Sucker Rods and Pony Rods**
> End straightness shall be measured by supporting the rod body at a distance of 6.00 in. (152.4 mm) from the rod pin shoulder. The rest of the rod shall be supported at a maximum of 6.00 ft (1.83 m) with centers in the same plane. The amount of TIR bend is measured via a dial indicator, laser or other comparable measuring device. The amount of bend shall be measured at the machined surface of the pin shoulder OD. The maximum allowable TIR values for all rod sizes 5/8 in. to 11/8 in. (15.88 mm to 28.58 mm) is 0.130 in. (3.30 mm).

The method used by Norris, as well any companies that perform inspections on sucker rods, must conform to the guidelines set forth by API. As a result, most methods are similar in that they involve rotating the rod 360° on adequately spaced supports while measuring the total indicator run out using an approved measuring device or system.

While the methods of measuring end straightness may be similar, the measurement devices vary. These devices range from simple dial indicators to sophisticated optical measuring systems. The current device used by Norris is an optical micrometer system from Keyence. This type of device can provide the accuracy and repeatability (0.12mil and 0.008mil, respectively) needed while being integrated into the production process without slowing the rate of production. However, the environment these devices are subjected to at Norris make this type of system less than ideal. Therefore, other technologies were pursued. Linear Variable Differential Transformers (LVDT) operate much like a dial indicator but output a digital signal rather than a dial reading. LVDTs come in many setups and can be used in industrial applications.

Such factors as durability and reliability must also be taken into consideration. The design must be able to withstand a maximum of 15,000 rods per day. The measuring system must be reliable and provide accurate and repeatable results, and a simple calibration procedure should be implemented to ensure that the system is operating correctly. Consideration should be given to these aspects in order to help minimize the maintenance costs and requirements.

Patent Searches

To aid in obtaining an idea of what technologies exist that could be used to measure total indicator run out, a patent search was used. From a patent search using Google Patents for "total indicator runout", the following patents were found that were of some interest:

US7197837	**Gauge assembly for measuring diameter and total indicated runout** Honda Motor Co. Issued: 4/3/2007 Device used to measure diameter and TIR on camshafts. www.google.com/patents/US7197837
US 2002/0077770	**Method and system for identifying and evaluating runout limits of rotational components** Kaminski and Wilson Filed: 12/20/2000 Method used to measure runout on rotating components, turbines. www.google.com/patents/US20020077770
US6757636	**Computerized electronic runout** Alstom Technology Ltd. Issued: 6/29/2004 Method/Device to measure runout using magnetic field sensing www.google.com/patents/US6757636

While these patents do not pertain to the measurement of end straightness for sucker rods, the information contained does provide insight on ways to go about measuring runout. No exact matches for the measurement of total indicator on sucker rods were found.

Design Concepts

Our first design concept consisted of placing the LVDT's inside of the CNC machine that is used to cut the threads on the sucker rods. Having the LVDT's placed here would be ideal because measuring the TIR would be one process. This would cut down on the time, as well as the user interface. The problem we encountered was that there would be no way to conform to API specifications if the LVDT was inside the CNC. API specifications state that the bracings must be at certain points along the rod. The distance from the front of the loading tube to the exit end of the chuck is approximately 40 inches; therefore there would be no way to incorporate a mounting system inside the CNC that conformed to API specifications. From here we decided the next best option would be to use the current mounting system since it already conforms to API specifications. We plan on building a bracket off of the current mount that holds the LVDT. The current system uses a pneumatic cylinder to push the rod into place to measure the TIR. To make the system less bulky and more user friendly, we have decided to place a roller in the middle of system that will roll the rod into place. An inductive proximity sensor will be used as a limit switch to stop the roller once the rod is in its correct place. This will trigger the actuator to lift the LVDT up until it is touching the shoulder of the rod. The rod will then be rotated 360 degrees and checked for TIR. Once one side of the rod has been measured for TIR, the same process will be done to the other side. From here the rod will either be passed and sent on, or failed and put into the scrap pile. Appendix B shows a CAD drawing of what the set up will look like. Appendix C contains the design layout for the set up.

Financial Analysis

Proposed Budget

Component Description	Part Number	Unit Price	Quantity	Price
Spring actuated LVDT	GP11-5-S	$525	2	$1050
AC powered signal conditioning	LDX-3A	$515	2	$1030
DC power supply for inductive sensor	PST-8	$165	1	$165
Inductive proximity sensor	E57	$84	2	$168
Pneumatic actuator	0.75DSRx1.000	$250	2	$500

sub total	$2913
miscellaneous	x 1.10
total cost	$3204

Cost Comparison

The estimated cost of the full Keyence system per station is $10,000. Our budget estimates the cost of our system to be $3,204. This represents a savings of $6,796 per station. Norris sucker rods currently run 9 stations at their Tulsa plant. Utilizing our system represents a total savings of $61,164.

Project Schedule

During the 2013 spring semester, we will design and build a set up like the one shown in appendix B. From here we will be able to run tests and work out the kinks in the system. Norris will fund the project and will be sending us the needed materials; LVDTs, actuators, PLC's, etc. The setup will be in the Bio-system's laboratory on campus and will conform to API specification 11b. Once the setup is working properly, we will then present Norris with the system. From here they can decide on whether to implement the system into their manufacturing facility.

Conclusion

Our main focus is to implement a system that will be able to check TIR for 100% of the rods leaving Norris. The system must be more users friendly for the operators, as well as more efficient. The current shadow system is unreliable and is causing discrepancies between Norris and the third party inspectors. The system we are designing will be much smaller, and will therefore be much easier to maneuver around, making the system more user friendly for the operators. As well, our design will provide a significant cost benefit.

References

Sucker Rod Image on title page: http://www.norrisrods.com/images/body_pic_suckerrods1.jpg

Norris Logo on title page: http://www.ipaa.org/meetings/images/NorrisSuckerRods.JPG

Specification for Sucker rods, Polished Rods and Liners, Couplings, Sinker Bars, Polished Rod Clamps, Stuffing Boxes, and Pumping Tees. API Specification 11B, 27th edition. May 2010

Appendix A

WBS 1.0 Current System Remake

Redesign of current system used for checking TIR.

WBS 1.1 – Project Oversight

Work with Norris to ensure successful completion of the project on time and on budget. Submit progress reports to the customer when a step has been completed. Get required information from Norris, such as the CNC specs, which will be crucial to complete the project. Task is complete when information is received and progress report defining the schedule is sent out.

WBS 1.2 – Requirements

New design will have to conform to API specifications. 100% of rods being sent out must be checked. Third party readings must match the readings coming out of Norris. Task is complete when all requirements are approved.

WBS 1.3 – System Redesign

Redesign current system used to check TIR at Norris based on the requirements outlined in WBS 1.2. Task is complete once the new system is in place and has been approved by the appropriate authority.

WBS 2.0 Documentation and Technology

Research available technology's and patents that could be used in the design process. Produce drawings for mounting system.

WBS 2.1 Research

Research patents and other technologies that could be used to determine TIR. Task is complete when an acceptable technology is found that does not conflict with patents.

WBS 2.2 Technology

Once technology has been selected, decide on how to integrate the technology into the current system. Task is complete when all specifications have been gathered and technology is integrated into the design.

WBS 2.3 Drawings

Produce drawings for mounting system. Task is complete once drawings have been approved and sent out for fabrication.

WBS 3.0 Approval

Review design with customer to ensure standards are met.

WBS 3.1 Review design

Work will be complete when the engineering has been approved and drawings have been released.

WBS 4.0 Fabricate Mounting System

Fabricate and install mounting system into CNC. Task will be complete once mounting system has been integrated into the CNC.

WBS 4.1 Materials

Gather materials needed to fabricate system. Task is complete once all materials have been received and verified.

WBS 4.2 Fabricate System

Work with shop to get part machined for mounting system. Task is complete once all parts have been fabricated and inspected.

WBS 4.3 Install System

Work with Norris to install mounting system into CNC machine. Task is completed once system is installed and ready for system integration.

WBS 5.0 Integration of Sensor System

Integrate sensors into mounting system. Work is complete once system is fully functional.

WBS 5.1 Install Sensors

Install new sensors into current system. Task is complete once all sensors have been installed.

WBS 5.2 Support System

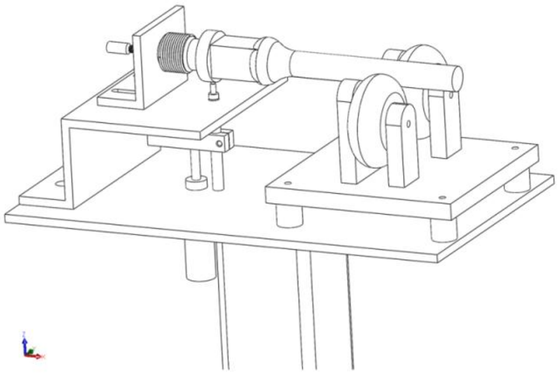
Integrate sensors into existing PLC. Task in complete once sensors have been integrated.

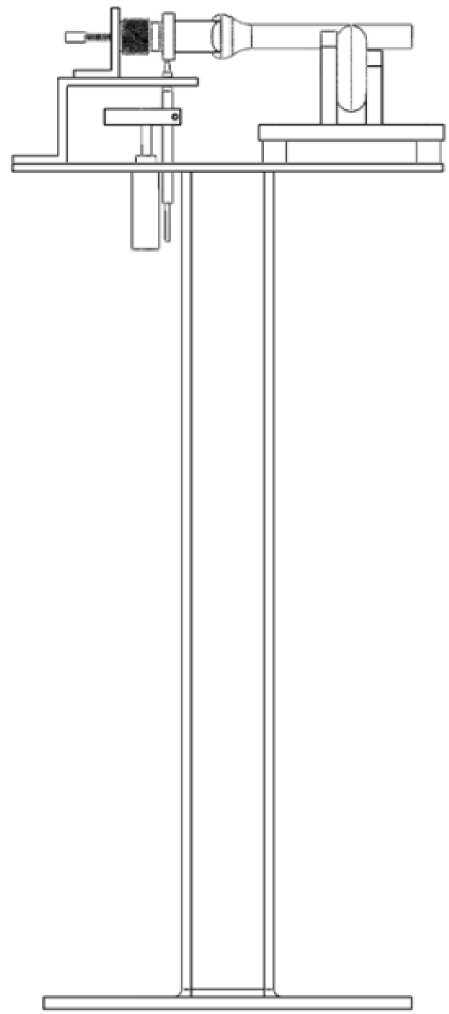
WBS 5.3 Functional Check

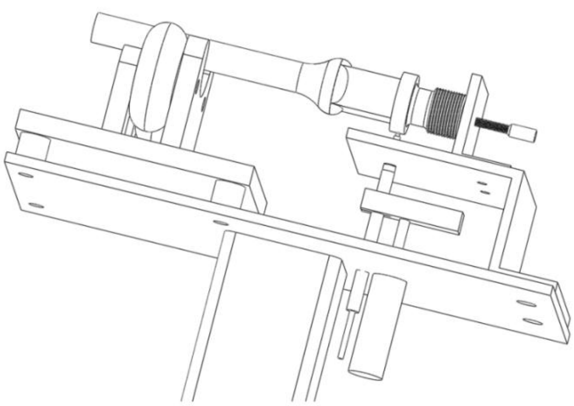
Conduct checks on all systems to ensure they are working properly. Task is complete once all systems have been checked and are working correctly.

Appendix B

Design

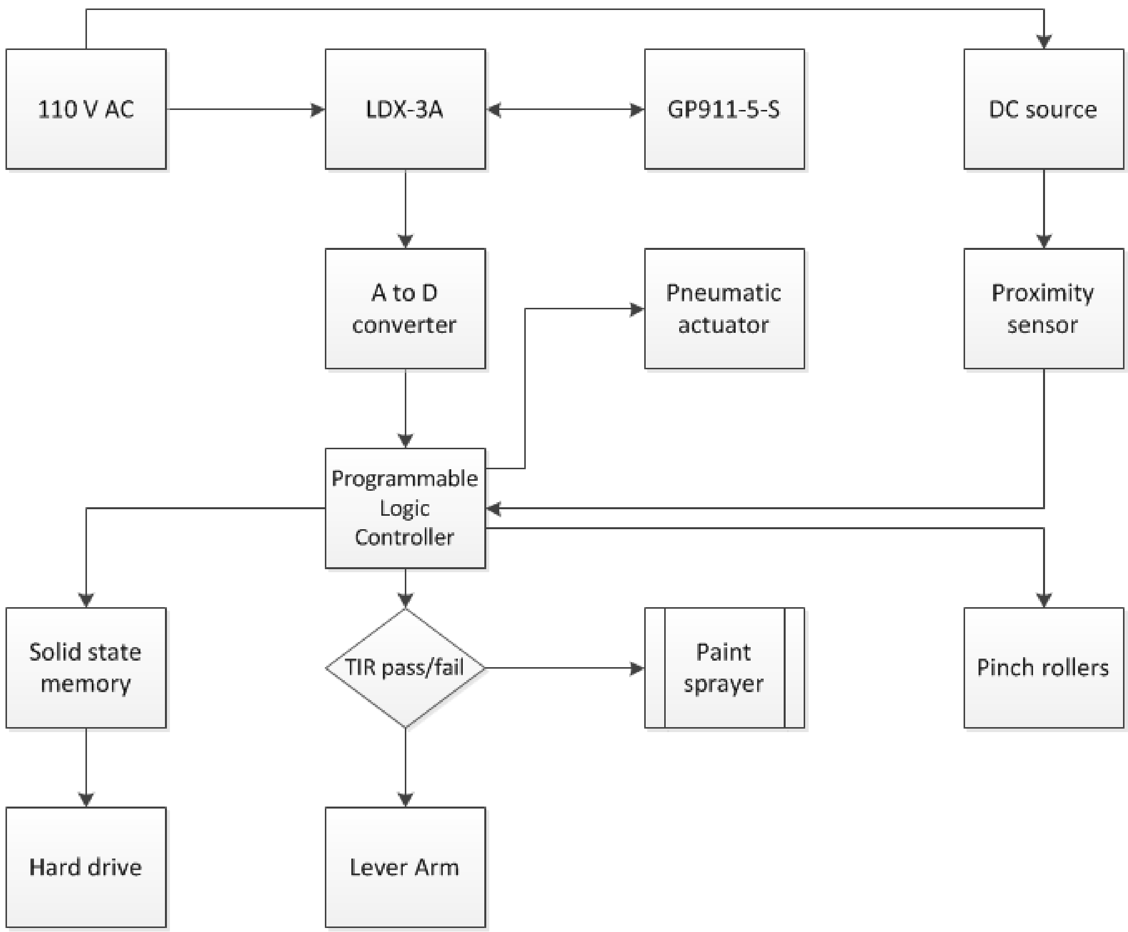






Appendix C

Design layout



NORRIS
A DOVER COMPANY

D.O.W. engineering solutions

T.I.R. Project

By: Andrew Dickey, Justin O'Neal, Daniel Whittlesey

D.O.W. Engineering

- Andrew Dickey
  - BioMechanical
  - Glenpool, OK
- Justin O’Neal
  - BioMechanical
  - Bristow, OK
- Daniel Whittlesey
  - BioMechanical
  - Ardmore, OK

Norris Sucker Rods

- One of the largest manufacturers of sucker rods
- Began in 1892 with wooden sucker rod production
- Produced first metal rod
- 6.4 million feet of rod produced each month
- Working with Tulsa facility

Sucker Rod Industry

- Used in the oil and gas industry
- Steel Rod 25’/30’
- Rods manufactured from hot rolled carbon or alloy steel
- Joins surface and downhole components
- Production based on oil and gas industry

What can set Norris apart?

- Check T.I.R on 100% of rods
- Market impact
- Premium rods sold at premium price
- Downhole guarantee

Problem

- Only 10% of rods produced are checked for TIR
- Norris has equipment installed to check TIR
- Discrepancy with third party
- User interference

T.I.R.

- Total indicator readout
- Must conform to API specification 11B
  - **A.6.2 End Straightness**
  - **A.6.2.1 Sucker Rods and Pony Rods**

    End straightness shall be measured by supporting the rod body at a distance of 6.00 in. (152.4 mm) from the rod pin shoulder. The rest of the rod shall be supported at a maximum of 6.00 ft (1.83 m) with centers in the same plane. The amount of TIR bend is measured via a dial indicator, laser or other comparable measuring device. The amount of bend shall be measured at the machined surface of the pin shoulder OD. The maximum allowable TIR values for all rod sizes 5/8 in. to 11/8 in. (15.88 mm to 28.58 mm) is 0.130 in. (3.30 mm).

Goal

- Evaluate current system
- Inspect 100% of rods
- More user friendly
- Less expensive system
- Capable of handling 15,000 rods per day

Patent Search

- **US7197837**

  Gauge assembly for measuring diameter and total indicated runout

  Honda Motor Co. Issued: 4/3/2007

  Device used to measure diameter and TIR on camshafts.

  www.google.com/patents/US7197837

- **US6757636**

  Computerized electronic runout

  Alstom Technology Ltd. Issued: 6/29/2004

  Method/Device to measure runout using magnetic field sensing

  www.google.com/patents/US6757636

Patent Search

- **US 2002/0077770**

  Method and system for identifying and evaluating runout limits of rotational components

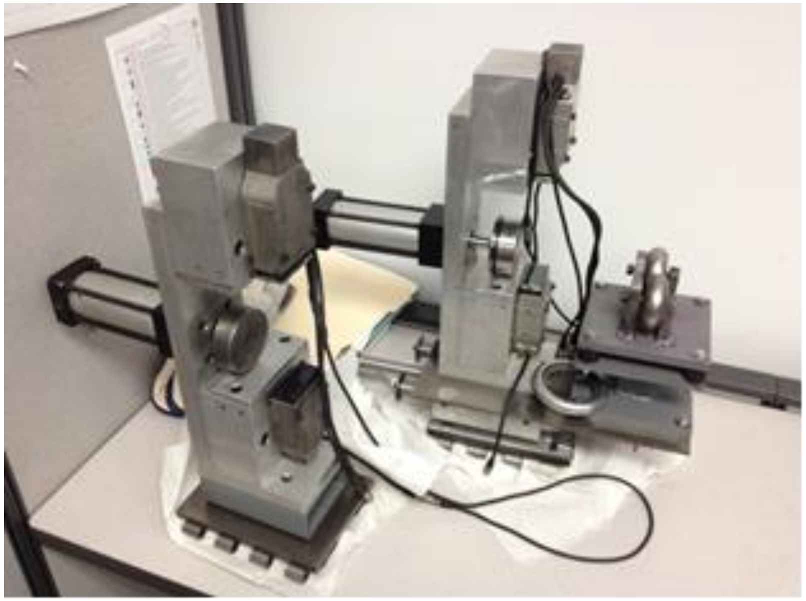
  Kaminski and Wilson   Filed: 12/20/2000

  Method used to measure runout on rotating components, turbines.

  www.google.com/patents/US20020077770
- No exact matches for the measurement of total indicator on sucker rods were found

Current System

- Keyence shadow system

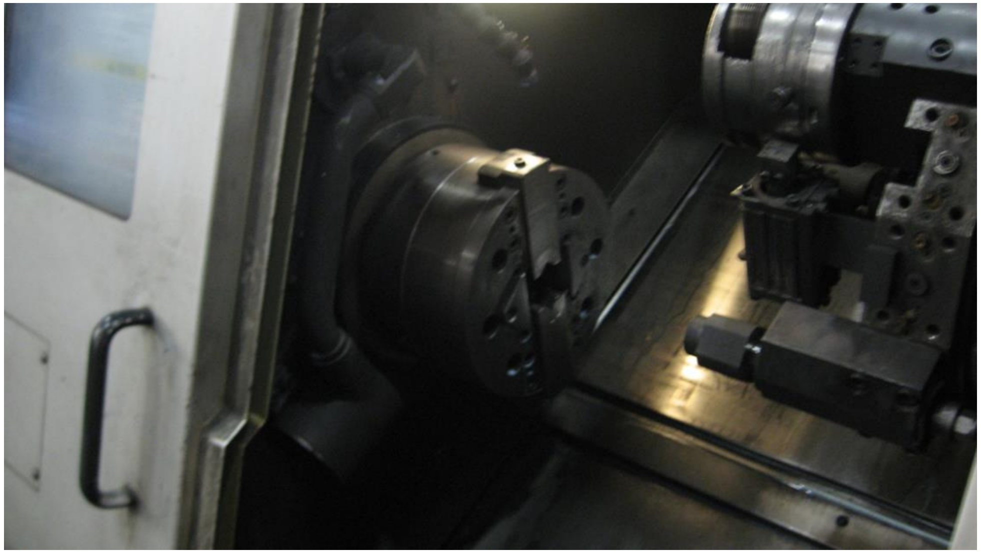


Design Concepts

- Evaluate current system
- LVDTs
- Measure T.I.R inside of CNC
- Use current mounting system
- Photoelectric sensors
- Rollers

Design Concepts

- Place LVDTs inside CNC

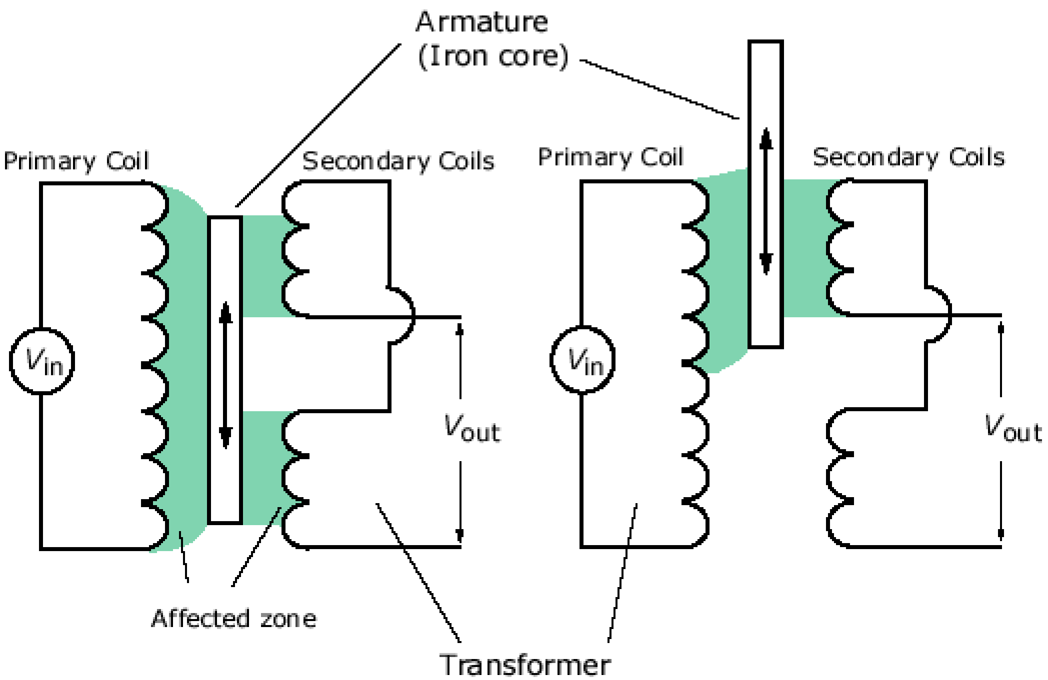


Design Concepts

LVDTs

- Linear Variable Differential Transformer
- Consists of a primary and secondary coil around a free floating iron core
- AC signal in the primary coil transforms iron core into an electromagnet
- Magnetic flux induces a voltage in the secondary coil linearly proportional to its displacement in the coil

LVDTs



Armature
(Iron core)
Primary Coil
Secondary Coils
V_{in}
V_{out}
Affected zone
Transformer
Primary Coil
Secondary Coils
V_{in}
V_{out}

LVDTs

- LVDTs are compact – < 4” in length
- LVDTs are accurate – repeatable within 0.15 microns
- LVDTs are Durable – stainless steel body with a IP65 rating (ingress protection from debris and fluids)

LVDTs

- GP911-5-S
- Spring loaded tip
- Repeatability – within 0.15 microns
- Stainless steel body

Actuators

- Parker Model 0.75 DSRx 1.000
- ¾” Bore
- 1” Stroke
- Stainless Steel Construction
- Rated to 150 psi

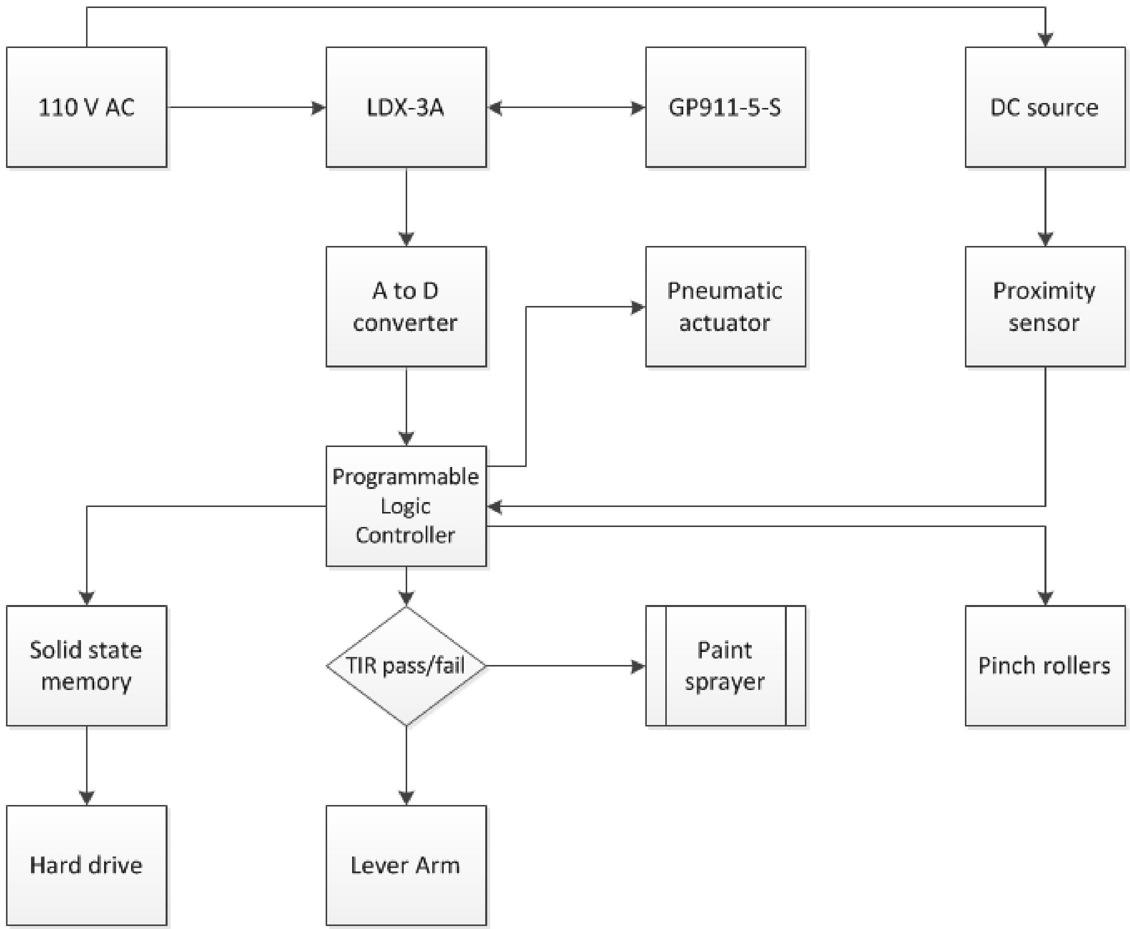
Proximity Sensor

- Omega E57
- Stainless steel body
  - Impact and shock resistant
- DC input/ output

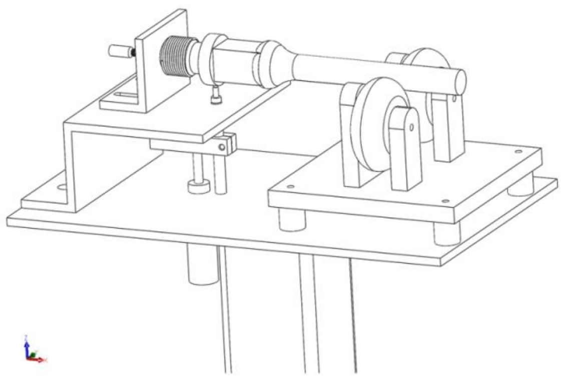
Signal Conditioner

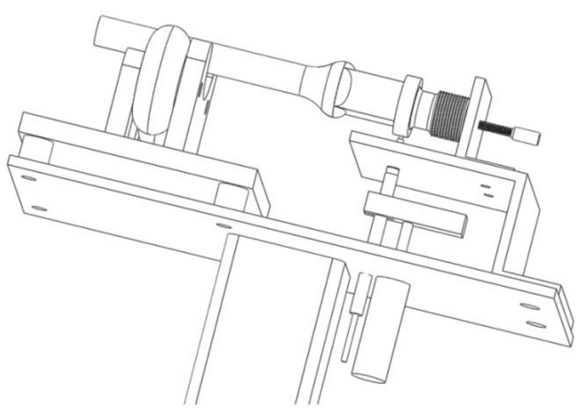
- LDX-3A
- Signal conditioner for LVDT
- 110V AC input ± 5Vdc output
- Provides proper voltage and frequency for LVDT
- Internal rectifier
- Hardened aluminum case

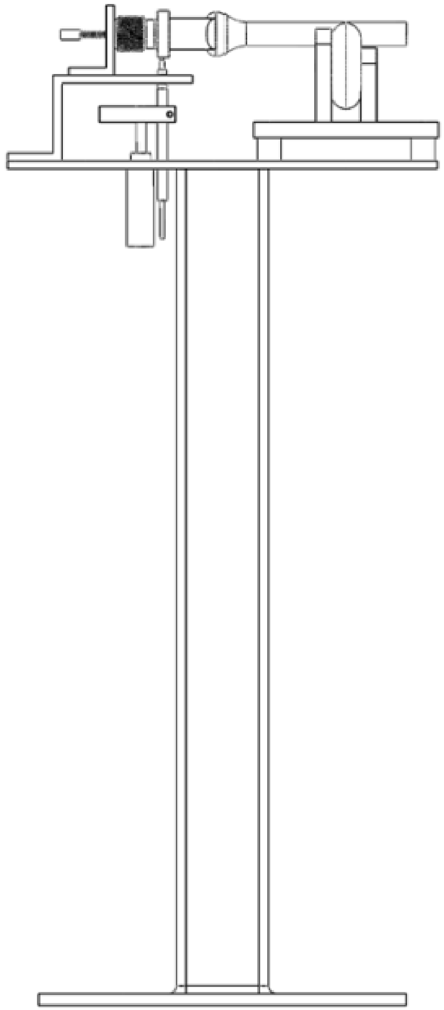
Design layout



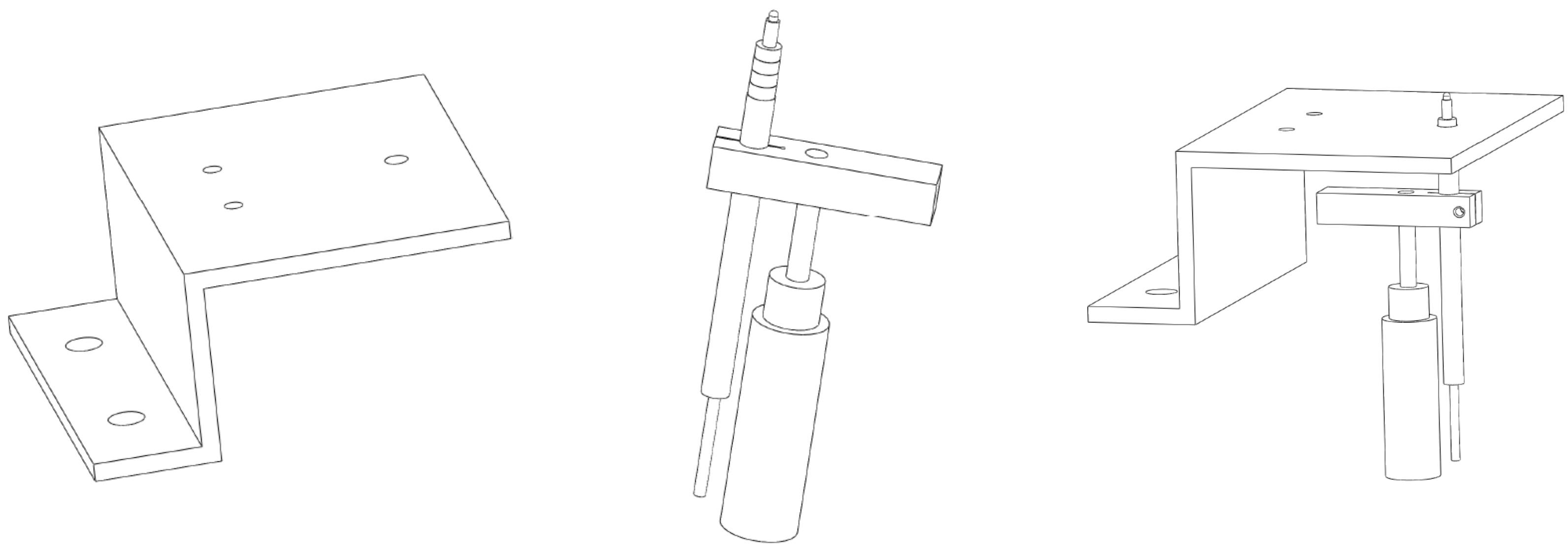
Proposed Design







Actuator/LVDT Assembly



Cost Analysis – Current System

- Keyence system
- LS-7501 two sensors one controller
  - $13,000

Cost Analysis – Proposed

Component Description	Part Number	Unit Price	Quantity	Price
Spring actuated LVDT	GP11-5-S	$525	2	$1050
AC powered signal conditioning	LDX-3A	$515	2	$1030
DC power supply for inductive sensor	PST-8	$165	1	$165
Inductive proximity sensor	E57	$84	2	$168
Pneumatic actuator	0.75DSRx1.000	$250	2	$500

sub total	$2913
miscellaneous	x 1.10
total cost	$3204

Conclusion

- Proposed System
  - Would be more user friendly
  - Will take some doing to implement
  - Lengths, constraints, etc
  - Cost less

- Current System
  - Has already been implemented
  - Cost is much higher
  - Bulky

Questions?