INSTITUTE OF TECHNOLOGY CARLOW

FACULTY OF ENGINEERING

Linear displacement electronic feedback for hydraulic cylinders.

By

Paul Heatherington

Thesis is submitted to Institute of Technology Carlow in fulfilment of the requirements of Master's in Mechanical Engineering

September 2019

Supervisors: Dr Patrick Buckley

Dr David Allen

DECLARATION OF ORIGINALITY

I hereby declare that this thesis entitled “Linear Displacement Linear feedback for Hydraulic Cylinders” is my own work, except where I have received help as stated in the acknowledgements. All quotations and summary of the work of others have been acknowledged where appropriate.

Permission is granted for this work to be used for purpose of evaluation by the lecturers or marking authorities within IT Carlow. Not to be shared outside Carlow IT without authors permission, as project would contain some sensitive information relating to Burnside customers, even though emphasis has been placed to reduce these sensitive elements where possible.

Student Name: (Printed) Paul Heatherington

Student Number(s):

Signature(s): ______________________________

Date: ______________________________

ACKNOWLEDGEMENTS

I would first like to thank Patrick Buckley who as my supervisor gave support all along the way from initial ideas to consider pursuing this research project when still an undergraduate, helping in getting funding application done and approved with the IRC and giving expert guidance throughout this research project.

Also, thanks to David Allen as my supervisor for his guidance and advice during this project. David was a great help on the electrical and development side of this project and was always easily available being on campus in IT Carlow every day.

For Sean Kavanagh who provided support on site in Burnside Autocyl as my employment mentor. Quick consultations and advice were available on an immediate basis to allow for quick decision making.

I would like to thank Pat Byrne, managing director of Burnside Autocyl and members of the Burnside Autocyl team. Without their support, this project would not have been completed.

I would like to thank Andrew Keppel and Solène Bouchet for their assistance in the workshop in IT Carlow.

To the IRC who believed in my initial application and who awarded funding for this research to take place. Without the funding this project would not have happened.

Also, to my family, to allow time away from home for the last 2 years, to allow completion of this project.

ABSTRACT

The purpose of this study was to research and develop a linear displacement technology that can be used to give positional feedback in hydraulic cylinders with the added ability to measure and monitor the operating temperature of the hydraulic oil. While there are solutions to this issue already in place, this study would focus upon their unique advantages and disadvantages.

The study would initially examine existing technologies comparing their advantages and disadvantages. Discussions took place with existing Burnside customers to see what their expectations were, so that their basic objectives would be met. During these meetings, the area of research was formulated with a shortlist of several potential technologies being identified. These technologies were subsequently examined in closer detail by acquisition of samples thus providing an in-depth understanding of the technological details.

The main objective was to produce a low-cost standard design sensor that had the ability to be used across multiple cylinder sizes and lengths. The study looks at integrating unique features that are not currently available in sensors, this being the incorporation of a temperature sensor.

Working on this study meant the acquisition of several new skills from the designing, constructing and testing of the electronic circuits, to the research, sourcing and purchasing of the individual components, along with learning how to manipulate and programme the Arduino Uno.

Various designs were explored in CAD to consider the best options. Individual electronic components were tested in isolation to explore limits of working conditions so the electrical signal would pass through metallic parts to work inside the hydraulic cylinders. Structural FEA analysis was performed on the pressurised and load holding sensor parts using Creo Simulate. The results correlated very well with researched results, leading to the construction and testing of the basic sub-assemblies of the sensor.

Production drawings were drafted to source machined parts, some were quite complex and involved multiple machining operations and suppliers. A short cylinder was constructed to operate by hand to test the positional sensor unit without oil and various iterations of the design

took place based on findings and were retested until satisfactory results were observed. After some modifications the dry testing of the sensor was successful. The sensor design was reconfigured to operate under hydraulic pressure and elevated temperature and a new longer cylinder was designed and constructed for more intense testing of the sensor. The testing took place in Burnside Autocyl and there were various iterations of designs and retesting until satisfactory results were observed from the equipment.

The objectives of the project were achieved through the development of the measuring sensor. The sensor designed and built was low cost, would work across multiple cylinder sizes with a working temperature sensor inside and would be suitable for operation inside a hydraulic cylinder. Further investments in electronics and injection moulding parts would be required in order to get production of the sensor to operate at a commercial level. The concept was proven to work, the sensor measures position and temperature as set out in the objectives of the research. There would be further developments with the capabilities of the measuring sensor as we move into the future.

TABLE OF CONTENTS

DECLARATION OF ORIGINALITY I

ACKNOWLEDGEMENTS II

ABSTRACT III

TABLE OF CONTENTS V

LIST OF FIGURES X

LIST OF TABLES XIV

SYMBOLS AND ABBREVIATIONS XV

1. INTRODUCTION 16

1.1 Overview 16

1.2 Burnside Autocyl 16

1.3 Objectives 18

2. PRODUCT DESIGN SPECIFCATION 19

2.1 Variables 19

2.1.1 Pressure. 19
2.1.2 Vibration and Noise 19
2.1.3 Operating Voltage. 20
2.1.4 Environment 20
2.1.5 Temperature 21
2.1.6 Moisture 21
2.1.7 Power loss and random start up positions 22
2.1.8 Precision, accuracy and range 22
2.1.9 Signal Outputs 22
2.1.10 Installation of sensor on cylinder 23
2.1.11 Cylinder stroke length 23
2.1.12 Sensor construction before becoming usable 24
2.1.13 Reliability 24
2.1.14 Electrical Construction 24
2.1.15 Length needed to incorporate sensor 25

2.1.16 Initialisation to get sensor up and running 25
2.1.17 Ability to be removed easily 25

2.2 Desirable functions 26

2.2.1 Overview 26
2.2.2 Maximum pressure in cylinder. 26
2.2.3 Number of operating hours 27
2.2.4 Electronic data storage 27
2.2.5 Maximum temperature recording in cylinder. 28
2.2.6 Sensor Construction 28

2.3 Conclusion on Product Design Specification 29

3. BACKGROUND & LITERATURE SURVEY 30

3.1 Hydraulic Cylinder 30

3.1.1 Hydraulic cylinder working 30
3.1.2 Safety components in hydraulic cylinders. 31

3.2 Sensors in cylinders 32

3.2.1 Types of sensors 32
3.2.2 Fixed Position Sensor 33
3.2.3 Fixed cylinder sensor in the hydraulic cylinder 34
3.2.4 Variable position sensor 35
3.2.5 Typical Application. 36
3.2.6 Comparing the two solutions. 36

3.3 LINEAR POSITION FEEDBACK SOLUTIONS. 37

3.3.1 Introduction 37
3.3.2 Possible Sensor Solutions 37
3.3.2.1 ....Internal Rod Style Transducer. 37
3.3.2.2 ....Technology used on Internal rod style transducer 39
3.3.2.3 ....Magnetostrictive 40
3.3.2.4 ....Variable resistance 41
3.3.2.5 ....Wire Actuated encoder. 41
3.3.2.6 ....External mounted wire sensor 42
3.3.2.7 ....Internally mounted wire sensor 45
3.3.2.8 ....Internal spool, External sensor type. 47
3.3.2.9 ....External Probe type 49
3.3.2.10 .....Rod Reading Sensor 52
3.3.2.11 .....Ultrasonic sensors 56
3.3.2.12 .....Frequency Measurement 59
3.3.2.13 .....Laser Measurement 60

3.3.2.14 .....Radar *61*

3.4 Selection of Technology 62

3.5 Patent search 65

3.5.1 Patent Methodology 65

3.5.2 Patent search results 66

3.5.3 Similar patents to planned research 66

3.5.4 DE102012209715 Patent 67

3.5.5 US2008141548 Patent 68

3.5.6 CA2876197 Patent 70

3.5.7 Conclusion on Patent search 71

3.6 Analysing a Similar sensor 71

3.6.1 Introduction 71

3.6.2 Siko Sensor. 71

3.6.3 Electrical Connections 72

3.6.4 Plastic Assemblies 72

3.6.5 Geared Assembly 73

3.6.6 Spring Coil Assembly 74

3.6.7 Housing 75

3.6.8 Evaluating magnets 76

3.6.9 Circuit Board 77

3.6.10 Evaluating encoders 80

3.6.11 Types of rotary encoder 80

3.7 Conclusion 83

4. DESIGN 85

4.1 Design Research 85

4.1.1 Introduction 85

4.1.2 Constant force power spring 86

4.1.3 Connection to cylinder 87

4.1.4 Wire type & Size 88

4.1.5 Encoder chip 88

4.1.6 Arduino Programming 91

4.1.7 Sensor signal through aluminium 94

4.1.8 Evaluating effects of changing housing hole diameter 96

4.1.9 Using Creo Simulate to verify effects. 97

4.1.10 Connection wire to rod. 99

4.2 CAD design of assembly and parts 101

4.2.1 Overview of Assembly 101

4.2.2 Coil Housing 102
4.2.3 Gearing 106
4.2.4 Pulley Retainer 107
4.2.5 Aluminium body 108
4.2.6 Pulleys and Pulley Shafts 110

5. BUILD 112

5.1 Sourcing Parts 112

5.1.1 Pulley Retainer 113
5.1.2 Coil Housing 113
5.1.3 Aluminium body 114
5.1.4 Pins for Rollers and Sensor shaft 115
5.1.5 Worm Gear and bevel Pin. 116
5.1.6 Hex screw 117
5.1.7 Chip Retainer 117
5.1.8 Coil Spring. 117
5.1.9 Electronic components 119
5.1.10 Pulleys, Swage Ferrule and Stainless wire 119
5.1.11 Static seal 120
5.1.12 Washers, circlips and M4 screws 120

5.2 Building test unit 121

5.3 Building Sensor 123

5.3.1 Pulley Retainer 123
5.3.2 Coil Housing 124
5.3.3 Joining coil housing and pulley retainer 125
5.3.4 Fitting wire to outside of coil retainer. 126
5.3.5 Assembling Gears 128
5.3.6 Joining to Aluminium body 128
5.3.7 Adding electrical components 130

5.4 Building of Test Cylinders 130

5.4.1 Dry operating Prototype 130
5.4.2 Pressurised working cylinder 137

5.5 Streamlining assembly process. 142

6. TESTING 144

6.1 Dry operating prototype 144

6.2 Pressurised working cylinder 149

7. RESULTS......154

7.1 Dry operating Prototype......154

7.2 Pressurised working cylinder......155

8. CONCLUSIONS AND FURTHER DEVELOPMENT......164

8.1 Conclusions......164

8.2 Further Developments......168

BIBLIOGRAPHY......170

9. APPENDICES......176

LIST OF FIGURES

Figure 1 Burnside Cylinder Applications 18
Figure 2 Different working Environments 20
Figure 3 Cold start-up and hot conditions scenarios 21
Figure 4 Different installation methods of sensors (Baluff, 2018) 23
Figure 5 Assembled components on breadboard and printed circuit 25
Figure 6 Sectioned cylinder labelled 30
Figure 7 Cylinder with valves fitted 31
Figure 8 Waste Compaction Truck 33
Figure 9 Reed Type sensor 34
Figure 10 Cylinder with continuous feedback sensor 35
Figure 11 Transducer inside cylinder 38
Figure 12 Cylinder with sensor stroking 39
Figure 13 Magnetostrictive effect explained 40
Figure 14 Resistance type Potentiometer 41
Figure 15 String pot sensor 42
Figure 16 String pot sensor on outside of cylinder 43
Figure 17 Inside a string pot sensor (TE, 2017) 43
Figure 18 External wire application 44
Figure 19 Internally Mounted Wire Sensor (Siko, 2017) 45
Figure 20 Wire actuated encoder installed in cylinder 46
Figure 21 Separating pressure 47
Figure 22 Internal spool, (Control, 2017) 48
Figure 23 Wire sensor solution (Waycon, 2016) 49
Figure 24 External Sensor Type (Wright, 2017) 50
Figure 25 External probe sensor 52
Figure 26 Rod reading sensor 53
Figure 27 Marking applied on rod 54
Figure 28 Sensor with fixed ends 55
Figure 29 Rod Markings 56
Figure 30 Wave forms 56
Figure 31 Principle of an echo sounder 57
Figure 32 Two types of external flow measurement (Greyline, 2018) 58
Figure 33 Frequency Measuring (Liebherr, 2017) 59
Figure 34 Laser used to measure lift height 60
Figure 35 Pulsed Radar 61
Figure 36 Espacenet Patent search 65
Figure 37 Example of Espacenet search results 66

Figure 38 DE2012209715 Patent ... 67
Figure 39 Cable revolution sensor ... 68
Figure 40 US2008141548 Patent ... 68
Figure 41 Patent US2008141548 sketch ... 69
Figure 42 CA2876197 Patent ... 70
Figure 43 CA2876197 Patent sketch ... 70
Figure 44 Connection Wire of Sensor ... 72
Figure 45 Plastic Assemblies ... 73
Figure 46 Geared Assembly ... 74
Figure 47 Spring Coil Assembly ... 75
Figure 48 Housing ... 76
Figure 49 Recess for Magnet in Block ... 77
Figure 50 Back of Housing ... 78
Figure 51 Exposed circuit board ... 78
Figure 52 Top of Circuit board ... 79
Figure 53 Magnet over Rotary encoder ... 80
Figure 54 Power spring (C&S, 2010) ... 86
Figure 55 Various wire connections available (Spaceagecontrol, 2018) ... 87
Figure 56 AS5601 CAD Model ... 89
Figure 57 3-D Printed Parts for the adaptor board ... 90
Figure 58 CAD and 3-D Assemblies ... 91
Figure 59 Arduino Encoder output ... 91
Figure 60 Mapping Voltage and current outputs ... 93
Figure 61 Programme in Arduino to scale ... 93
Figure 62 Holder for testing through the aluminium block ... 94
Figure 63 Assembled Jig with Aluminium block ... 95
Figure 64 Shaft holding magnet on outside ... 97
Figure 65 Meshing and adding pressure loadings ... 98
Figure 66 Areas off peak stress on Aluminium block ... 98
Figure 67 Comparing Results Creo Simulate ... 99
Figure 68 Wire Connection using a thimble ... 100
Figure 69 Retaining with lock screw ... 101
Figure 70 First designed assembly labelled ... 102
Figure 71 Coil Housing ... 103
Figure 72 Coil Housing and Assembled parts ... 103
Figure 73 Web and increased radius ... 104
Figure 74 Oil inlet and wire guide ... 105
Figure 75 Raised spigot for coil ... 105
Figure 76 Gearing system ... 106
Figure 77 Evaluating number of gear teeth ... 107
Figure 78 Pulley Retainer ... 107
Figure 79 Pulley retainer and mating parts ... 108

Figure 80 Aluminium body 109
Figure 81 Aluminium body mating parts 109
Figure 82 Pulleys and Pins 110
Figure 83 First assembly 112
Figure 84 Pulley Retainer 3-D Print 113
Figure 85 Coil Housing prints 113
Figure 86 Turned aluminium body 114
Figure 87 Fixture to secure turned part 115
Figure 88 Milling of Aluminium Housing 115
Figure 89 Pin for Roller and shaft 116
Figure 90 Ultimaker 2 parts as made and in setup for 3-D print. 116
Figure 91 Screw for connection to cylinder 117
Figure 92 Coil Spring connections 118
Figure 93 Coil Springs as delivered. 118
Figure 94 Rotary Encoder and Adaptor Board 119
Figure 95 Pulleys and Swage Ferrule 120
Figure 96 Stainless Steel Components 121
Figure 97 Test unit design 121
Figure 98 Connection 122
Figure 99 Completed test unit 122
Figure 100 Display on laptop 123
Figure 101 Machining pulley retainer 123
Figure 102 Fitting pins into retainer 124
Figure 103 Loading coil 124
Figure 104 Fitting Pin and wire 125
Figure 105 Joining 125
Figure 106 Getting wire started 126
Figure 107 Adding wire 126
Figure 108 Adding nut 127
Figure 109 Adding gears 128
Figure 110 Fasteners 129
Figure 111 Joined to Aluminium body 129
Figure 112 Electrical components 130
Figure 113 End Cap 131
Figure 114 Tube machining 132
Figure 115 Rod machining 133
Figure 116 Dry Cylinder assembled 133
Figure 117 Sensor into base 134
Figure 118 Assembling Gland and Piston 135
Figure 119 Assembling sensor 135
Figure 120 Adding temperature sensor 136
Figure 121 Sensor and dry operating cylinder assembly complete 136

Figure 122 Final sensor assembled 137
Figure 123 Long machined tube 138
Figure 124 Cylinder end features 139
Figure 125 Assembly Pressurised Cylinder 140
Figure 126 Assembly Instructions 141
Figure 127 Adding spacer to rod 141
Figure 128 Modified Spanner 142
Figure 129 Pull through tool 143
Figure 130 Guidance added for pin 144
Figure 131 Guidance of bevel pin 145
Figure 132 New gear shafts 146
Figure 133 Floating pin redesign 147
Figure 134 Coil pickup Internal 147
Figure 135 Gear redesign 148
Figure 136 Measuring Cylinder 149
Figure 137 Cylinder mounted for testing 149
Figure 138 Wire failures inside cylinder 150
Figure 139 Various solutions tested 151
Figure 140 Oil flow direction changed 151
Figure 141 Redesign of coil housing 152
Figure 142 Tapers added 153
Figure 143 Outputs from sensor 154
Figure 144 Dismantling of sensor 156
Figure 145 Stainless parts fitted 157
Figure 146 Display outputs 157
Figure 147 Final hydraulic retesting 158
Figure 148 Measured stroke verses stroke output extending 159
Figure 149 Measured stroke verses voltage output 159
Figure 150 Measured stroke verses Current Output 160
Figure 151 Measured stroke verses stroke output retracting 161
Figure 152 Voltage output verses measured stoke (retracting) 161
Figure 153 Measured stroke verses Current output (retracting) 162
Figure 154 Examination of wearing parts 163
Figure 155 AS5601 Rotary Position Sensor 181
Figure 156 AS5161 Magnetic Position Sensor 182
Figure 157 AS5601 Adaptor Board 183
Figure 158 Single encoder to measure cylinder stroke 184
Figure 159 Piston magnet 189
Figure 160 TSYS01 Temperature sensor data sheet 190

LIST OF TABLES

Table 1 Characteristics of linear position sensors (Seco, et al., 2005). 22
Table 2 Technology Decision making matrix 63
Table 3 Example Effect of resolutions available from rotary encoder 81
Table 4 Wire sizes from various manufacturers 88
Table 5 Parts List 112
Table 6 Results of outputs at end limits 155
Table 13 Title search patent results 176
Table 14 Title or Abstract results 1-7 177
Table 15 Title or Abstract results 7-10 178
Table 16 Title or Abstract results 11-12 179
Table 17 Title or Abstract results 13-17 180
Table 18 Ø6 x 3mm Magnet Plastic Frame 185
Table 19 Results Ø6mm x Ø3mm x 5mm long Ring (Aluminium block) 186
Table 20 Results Ø6mm x Ø3mm Solid (Aluminium block) 187
Table 21 Shear results 188
Table 22 Evaluating Gearing 188

SYMBOLS AND ABBREVIATIONS

Symbol	**Meaning**
R&D	Research and Development
CAD	Computer aided design
OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controller
ROM	Read-only memory
LVDT	Linear Variable Displacement Transformer
CAN	Controller Area Network
OD	Overall diameter
ID	Inside Diameter
EM	Electromagnetic
FMCW	Frequency-Modulated Continuous Wave
VCO	Voltage Controller Oscillator
UWB	Ultra-wide band
LIDAR	Light Imaging Detection and Ranging
DAC	Digital to analogue convertor
AGC	Automatic Gain Control
IC	Integrated Circuit
mS	Milliseconds
3-D	Three dimensional
IP	Ingress protection
EMI	Electro-magnetic interference

1. INTRODUCTION

1.1 Overview

This thesis is concerned with developing a linear displacement feedback and temperature monitoring solution to be able to work in conjunction with the workings of a hydraulic cylinder. The research work was necessary to improve lead times and functionality of the sensor for Burnside Autocyl's warranty requirements and customer's needs. The research started with investigating the various linear displacement technology's that are existing in the marketplace today. There are many solutions available to buy from various suppliers worldwide. The various available different solutions have different advantages and disadvantages based on price, availability lead-times and cylinder adaption costs needed to incorporate the specific solution in a hydraulic cylinder.

For small cylinders adding a sensor would double or triple the material cost of the cylinder. The hydraulic cylinder market is very competitive around the world. The availability of a unique solution to offer the customer can mean the difference between securing multimillion-euro contracts with the large OEMs (original equipment manufacturer) in Europe/Global or losing these valuable contracts to the competitors.

In most cases minimal use of space is at a premium so having the final sensor solution as small as possible is of utmost importance, thus end users constantly try to get maximum stroke from minimum closed lengths, so they can make machines as light and as small as possible. This makes life difficult for the design Engineer who must consider many different aspects to ensure an optimum solution is found.

1.2 Burnside Autocyl

Burnside Autocyl Tullow Ltd has been a worldwide leading manufacturer of hydraulic cylinders for over 40 years, (Burnside, 2018). The company was set up in 1974 to manufacture hydraulic cylinders in a single plant in Ballymoon. Since then Burnside Autocyl has gone on to have five manufacturing plants in county Carlow. Burnside has also recently started production in America.

The Burnside Autocyl company operate a just in time manufacturing system for delivery of their cylinders, which means the customer only receives the cylinders as they want them. As such means the company must be flexible and efficient in delivery of their service from concept design and initial testing right through to final delivery of product to the customer's door, (Burnside, 2018).

The machinery that utilises hydraulic cylinders are becoming more advanced, resulting in an increasing need for the hydraulic cylinder to become more integrated with the machines with advanced technology, (Heney, 2015). One of the customer's main requirements is to know the current position of the piston head in the cylinder. This is done by means of a sensor in the cylinder which feeds information to a PLC (programmable logic controller) or to the operator to inform them where the cylinder in positioned in terms of stroke or whether the cylinder is fully retracted or fully extended, (Group, 2018).

Burnside Autocyl, to date, utilises third parties to supply various technology solutions. This can be problematic at times because the product may not be available when required. A number of the cylinders where these third-party sensor solutions are utilised required to be turned around within the space of a week or two while the lead-time for the sensor solution can be anywhere from four to ten weeks, this presents a problem in that Burnside cannot deliver the cylinder in time because there is no sensor available, (Byrne, 2018).

Some sensor solutions are dependent on actual cylinder stroke; this means the sensor cannot be ordered until cylinder stroke is known. The OEM's customise their machines based on their customers' requirements, the final cylinder stroke lengths are not known until consultation with end user, (Cranes, 2018). Because of this the sensor cannot be ordered until this information is extracted from OEM's customer and supplied to Burnside.

Burnside Autocyl delivers into mainland Europe, which can put them at an up to a two-week disadvantage to Burnsides main competitors which are based in Germany, France and Italy. Even if Burnside is using the same sensor supplier as the continental cylinder competitors, it can take up to one week to deliver the sensor from the sensor supplier to Ireland. Once the sensor is inside the cylinder, it can take up to another week to get the cylinder delivered with the sensor included back to the customer. If Burnsides competitors are in the same country as the customer and sensor supplier, this is a major drawback for Burnside as a selling point, as they are up to two weeks' lead-time disadvantage behind the companies Burnside are competing with for new and holding onto existing business. The quick and reliable deliveries of cylinders with sensor solutions are key to holding onto business in the current competitive market.

Figure 1 illustrates an overview of the end applications of hydraulic cylinders. The cylinders are fitted on all types of machines from low end farm machinery to high tech multi-million-euro machines. In all cases safety is paramount.

Figure 1 Burnside Cylinder Applications

1.3 Objectives

The aim of the research was to develop a linear position feedback sensor for determining the position of the piston stroke in a hydraulic cylinder and record the temperature of the hydraulic fluid in the cylinder. This would involve the design of the sensor, test rigs followed by intensive testing and modifying phases. The ideal solution would be suitable to work across multiple stroke lengths and different bore cylinders whilst utilising common parts. All existing technologies and solutions were to be examined on their merits, evaluated and a decision in which direction would be best to pursue for the development of the sensor. The requirements for the sensor will be examined in the product design specification.

2. PRODUCT DESIGN SPECIFCATION

2.1 Variables

For the sensor to operate there are many variables that need to be considered upfront, so all characteristics are allowed for in initial evaluation. All variables would need to be well-thought-out when designing a new sensor solution that can work in conjunction with a hydraulic cylinder and be reliable in the demanding working environment of a hydraulic cylinder. These variables would be looked at now.

2.1.1 Pressure.

One thing constant about most types of hydraulic cylinders it they all operate at high working pressure, (Meyerhoefer, 2010). The general trend which has been seen in Burnside over the last number of years is that the working pressure of the cylinders has been steadily increasing. In the past, working pressure would have been in the region of 180-210 bar, with newer technologies in hydraulic pump designs the general trend seen by our customer is that working pressures can be anywhere in the region of 210 -350 bar. This increased pressure means hydraulic components can be smaller for compact machines, (Cosford, 2015).

2.1.2 Vibration and Noise

A lot of the hydraulic cylinders which are produced by Burnside are used in the mobile application industry. They may range from a nice smooth-running forklift cylinder mast lift cylinder to a more demanding plough height adjustment cylinders with constant vibration, see Figure 2.

Figure 2 Different working Environments

Vibration is usually measured in g force. The sensors need to be able to resist a high single shock rating and continuous vibration rating like on a plough or in the wood cutting industry machines, (Hankinson, 2009). Careful selection of overall design needs to be considered to cope with these external factors.

2.1.3 Operating Voltage.

For the mobile machinery market where Burnside cylinders are fitted, power is generally fed from the battery of that vehicle. Because they are mobile, AC current is not involved. The battery outputs are typically in the range of 12V DC or 24V DC, (Decker, 2016). The sensor needs to be able to cope with either of these inputs and still function as intended.

2.1.4 Environment

Burnside is now a world leader supplier of hydraulic cylinders. There are production plants in the USA and in Ireland. Production of cylinders in Ireland is shipped to various OEM's around Europe. For USA production plant, the cylinders go to OEMs in Canada, North America and South America, meaning that the operating environment of final location of cylinder would be diverse.

2.1.5 Temperature

If the hydraulic cylinder is working constantly and located in a hot country the operating temperature of the cylinder would be very high. The expected maximum oil temperatures under extreme conditions can hit +100°C.

Based on experience temperatures can drop to levels in the range of -40°C. However shortly after start-up these temperatures would rise above 0°C as the oil temperature heats up during the first few working cycles of the cylinder. Based on temperatures mentioned above cylinder environment would be classified as harsh environments. (Howard, 2017)

Figure 3 Cold start-up and hot conditions scenarios

2.1.6 Moisture

Moisture levels would be as high as 100% humidity if there is a constant changing temperature between hot and cold operating conditions. All external tapping points would need to be sealed to an appropriate IP (ingress protection) rating suitable for all potential working environments. IP ratings are used to define levels of sealing effectiveness of electrical enclosures against invasion from foreign bodies. Moisture hardening of electrical components is also an option, (Hostick, 2013).

2.1.7 Power loss and random start up positions

When the operating machinery where the hydraulic cylinder is mounted is switched off while not in operation, a power cut is inevitable to the sensor in the cylinder. Once the machine is started again, the sensor needs to know what position it is in after starting up and the appropriate feedback given to the controller without any other intervention by the operator. The sensor needs to be operational to give feedback at any given cylinder stroked position during start-up. If a sensor must conduct some sort of calibration step upon start-up it is classed as incremental. If the sensor doesn't need to then it is absolute, (Howard, 2018).

2.1.8 Precision, accuracy and range

There are many current suppliers of various technological solutions that supply into the hydraulic cylinder market. In most cases the customer would only be interested in ±1mm or ±2mm accuracy. Would cheaper alternative solutions be used that would fulfil the needs for the hydraulic cylinder market?

The worst-case scenarios of extreme may need to be considered and how it affects outputs to the determine technology level needed for the required sensor. An overview of ranges and precision can be found in Table 1.

Sensor	Meas. range	Contact	Abs/inc	Precision (μ m)
LVDT	Small	No	Abs	250(*)
Potentiometric	Medium	Yes	Abs	400
Magnetostrictive	Large	No	Abs	200
Optical encoder	Large	No	Inc	5
Laser interferometer	Very large	No	Inc	0.1

Table 1 Characteristics of linear position sensors (Seco, et al., 2005).

2.1.9 Signal Outputs

In most cases OEMs would want a varying scale of output as the cylinder travels between extremes of open and closed centres. Typical industry standards tend to go from 0 volts out to 4.5 (or 0-10) volts as the cylinder is changing from fully retracted to fully extended or output or in reverse for 4.5 volts to 0 (or 10-0) volts as the cylinder is changing from fully retracted to fully extended. Other more modern outputs are Can Open, (Nyce, 2001).

2.1.10 Installation of sensor on cylinder

There are varying solutions in the market that have the sensor on the outside of the cylinder and connected internally to the piston in varying different ways as illustrated in Figure 4. An advantage of this externally mounted sensor is that in general is easier to service or replace the sensor when it reaches end of life, damaged or broken. It would be easier to install the external sensor in the cylinder initially. A negative point would be that it can be more susceptible to damage from external falling elements impacting the sensor.

Figure 4 Different installation methods of sensors (Baluff, 2018)

Internally mounted sensors may be the preferred choice as they are naturally protected from external elements and use no external space as illustrated in Figure 4. However, they can require more building length to incorporate within the cylinder body. External sensors are an advantage where building lengths are at a premium.

2.1.11 Cylinder stroke length

For the sensor being considered, there are important questions regarding cylinder stroke length? Would there be any need to design for an extra-long sensor if design would never or rarely be required in industry? Also, would there a minimum stroke length that would be needed for the sensor to work? Would more than one sensor design need to be considered, one for short strokes and another design for long strokes?

2.1.12 Sensor construction before becoming usable.

Can a sensor be designed that can be kept on the shelf and called up when it is needed? This would help reduce construction and inventory costs. The ideal is one standard product and programme as necessary for each cylinder length. If an individual sensor must be constructed for each cylinder length, how quickly would this be turned around by a local based supplier and how practical would this be?

2.1.13 Reliability

Cylinders manufactured in Burnside, are in most parts, guaranteed for two years. If sensors were to fail before this time, then this would be a major issue. The duty cycle of a cylinder design would be all important when considering the construction of the same, (Hydraulics, 2016). Would a different low-cost sensor be practical to design for a low duty cycle cylinder, or would it be more practical to design a higher end sensor that would cover all requirements?

2.1.14 Electrical Construction

Once construction plans are established after survey, is it planned to make a mule from large commodity electrical components and test as a dry run without pressure or is a larger investment needed on final miniaturised solutions that would fit in the cylinder?

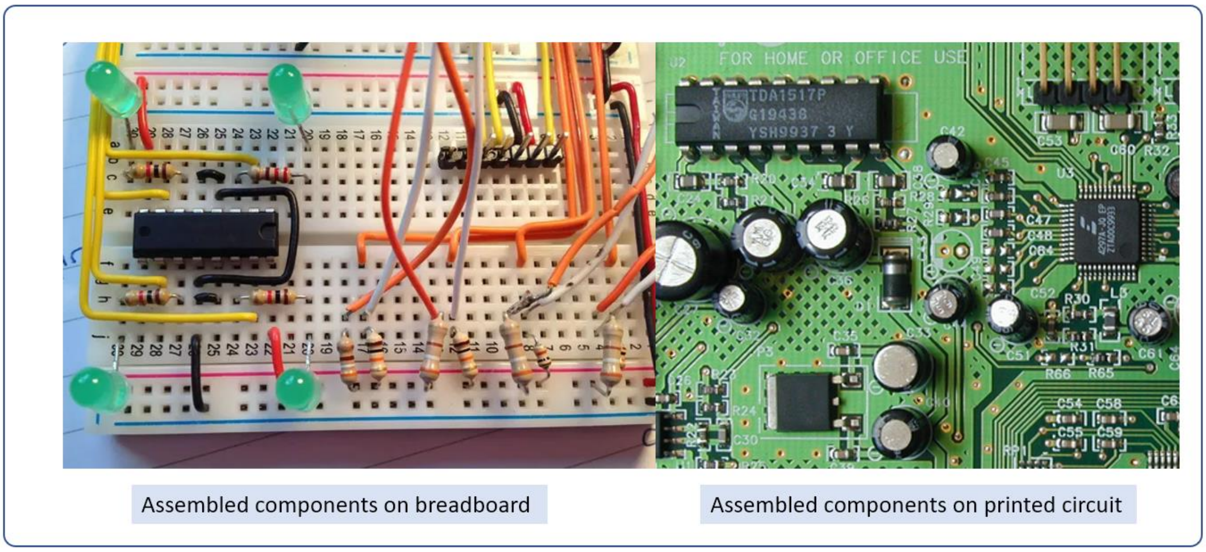


Figure 5 Assembled components on breadboard and printed circuit

It may be better to build from large commodity electrical items first. The more standard and available the parts are for production the more long-term benefits there would be. Examples of typical circuit boards and electrical components are shown in Figure 5.

2.1.15 Length needed to incorporate sensor

OEMs place a large emphasis on keeping building length as small as possible. If the length required to incorporate the sensor is too large, then it would be undesirable and would have no demand. The solution needs to be at least as compact as existing solutions that are available today from other suppliers. If gains can be made here and made smaller this would be a big advantage over current available solutions.

2.1.16 Initialisation to get sensor up and running

When the sensor is installed in the cylinder, would there be any programming tools required to get the sensor up and running? If so, what would the cost be for this equipment? Would it have to be made up with a special tool or programme, or would it be programmed by a laptop or PLC? Assembly and testing time for the sensor would also be a part of that so strives should be made to keep this assembly time as small as possible.

2.1.17 Ability to be removed easily

Faults do happen with sensors from time to time. No product, no matter how well it is designed, is going to be perfect 100% of the time. Variables such as tolerance errors, assembly errors of

cylinders and sensor can cause reduction of the life of the sensor and failure before the warranty period runs out.
When that happens, it would be better if the sensor would be removed from the cylinder easily and replaced without removing the cylinder from the machine.

2.2 Desirable functions

2.2.1 Overview

Today there are many available sensor solutions that can be bought from the marketplace. Some are designed to work with hydraulic cylinders, and some are not but they would be adjusted to work with cylinders. All sensor solutions are designed and made to give positional feedback in some form or another. Burnside as a consumer for these sensor products, can only incorporate and use them as they are delivered. However, when there are no initial constraints, are there other desirable functions that would be incorporated as part of the sensor solution that would add value with little extra cost, or if available to offer as part of a cylinder solution that would separate Burnside from competitor's solution and give Burnside the edge to secure new business when price differences and service offerings are marginal between competitors.

Many OEMs are now looking to offer something that their competitors are not offering and are looking to be the leaders of new technology. The ability to incorporate a unique feature as part of the sensor solution would allow Burnside to move ahead of the close cylinder competitors.

2.2.2 Maximum pressure in cylinder.

From time to time cylinders would be returned to Burnside under warranty with broken rods or broken ends with the explanation cylinder was broken during normal usage. If the cylinder is returned to the OEM and under their warranty cover it is sometimes hard for them to prove the cylinder was used outside normal allowable working range, and therefore the cylinder warranty is deemed invalid.

It is the same when the cylinder is returned to Burnside from an OEM, Burnside would know from experience and prior endurance testing if the cylinder was misused but, sometimes, this can be hard to prove. If there was a simple pressure/temperature sensor measuring maximum internal recorded pressure/temperature and that figure is stored permanently to internal memory, this would prove useful for Burnside or the OEM to invalidate a potential claim. Burnside would have the technology that their competitors would not have available to them.

2.2.3 Number of operating hours

Normally cylinders supplied by Burnside are warranted for two years. These two years would count regardless of whether the cylinder is sitting on a machine for 11 months of the year in warehouse storage or if operating 24/7 in the workplace.

If there was another way to accurately monitor active usage it may be possible to change the warranty period from yearly time to active time when working. A possibility proposed is to monitor working time, by using the sensor to record time in use. Basically, when the sensor is powered up it is counting time and when the sensor is returned to Burnside Autocyl the actual usage can be determined.

This would bring benefits to Burnside when cylinders are running around the clock and the cylinder is returned after 1 year and at the end of its natural life. Being able to determine this from a normal cylinder is not possible. Burnside would request operating hours of the machine to get a guide number of active hours, but this information would easily be manipulated by the machine to record a lower number of active hours.

Alternatively, if machine usage was on a low duty cycle, maybe the cylinder would be guaranteed for the number of operating hours rather than number of years. If the cylinder was only normally recording 10,000 cycles a year and natural life of cylinder was 200,000 cycles, a 50,000-cycle guarantee would equate to a natural five-year usage and give a benefit to the machine operator of an extra five years. This would give extra piece of mind to the machine owner and OEMs. This may help in the promotion, sale and service of the cylinder, which would help generate extra revenue from new and existing customers.

2.2.4 Electronic data storage

In the modern day when companies are getting more environmentally conscience, efforts are being made to reduce their carbon footprint. Today in Burnside there is a large paper trail which follows the cylinders through the production process. Machine operators record that they performed certain procedures, dimensional checks, and performance checks along with their signature record.

This is a very un-environmentally friendly procedure and uses lots of paper which needs to be stored by Burnside for two years from dispatch of cylinders. When a cylinder comes back under warranty, these records must be retrieved from bulky storage cabinets and are sometimes not always easy to find due to the vast amount of paperwork. The electronic storage of the data relating to the cylinder would be more environmentally friendly.

If this information would be stored electronically with the cylinder and uploaded as part of sensor memory, this would make it much easier to retrieve information when cylinder was returned. Statistical analysis would be built up on certain problematic areas and this information would be used to improve processes, prompt for better training or highlight a need for tightened quality checks. This would reduce cost and increase overall efficiency.

2.2.5 Maximum temperature recording in cylinder.

Intermittently Burnside would receive back a cylinder inside the warranty period with the seals overheated. Most times this would come from the cylinder operating at excessively high temperatures. Burnside as a rule guarantee seals would run comfortable up to 80˚C.

Cylinders would come with leakage issues and the user would say the cylinder was run under normal conditions. After a strip down of cylinder and examination of seals it becomes clear that the cylinders were used above the maximum temperature advised to the customer and on Burnsides cylinder drawings.

Without proof it can be hard to discount a claim. However, if a temperature probe would be installed as part of the sensor assembly and set to record a maximum temperature achieved by the cylinder, this would be a way to invalidate an unfair claim and protect OEM and Burnside from uncontrolled risk. The maximum temperature would be recorded in part of the sensor's ROM (Read only memory). When a cylinder is returned, this data would be read and used to validate if the cylinder was used within advised upper and lower parameters.

2.2.6 Sensor Construction

Sensors in the marketplace vary wildly in style and construction. Some are contactless, and the moving parts used to record the movement do not actually contact the oil or parts, which means they would not wear with usage.

Other solutions involve wearing parts involving friction where the interface between moving parts meet one another. If a contact solution is pursued based on the literature review and feasibility study, then the solution needs to be proven to be able to meet the most demanding applications and proved out for reliability, (Herceg, 2018).

Contactless technology would eliminate this risk but depends on the cost and benefits of both solutions. This technology may be applicable to other areas of industry such as food, dairy chemical and pharma industries.

2.3 Conclusion on Product Design Specification

There are many inputs and external factors that need to be considered when designing the sensor for the hydraulic cylinder. During the design phase and selection of technology all these variables will be considered in the design process to achieve optimum solutions.

3. BACKGROUND & LITERATURE SURVEY

3.1 Hydraulic Cylinder

3.1.1 Hydraulic cylinder working

A hydraulic cylinder is a mechanical device that is used to deliver power in a linear pulling and pushing motion. Hydraulic cylinders haven't changed much over the years but are required to adopt greater functionality and efficiency, (Hydadmin, 2009). The basic double acting cylinder has common components included in their design. Figure 6 shows a cross section of a hydraulic cylinder.

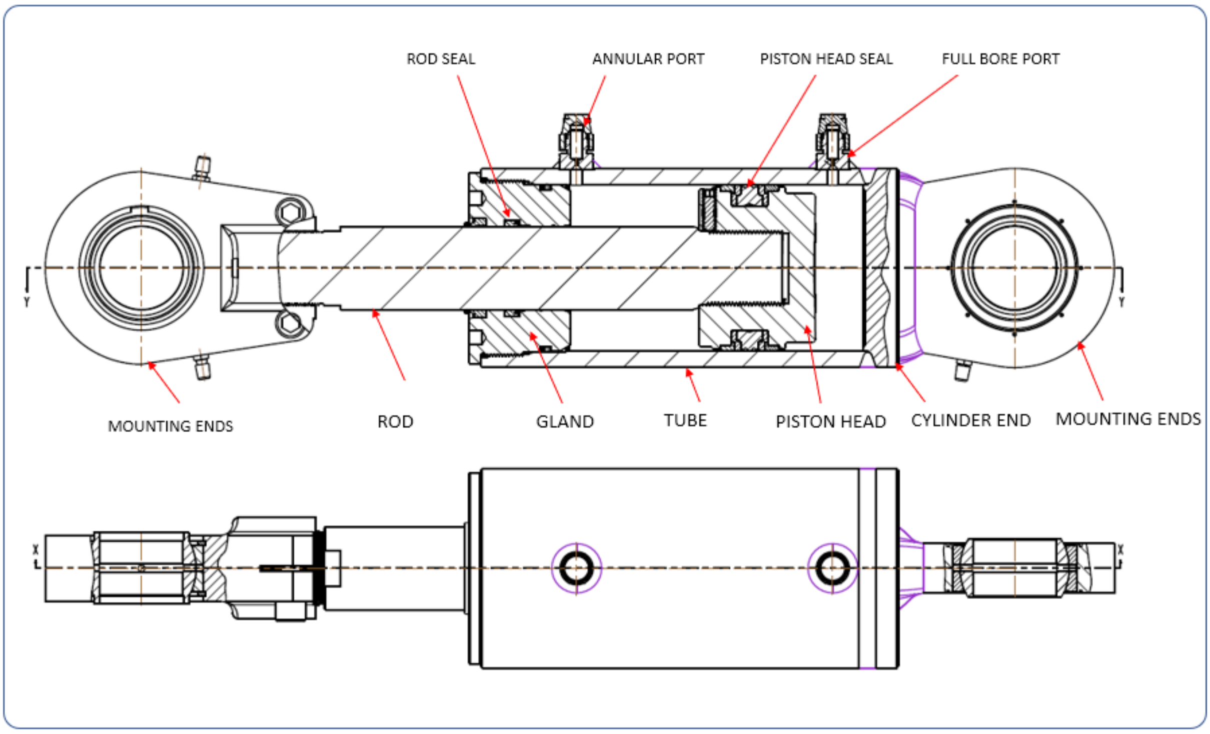


Figure 6 Sectioned cylinder labelled

Hydraulic oil is pumped in through ports on each end, full bore side port to extend the cylinder and annular side port of cylinder to retract. Oil pressure acts on the surface area of the piston head, which has a seal which keeps the pressure on the same side the pressure is acting on up as far as the seal. The gland is used to guide the rod when it is moving and driven by the piston head, the gland also contains a rod seal to keep the fluid inside the cylinder. The tube is capped off at the end with a screwed or welded cylinder end, so fluid cannot escape. There are normally mounting ends on each end of the cylinder, so cylinders can be mounted on the machines and used as connection points to deliver the power, (Lee, 2014).

3.1.2 Safety components in hydraulic cylinders.

Many times, hydraulic cylinders are utilised in safety critical areas. It is important that the hydraulic cylinder does not move when they are not supposed to, that is when the cylinder is not been controlled by the operator. To ensure this, they would be fitted with low cost (around €8) hose-burst valves to slow decent of cylinder coming down in event of a hose failure, to more expensive (around €25) load holding valves such as P/O (pilot operated) check valves to stop the cylinders movement when it is not in operation. Also, more complex counterbalance valves can be added to control the velocity of cylinder when moving or been subjected to forces from external elements, (McIntyre, 2016) .

The valves that would be fitted on hydraulic cylinders are illustrated in Figure 7. These valves are included to provide safety features to the hydraulic system by preventing unwanted movement of the cylinder during operation or when holding a load in place whilst in a stationery position.

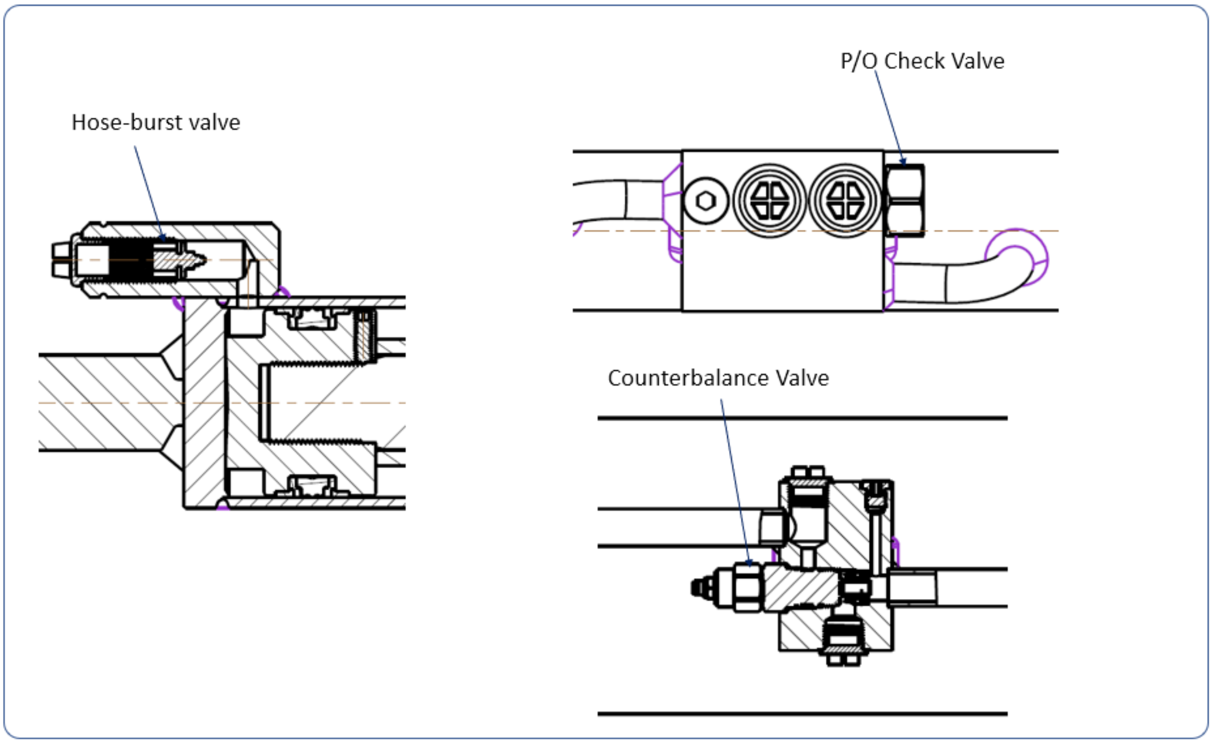


Figure 7 Cylinder with valves fitted

For positional safety the use of sensors or switches can be used on the cylinder to determine cylinder position and carry out defined functions when cylinders are in certain positions or clear of certain areas. In some cases, other functions of the machine can only take place when a cylinder is in a fully retracted position. It is the job of the sensor within the cylinder to inform the operator or PLC with this positional information so informed decisions or synchronized operations can take place. Hydraulic cylinders are becoming more automated and integrated within the overall machine system in which they are incorporated, (Vázqueza & Freidovich, 2016).

Hydraulic cylinders are now key components and are an integral part of automation when synchronizing with other parts of the machine. The synchronizing improves overall safety and efficiency. The addition of sensors and technology adds value to the machine, (Zhang & Ning, 2018).

Some of the sensor solutions are not ideally suitable for the customers' needs in Burnside or are too costly to integrate within the hydraulic cylinder. This research would address the problem of these deficiencies and look to find a suitable cost competitive solution over what is available today.

3.2 Sensors in cylinders

3.2.1 Types of sensors

Sensors currently being used in hydraulic cylinders are of two specific types, end of stroke positioning and continuous feedback over the full stroke length. There are advantages and disadvantages for both types, in terms of price, availability, reliability and technology. End stroke positioning would provide an on/off signal when the sensor is activated. If a switch is used at both ends of the cylinder, then two sets of cables would be required. A continuous feedback sensor would constantly vary the output signal as the piston is travelling within the full stroke of the cylinder. Continuous feedback enables servo-hydraulic motion control of piston head position and velocity, (Balluff, 2017). The two basic types of sensor would be looked at below.

3.2.2 Fixed Position Sensor

The end of stroke positioning sensor is used in cylinders where the sensor needs to detect when the cylinder is nearing the outward stroke, return stroke or both. Position switches provide a versatile and cost-effective way to monitor the piston head position in hydraulic cylinder, (Parker, 2018).

An example would be, if a machine is running quick to optimise efficiency of the running cycle, both the flow of oil into the cylinder and the running speed of cylinder would be maximised for most of the stroke cycle. A good example of this would be a road going waste compactor as illustrated in Figure 8.

Figure 8 Waste Compaction Truck

When the cylinder comes to the end of the stroke there is a loud bang which is undesirable. To take away this bang, a switch is used to detect when the cylinder is near the end of the stroke. The switch is placed approximately 20-30mm from the end of the stroke, and when activated, a signal is sent to the pump to turn off or slow down the oil supplying the cylinder. The momentum of the cylinder slows as the power is cut to supply or restrict flow to the cylinder. The power cut to stop flow is activated by the switch in the cylinder. However, the cylinder would continue to stay moving due to momentum and by the time end of stroke has been reached, velocity would be near zero and there is no impact noise, (Womack, 1988)

3.2.3 Fixed cylinder sensor in the hydraulic cylinder

In Figure 9 there is a fixed position type sensor that is used by Burnside today.

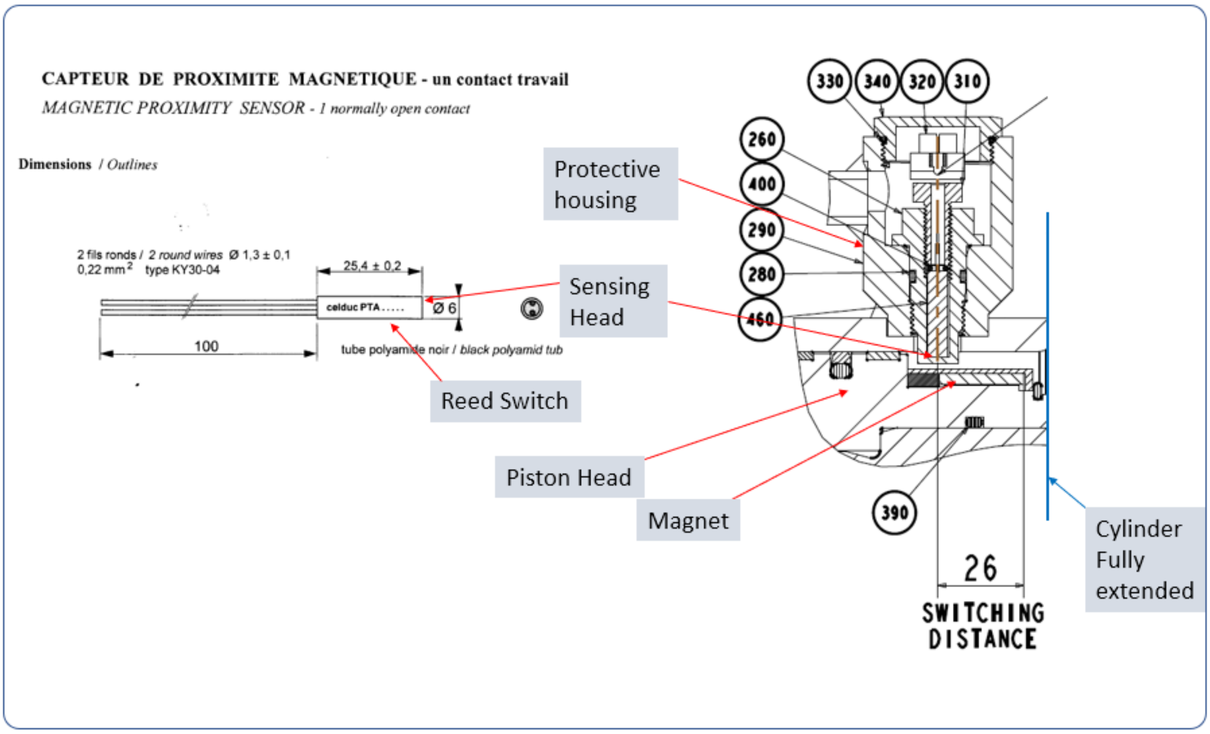


Figure 9 Reed Type sensor

The piston head moves inside the tube when it is working. The sensor assembly senses when the piston head is near the end of the stroke and provides the signal. The sensor is normally open when not activated, i.e. when the piston is away from the sensor. Today Burnside purchase the reed switch from Celduc Relais, (Relais, 2013).

The sensor operates by having a magnet attached to the piston head, when this magnet comes under the sensing head of the reed switch, the magnetic field closes the reed switch. This closed circuit is then used to pass a small current through the sensor and tells the operator or PLC that the piston head has reached the predefined position. This is an overview of a fixed position sensor. The reed switch is relatively inexpensive and require no standby power, (Reddy, 2016).

3.2.4 Variable position sensor

In the past, fixed position sensors have been used extensively by Burnside. They work well, but on the newer generation machines, they are being replaced by variable sensor solutions. The variable sensor has the advantage that as the piston is moving within the cylinder the sensor is giving continuous feedback to the operator on its current position. There are many different existing solutions for this type of sensor but for now and to explain the function, the operation of a rod type sensor would be explained. The rod style sensor is a probe inserted inside the rod of the cylinder.

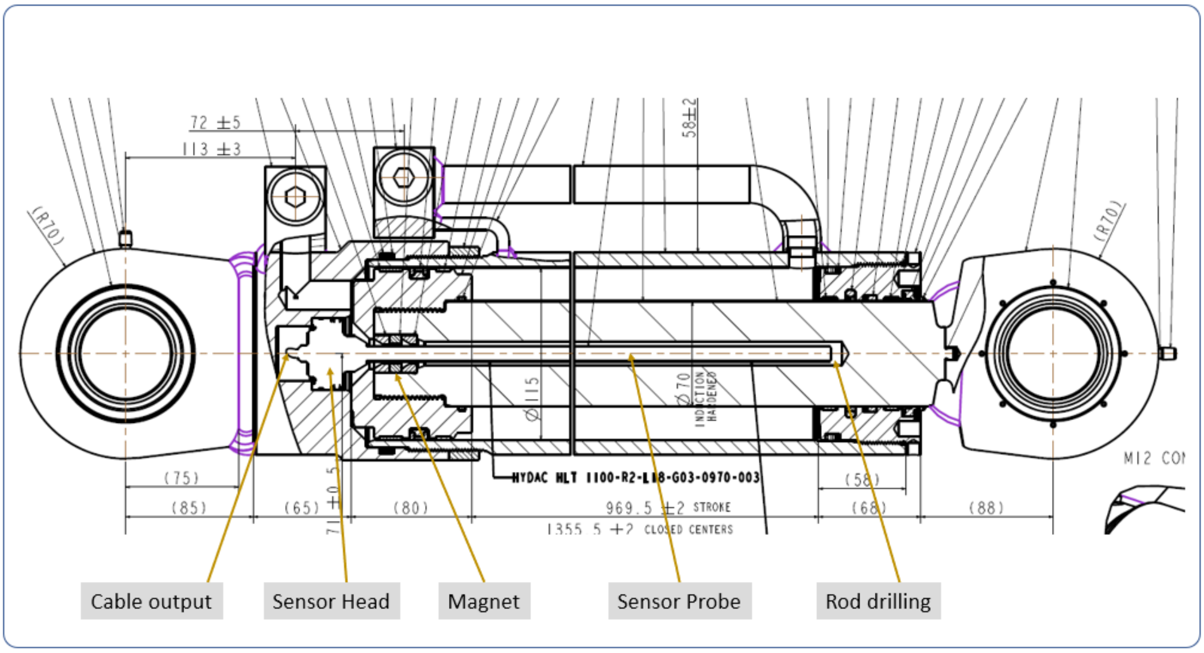


Figure 10 Cylinder with continuous feedback sensor

In Figure 10 a section of a hydraulic cylinder can be seen with a continuous feedback sensor fitted inside it. For this type of sensor, when the cylinder is fully retracted it would give a low current or voltage output on the output cable. Figure 10 shows the cylinder in the fully retracted position. The sensor is made up a sensor head and sensor probe. The sensor head is mounted inside the bottom cap of the cylinder, while the probe is connected to the head and inserted inside the drilled hole in the rod.

When the sensor is working the probe is fed with an electrical pulse through the inside of the shaft, with a magnet connected to the piston rod assembly. As the cylinder is extending the piston rod assembly moves out with it. The magnet moves along and disrupts the signal inside the sensor probe. The sensor head has electronics to interpret this signal and convert its current position to a variable output which is fed to a PLC or operator. The PLC or operator can use this information to make informed decisions and change variables on the machine, so the pump turns off quicker and banging noise is reduced, eliminated or can be synchronised with other cylinders to perform advanced functions.

3.2.5 Typical Application.

The application shown in Figure 8 on page 33 is considered, where the fixed switch was used to slow the cylinder before the end of the stroke on the compactor truck, the continuous feedback sensor responds to inputs, the oil flow velocity can be adjusted as and when needed through a PLC or control unit situated on the truck itself. If the noise is excessive from piston hitting the end of the stroke too fast, the operator can then adjust the pump to cut out before the end of the stroke. This is achieved by using output signal from sensor to turn off pump sooner. This is one of the advantages of the continuous feedback solution.

3.2.6 Comparing the two solutions.

The end of stroke positioning would inevitably have a lower cost than continuous position sensing, (Balluff, 2017). If the end of stroke positioning solution would suffice to control the application, then this is the one to use. If the end of stroke position needs to be somewhat variable, then continuous feedback is needed from the sensor to achieve variable stroke position.

Burnside Autocyl already have access to a few fixed position sensor solutions which can be adapted and customised at short notice to suit individual customer requirements. However, Burnside has difficulty accessing variable position sensors when they are needed at short notice.

3.3 LINEAR POSITION FEEDBACK SOLUTIONS.

3.3.1 Introduction

The sensor must integrate as efficiently as possible with the hydraulic system using information from the outcome of this literature survey. The optimal sensor would depend on the range and resolution needed for each hydraulic cylinder.

A sensor is a device which measures or detects some condition or property and records or indicates or responds to the information received. The sensor can convert an input voltage to a varying current or voltage output which can be measured and translated into an actual stroked position of the rod on the cylinder, (Jones, 2009).

Adding sensors gives an advantage to Burnside for hydraulic cylinders in that they add value to the cylinder and a premium can be charged to the customer for a good product. The idea is to look as wide as possible to find potential ideas for the best solution.

3.3.2 Possible Sensor Solutions

3.3.2.1 Internal Rod Style Transducer.

Linear variable differential transformers (LVDT) have been used throughout the decades since 1946 for the accurate measurement of displacement and positioning, (LVDT, 2015), (Ametek, 2013).

A LVDT is an electromechanical device used to convert a linear motion to a variable electrical current or voltage. Linear displacement is the movement of an object in one direction in a single axis. (Omega, 2016). In Figure 11, a sketch of an internal transducer inside a cylinder is shown. The assembly consists of the cylinder tube assembly, rod assembly, sensor head, sensor rod, electrical connection point and a magnet.

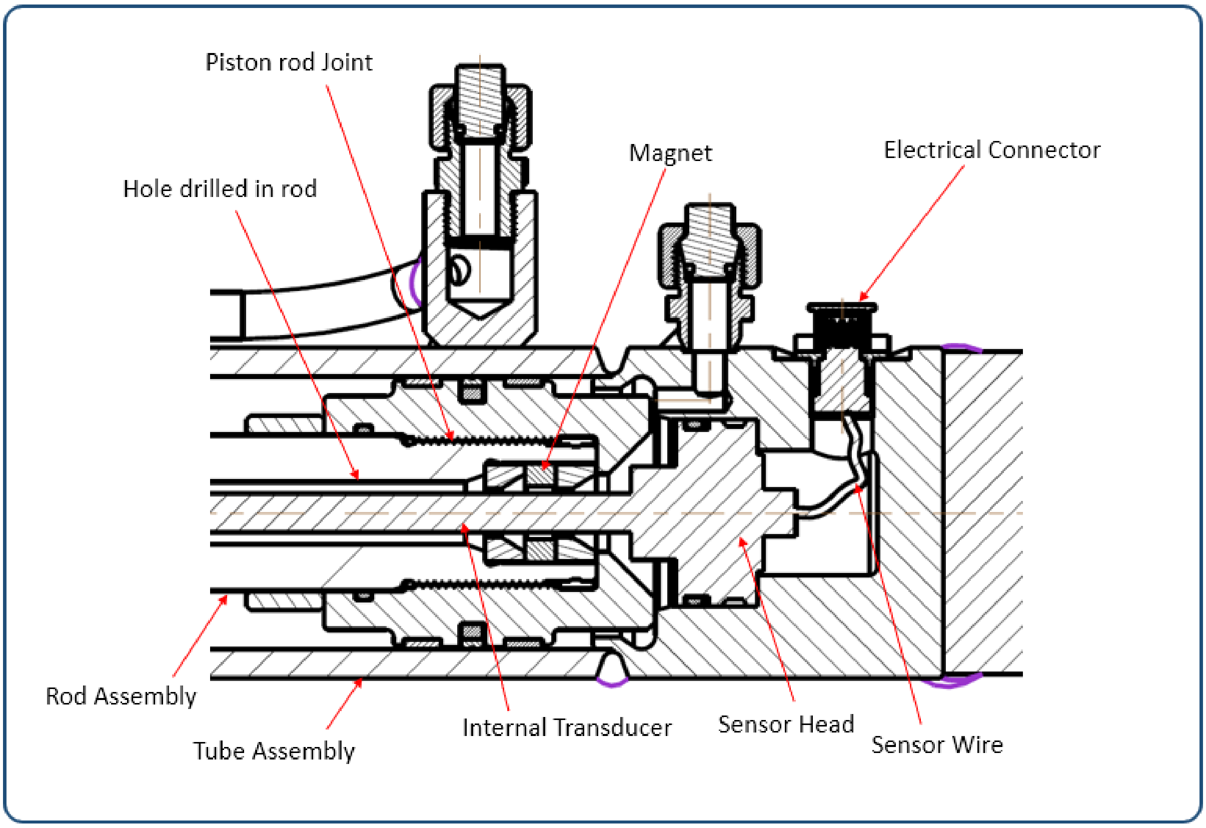


Figure 11 Transducer inside cylinder

The sensor head and sensor rod have an outer steel construction and are joined together by a weldment and is pressure tight. The electronic workings of the sensor are contained inside the sensor head and isolated from the cylinder oil pressure which is on the outside. There is a hole drilled inside the rod assembly so there is room for the internal transducer to be installed. This drilling is a negative point for the hydraulic manufacturer as it weakens the rod structure area at the rod piston joint and it also costs time and money to do the drilling operation.

The head of the sensor is installed inside the tube and a wire is run from the back of the sensor head to a connection interface on the outside of the cylinder. This is where the power is connected to turn on the sensor. The output lines are also on this connector, so the varying output can be read out as the piston rod is moving.

The cylinder is shown in the fully retracted position. The magnet is connected to the piston rod assembly and as the rod moves out it bring the magnet with it. The sensor can detect the changing magnet position and varies the output proportionally to its changed position. Outputs can vary depending on what the end user requires. Outputs are usually either, current, voltage or CAN bus (Controller Area Network) outputs.

Figure 12 shows the cylinder being extended and how the output varies as the cylinder travels out. When the sensor is fully retracted and turned on, it is better practice to start at 0.5V instead of 0 volts or 4mA instead of 0mA so it is known the sensor is functioning when turned on and fully retracted.

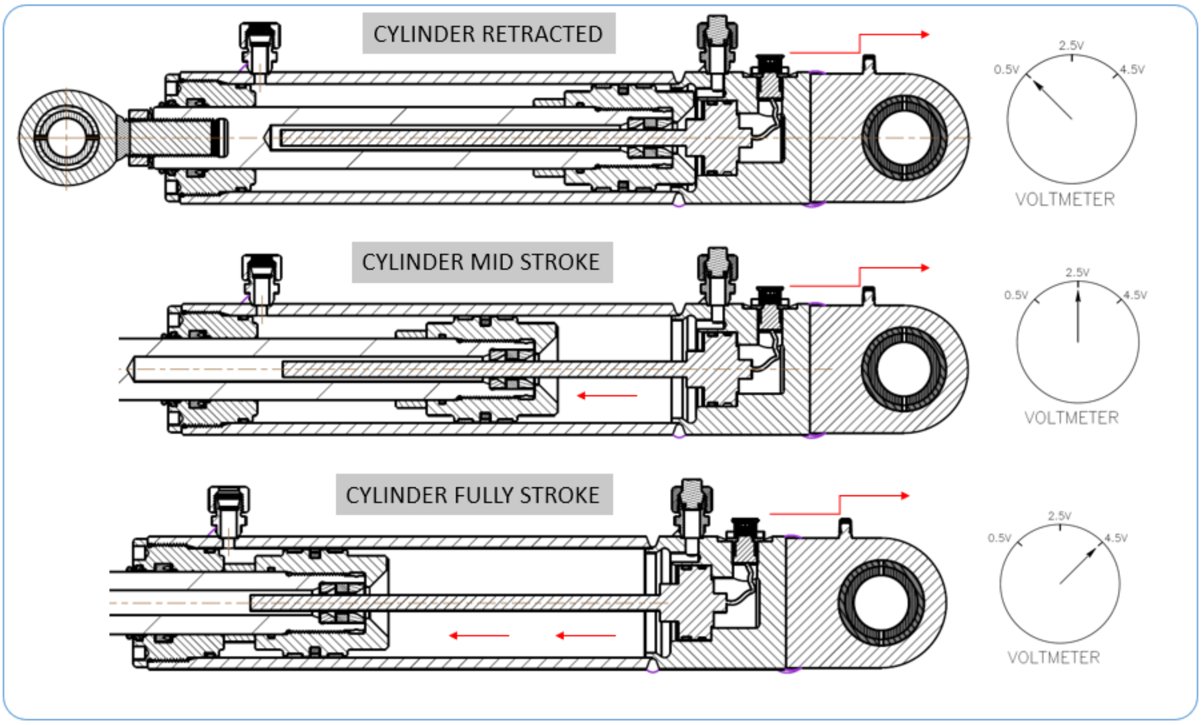


Figure 12 Cylinder with sensor stroking

This type of rod sensor, from research, appears to be the most commonly used type and most readily available type of sensor for the hydraulic market based on availability from companies such as Rota Engineering (Engineering, 2019), MTS (MTS, 2019) and Balluff (Sensors, 2019)
.

3.3.2.2 Technology used on Internal rod style transducer

From research there are three main technologies used in positional feedback sensors using a rod style transducer, Magnetostrictive, variable resistance and variable inductance. Magnetostrictive appears to be the most popular choice of technology by all suppliers. Variable resistance appears to be abandoned as a technology solution for linear transducer solution for hydraulic cylinders, (Herceg, 2013).

3.3.2.3 Magnetostrictive

This is the most popular solution for this technology. This type of sensor falls into non-contact category as the moving parts do not actually touch one another. Each sensor contains a ferromagnetic waveguide, a position magnet and a strain pulse converter. In Figure 13, the Magnetostrictive technology is explained.

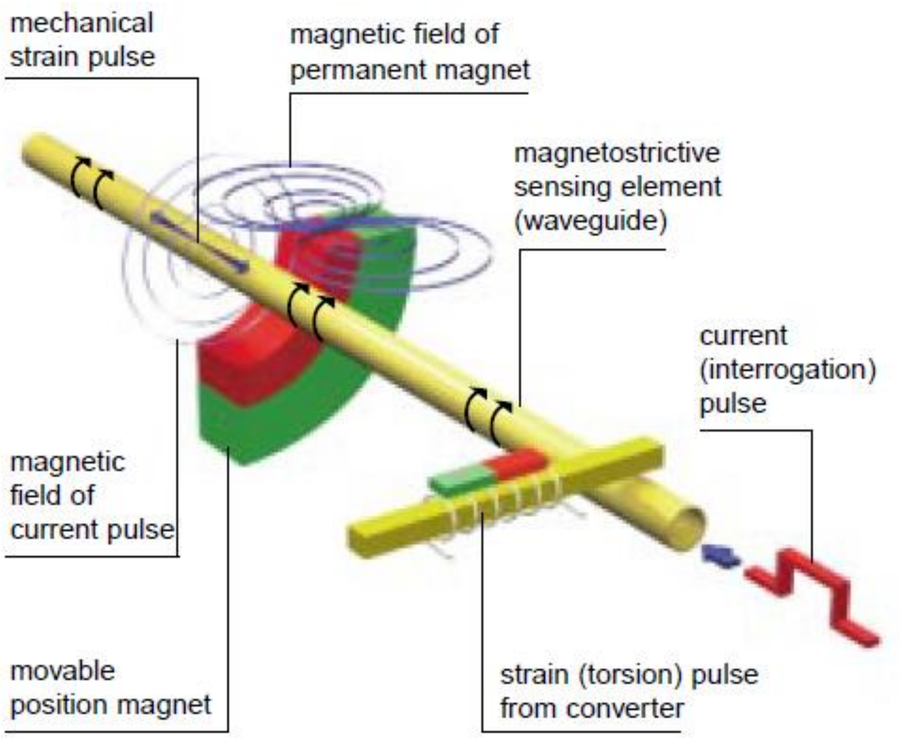


Figure 13 Magnetostrictive effect explained

A current pulse generated by the sensor element is sent down the wave guide. This creates a momentary radial magnetic field as the pulse passes through. The permanent magnet creates a magnetic field where it is located around the waveguide. The magnet creates a torsional stain pulse as the current pulse passes by it. This torsional strain pulse is sent back towards the sensor, and this returned pulse is processed by the sensor. As the initial speed of the ultrasonic wave is precisely known, the time taken to get to the magnet and back can be directly correlated into distance. This is the basic principle of how Magnetostrictive rod style transducer works, (MTS, 2017)

3.3.2.4 *Variable resistance*

Variable resistance transducer is based on contact technology so parts in contact do wear after some time. They are used where cost is a factor and are not as accurate in resolution as Magnetostrictive or variable inductance types, (Herceg, 2013).

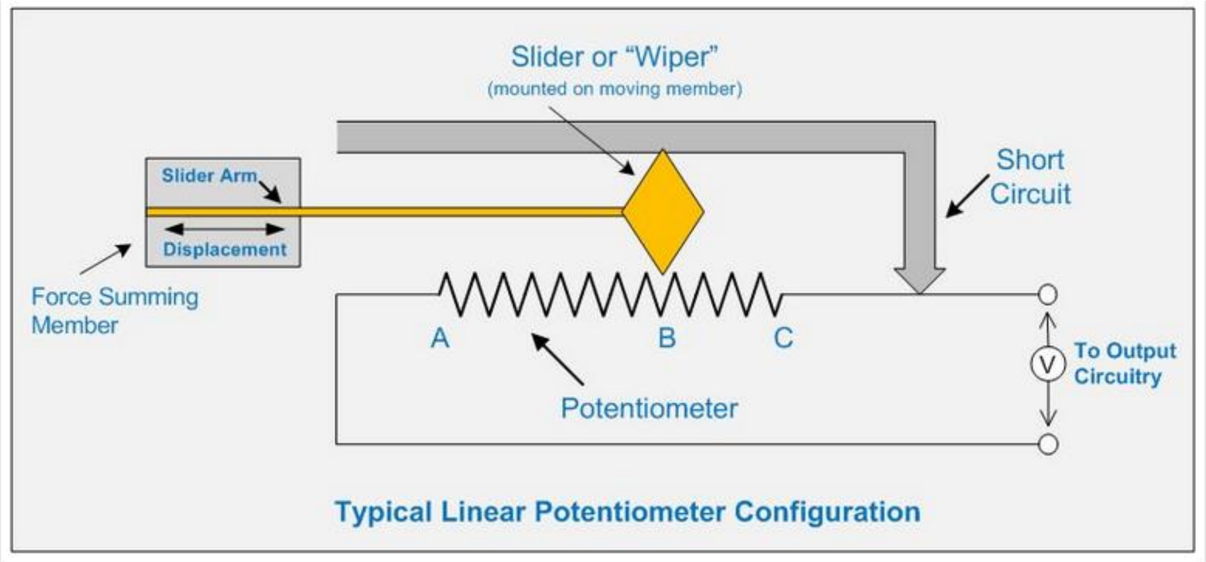


Figure 14 Resistance type Potentiometer

The rods are drilled like on the Magnetostrictive solution and there is a tube inserted inside rod which acts an insulated rod carrier. Attached to the piston rod there is a slider which moves up and down along the potentiometer rod. As the slider moves along with the piston its resistance changes in a linear fashion. By using this varying resistance reading indirectly the piston position can be determined. (Herceg, 2013).

Therefore, resistance type transducers are no longer seen readily in the marketplace due to customer demands of longer warranty times. The main reason this contact technology would be eliminated from the start is because of wear due to vibration where cylinders are fitted on mobile machinery and equipment. (Howard, 2018)

3.3.2.5 *Wire Actuated encoder.*

There are three different versions of this available in the marketplace today.

3.3.2.6 External mounted wire sensor

In this version the sensor is completely outside the cylinder. They come in varying sizes depending on length of stroke needed, with a maximum travel length of 15 metres. (Siko, 2018). Nearly all of Burnside cylinders would fit inside a 5-metre stroke range. External string pot sensors have the advantage in that if they get damaged, they can be easily removed and replaced.

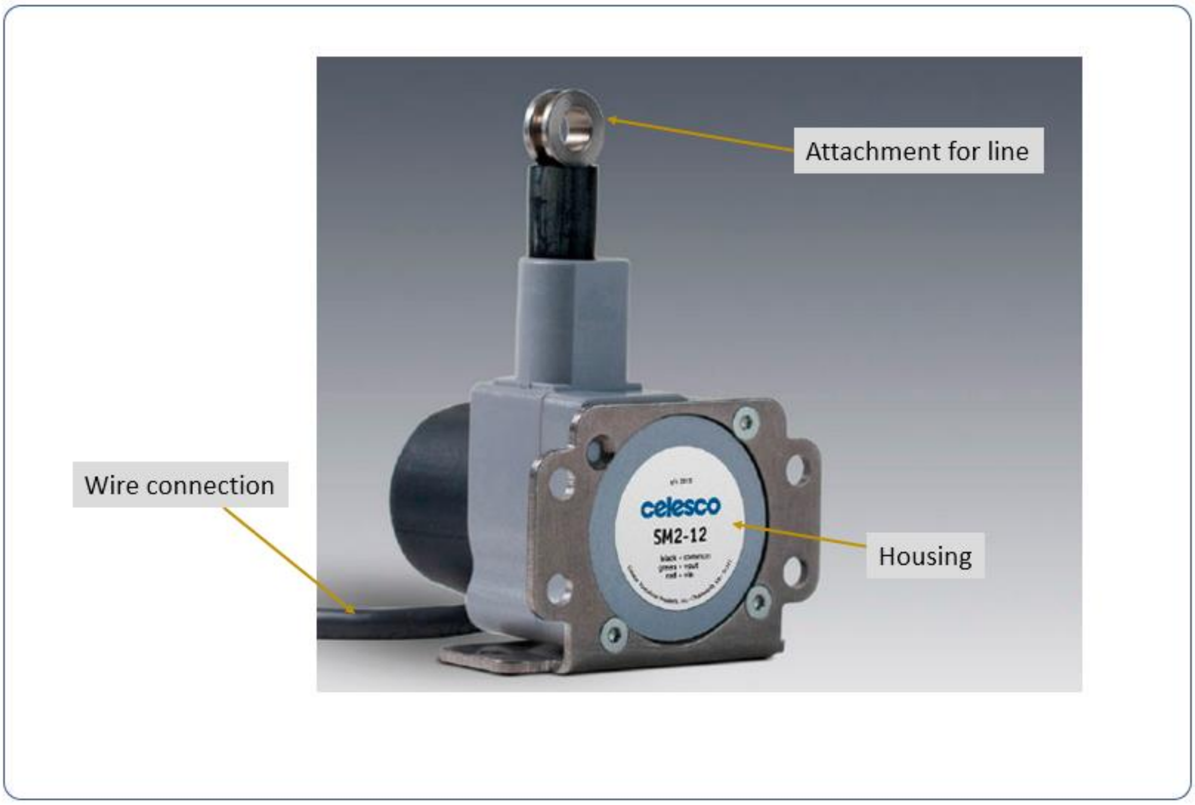


Figure 15 String pot sensor

In Figure 15 a string pot sensor assembly can be seen in isolation. The housing of the sensor can be attached to the body of a cylinder, which can be done by welding a bracket to the front of the tube. The housing is attached by two or three bolts as required, with the attachment on the line, either attached to another bracket welded to the rod eye or to a part of the machine which the cylinder is attached to, as seen in Figure 16.

In this case there is a small mounting bracket welded near the front of the tube with two x M6 tapped holes. The eye is attached to a welded round spigot on the rod end. As the cylinder strokes the string gets pulled out of the sensor assembly and gives positional feedback to the operator on the cylinder’s position.

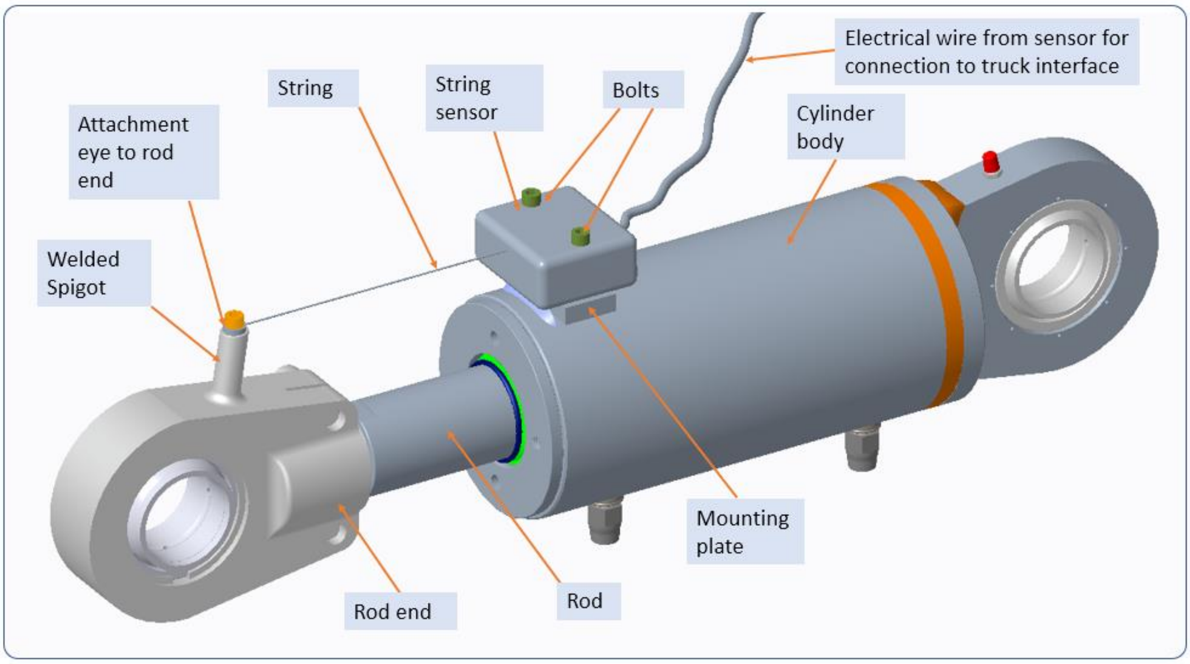


Figure 16 String pot sensor on outside of cylinder

Inside the string pot there is a spool which contains the wire which is being pulled out as can be seen in Figure 17. As the cylinder extends the high tensile wire is pulled out of the string pot sensor. On the return stroke there is a power spring to ensure the string is taut and the spring recoil force reels in the wire.

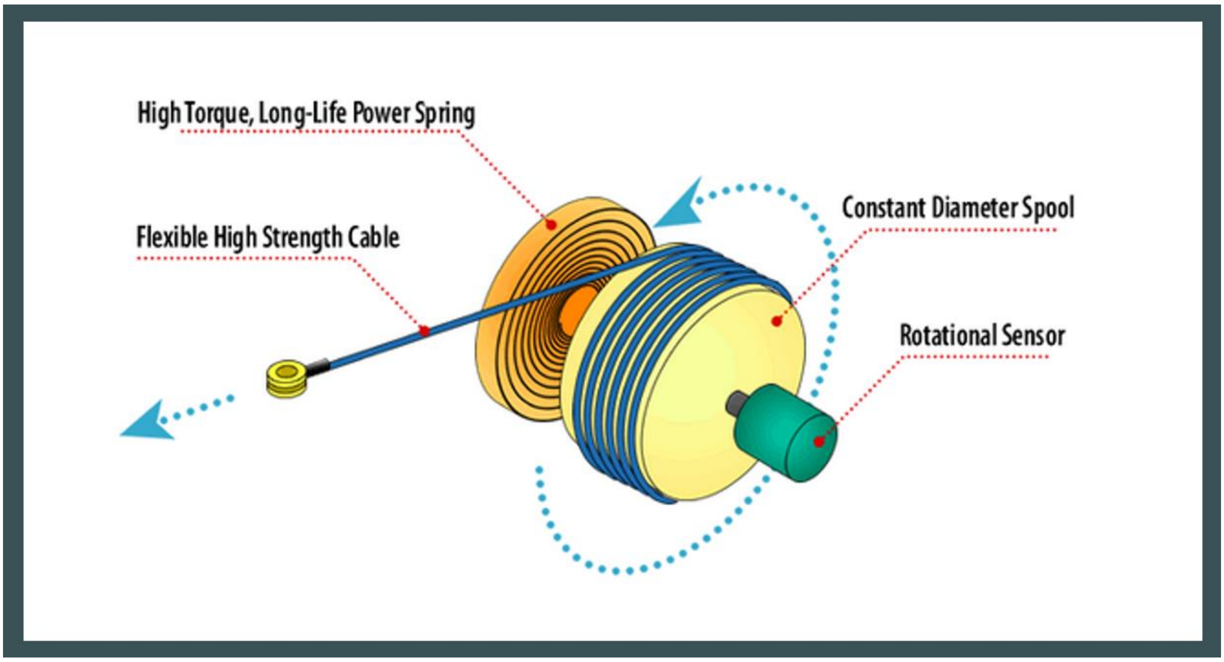


Figure 17 Inside a string pot sensor (TE, 2017)

The rotational sensor measures the angle of rotation and therefore can establish distance travelled because the OD (overall diameter) of the spool is known. This rotational distance is converted into a proportional electrical signal and therefore information on distance travelled is available.

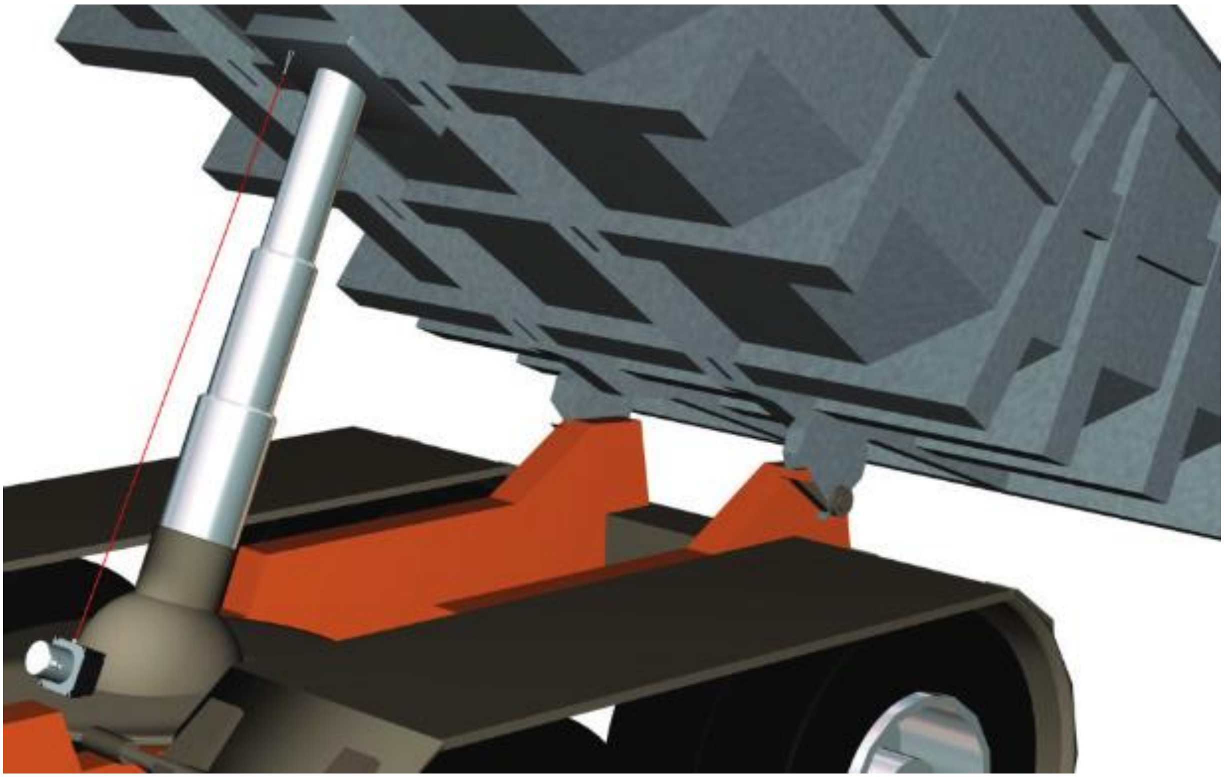


Figure 18 External wire application

In Figure 18 illustrated, the wire is situated outside the cylinder. This leaves it particularly vulnerable to damage from external elements. Also, if this sensor is used in a dirty environment such as tipper body shown, dirt can get onto to the wire and would get back into the spool which would stop the sensor working quickly.

In extreme environments where there is wet and cold, the wire would get wet during the operation. When the coil is retracted and left overnight outside, there would be the possibility of freezing. This would mean the coil would not move as it would be frozen in its stationery position and the wire would snap during the first operation.

Once there is a clean line of sight for the string to travel uninterrupted between fully open and closed positions the sensor would work. This would make this sensor solution ideal to fit in places where cylinder is fitted in difficult to access positions.

3.3.2.7 Internally mounted wire sensor

There is also an internally mounted string sensor which goes inside the cylinder like the transducer type. There are different models available for the varying stroke needed. The workings are very like the external wire mounted sensor and works with the same principle.

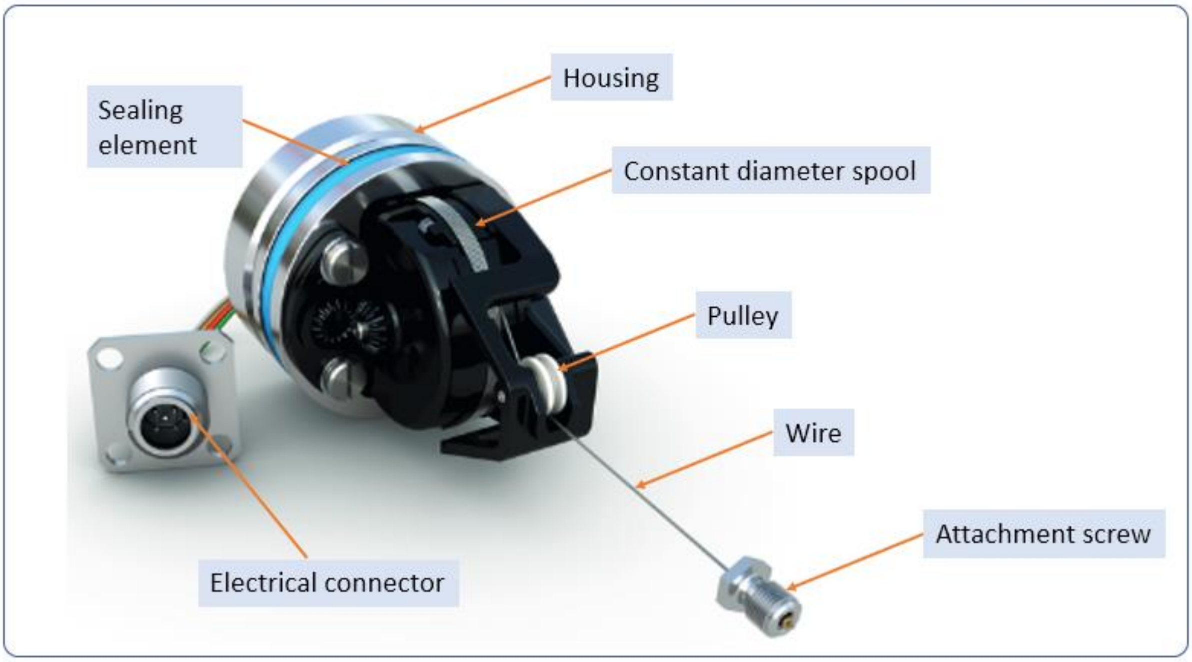


Figure 19 Internally Mounted Wire Sensor (Siko, 2017)

The housing contains the electronics needed to run the sensor. The main difference is this sensor is more compact and is designed to resist the internal hydraulic pressure of the cylinder. There is a sealing element on the outside of the housing to protect the back of sensor from pressure. An attachment screw is used to connect the wire to the moving element of the cylinder, rod or piston head, and the wire is connected to the screw in such a way that it is free to rotate to prevent twisting and binding of the wire during installation and usage.

A pulley is used to guide the wire from the spool down to the same centre as the centre of the housing. An electrical connector is used to supply voltage, and to receive an output signal. An internal spring recoils the wire as the piston head returns inside the cylinder. An electrical connector is used as a connection interface.

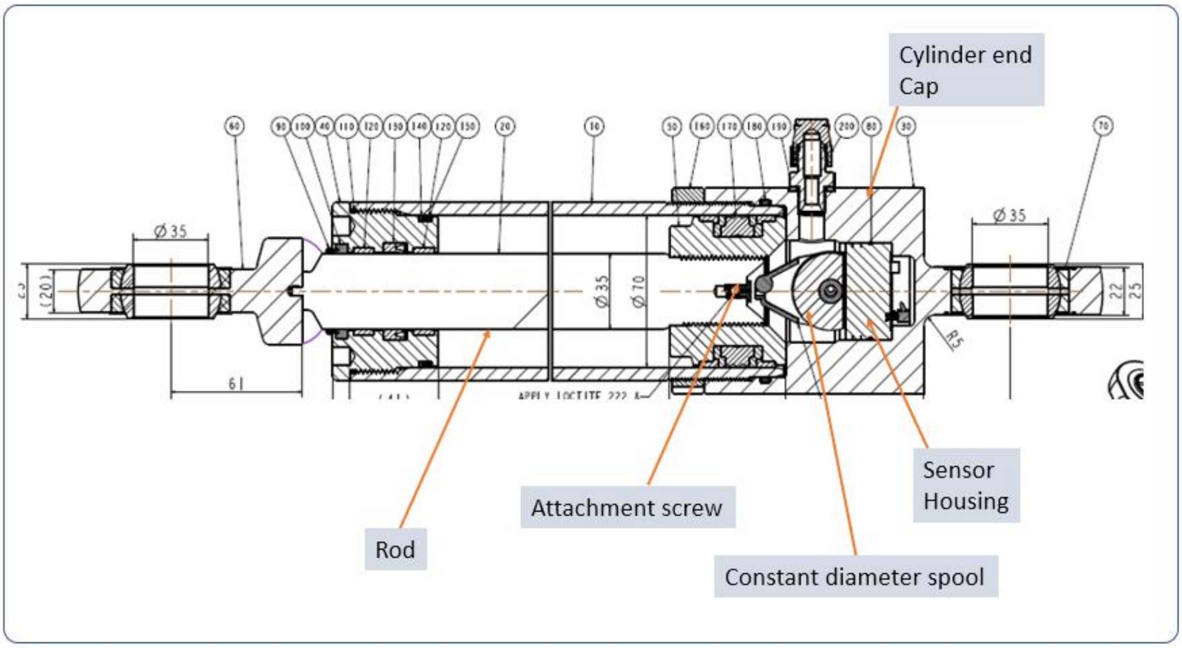


Figure 20 Wire actuated encoder installed in cylinder

In Figure 20, the sensor can be seen installed inside the cylinder. The rod extends as it pulls the wire that is wrapped around the constant diameter spool, against a power coil spring. The power coil spring pulls back the wire as the rod is retracted. The movements are recorded by an encoder.

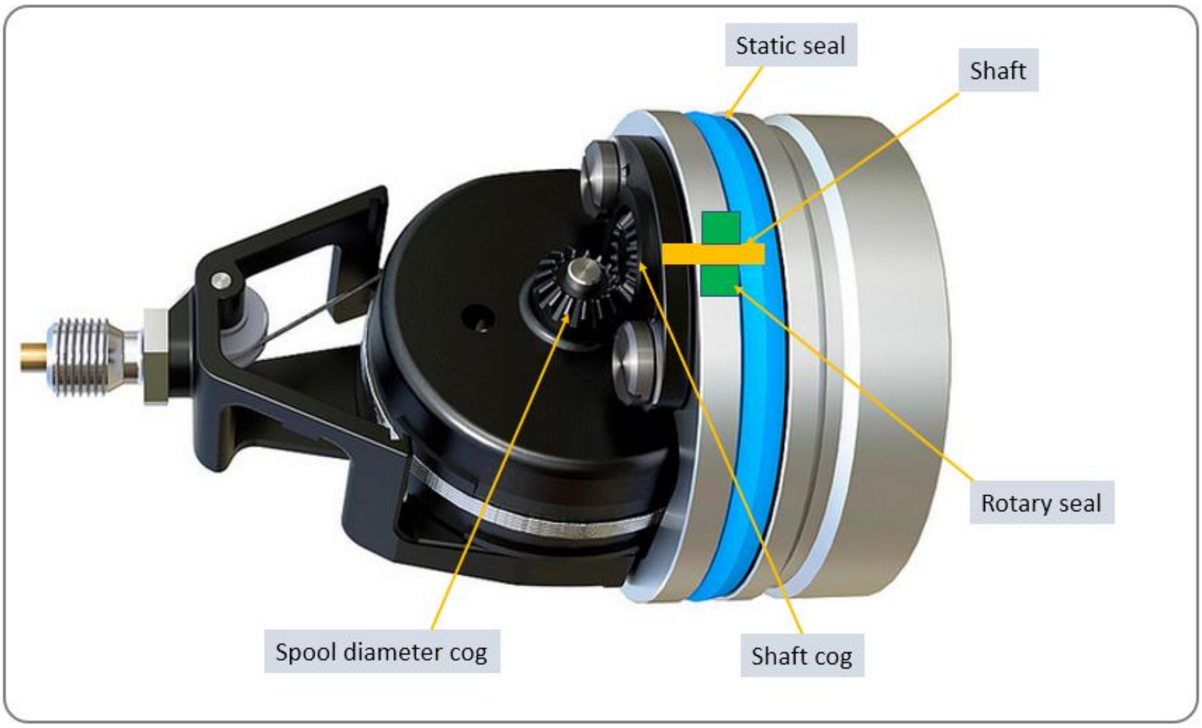


Figure 21 Separating pressure

The sensor is used in a hydraulic cylinder with pressure and electronics used for the sensor to function. These areas need to be separated at some point and a pressure seal created between them to protect the electronics. For the outside the housing is stationery so a static seal can be applied as shown in Figure 21.

The spool is positioned so the wire is coiled naturally onto the spool. To get the rotary action as required into the housing bevel gear cogs are used. The bevel gears transmit the rotational movement from the rotary shaft by ninety degrees to get rotational movement as required by the manufacturer.

3.3.2.8 Internal spool, External sensor type.

The third variation found available is a combination of the previous types External mounted wire sensor on page 42 and Internally mounted wire sensor types on page 45.

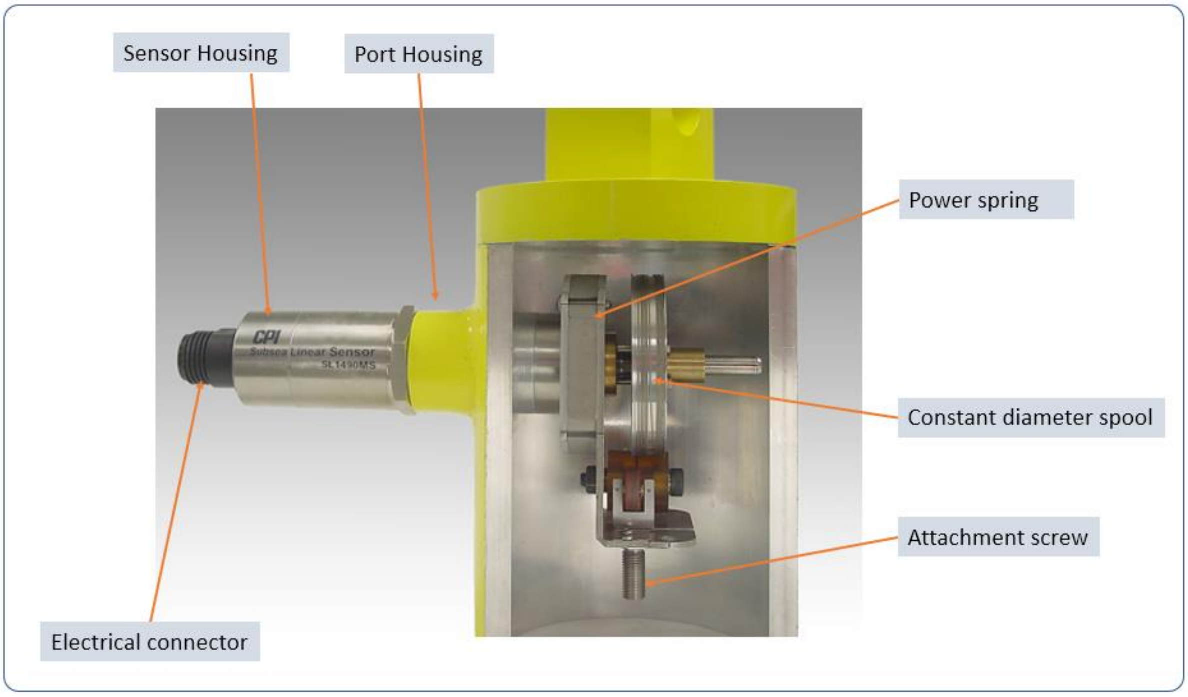


Figure 22 Internal spool, (Control, 2017)

In Figure 22 Internal spool, it can be seen how this external sensor type is constructed. The mechanical part of the sensor is inside the cylinder. The mechanical side contains a constant spool diameter, the attachment screw and the power spring to keep the wire taut when the cylinder is retracting.

The sensor housing is screwed into the port housing and connected to the mechanical elements inside. The electrical connector transmits power to the sensor is powered up and the outputs received through the same connector.

Another example of a wire sensor with external electronic connection can be seen in Figure 23. The wire and mechanics are installed in the pressure area of the cylinder and the sensor element, which is an absolute encoder, is attached outside the cylinder. (Waycon, 2016)

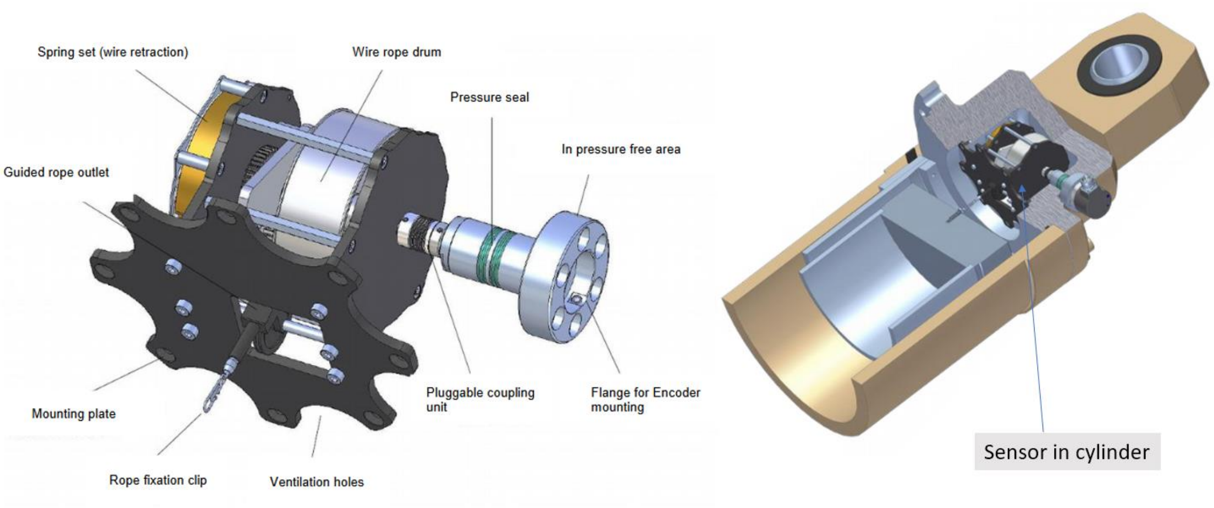


Figure 23 Wire sensor solution (Waycon, 2016)

The downsides are that the sensor outside may be susceptible to impact damage and possible exposure to harsh outside external weather environments which can cause reliability issues, (Balluff, 2018). The sensor electronics in this type of sensor can be affected by outside EMI (electro-magnetic interference) which can impact the working of the sensor, (Zieseri, 2015). Protrusion outside cylinder tube may also cause installation issues on the machine where used, if space is tight in this area. Additionally, to assemble the outside electronics to the inside mechanical elements can be tricky if situated down inside long tubes.

3.3.2.9 External Probe type

From research there is an external probe type available which has the transducer on the outside of the cylinder tube. This probe is positioned as close to the outside of the tube as possible (see Figure 24.

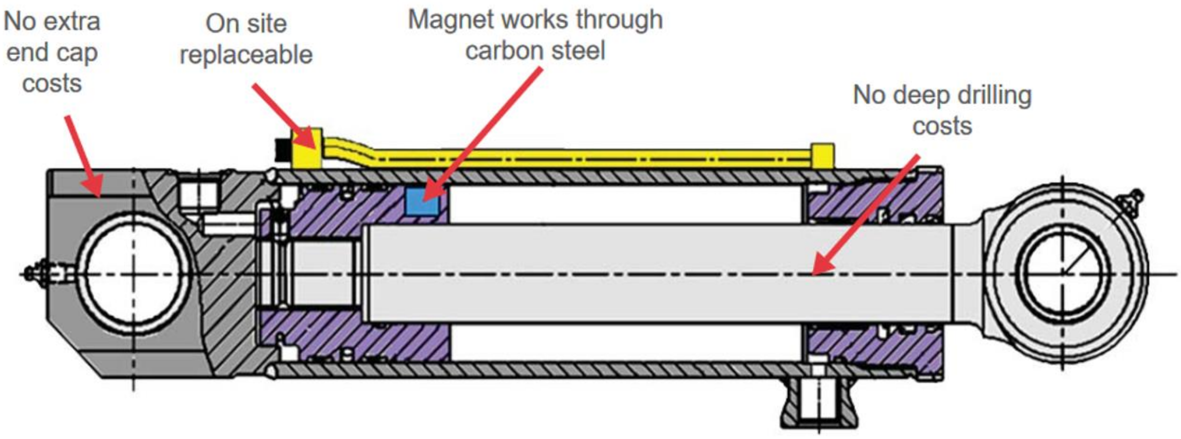


Figure 24 External Sensor Type (Wright, 2017)

The external probe is secured on both ends of the cylinder with a bracket or clips. There is easy access is available if there is a problem with the external sensor and can be replaced easily.

This sensor, in theory, is more susceptible to more EMI as it is outside the confines of the envelope of the cylinder barrel, (Zieseri, 2015).

There is a magnet fitted to the inside of the cylinder which sends a magnetic field out through the tube wall of the cylinder. As the piston is travelling inside the tube the probe sensor on the outside can detect the magnetic field which is generated by the magnet inside.

The magnet needs to quite large (e.g. 21mm high and 36mm wide for a Ø80mm bore cylinder, based on prior experience) as shown in Figure 159 on page 189, to generate a large enough magnetic field which would pass through the tube wall of the cylinder.

As the magnet needs to be quite large in structure to generate the magnetic force needed to activate the sensor, this would limit uses in cylinders where there are small tube bores or cylinders where there are small annular areas between the tube ID (inside diameter) and the rod.

A big advantage of this type of setup is the rod does not have to be deep hole drilled. This means the structure of the rod under tension at the threaded joints is stronger because there is more material available to take the load and less stress concentration because the rod is solid on the inside. Also, the time and cost involved in deep hole drilling is eliminated.

A hydraulic cylinder is a pressure vessel tube; therefore, wall thickness needs to be increased in proportion to the increase in working pressure. The magnetic field needs to pass through the tube wall, this limits the thickness of tube wall that can be used to give satisfactory reliability for the working of the sensor.

As the magnet and the transducer do not meet one another there is no wear of the external probe part. Consideration however may need to be given to the magnet inside the tube. The points that might need to be considered are as follows:

- would the plastic cover around the magnet wear over time and would it need replacing?
- If this wear did take place would this plastic enter the hydraulic oil and cause possible contamination of the hydraulic system?
- Another consideration, would the plastic cover damage the internal surface finish of the tube which would be skived and burnished to give long lasting life for the seals?
- Alternatively, if the plastic wore away, would the magnet damage the inside surface of the tubing which would render cylinder obsolete as would leak internally due to the damage?

This type of sensor typically uses Hall effect technology, (Hitchcox, 2013). The sensor uses a processor to transmit and receive signals from hall effect chips which are printed on a circuit board which is mounted inside the sensor probe. The magnet passing over these chips causes a voltage drop which can then be translated into magnet position under this point.

A limitation of this technology is the resolution would not be as good as other sensor technologies but with 1-2 mm positional accuracy would be suitable for most end users.

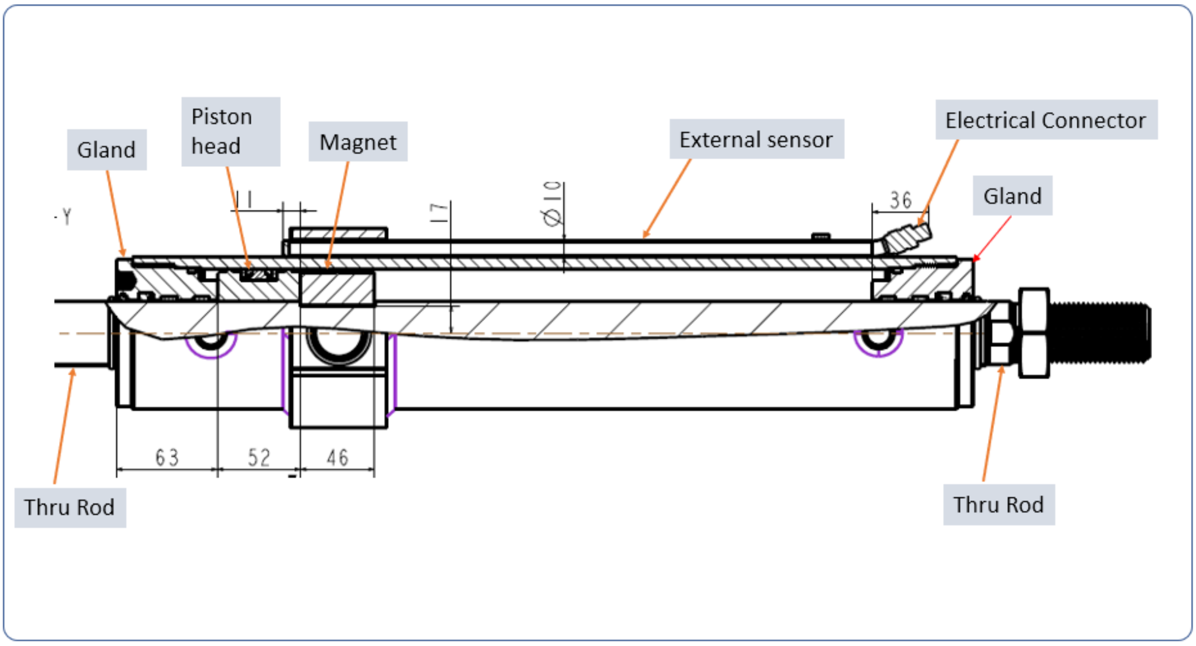


Figure 25 External probe sensor

An example of where an external probe would be a necessary type solution for a special cylinder setup is seen in Figure 25. In this case the cylinder is used in a steering application where there are rods sticking out both sides of the gland, there is no room to put the barrel of the sensor in the bottom end. Another solution is required.

From discussion with a supplier of this technology the scale of the magnet shown is needed for Ø80mm bore tubing. The size of the rod in this case is Ø40mm. As can be seen the magnet needs to be below the outer diameter of the rod. In proportion to the cylinder size the magnet is quite large. This would limit usage on many applications where there is a small annular volume available.

3.3.2.10 Rod Reading Sensor

Another type of sensor which does not require gun drilling of the rod uses a rod reading type of sensor. This sensor can read a scale which is put on to the rod. The scale is normally etched directly onto the surface of the rod. There is an optical reader which is bolted near the gland of the cylinder. Little modification of a standard cylinder is needed to incorporate the optical reader. Just some mounting points are needed. (Sharpley, 2014)

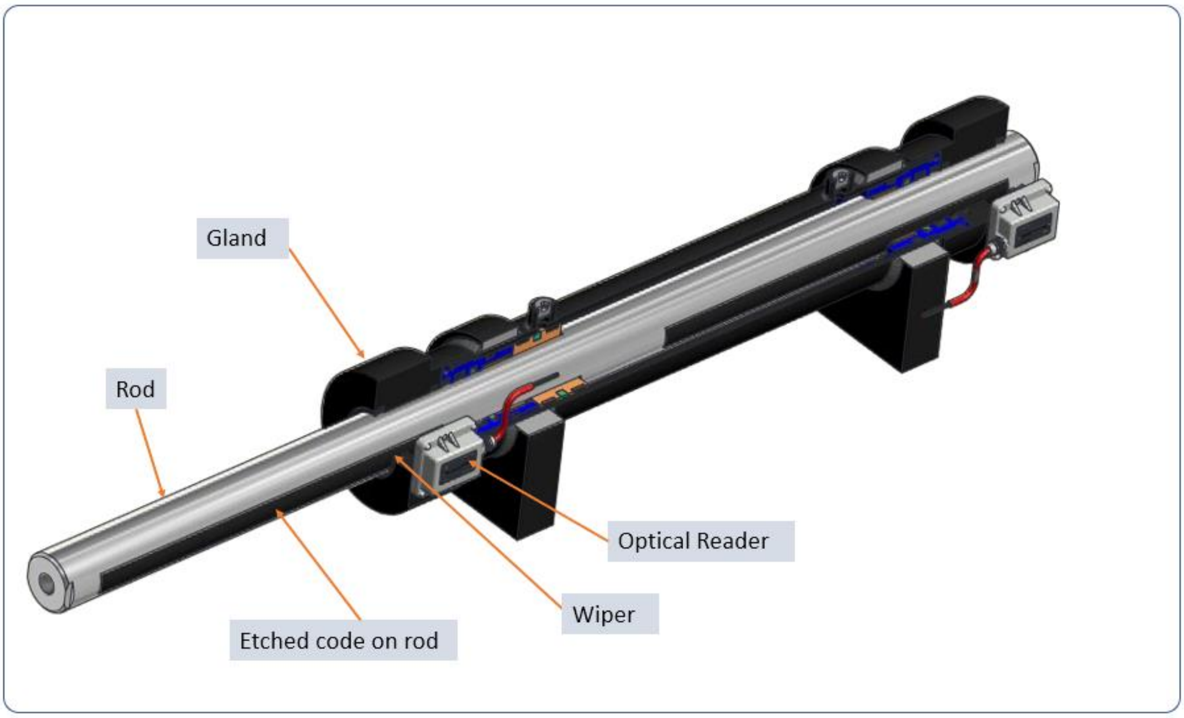


Figure 26 Rod reading sensor

In Figure 26, it can be seen how the sensor is mounted. In this case the cylinder is using a through rod design. For this type of cylinder construction, a gun drilled rod and barrel type sensor would not be used. This type of cylinder construction is typical for steering type applications where equal speed is required in both directions.

This type of setup was absolute positioning. This means the position of the rod is immediately determined without the rod having to move to a reference point. For this type of sensor, like the external probe type, orientation of the optical reader with etched code on the rod is important for the sensor to work. In Figure 26 the bar coding can be seen applied only on a partial width of the rod. This would reduce the costs in applying the bar coding as compared to all around 360 degrees' application.

Figure 27 Marking applied on rod

The sensor is normally positioned so it can read the code from the rod after it passed under the wiper in the gland. This means if there is dirt on the rod on the return stroke as it approaches the sensor the dirt would be cleaned off by the wiper, ensuring that the sensor can read the code properly.

The rod markings are applied at such an angle that it allows for some misalignment when lining up for mounting. Figure 27 shows that markings can be applied all around the rod as well as an option but would add cost as compared to a marked strip.

An advantage of this type of sensor is the little extra building space taken up to include the sensor. The mounting of the sensor is on the outside of the gland. However, this may present issues to align with a fixed weldable non-rotational type of end like shown in Figure 28. The ends are fixed in orientation, another way other than a standard screwed gland may need to be considered to ensure the gland optical reader ends up in the correct position to read the bar code.

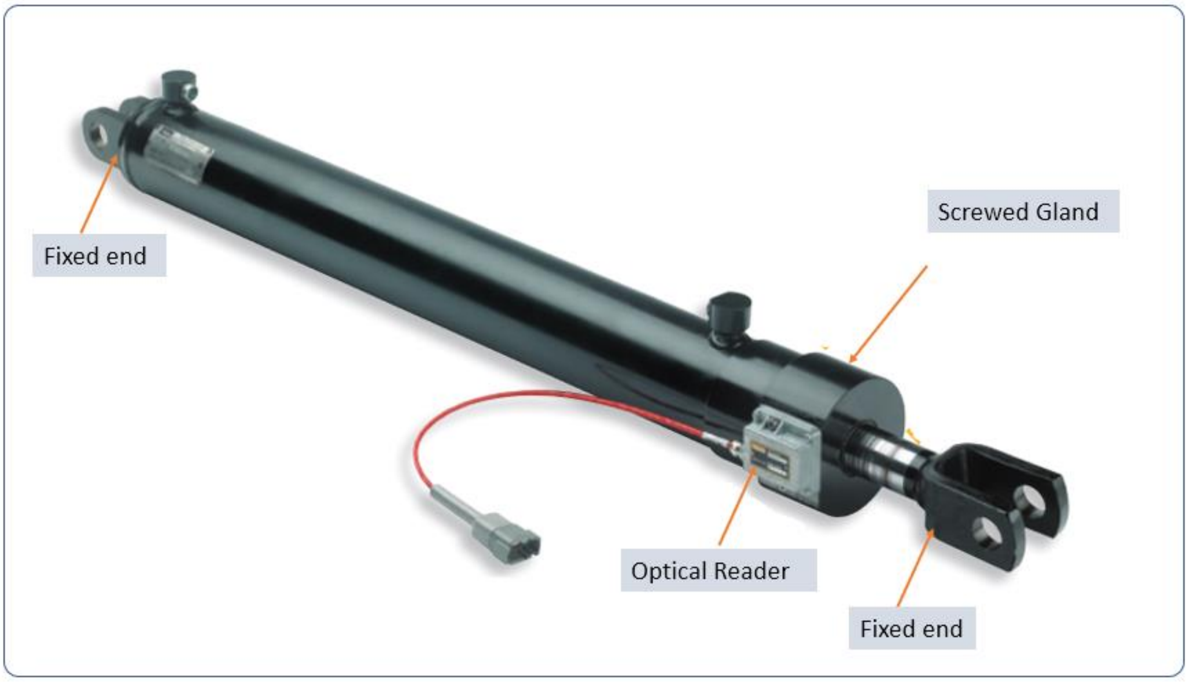


Figure 28 Sensor with fixed ends

The sensor is mounted with two screws making maintenance or replacement of sensor easier. However, if the rod gets damaged through impact damage getting a replacement rod may be costly and require lengthy down time of the machine where the cylinder is used, to source bar coded rod if upfront provision is not made for such a situation.

The optical reader reads the rod between the wiper and the rod seal; therefore, the encoder does not need to be manufactured to a pressure resistant construction.
The sensing head is sealed by bolting down flat onto a clean sealed surface, the sensor should continue to work in a clean environment, protected between the wiper and the pressure rod seal. The working principle of the sensor makes it easily affordable to incorporate dual double or triple redundancy for increased reliability, (Besch, 2016).

However, a risk for this type of application is that the markings may be worn away on the rod as can be seen in Figure 29.

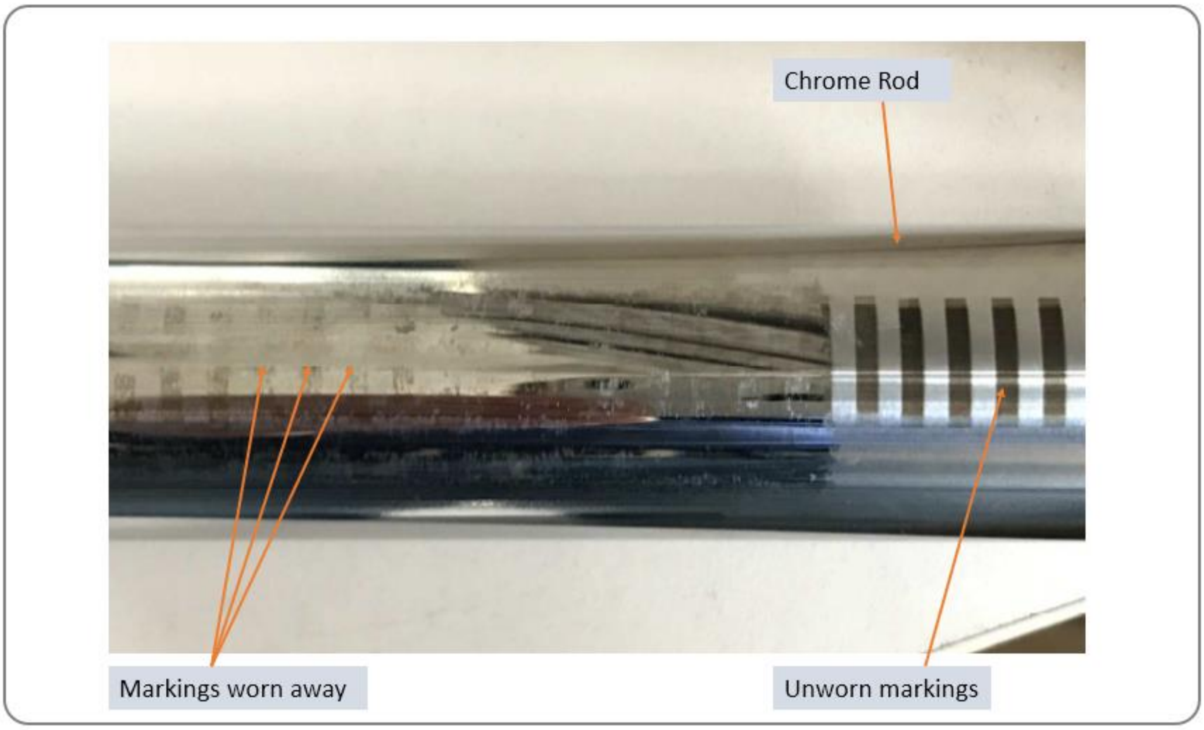


Figure 29 Rod Markings

Adding coding may affect lead-time for delivery of the chrome, therefore impacting Burnsides ability to deliver sensor cylinders with short lead-times. If coding or marking would be applied to chrome after arriving in Burnside, then would the process be costly or complex to conduct?

3.3.2.11 Ultrasonic sensors

Ultrasonic sensors use electrical energy to generate sound which is then transmitted and received back to a receiver. These signals can be used to detect or sense the presence of targets, (Banner, 2017). Ultrasonic use sounds outside the hearing range of humans, typically above 20 kHz.

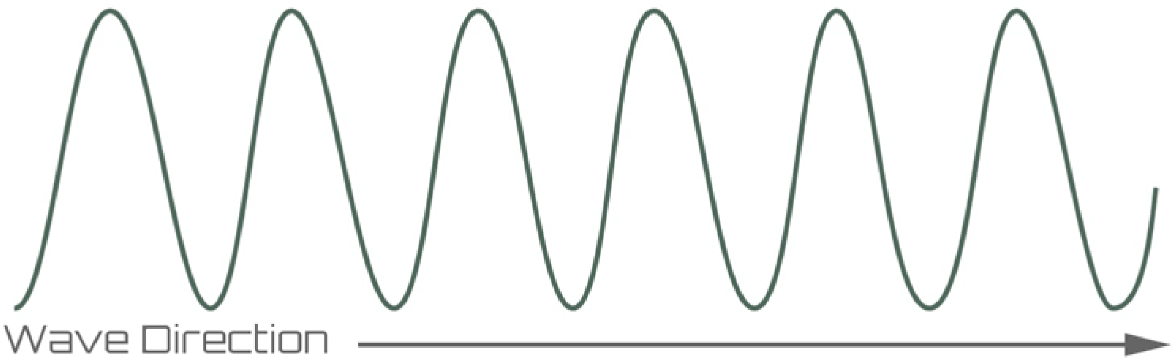


Figure 30 Wave forms

The number of waves in a second that is produced by the sound can be measured in Hz.
The speed of sound varies and depends on what medium it is passing through. Sound travels faster through liquid than through air and quicker through solids than liquids in the hydraulic cylinder to create ultrasonic waves a transducer is used. The transducer converts electrical energy to mechanical energy in the form of sound waves, (Scienceclarified, 2018).

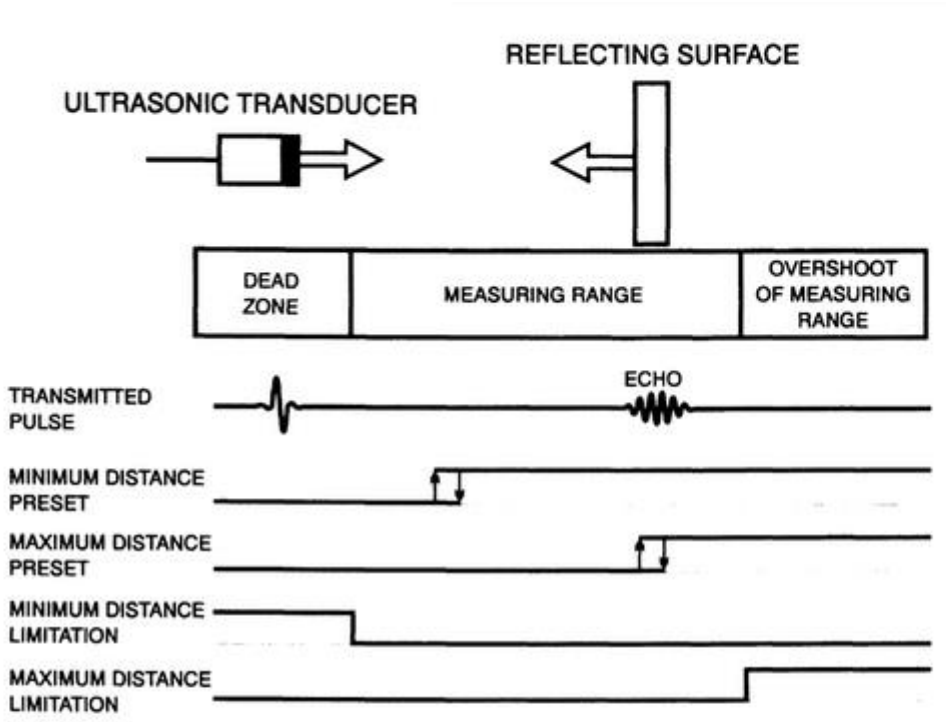


Figure 31 Principle of an echo sounder

In Figure 31 an ultrasonic transducer is used to measure the depth of the ocean floor from a ship on the surface. The system would be modified to measure distance from the transducer to the piston and calculate the position in the cylinder. The ultrasonic transducer sends a short signal emitted towards the intended target. When the signal meets the target, the returned signal is reflected, called the echo. The returned echo is detected, and the time measured from sending to receiving. By knowing the speed of the frequency signal sent in the medium used. The position of the target can be determined. There is a minimum and maximum range depending on the type of technology selected, (Kocis, 1996).

If flow into a pressure vessel would be accurately measured and the volumes of each side of the pressure vessel known, then, in theory, the speed of piston would be determined, and the position once initial start-up position was known.

Doppler and Transit time are popular types of flowmeter when measuring for the outside of a liquid flow vessel. The two principles use different methods to measure the flow inside a pipe.

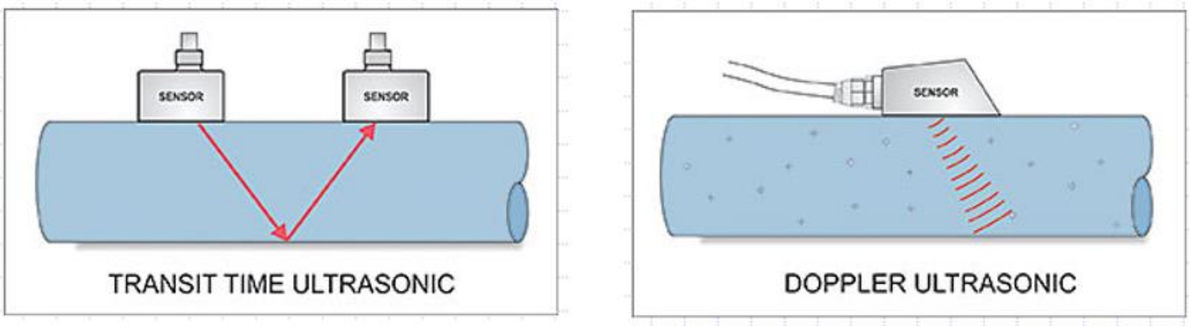


Figure 32 Two types of external flow measurement (Greyline, 2018)

In Figure 32, the two different types are shown. The two types involve using a sensor on the outside of the pressure vessel. Each transducer has a Piezo-electric crystal. These crystals send an electronic pulse through the wall of the flow vessel. The returning echo is received and using this information the flow volume inside the vessel can be determined.

3.3.2.12 Frequency Measurement

There is a sensor developed which determines the position of cylinder by using frequency measurement. An example of the system workings is shown in Figure 33.

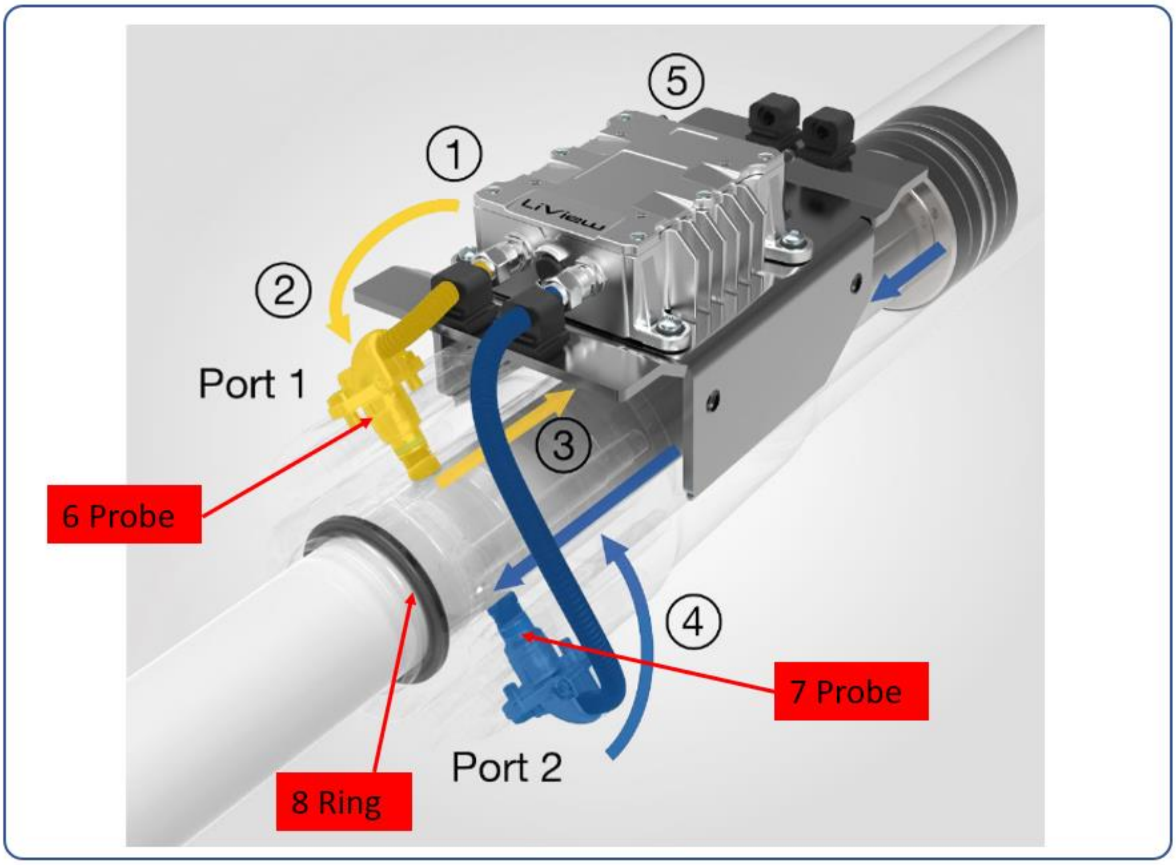


Figure 33 Frequency Measuring (Liebherr, 2017)

An electronics unit at position 1 can be placed on the cylinder or near the cylinder. The electronic unit generates a high frequency electrical signal and sends the signal from the electrical unit into port 1 via a probe shown in yellow (6 probe). The probes are situated inside the cylinder on the annular side just in front of the gland. The signal is sent (shown as 3) at the end of the probe down the annular area between tube ID and rod diameter until it meets the piston head.

When the signal meets the piston head the returning signal (echo) is reflected up the annular area towards the gland of the cylinder. The returned echo is then sensed through the second probe (shown as 4). This received echo is then sent back to the processing unit, which can determine the piston head position and the piston head speed.

There is a HF termination ring shown as a black ring (8 ring) inside the gland. This prevents the returned echo signal being sent back into the cylinder.

The sensing solution is flexible in that one solution can be used for all size combinations and kept on the shelf ready for use for the various stroke cylinders as needed. Sensing lengths of up to 10M are possible which would cover all cylinders in Burnsides current stroke range.

The sensor can work in combination with the hydraulic oil and the probes are designed to work with systems pressure of up to 400 bars. This sensor is used exclusively by Liebherr for their own produced cylinders and not available to purchase by cylinder manufacturers.

3.3.2.13 Laser Measurement

Laser measurement is used in forklift applications to measure the lift height of the mast. This is external to the hydraulic cylinder but still used indirectly to measure the stroke of the cylinder. The set up consists of a laser measurement system unit as seen in Figure 34.

Figure 34 Laser used to measure lift height

The laser would be situated on the base of the mast or alternatively attached to the side of the cylinder with a bolted construction. The laser points up to a target which is a flat piece of plate attached to the top of the mast. Laser accuracy is quite good and repetitive (Ullrich, 2015).

However, as a mast is extending, there is play in the roller of the mast which may have two or three stages depending on construction and lift height. When the mast gets higher the deflection of the mast and the plate can be quite substantial. Therefore, the plate needs to be oversize to compensate for maximum deflections. These deflections are at their worst when fully extended and masts loaded to maximum lifting capacity.

The limits of this type of solution would be the environment. If dusty or foggy conditions were present, this may restrict light to hit target. If an object passes between intended target and laser measurement system a reduced stroke would be indicated and would create problems.

Also, for some cylinders with long strokes it may not always be possible to include a large enough target to compensate for the deflections, especially on mobile hydraulics where space can be restricted.

Also, as the laser measurement systems can be quite bulky, they would be susceptible to damage. However as mounted externally they would be easily replaced.

3.3.2.14 Radar

A pulsed radar (Radio detection and ranging) is a device which sends a short but powerful pulse and then in intermediate period receives the echo signal back. Pulse type radars are typically used for long measurement such as a determining the position of aircraft in the sky.

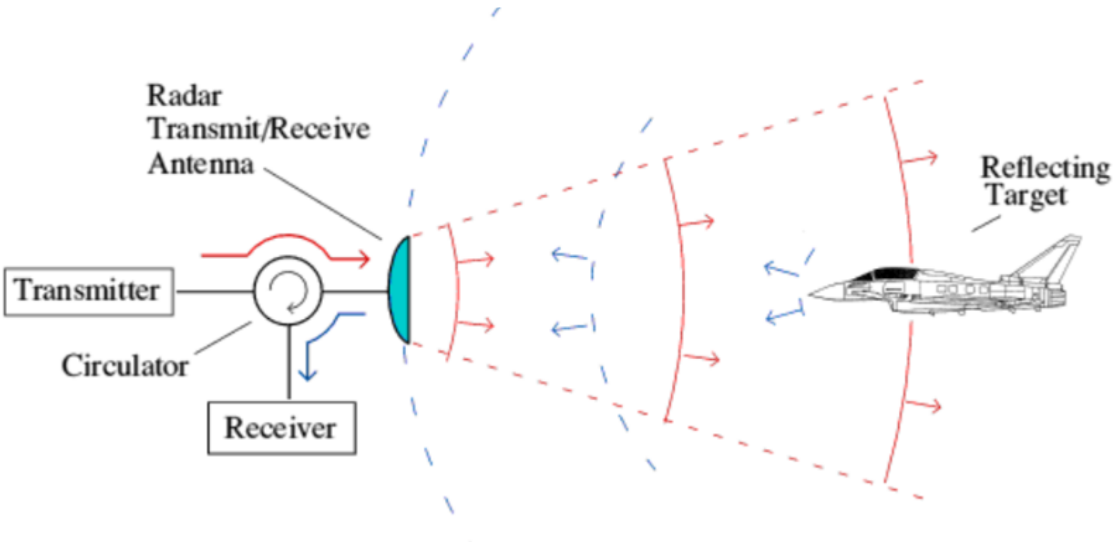


Figure 35 Pulsed Radar

In Figure 35 it can be seen how the radar works. The radar has a transmitter which send EM (electromagnetic) pulses. Part of the radar includes a receiver which is used to detect any returned signal from a reflected objected. The transmitter, antenna and receiver are all connected using a circulator. The circulator ensures that the transmitted power is sent to the antenna while all the reflected signals is returned to the receiver, (Lesurf, 2017).

As pulsed radar work at long range lengths, the precise image of the object cannot be detected and does not allow for the detection of small objects but can operate at longer distances. However, they are good to measure proximity of objects at long distances.

For hydraulic cylinders' stroke measurement in principle would always work in a linear direction, the piston head would be moving either directly towards or away from the sensor when positioned directly behind the piston head.

3.4 Selection of Technology

After evaluation of all the technology's available in the literature review, they are wide and diverse in nature. Some technologies, Burnside are familiar with and use today, some which are new and not available commercially to hydraulic cylinder manufacturers. All have benefits and weaknesses compared to competing solutions. The technologies were grouped in basic types and a weighted table decision matrix was created to assist in the selection of technology to pursue for research as shown in Table 2.

Decision making Criteria matrix for sensor					
Scoring 1-5; 1-Negative 5-Positive					
Technology		Criteria			Score
Section	Technology	Price	Flexibility	Feasibility to develop within 2 year time frame	Score
3.3.2	Internal Rod Transducer	3	1	2	6
3.3.3	Wire Actuated Encoder	3	5	4	60
3.4	External Probe type	2	2	3	12
3.5	Rod Reading Sensor	2	3	2	12
3.6	Ultrasonic Sensor	3	4	2	24
3.7	Light Based Measurement	2	3	3	18
3.8	Microwave	3	3	2	18

Table 2 Technology Decision making matrix

Some solutions were overly complex and would require multiple highly advanced disciplines to evaluate and develop. These were weighted at 2 & 3 in the table. Some solutions were inflexible in that dedicated manufacturing solutions would be needed for each stroke length.

The wire-based encoder sensor solution was decided upon based on the evaluations. The wire encoder solution would be suitable to work across multiple stroke lengths and different bore cylinders whilst utilising common parts. Solution would also be an attractive solution for Burnside to be able to source these in large volume and set to appropriate stroke length as required to meet complex and varying demands. This would address being able to deliver cylinders with short lead-times.

This type of sensor yielded the best cost effective most suitable for Burnsides needs. The cost effectiveness would allow Burnside to stock in reasonable quantities. The sensor type gives flexibility with different lengths of cylinders. Many options would be available on material sourcing and the mechanical and electrical parts would be made done locally and joined together in Burnside or outsourced internationally to get better prices and sensors stored in Burnside until required. Also based on other technologies there was some scope to save on building length to incorporate the sensor within the cylinder, which was very important for the machine builder using Burnsides hydraulic cylinders. If gains on building length were made, major advantages over another sensor solution would be achieved.

As a unique feature not available in the marketplace today and as part of proposed linear position sensor solution, a temperature sensor would be incorporated within the unit to measure the temperature of the oil. This temperature feedback would be used as a unique selling point to offer extra feedback information to the customer. The machine owner would use this information to monitor oil temperature within the cylinder and plan maintenance schedules for seals based on changing temperatures of the oil over time or identify other problems within the hydraulic system and address the problems using preventative maintenance before major costly failures would occur.

3.5 Patent search

3.5.1 Patent Methodology

After seeking advice from colleagues here in the college https://worldwide.espacenet.com/ was recommended as the website to look for relevant patents on the chosen direction that was decided to pursue on wire type sensors for use in hydraulic cylinders. The patent search was carried out in this Espacenet website using a range of word searches on wire hydraulic sensors. It was found that unless lots of specific words were used together in the one search that the results table was returning too many hits. This meant the advanced search function was used as shown in Figure 36.

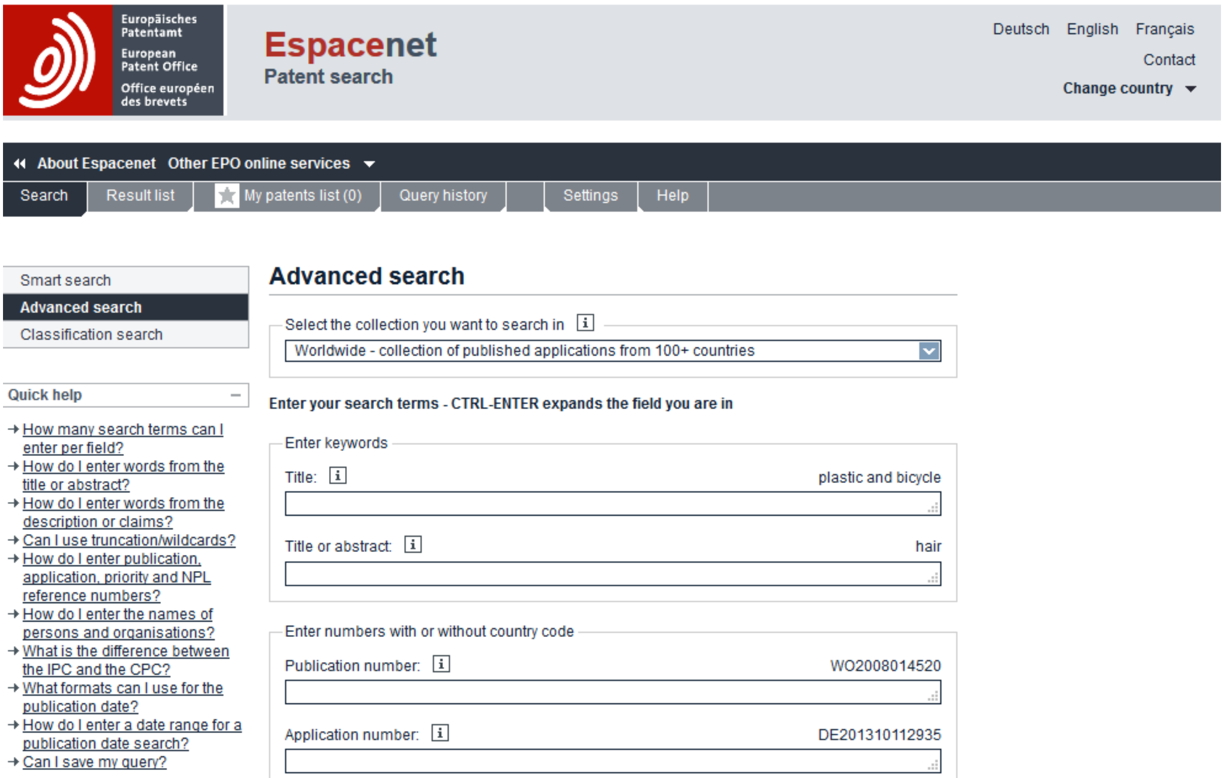


Figure 36 Espacenet Patent search

All the keywords on the patent search needed to be added to the title search bar. Using too few words brought up too many hits, that would take a long time to go through all the returned results like seen in Figure 37, where quantity of over 1500 results on each search was returned. This meant that there would need to be multiple word searches each time and different combinations of each. The most recent patents were returned first which meant as they got old the patents became less relevant and obsolete and further patent returns would be ignored.

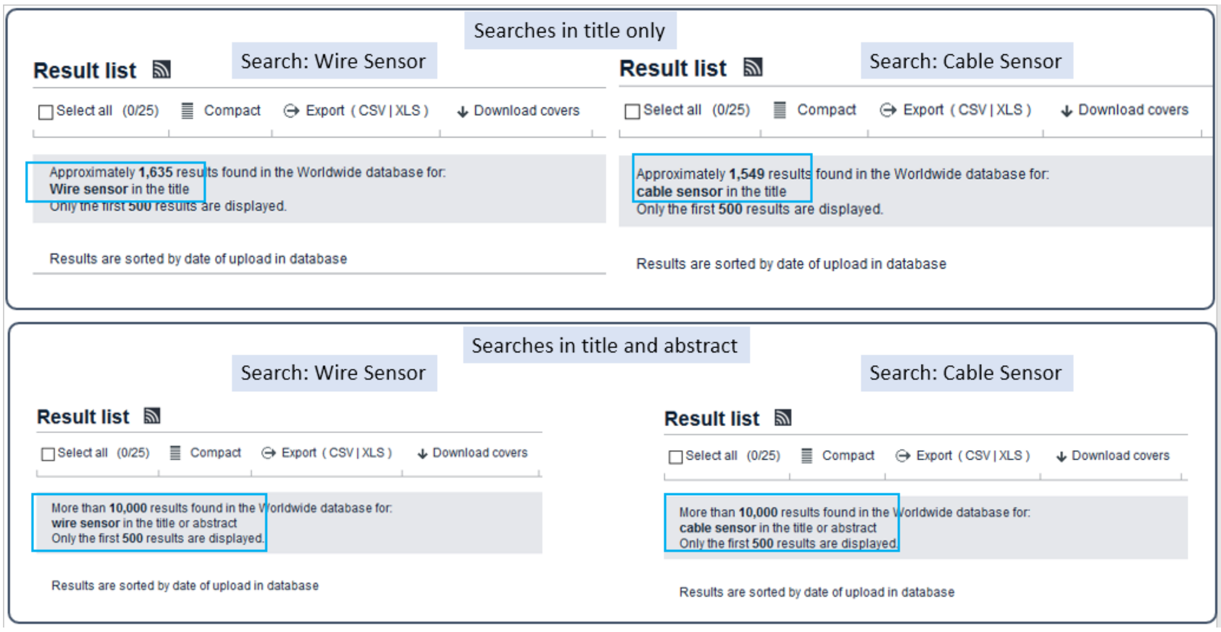


Figure 37 Example of Espacenet search results

If same searches looking at the abstract and title contents even more results were returned. In fact, for two specific technology terms related to this project returned over 10,000 results each time which meant strategic searches using combinations of words specific to the wire sensor topic had to be chosen to minimise the time looking for relevant patents close to the chosen development plan.

3.5.2 Patent search results

An overview of the relevant search terminology used and in which combination are shown in Table 7, Table 8, Table 9, Table 10, Table 11 in Appendices from pages 176 to 180.
What was noted was that there were so many patents submitted for the same thing with small variations or themes and these were submitted for patent application.

3.5.3 Similar patents to planned research

Examples of some of the closest significant patents to planned research are shown below.

3.5.4 DE102012209715 Patent

Bibliographic data: DE102012209715 (A1) — 2013-12-12

In my patents list | Report data error | Print

Cable length transmitter for working cylinder e.g. hydraulic cylinder, has detection device provided with electromagnetic revolution sensor for detecting number of revolutions of magnet attached to cable drum

Page bookmark	DE102012209715 (A1) - Cable length transmitter for working cylinder e.g. hydraulic cylinder, has detection device provided with electromagnetic revolution sensor for detecting number of revolutions of magnet attached to cable drum
Inventor(s):	HALDER ERNST [DE]; HELLSTERN RUEDIGER [DE] +
Applicant(s):	SIEDLE HORST GMBH & CO KG [DE]; HYDROPNEU GMBH [DE] +
Classification:	**- international:** ***F15B15/28; G01B7/02; G01B7/30; G01P3/487***
	- cooperative: **F15B15/283**; **G01B7/02**; **G01B7/30**; **G01P3/487**; F15B15/2861
Application number:	DE 201210209715 20120611
Priority number(s):	DE201210209715 20120611

Figure 38 DE2012209715 Patent

This patent DE102012209715 Patent, Figure 38 is concerned with the position of a piston in a hydraulic cylinder. In the sketch Figure 39, the detection device is provided with a revolution sensor for detection of several revolutions of the magnet. Position of the piston can then be determined. This patent is quite vague and was applied for in 2013.

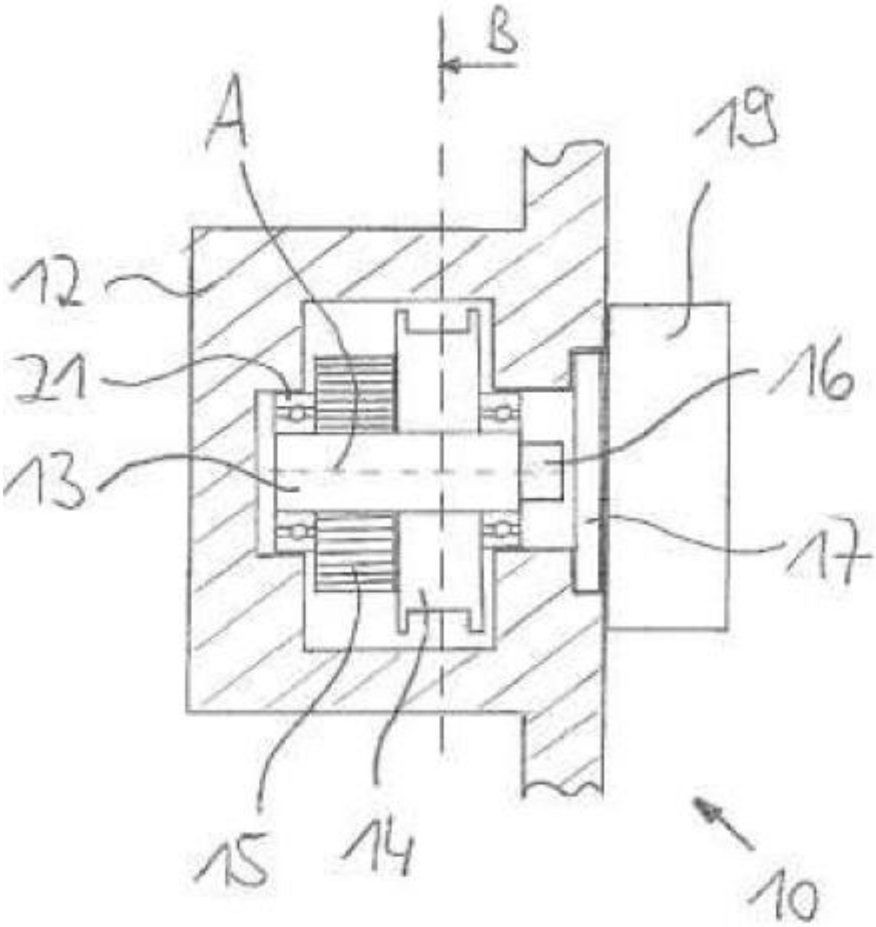


Figure 39 Cable revolution sensor

3.5.5 US2008141548 Patent

Bibliographic data: US2008141548 (A1) — 2008-06-19

In my patents list | Previous 1 / 3 Next | Report data error | Print

CABLE LENGTH SENSOR

Page bookmark	US2008141548 (A1) - CABLE LENGTH SENSOR
Inventor(s):	BIRCHINGER THOMAS [DE]; HRUBY JAROSLAV [CZ] +
Applicant(s):	MICRO EPSILON MESSTECHIK GMBH +
Classification:	**- international:** *G01B3/11*
	- cooperative: **B66D5/32; G01B3/11**
Application number:	US20080026792 20080206 Global Dossier
Priority number(s):	DE20061008947 20060223 ; DE20071006813 20070207 ; WO2007DE00347 20070223
Also published as:	CN101351682 (A) CN101351682 (B) EP1987315 (A1) EP1987315 (B1) US7533472 (B2) → more

Figure 40 US2008141548 Patent

This patent US2008141548 Patent is concerned with a displacement sensor which a drum with a wire cable wrapped around it. The cable is slightly pre-tensioned at the start. The end of the cable is connected to object being measured. The drum is connected to a sensor element.

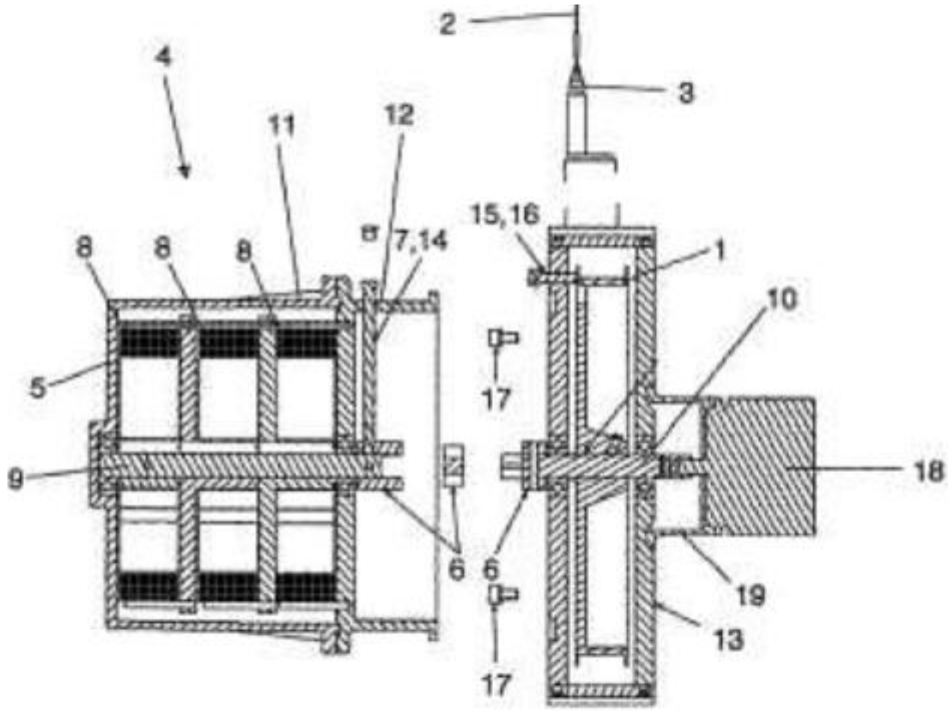


Figure 41 Patent US2008141548 sketch

In Figure 41, the drawing of the patent can be seen. This patent appears to focus more on the coil and drum element with sensor element only mentioned as secondary information. For the proposed research the unit would be considered a complete unit.

3.5.6 CA2876197 Patent

Bibliographic data: CA2876197 (A1) — 2014-01-03

In my patents list | Report data error | Print

SYSTEM AND METHOD OF MANUFACTURE FOR A LINEAR POSITION SENSOR

Page bookmark	CA2876197 (A1) - SYSTEM AND METHOD OF MANUFACTURE FOR A LINEAR POSITION SENSOR
Inventor(s):	GLASSON RICHARD O [US] +
Applicant(s):	CONTROL PRODUCTS INC [US] +
Classification:	- **international:** ***F15B15/28; G01B7/004***
	- **cooperative:** **F15B15/20; F15B15/283; F15B15/2892; G01B3/11; G01B7/003; G01D11/245;** F15B2201/31; F15B2201/515; Y10T29/49002
Application number:	CA20132876197 20130604
Priority number(s):	US201261664558P 20120626 ; WO2013US44106 20130604
Also published as:	EP2864646 (A1) EP2864646 (A4) EP2864646 (B1) US2015184990 (A1) US9234735 (B2) more

Figure 42 CA2876197 Patent

In CA2876197 Patent the sensor includes a sensor, conduit and an enclosure. A wire passes through a conduit and is connected to the piston whose stroke is being measured. It can be seen in Figure 43 the connector is position 14. The enclosure for the sensing element is located as position 20. The developer of this product is Control products Inc. and this product is primarily focused on replacing redundant or non-functioning Magnetostrictive sensors.

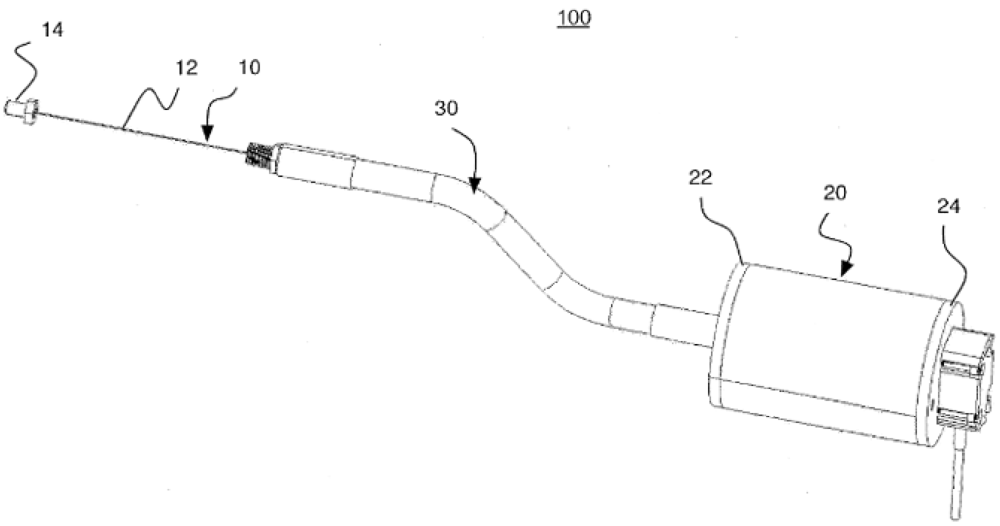


Figure 43 CA2876197 Patent sketch

3.5.7 Conclusion on Patent search

No major block intellectual properties were noted for this type of wire type sensor as far as would be found through the patent searches. Various small variations would be found between different manufacturers of sensor, but there are multiple manufacturers using the same basic concept of planned wire sensor design with coil spring to retract wire upon the stroke return.

The strategy is to optimise the best of these all elements as researched and optimise to best suit Burnside in terms of assembly process and workings. There appeared to be an industry standard of Ø48mm bore housing for most hydraulic type internal sensors, so this was used as a starting point in the design which must fit within this dimensional envelope.

3.6 Analysing a Similar sensor

3.6.1 Introduction

It was decided to take a wire type sensor and analyse to see if anything would be learned from it in development for the new sensor. The brand chosen was Siko. There are other brands of wire sensors available, but this manufacturer was European based and easier to get hold of a sample. A sensor was acquired so a strip down would take place.

3.6.2 Siko Sensor.

The Siko sensor SGH10 is a wire-actuated has a stroke measurement range of 0mm to 1000mm and works with operating voltages between 9V to 32V DC. It can resist working pressures of up to 500 bars. There is flexibility in that the sensor has a teach in function, where the sensor can be programmed to suit any stroke length cylinder in the measurement range.

The wire of the sensor is secured to the piston head using a screw attachment. When the piston head extends the wire that is wound on the wire drum as it is pulled out. The resulting rotation of the drum is detected by a contactless sensor system and converted into a linear position, (Siko, 2017).

The magnets used to measure the rotation are scanned by the contactless sensor system through the pressure resistance base plate of the sensor. The electronics are fully contained and located on the non-pressure side of the sensor. The entire measurement system is incorporated inside the cylinder. Because the sensor is inside the cylinder it cannot be damaged by external environmental conditions. This Siko sensor can be seen in Figure 19 on page 45.

3.6.3 Electrical Connections

The housing of the sensor is linked to the external connection interface of the sensor by a short wire. For the side that connects into the housing of the sensor there is an 8-pin connector.

On the side that is exposed to the outside of the cylinder there is a 5-pin connection system for a plug-in connector. There are five wires between the two connection points. The connection can be seen in Figure 44 beside the sensor housing.

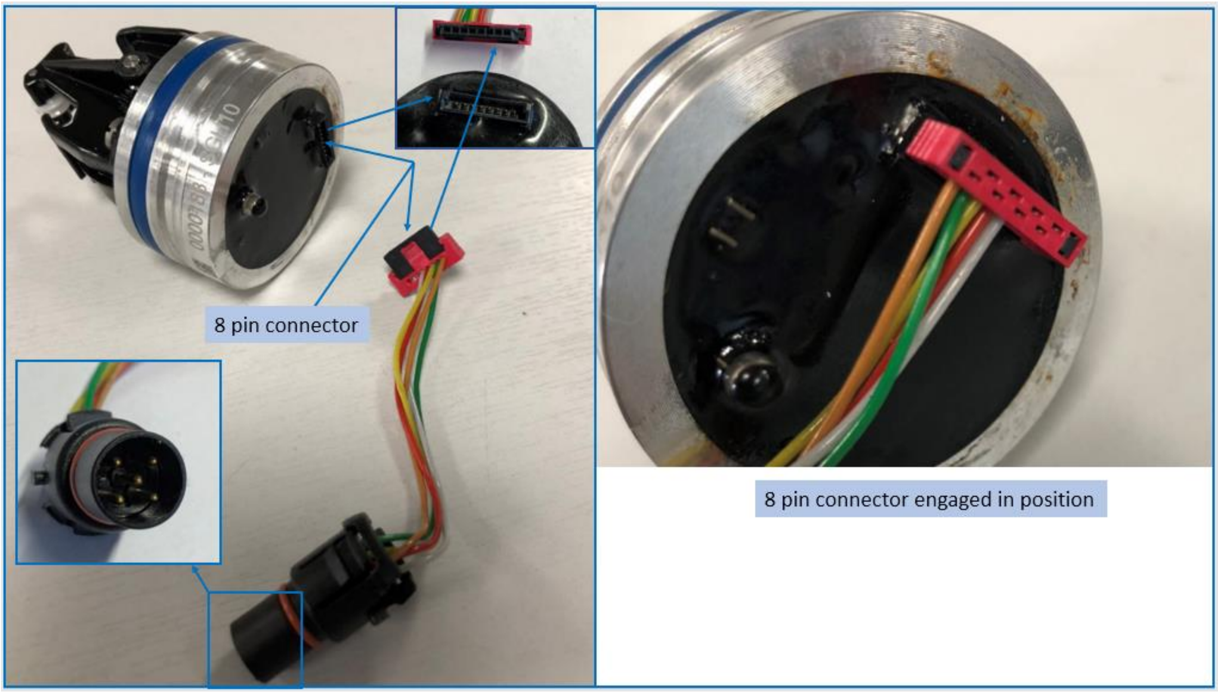


Figure 44 Connection Wire of Sensor

3.6.4 Plastic Assemblies

At the front of the sensor there is a plastic assembly housing the recoil spring to pull back on the wire. There were two screws holding the spring coil assembly and two screws holding the rotary magnet assembly, as shown in Figure 45.

The housing body is made from aluminium and is recessed to allow the spring assembly to fit inside the body. This saves on space on the building length of the sensor. There are four tapped holes in the body for the screws to bolt on the plastic assemblies. There are two machined recesses to allow to magnets to be positioned on the end of plastic holders.

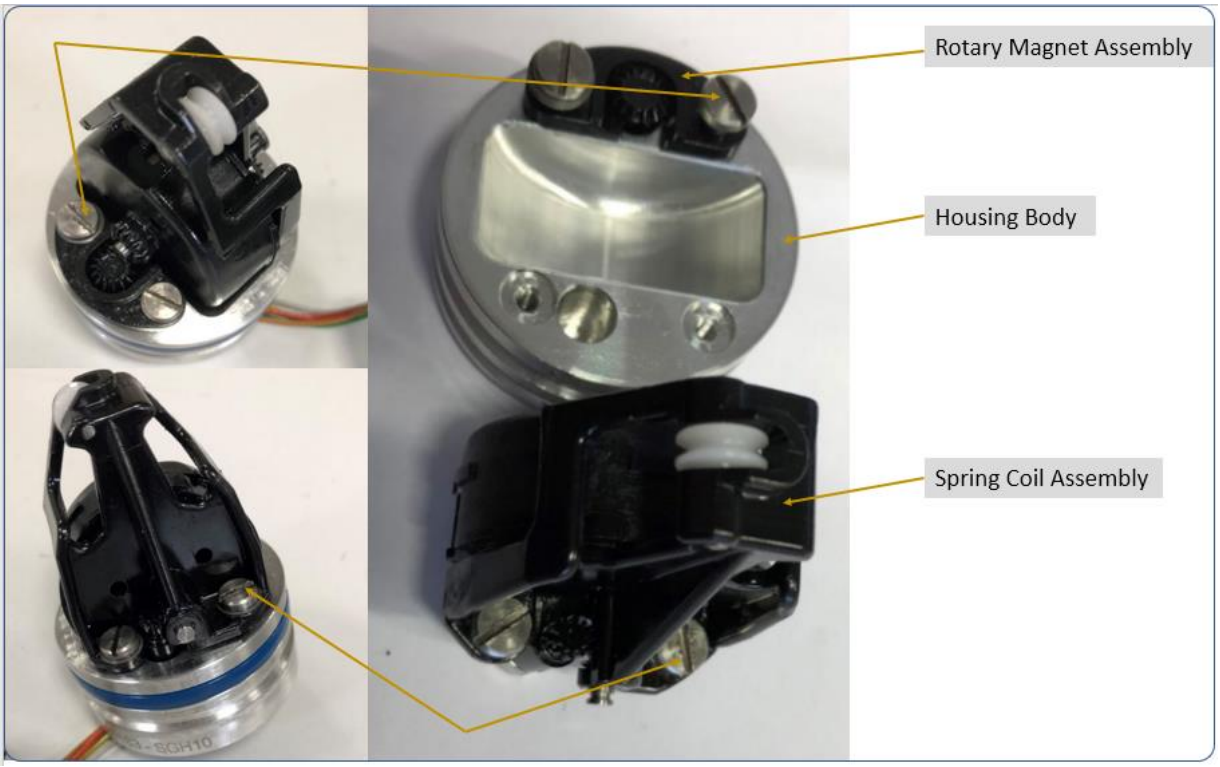


Figure 45 Plastic Assemblies

3.6.5 Geared Assembly

The main plastic assembly which contains the coil spring has a steel pin running right through it. On one side there is a set of plastic bevelled gears which changes the rotary direction by ninety degrees into another plastic assembly which is retained by two screws to main body. On the end of this plastic assembly there is a ring magnet which is just pushed onto the end of the plastic assembly. The unassembled parts can be seen on left hand side of Figure 46.

On the right-hand of Figure 46 the opposite side of the assembly can be seen. On the same pin which passes though the spring coil assembly there is a worm gear. The gear connects to a worm wheel which in turns connects to an identical sized magnet. This also transmits rotational direction by ninety degrees.

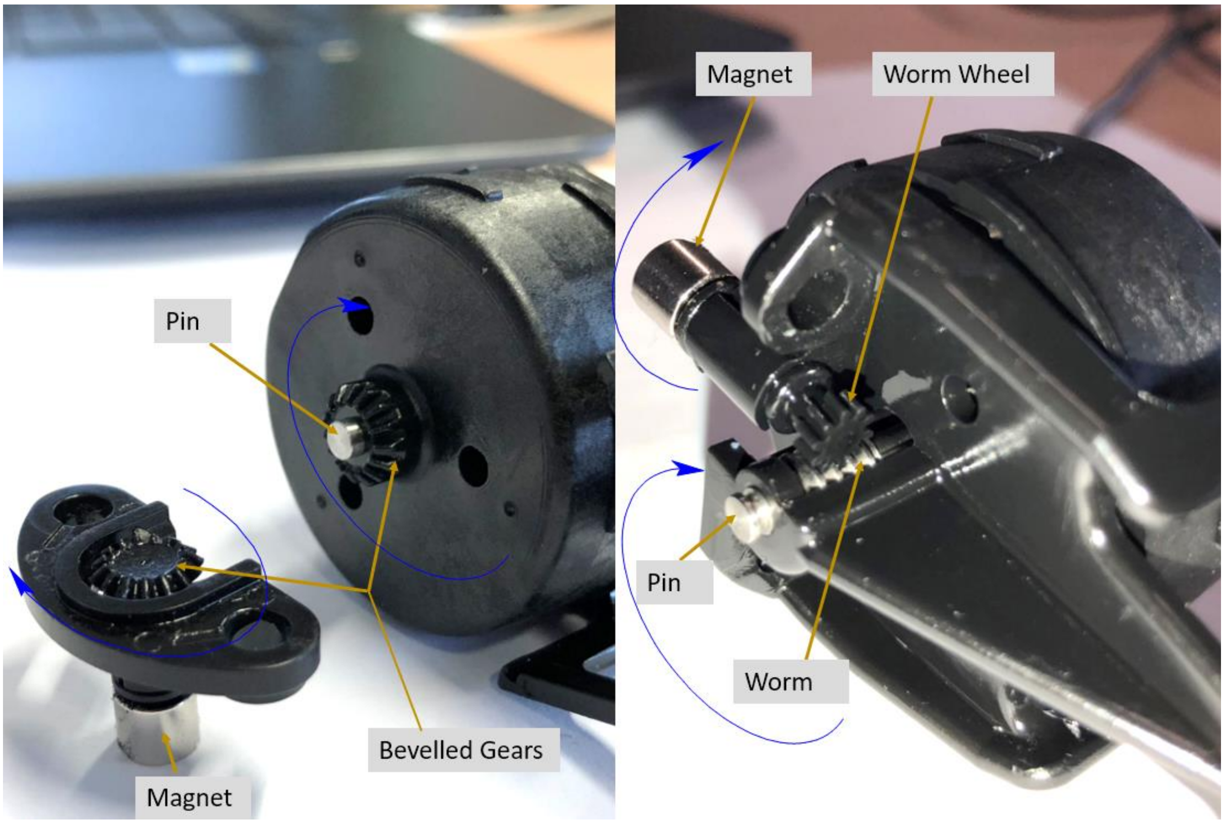


Figure 46 Geared Assembly

3.6.6 Spring Coil Assembly

The spring coil assembly is split into two parts. They are pushed together and held in place with a small snap circlip on the end of the shaft. There are holes in the side of the outer plastic casing, so this chamber becomes fully flooded with oil and pressure would be equalised both sides. The assembly as split can be seen in Figure 47.

When one side of the housing is held stationery and the coil spring wound, the spring generates mechanical energy. When rotated a few rotations and released the mechanical energy is released and the coil and spool unwind. This mechanism is how the wire is pulled back when the hydraulic piston rod is retracted.

This coil system is used to keep a constant tension on the wire. As the cylinder is retracting the coil spring uses its stored mechanical energy to pull the wire back in and wind itself around the outside of the plastic housing, ready for the next extension of the cylinder.

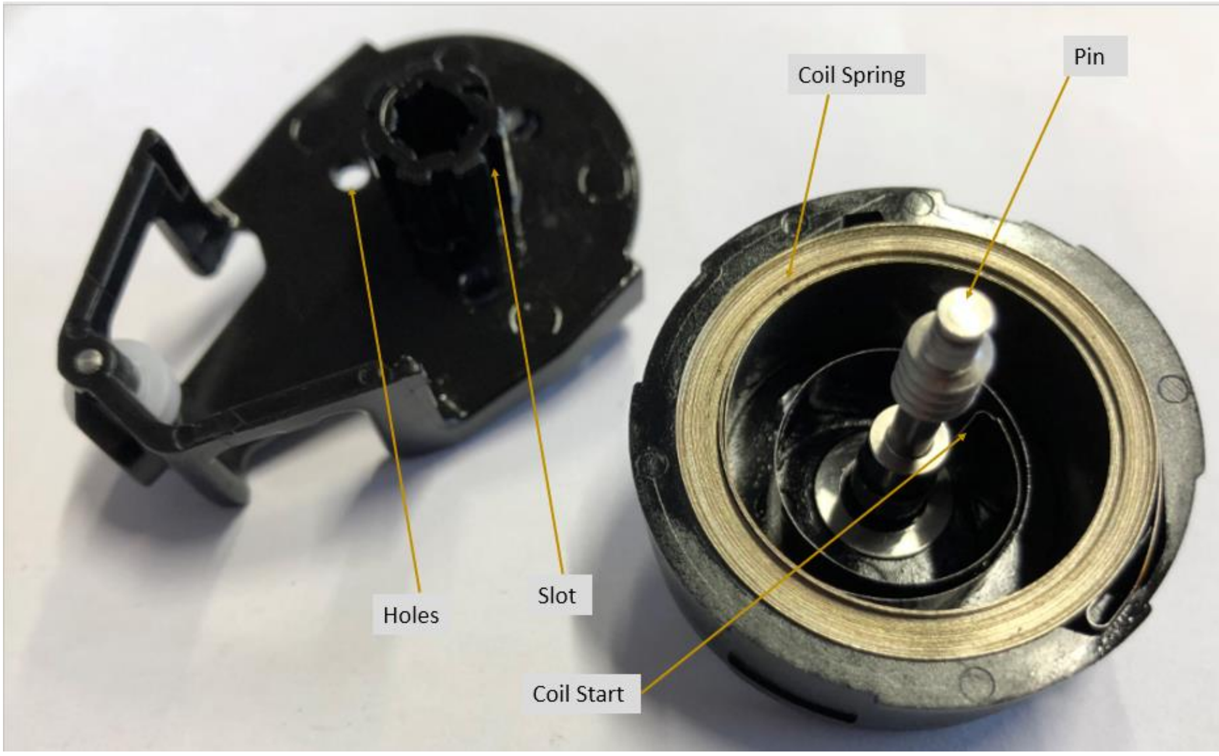


Figure 47 Spring Coil Assembly

3.6.7 Housing

The housing is constructed from aluminium and there are two machined recesses for the rotary magnets to turn. The machined recesses do not pass all the way through the housing, so the housing is fully pressure resistant to protect the electronics on the opposite side. The front of the aluminium housing can be seen on the left-hand side of Figure 48. The outside of the housing had a blue polyurethane static seal to prevent pressure from getting around the outside of the housing.

Figure 48 Housing

The back of the housing is sealed with a hard-black resin. It was decided to remove the outer metal surrounding the resin core. This worked well. Once the metal holding the resin was removed the circuit inside would be removed.

3.6.8 Evaluating magnets.

For the sensor evaluated, there were two rotary encoders or magnet sensors situated on the circuit board. These are illustrated on item (a) of Figure 49. On the opposite side of the aluminium barrel there were two rotary magnets which position themselves in front of the rotary encoder. The magnets were dimensionally Ø6mm on the OD, Ø3mm on the ID and 5mm long. They are pushed onto plastic clips which can be seen item (a) of Figure 49. The hole in the block was Ø7mm ID so there was 1mm diametrical clearance. When the magnet is positioned there is a 1mm gap between the bottom of the magnet and the front face of the recess in the aluminium block.

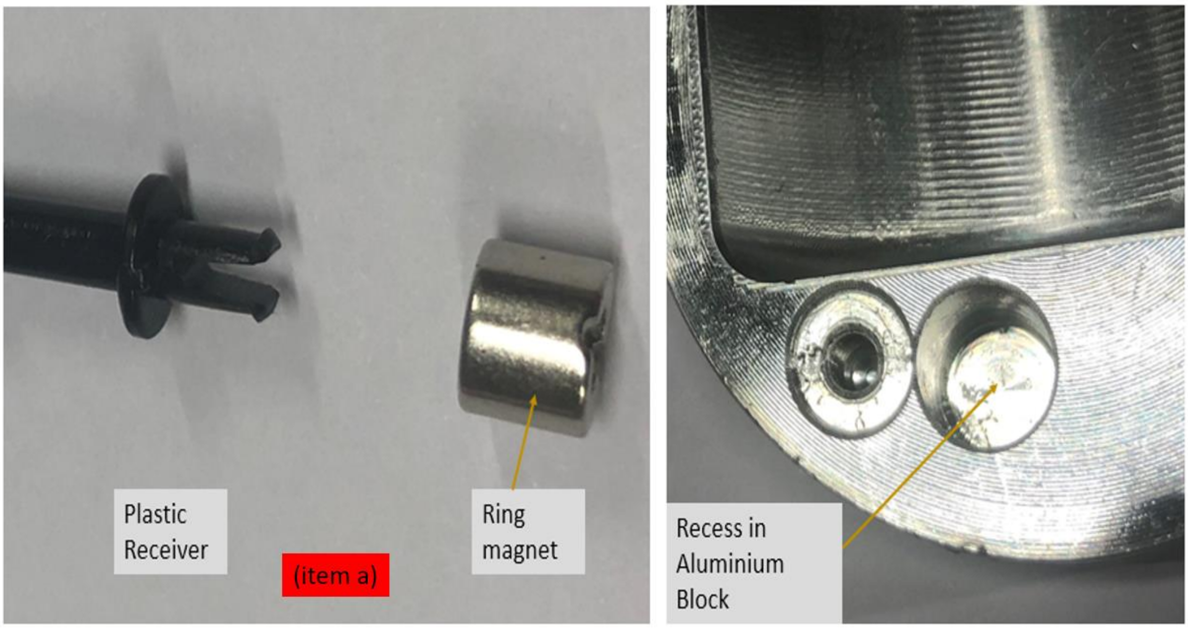


Figure 49 Recess for Magnet in Block

There is 3mm of aluminium between the bottom of the recess and the far side of the aluminium block where the circuit board is situated. There is a 1mm air gap between the rotary encoder and the aluminium. This makes a total clearance of about 5mm between the front face of magnet and rotary encoder chip.

3.6.9 Circuit Board

There were three raised locators machined into the back of the aluminium housing. These can be seen on the left-hand side of Figure 50. The circuit board is placed onto these for location purposes and the resin can flow underneath the circuit to ensure it is completely sealed. On the right-hand side of Figure 50, raised inserts can be observed.

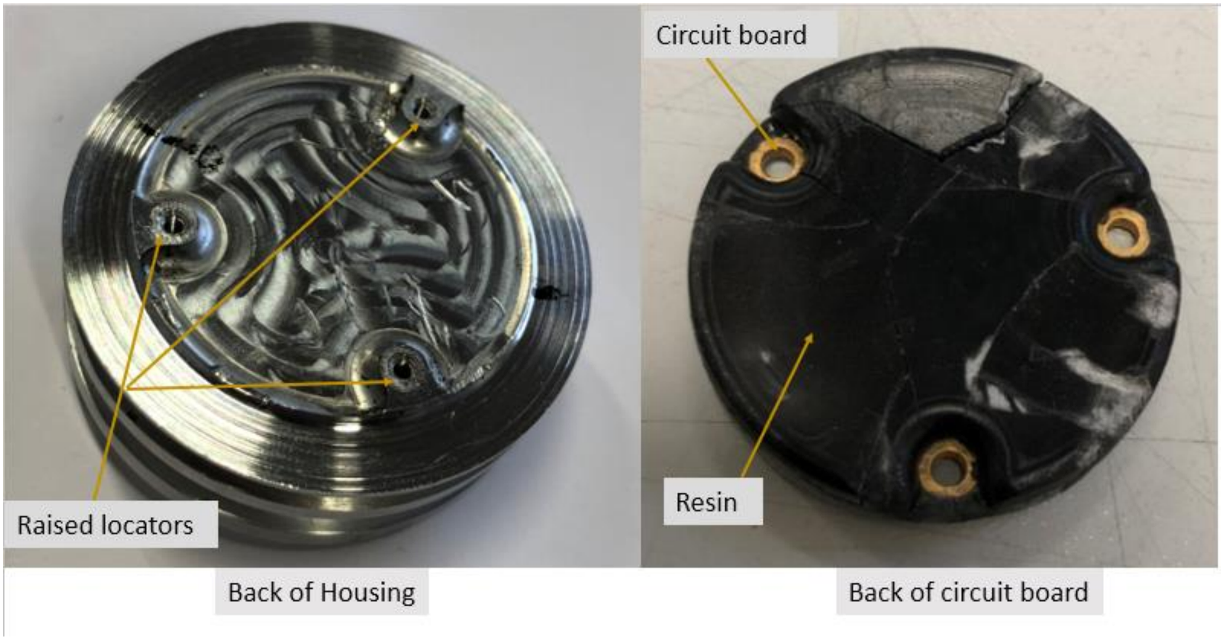


Figure 50 Back of Housing

In Figure 51 on the left side the partial circuit board is seen as the resin was taken away. The electrical components were completely sealed inside the resin. This would make the circuit resistance to moisture or humidity if present in actual field working conditions.

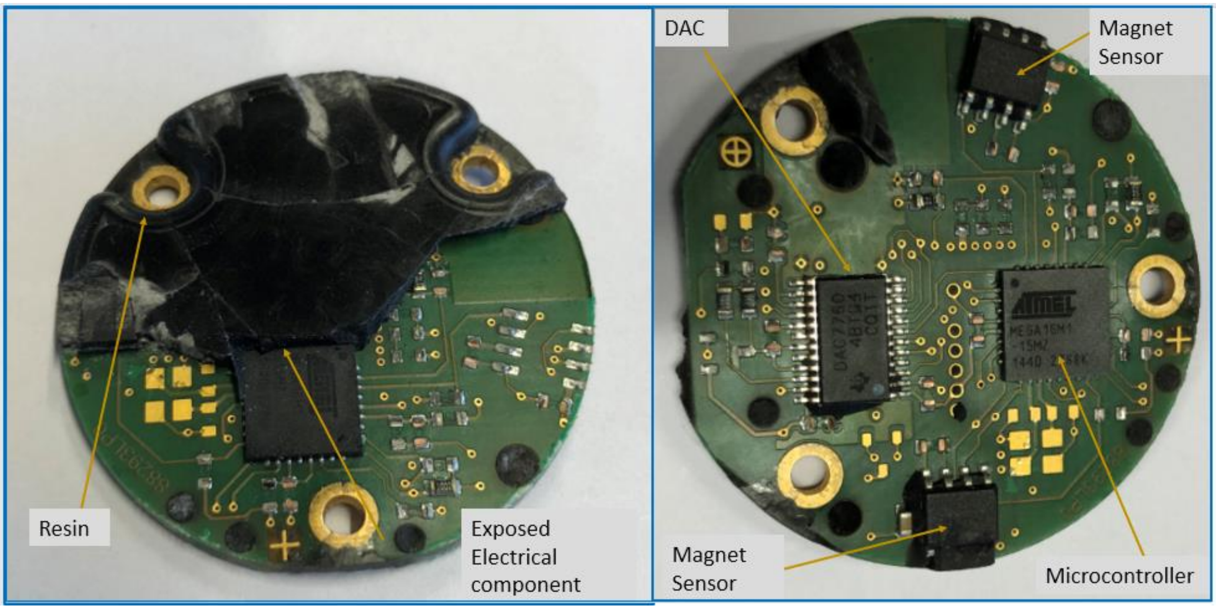


Figure 51 Exposed circuit board

The circuit board can be seen completely exposed on the right-hand side of Figure 51. There were two sensors which would have been located under the position where the rotational magnets would be moving.

There was also a microcontroller and a DAC (digital to analogue convertor) chip located on the board. This was a double-sided printed circuit board and there were some other items located on the opposite side of the board also.

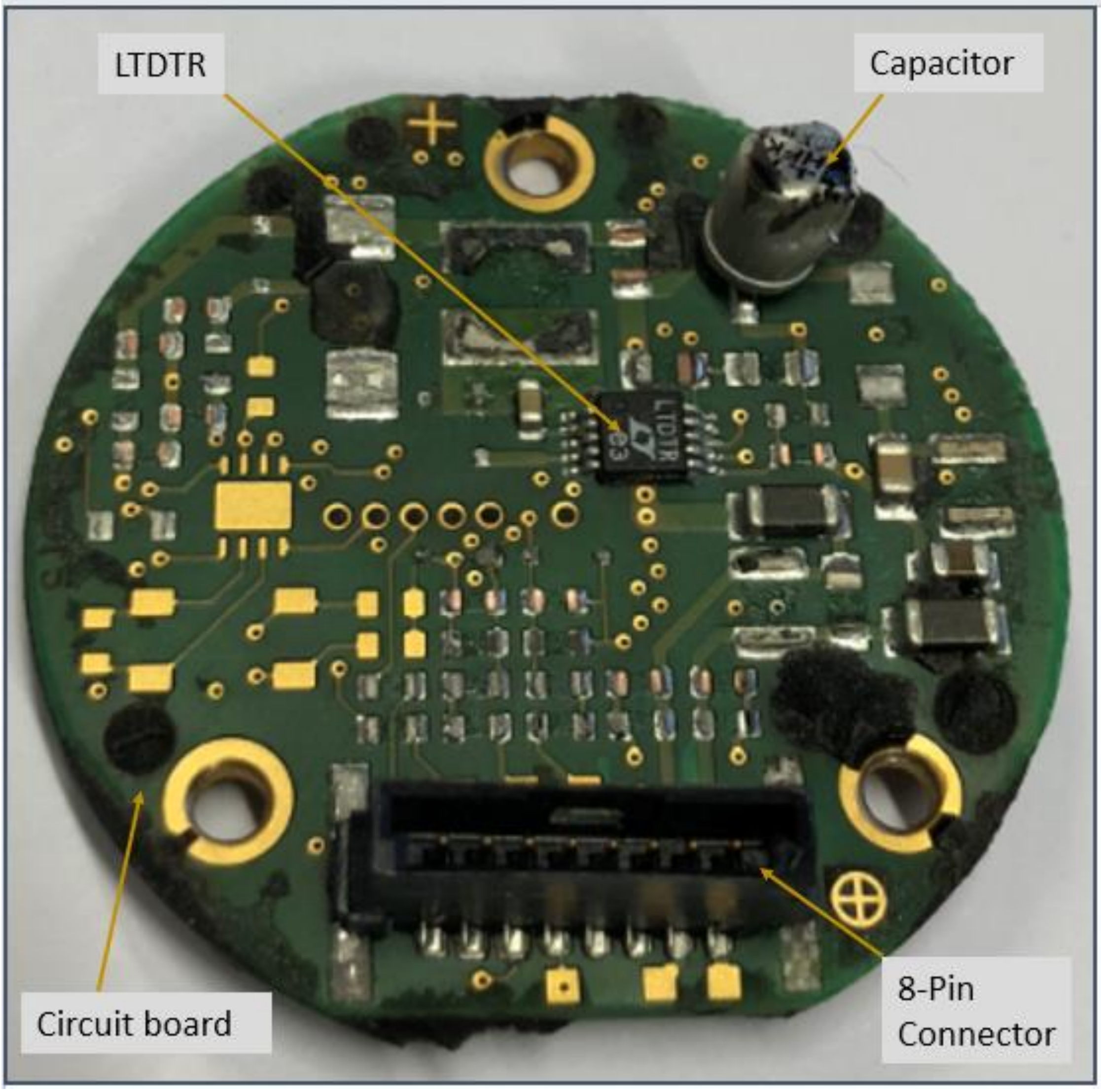


Figure 52 Top of Circuit board

In Figure 52 the electrical components can be seen, an 8-pin connector and capacitor. This was also covered in resin and can be seen in its resin state in Figure 48. The main parts on this side of the circuit board are the 8-pin connector which is raised clear of the resin. The capacitor is also visible when resin is covered. The only main electrical component of significance is the LTDTR chip which is a step-down DC/DC convertor.

3.6.10 Evaluating encoders

For the Siko sample it was not possible to identify the type of rotary encoder used on the circuit. However rotary encoders are readily available items used for sensing in many applications. They can be paired with drives and automated equipment for applications such as customer electronics, elevators, and conveyor speed monitoring to location control on automated industrial machines and robotics, (Eitel, 2014).

3.6.11 Types of rotary encoder

Rotary encoders are available in bit resolution. The higher the number of bits the more output positions are given for each turn of the magnet over the rotary encoder chip.

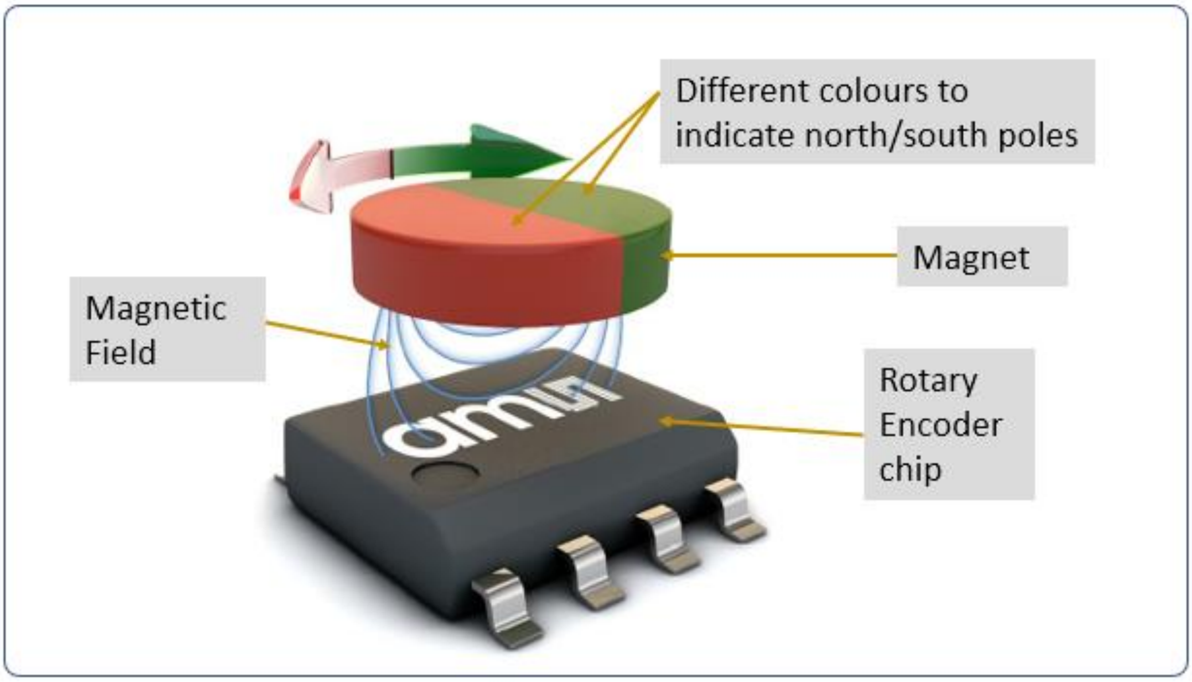


Figure 53 Magnet over Rotary encoder

In Figure 53 a pictorial representation of a magnet can be seen rotating over a magnetic sensor. The split pole magnet is polarised to have a north and south side, and this provides a saturated magnetic field in the plane of the sensor.

Limitations on stroke would depend on development of the coil for the sensor. These considerations are looked at in section 4.1.2 on page 86 . Cross referencing of cylinder stroke to rotary encoder resolution needed to be looked at together. Some theoretical resolution can be seen in Table 3.

This considers just using one rotary encoder and utilising less than one full revolution of the magnet over the sensor. This would allow for a unique output from the rotary encoder upon start-up of the sensor in any random position so that it is known where the cylinder is, even if it has moved position after the power has been switched off. The resolutions looked at are 11 bits in the AS5601 and 14 bits output in AS5048A as examples in Table 3.

Result	Rotary encoder	Resolution 360° turn of magnet over encoder	Angle used	Resolution	Stroke Cylinder	Resultant resolution in mm of stroke
1	AS5601	2048	270	1536	500	0.33
2	AS5601	2048	300	1707	500	0.29
3	AS5601	2048	330	1877	500	0.27
4	AS5601	2048	270	1536	1000	0.65
5	AS5601	2048	300	1707	1000	0.59
6	AS5601	2048	330	1877	1000	0.53
7	AS5601	2048	270	1536	1500	0.98
8	AS5601	2048	300	1707	1500	0.88
9	AS5601	2048	330	1877	1500	0.80
10	AS5048A	16384	270	12288	500	0.04
11	AS5048A	16384	300	13653	500	0.04
12	AS5048A	16384	330	15019	500	0.03
13	AS5048A	16384	270	12288	1000	0.08
14	AS5048A	16384	300	13653	1000	0.07
15	AS5048A	16384	330	15019	1000	0.07
16	AS5048A	16384	270	12288	1500	0.12
17	AS5048A	16384	300	13653	1500	0.11
18	AS5048A	16384	330	15019	1500	0.10

Table 3 Example Effect of resolutions available from rotary encoder

Looking at the two sensors, the lower one (results 10-18) had the greater resolution. A single rotary encoder could be utilised when appropriate gearing is used to ensure that less than one revolution of the encoder would be used during the full stroke of the cylinder. Potential encoders such as AS5601 as seen in appendix, Figure 155 on page 181 with 2048 configurable positions, or the AS5048A seen in Figure 156, page 182 with 16384 different positions per revolution would initially be considered as potentials for the rotary encoder.

How a single rotary encoder would be used is shown in appendix, Figure 158 on page 184. Here only one sensor is used to measure the position of the cylinder. For this solution a proposal of a working output range of one to nine volts output over the full stroke range and 75% utilisations of one revolution of the single rotary encoder through appropriate gearing is envisaged.

Under item one, of page 184 the output starts at one volt. Zero volts was not used as an initial position so when the cylinder is fully returned and the sensor is turned on, we know the sensor is working as it has a reading. In this case the encoder is at zero degrees. Under item two, the cylinder has stroked 25% of its stroke length. Through gearing this turns the magnet 67.5˚ over the encoder.

As the cylinder further extends in item three, to midway of the cylinder stroke, the voltage reading is also halfway in the range of one to nine volts at five volts' output. The magnet has turned half of its planned 270˚ allowances at 135˚

In item four, the cylinder has fully extended, and the encoder has rotated 270˚. The fact that the sensor has not overlapped in any position means there would be a unique output from the encoder at any point along the cylinder stroke which could be picked up immediately upon start up and translated into a relevant output based on actual current cylinder position.

This would be the preferred and simplest method of translating the cylinder linear motion into a voltage output.

This theory would form the basis for our practical test on the rotary sensor and would better inform on how many encoders would be needed for the circuit to work as required. The preference is to start with one encoder and see if the sensor can function as needed on dry prototypes in the lab.

3.7 Conclusion

Breaking the sensor assembly down into modules allowed for a greater understanding of the operation of the assembly which allowed for the development of the new sensor. As there were two main parts for this project, expertise was broken into two separate parts, so support structures were fully utilised effectively.

On the electrical side Dr David Allen was used to support the development on the electrical side of this project. The plan was to look at the electrical components as documented on the circuit, identify why they were used, identify similar available components and build a core circuit in principle which would meet our needs. The plan was to build the circuit on an Arduino board with the electronic components exposed on the non-pressure side of the housing for the transducer. Full functionality needed to be tested and proved using off the shelf components. This would allow costs to be kept to a minimum and allow full control of development within the constraints of the supervisors, researcher and budget.

Dr Paddy Buckley would guide on the mechanical side. What would be looked at in detail, is the mechanical details to see where improvements would be made. Currently there were two rotational magnets. Whether these two magnets would still be required, needed to be determined on the electrical side. If two magnets were still needed, is the transmitting of rotational movement between the moving parts being optimised?

Other aspects that needed to be looked at on the mechanical side were the connecting wire, coil springs, housing size, possible construction methods and sourcing of materials for a sample for testing. Also, determining the longest possible stroke and keep overall envelope with sensible usable limits. It was expected that the coil spring would determine this maximum stroke length, but maybe this was something that would be improved on, to give some extra stroke length on what is available in wire sensor just reviewed.

After discussions it was decided to incorporate a feature not available in any transducer available in the market today. The feature was a temperature sensor. It was believed, in principle, a temperature sensor would be added to the non-pressure side of the housing of the transducer. As heat travels from oil into the housing of the sensor, in theory the temperature of the sensor should read the same as the oil temperature. This would be developed and proven out. If there were differences correction factors would be added based on test results to give more accurate results.

It was hoped that the highest temperature would be recorded in memory within the sensor. If the cylinder is returned within warranty, under claim and the issue is temperature related, the temperature figure would be read off to see if cylinder was used within permitted acceptable limits. If used over maximum temperature this information would be used to protect Burnside and invalidate claim. Maximum pressure was also considered but would involve tapping into the pressure side of the sensor from the electrical side. It was decided best not to go down this route as may be problematic and limit working pressure available for the sensor to work in.

This would make the new sensor unique and far superior to any individual sensor solution currently on offer in the market today.

4. DESIGN

4.1 Design Research

4.1.1 Introduction

Once a decision was made on the proposed direction for development of the sensor, some broad range consultations and group meetings were organised to get expertise opinions from the electrical industry. A visit was organised with representatives from Microchip company. Representatives from Burnside were also present. This was to get a good cross reference what todays hydraulic cylinder customers' expectations are, and their expectations for the future.

From the outcome of this meeting it was agreed that adding a temperature sensor was a good idea. The aluminium base would be drilled down to allow the oil to get in front of the temperature sensor. For the recording of temperature this would be integrated into final circuit board developed for the commercial market.

For this project absolute positioning would be a necessity. When the sensor is started up in any random position, the exact position would need to be known straight away by the operator. Battery backup principle of position during powering down would not be considered due to potential of cylinder moving position when powered off.

There were some electronic parts ordered so some initial encoder tests can be made with an Arduino board and some magnets. As AS5161 sensor is only currently available surface mountable, an AS5601 adaptor board was ordered so it would be easier to connect to an Arduino board and conduct some initial tests on getting basic rotary encoders up and running as a first step. Different tests with different magnets strengths, varying proximity of magnets and with different offsets would also be tested. Also passing the magnetic field through varying thicknesses of aluminium would also be tested to see how the encoder performed.

4.1.2 Constant force power spring

As the cylinder is extending there needs to be tension in the wire so a true reading is recorded by the rotary encoder. To do this a constant force coil spring is used to keep the wire under tension.
As the shaft begins to turn the material starts to wind flat against the shaft. This winding action creates a torque for as many turns as it can be wound until there is no material left. Pre-stressed springs are spooled to a dedicated diameter, (Lesjöfors, 2018).

The coil material is made from a pre-stressed flat strip of spring material typically 301 stainless steel. The full load rating is the spring is achieved after one and a quarter turns of its diameter. The loading is determined by the coil thickness and the width of the plate. Fatigue life varies from two thousand cycles to over a million cycles, (Spring, 2018).

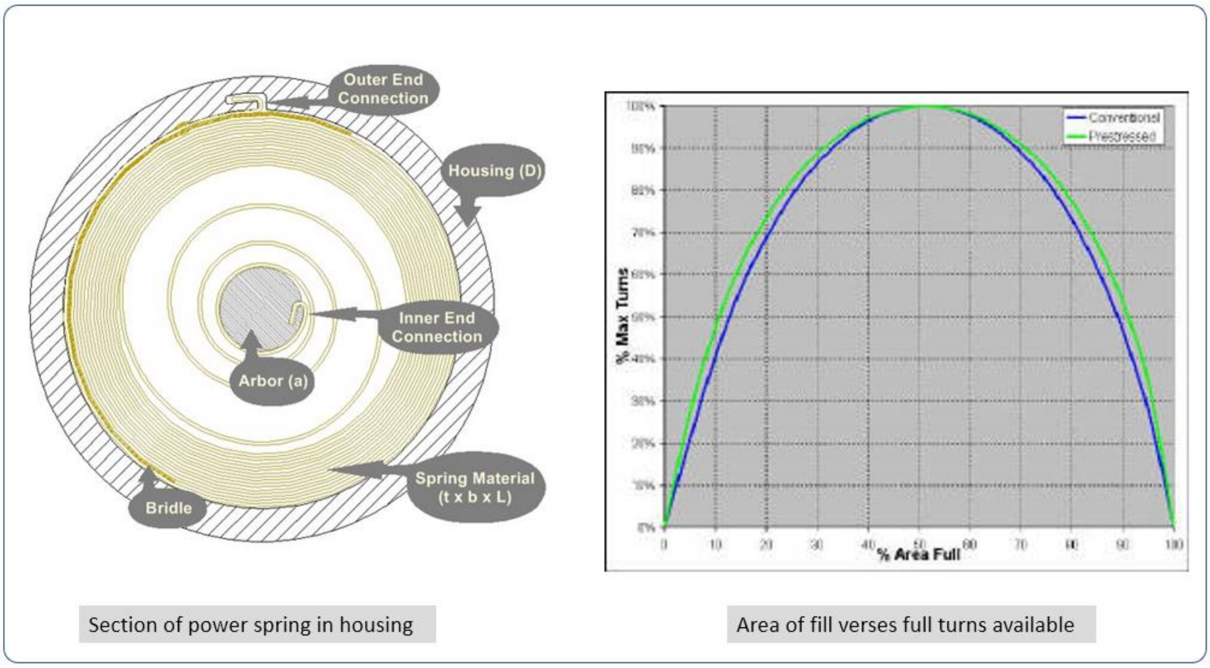


Figure 54 Power spring (C&S, 2010)

Figure 54 shows a section of a power spring inside a housing. The power springs are available as conventional and pre-stressed. Conventional springs are easier to manufacture but have lower torque. Prestressed springs have higher torque but have lower duty cycle life, (C&S, 2010).

There is an amount of space between the housing and the arbor with no coils. The amount of this area taken up by the spring determines the maximum number of turns achievable. As the spring approaches fifty percent fill the number of turns does not increase. This parabolic shape can be seen on the right-hand side of Figure 54. Commonly 45-50% of the space is used as anything over this percentage wastes material and reduces number of turns available. (C&S, 2010). As the spring goes from the preload position to full extension and back again to initial preload, this is considered one cycle.

The plan was to decide approximately, the overall diameter of the inside of the housing which would be used, along with the available width and stroke needed, to engage with a spring maker. The spring manufacturers expertise can be utilised to develop the best spring, which can then be used in a prototype model for testing.

4.1.3 Connection to cylinder

There are many types of connection available for connecting a wire to the cylinder. Some example of different wire connectors can be seen in Figure 55.

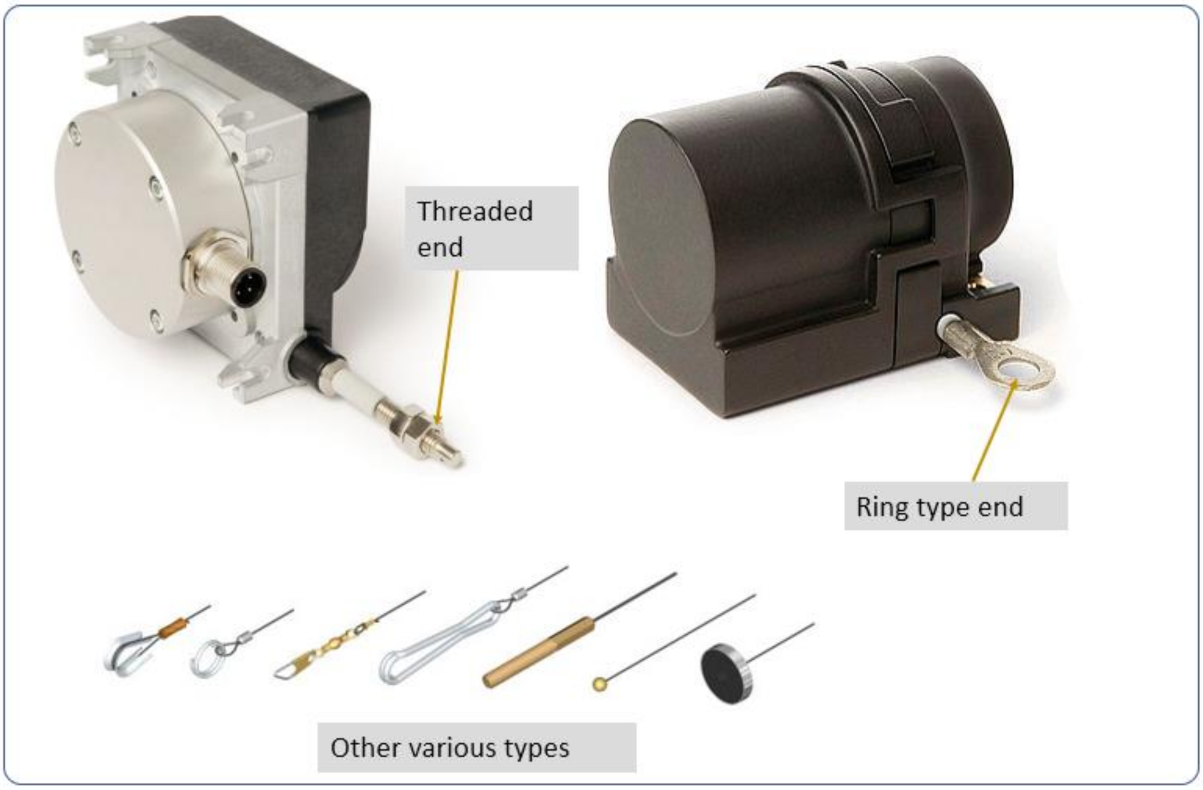


Figure 55 Various wire connections available (Spaceagecontrol, 2018)

As the connector protrudes out from the front of the sensor, this is using up building space. The objective should be to keep this distance as small as possible. Some connectors take up more space than others when looking at the different types above.

4.1.4 Wire type & Size

Wire for sensors are typically constructed from a high strength fabric material or stainless-steel rope with varying diameters from Ø0.45mm to Ø0.87mm. An example of the wire used by different manufacturers from evaluating specification sheets are shown in Table 4.

Wire diameter Ø (mm)	Material	Brand	Model	Maximum stroke (M)	Max Extension force (N)
0.54	Stainless Steel	Siko	SG62	6	8
0.87	Stainless Steel	Siko	SG150	15	15.5
0.45	Stainless Steel	Siko	SG21	2	11
0.48	Stainless Steel	Wachendorff	SZG93	2.5	5
0.6	Stainless Steel	Elap	HLS-M	3	10
0.5	Stainless Steel	Kubler	DW70	1.25	5.5
0.51	Stainless Steel	BEI Sensors	CD0050	1.25	6.5
0.45	Stainless Steel	Micro-Epsilon	WDS-1500 Z60-M	1.5	5
0.8	Stainless Steel	Micro-Epsilon	WDS-3000 P96-M	3	10
0.45	Stainless Steel	Kubler	D5.301.A221.000	2	10
0.5	Stainless Steel	Turck	DW70	1.25	5.4
0.55	Stainless Steel	Pepperl-fuchs	ECA10TL	3	330
0.45	Stainless Steel	Sick	BCG05-K1KM01PP	1.25	1.4

Table 4 Wire sizes from various manufacturers

Forces to overcome spring loading are also shown in Table 4. However, these forces would be dependent on the temperature of the oil. When the oil is cold and more viscous the resistance of the coil would be larger so pulling forces may be higher than indicated on cylinder start-up. Oil temperature should build up within 1-5 minutes of operation to normal levels.

To establish the working limits of the rotary encoder, it was tested in isolation to establish, in theory, how it would perform. For the testing an adaptor board was required. The AS5601 as shown in Figure 157 on page 183 was utilised.

4.1.5 Encoder chip

An Arduino Uno microcontroller was used in order to enable the chip to be run from a laptop. This would allow for easier development between both bases in Burnside and IT Carlow as the equipment would be set up quickly between bases.

The first issue was to be able to rotate a magnet directly over the centre of the chip. The chip on the board was small at 4.9mm x 3.9mm so accurate location over the chip had to be precise. The chip manufacturer recommended a maximum allowed displacement of the rotational axis of the reference magnet from the centre of the chip at 0.25mm maximum when the magnet OD was 6mm. (AMS, 2018)

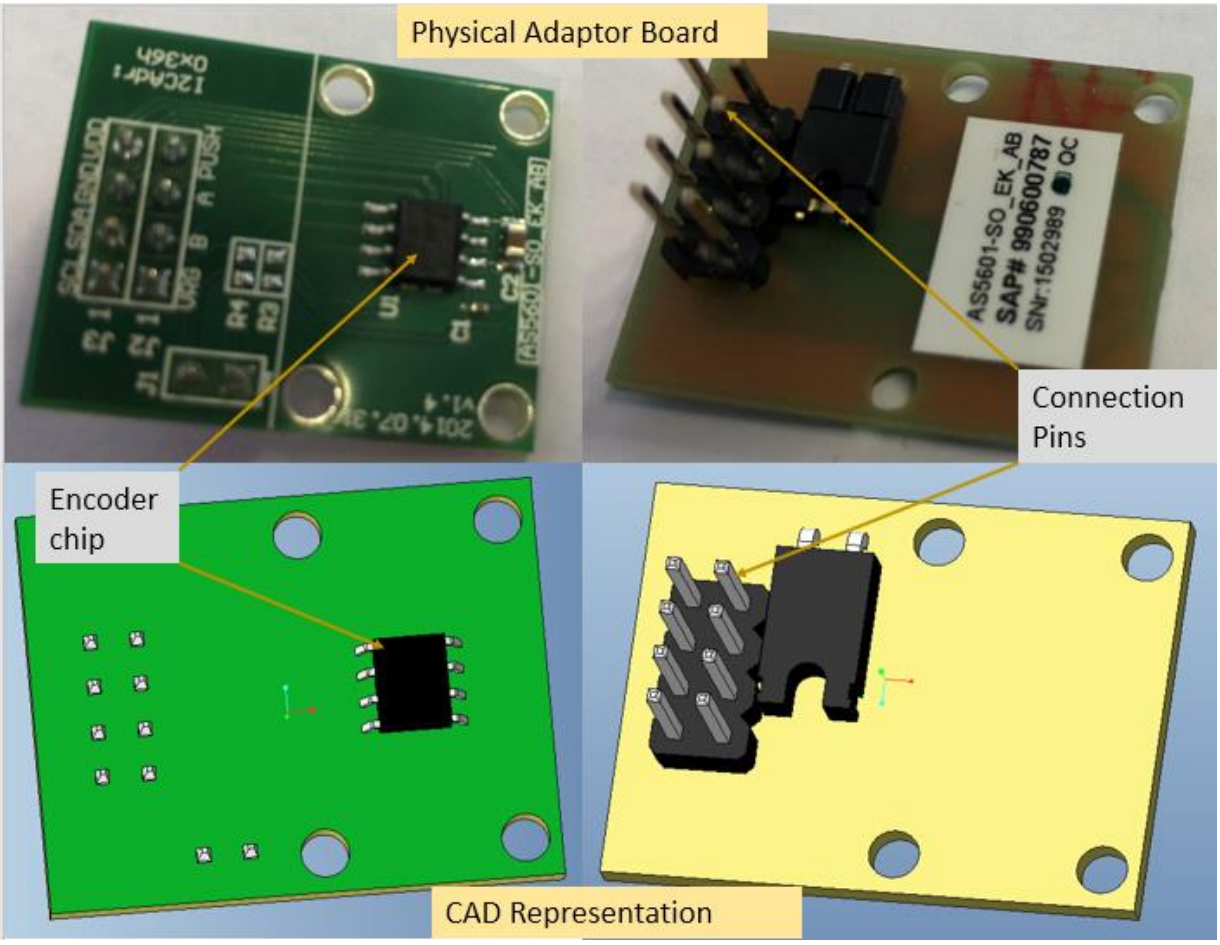


Figure 56 AS5601 CAD Model

The physical adaptor board and CAD model representation can be seen in Figure 56. The positioning of the magnet over the encoder chip was crucial a frame was designed in CAD to hold the magnet over the correct position in the centre of the chip. There were several parts designed up so that position would be as intended. The parts were designed in CAD to fit around the adaptor board and printed on a 3-D printer. The parts as printed can be seen in Figure 57.

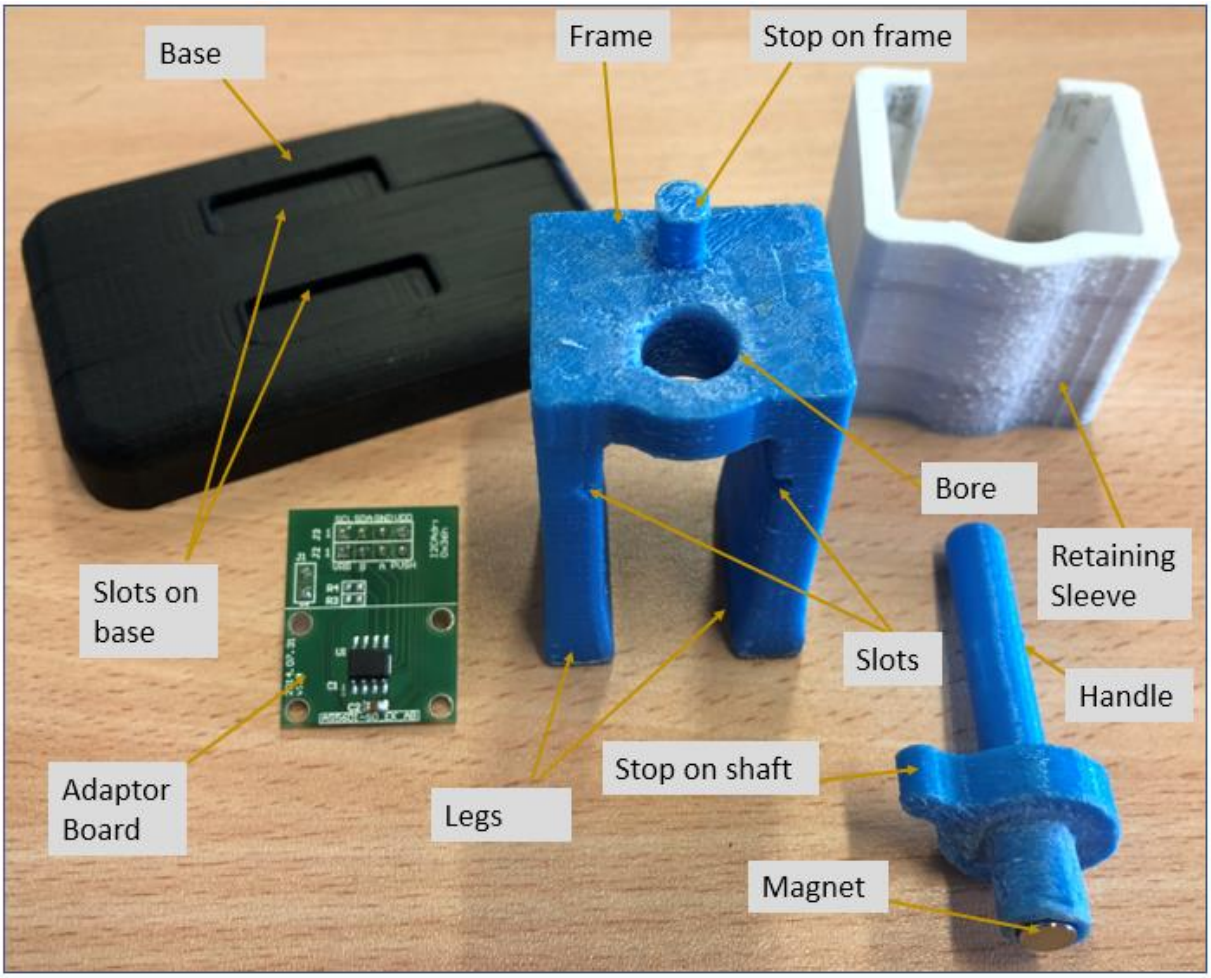


Figure 57 3-D Printed Parts for the adaptor board

A handle was printed to hold the magnet. The magnet was supplied by AMS along with the adaptor board. As there was no hole in the magnet to mount, a bored recess was allowed for it in the handle to retain the magnet with a small push interference fit. The completed assemblies in CAD, and when 3-D printed, can be seen in Figure 58.

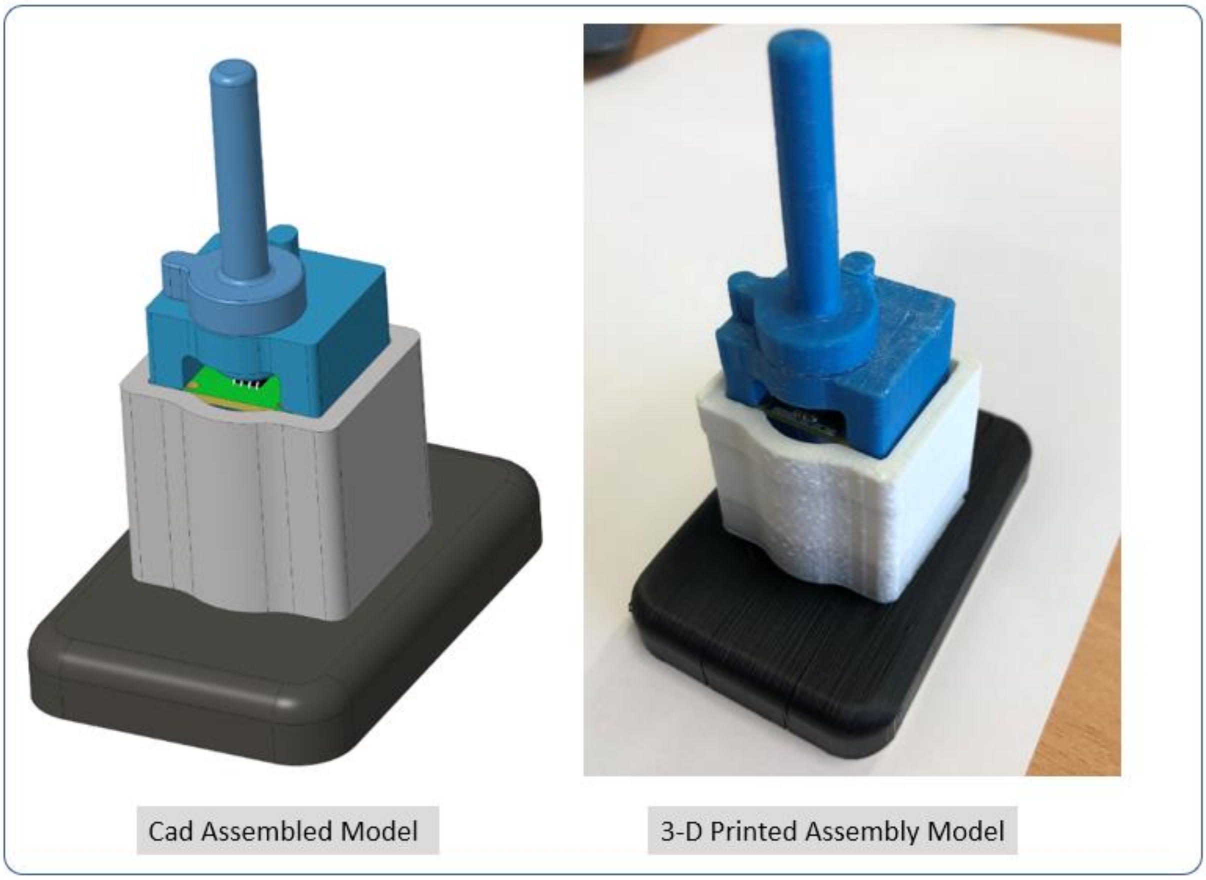


Figure 58 CAD and 3-D Assemblies

4.1.6 Arduino Programming

To complete this project a working knowledge of Arduino was required. In order to speed up development, it was decided to use a pre-written code for the adaptors. One was found at this link: https://github.com/bitfasching/AS5601 but was unable to get Arduino delivering an output using it. After more searching one that worked was found at https://github.com/JanJansen47/AS5601. When operating the Arduino serial monitor an output that was looking like below in Figure 59.

```
Angle: 1161 Encpos: 1330 AGC: 90
Angle: 1186 Encpos: 1330 AGC: 90
Angle: 1220 Encpos: 1330 AGC: 90
Angle: 1245 Encpos: 1330 AGC: 90
Angle: 1280 Encpos: 1330 AGC: 92
Angle: 1339 Encpos: 1330 AGC: 92
```

Figure 59 Arduino Encoder output

The AS5061 gave an angular output with a resolution of 2048 positions over a full 360° rotations. The programme also displayed the unique encoder position upon start-up and continued to display this setting until moved.

Also displayed was a figure called AGC (Automatic gain control) with a range 0-255 counts. The AS5601 uses AGC in a closed loop to compensate for variations of the magnetic field strength due to changes of temperature, air gap between IC (Integrated Circuit) magnet and magnet degradation. The AGC indicates the gain. The manufacturer stated for the most robust performance the gain should be in the centre of its range (range was 0-255 counts in 5-volt mode), (AMS-5601, 2016).

To test for absolute positioning the end stops on the frame was used to simulate end stops in a hydraulic cylinder which would be the extremes of the stroke of the cylinder. The programme was run, and the end stops angular position were noted. The Arduino was powered down and the magnet was moved to a random position. The Arduino was powered up again and the programme rerun. Again, the angular positions were noted at the end stops. Positional outputs were the same as the first time around with surprising accuracy. The values were identical with a 2mm air gap. This gave good confidence that the strategy been approached for the sensor was a good one.

It was hoped to be able to either use an output of a scale between 0-10 volts or between 4-20mA like the electronic output would be in the final product. However, for now a digital representation on screen was deemed enough. To do this some sub-programmes were written within Arduino to map the result from 0-2048 position over 360° to current and voltage outputs.

```
Angle: 44    Output Milliamps (4-20 volt range): 4.00000    Output volts (0-10 volt range): 0.0000000000
Angle: 104    Output Milliamps (4-20 volt range): 4.00000    Output volts (0-10 volt range): 0.0000000000
Angle: 180    Output Milliamps (4-20 volt range): 5.00000    Output volts (0-10 volt range): 0.0000000000
Angle: 221    Output Milliamps (4-20 volt range): 5.00000    Output volts (0-10 volt range): 1.0000000000
Angle: 275    Output Milliamps (4-20 volt range): 6.00000    Output volts (0-10 volt range): 1.0000000000
Angle: 300    Output Milliamps (4-20 volt range): 6.00000    Output volts (0-10 volt range): 1.0000000000
Angle: 350    Output Milliamps (4-20 volt range): 6.00000    Output volts (0-10 volt range): 1.0000000000
Angle: 370    Output Milliamps (4-20 volt range): 6.00000    Output volts (0-10 volt range): 1.0000000000
Angle: 403    Output Milliamps (4-20 volt range): 7.00000    Output volts (0-10 volt range): 1.0000000000
Angle: 450    Output Milliamps (4-20 volt range): 7.00000    Output volts (0-10 volt range): 2.0000000000
Angle: 494    Output Milliamps (4-20 volt range): 7.00000    Output volts (0-10 volt range): 2.0000000000
Angle: 546    Output Milliamps (4-20 volt range): 8.00000    Output volts (0-10 volt range): 2.0000000000
Angle: 579    Output Milliamps (4-20 volt range): 8.00000    Output volts (0-10 volt range): 2.0000000000
Angle: 623    Output Milliamps (4-20 volt range): 8.00000    Output volts (0-10 volt range): 3.0000000000
Angle: 685    Output Milliamps (4-20 volt range): 9.00000    Output volts (0-10 volt range): 3.0000000000
Angle: 744    Output Milliamps (4-20 volt range): 9.00000    Output volts (0-10 volt range): 3.0000000000
```

Figure 60 Mapping Voltage and current outputs

When mapped the scale worked but the serial monitor was giving outputs to the nearest decimal place as seen in Figure 60. From research it was discovered that output would need to be floated to convert from the integer value. The map would then take place.

```
// ***********************************************************************

// Convert angle from 0-2048 angular positions to 4-20Ma output

const float x = reading/2 ;
Serial.print("    Output Milliamps (4-20 Ma range):    ");
float c = ( (x / 2048) * 16 ) + 4;
Serial.print(c,5);
  // ***********************************************************************

  // Convert angle from 0-2048 angular positions to 0-10 volts output

const float y = reading/2 ;
Serial.print("    Output Volts (0 - 10 volt range):    ");
float d = ( (x / 2048) * 10 ) + 0;
Serial.print(d,5);

//************************************************************************
```

Figure 61 Programme in Arduino to scale

The initial gap was set up at approximately 1mm between the face of the magnet and the face of the IC. The sensor was tested at room temperature, 20˚C. The results of this can be seen in appendix, Table 12 on page 185. On the left column is the gap between parts. The second column is the AGC result from the sensor at that distance. Whether the sensor was working correctly at that distance was also noted. Another check done was to see if the outputted value at that distance changed when the magnet was held stationery.

This test was conducted with 0.5mm of a step increase between magnet and IC and the result noted. The gap was controlled by adding increasing widths of 0.5mm wide slip gauges between the handle shoulder and the top face of the frame. As the gap increased the AGC value also increased. At a gap of 2.5mm the AGC value maxed out at top value of 255. However, the sensor continued to work as required.

These consistent readings continued right up to a gap of 11mm between sensor and magnet. Then when the magnet was left stationery, the output began to waver slightly even though no movement of the magnet was taking place.

4.1.7 Sensor signal through aluminium

To determine the effects of the magnetic field as they passed through the aluminium material some tests would be required.

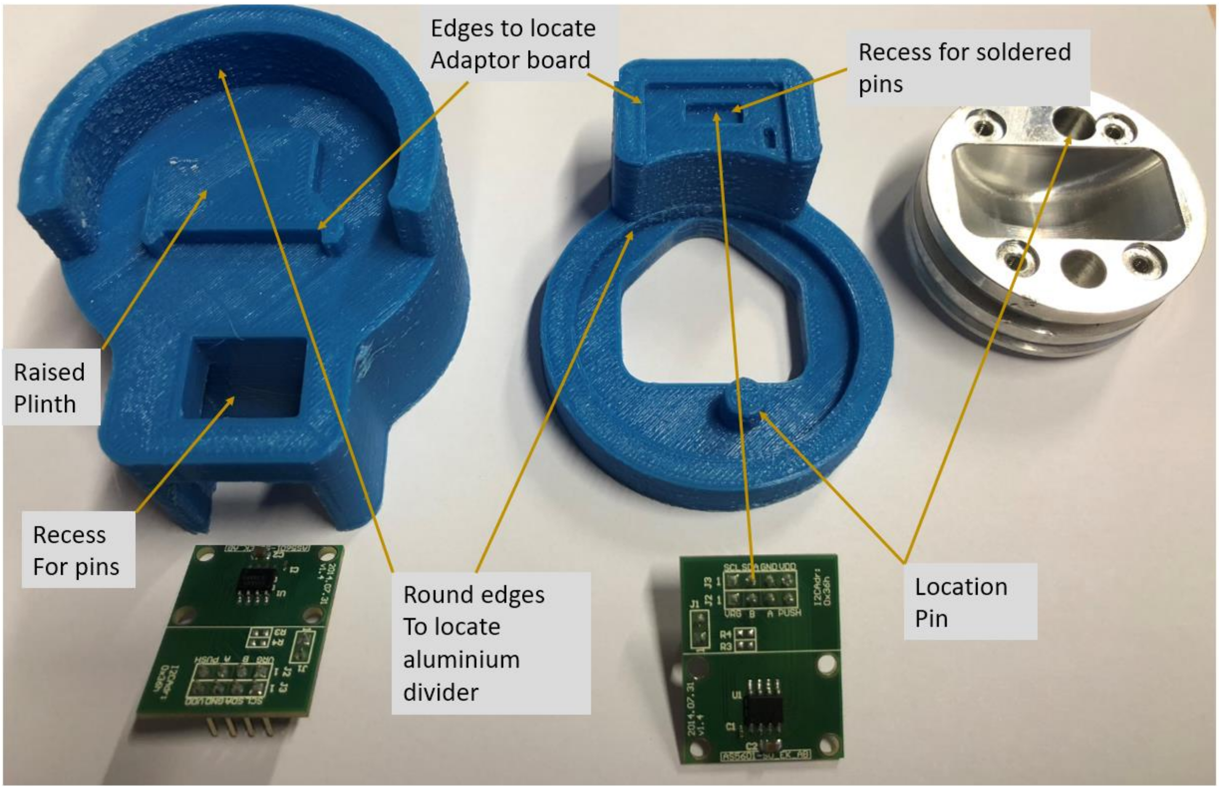


Figure 62 Holder for testing through the aluminium block

The use of an existing old aluminium block meant it saved on metal machining time and long lead-times in the current production environment. A two-piece snap together 3-D printed jig was used to position both parts together in terms of positional location and distance apart. The two pieces separated can be seen in Figure 62.

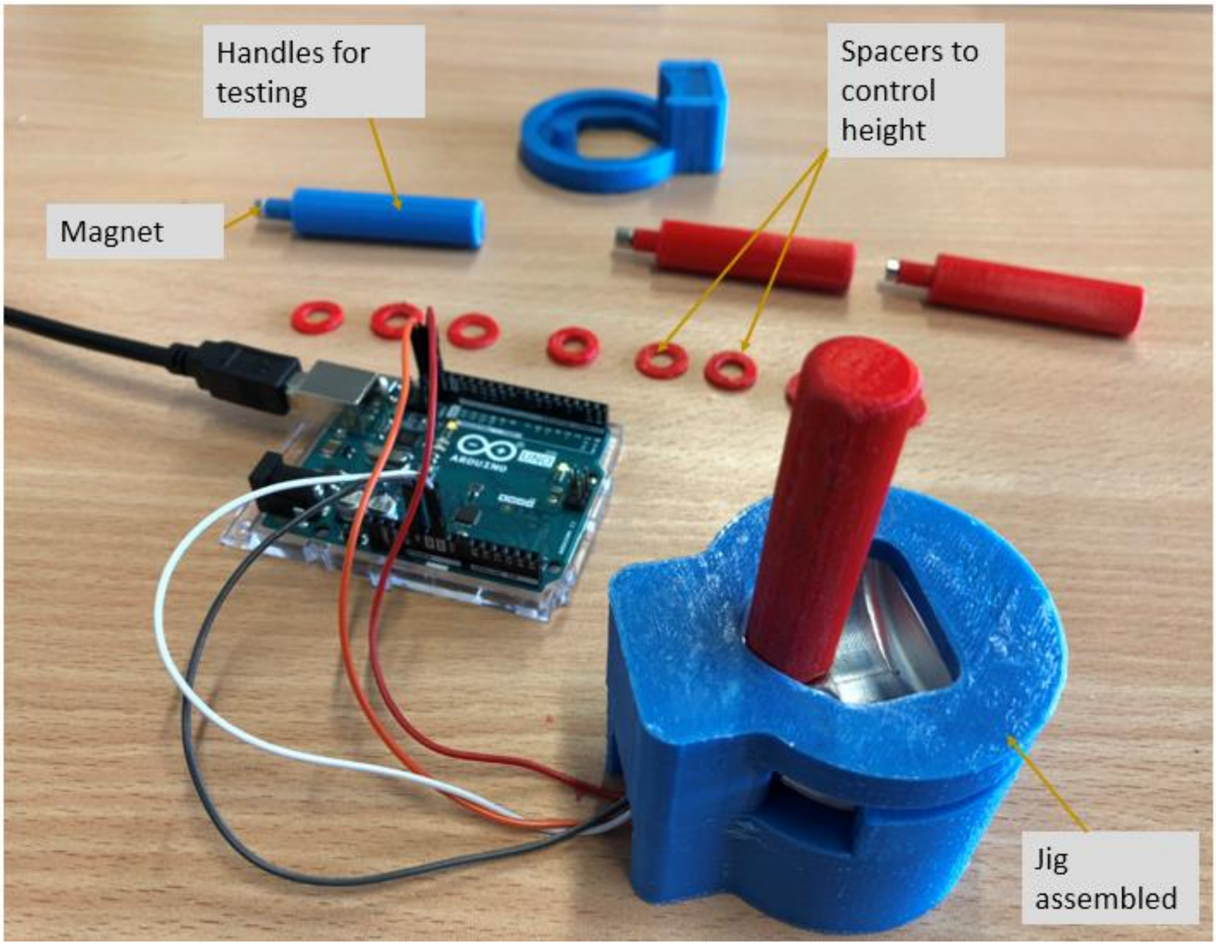


Figure 63 Assembled Jig with Aluminium block

The parts were put together with the programmed Arduino board as shown in Figure 63. The existing aluminium block had 3.5mm of thickness when the magnetic field was passing through, so this was kept the same. The gap at the pressure side was initially start at zero gap and then increased at 0.5mm gap intervals to observe the effects.

The first magnet to be tested was the one supplied in an old rotary sensor. It had dimensions of Ø3mm ID x Ø6mm OD and was 5mm long. The magnetic grade of the magnet was unknown, but it was used by another manufacturer to sense another unknown specification of magnetic encoder. The test results can be seen in Table 13 on page 186.

From the results, stationery outputs were steady up to a gap of 4.5mm between the magnet and the aluminium block. This equated to a total gap of 8.5mm between the magnet and rotary encoder. At the next step with a total gap of 9mm between the magnet and rotary encoder the angular output began fluctuating between two angular positions even though magnet was stationery.

Tests continued at increasing heights of 0.5mm intervals. With each increase up to final height of 17mm the sensor continued to work as it should. However, at 17.5mm height the angular positions were changing over about 13 divisions on a 0-2048 scale. For Neodymium magnets the magnetic field has been proven to decrease with temperature increase, (Calin, 2011). These reduced magnetic effects would be proven in a first endurance test carried out using hydraulic oil in a pressurised chamber.

The next magnet to be tested was the magnet supplied with the AS5601 encoder adaptor board. In this case for setup the magnet was glued to end of the shaft. This would be satisfactory to conduct rotary tests.

The results of the test with the solid magnet can be seen in Table 14 on page 187 Appendix. For these tests static outputs remained constant until a total height of 14mm was reached. At this height there was movement of one angle position on 0-2048 scale. When compared to the ring magnet the height at which this happened was 9mm. This proved the solid magnet was more stable over a greater distance than the ring magnet and can be seen comparing Table 13 and Table 14 on pages 186 and 187.

Based on these documented tests the solid magnet would be the correct initial choice. However, the mounting method would need to be different than gripping magnet on the inside. To do this the magnet would need to be gripped on the outside. This would mean the hole size in the aluminium block would need to be larger to accommodate this magnet.

4.1.8 Evaluating effects of changing housing hole diameter

An interference fit would be used to join the magnet and shaft together where the hole on the inside of the shaft would be smaller than the magnet. This can be seen in Figure 64.

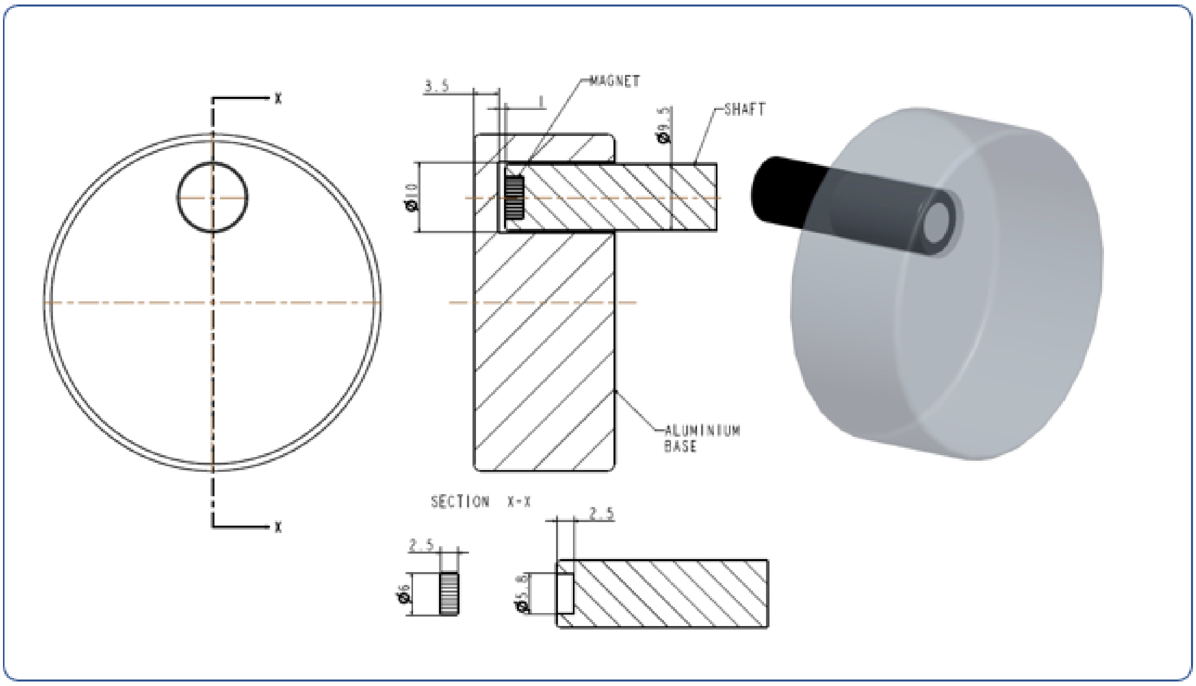


Figure 64 Shaft holding magnet on outside

The hole was Ø5.8mm, and the magnet was pushed into position with an interference fit. In order to determine the effects of the pressure on the larger hole it was decided to run the aluminium body through Creo Simulate stress analysis package, using Ø7mm and Ø10mm holes, to see what the affects would be. To get more accurate results the recess was added.

4.1.9 Using Creo Simulate to verify effects.

It was decided to use Creo Simulate to validate the stresses with 3.5mm of material thickness and Ø7mm hole to prove that these were approximately the same as Ø10mm hole and 5mm left material thickness. The results using Creo gave similar stresses in the peak areas. In Figure 65 on the left we mesh the aluminium block so calculations would be performed. Pressure loadings can be seen on the right side in purple as they were applied to surfaces where pressure from inside the cylinder would be present up to the sealing element.

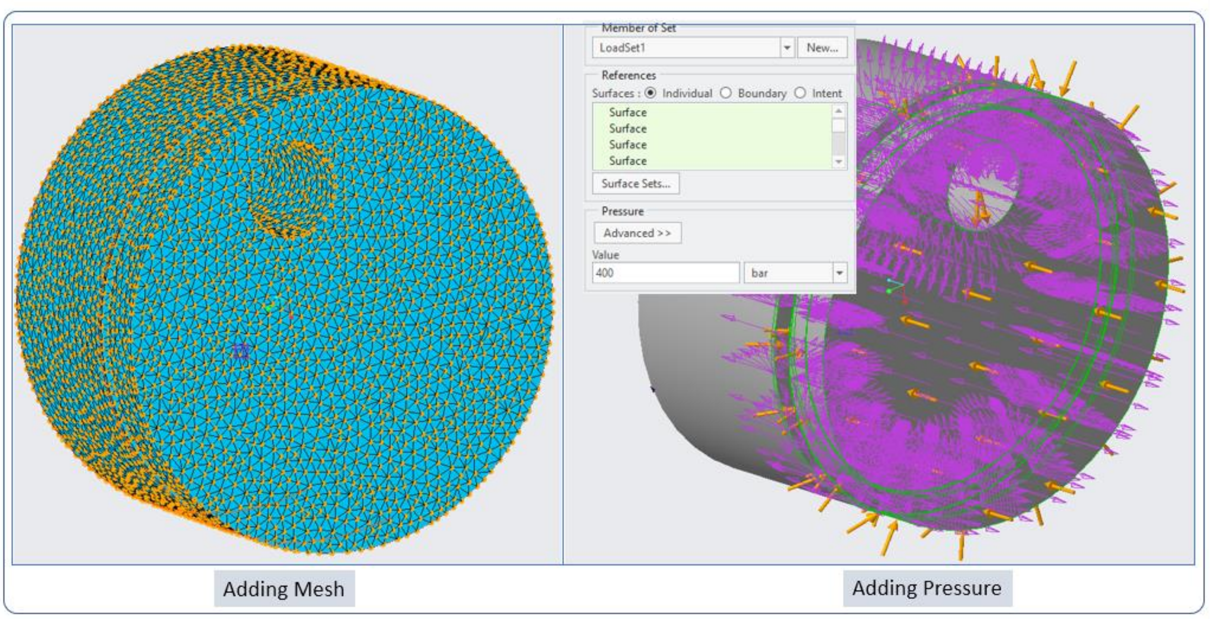


Figure 65 Meshing and adding pressure loadings

From Figure 66 the areas of interest are at the outside circumference of the drilled hole where the material is trying to shear from the pressure and the other area of interest is on the dry side of the aluminium block where the pressure is trying to bulge the material in the centre.

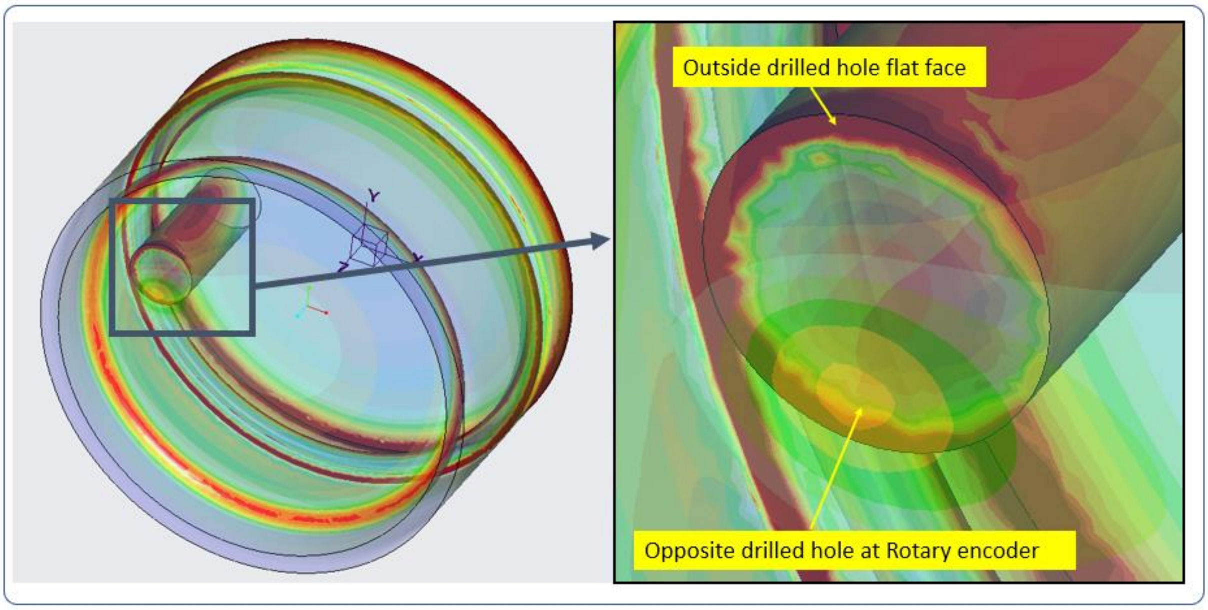


Figure 66 Areas off peak stress on Aluminium block

The stresses were compared from Ø7mm hole and 3.5mm depth of material and Ø10mm hole at 5mm of material. The compared results can be seen in Figure 67. The result on the left, with Ø7mm hole, shows stress in the outer shear circumference at around 117N/mm². The stress in the centre is lower at 53N/mm². When compared to the stresses on the right-hand side with Ø10mm and 5mm aluminium wall, the stresses are similar and slightly lower with 114N/mm² at outer circumference and 52N/mm² at the centre in front of the sensor. This second validation through Creo proves that Ø10mm hole and 5mm wall and Ø7mm hole and 3.5mm wall are similarly stressed. This gives confidence to proceed with these larger hole dimensions as part of the initial prototype design.

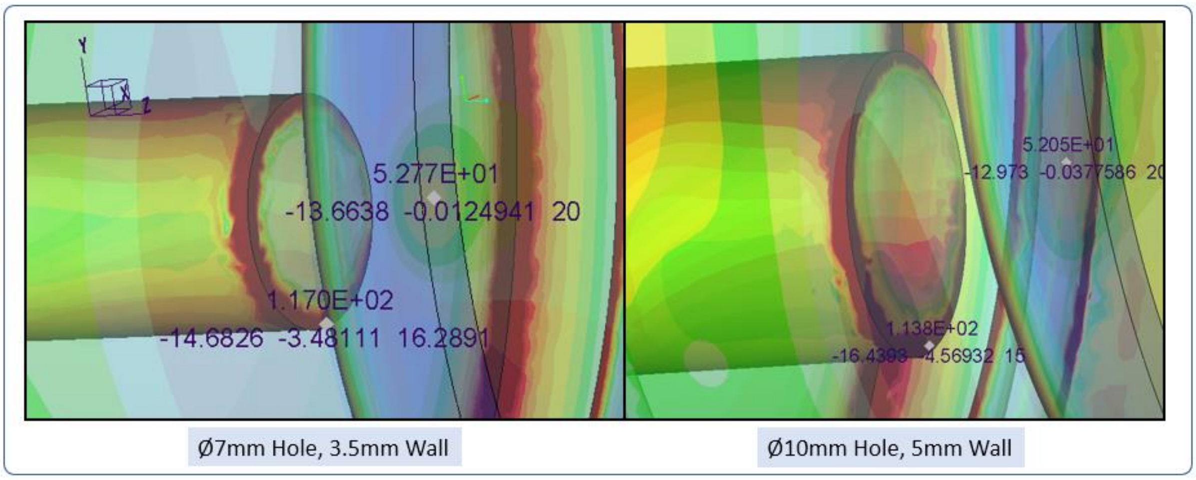


Figure 67 Comparing Results Creo Simulate

4.1.10 Connection wire to rod.

The main aim is that the connection should be easy to install on a compact assembly bench and the wire should not get twisted during installation. The first connection looked at was a connection common with pull wire sensors which was outside the cylinder and has a ring to attach to the moving object where displacement was to be measured.

The connection as drawn in CAD to be evaluated is shown in Figure 68. Wire thimbles are used to protect the eyes of the cable by providing a solid steel barrier between the cable strands and other rigging used to pull the wire.

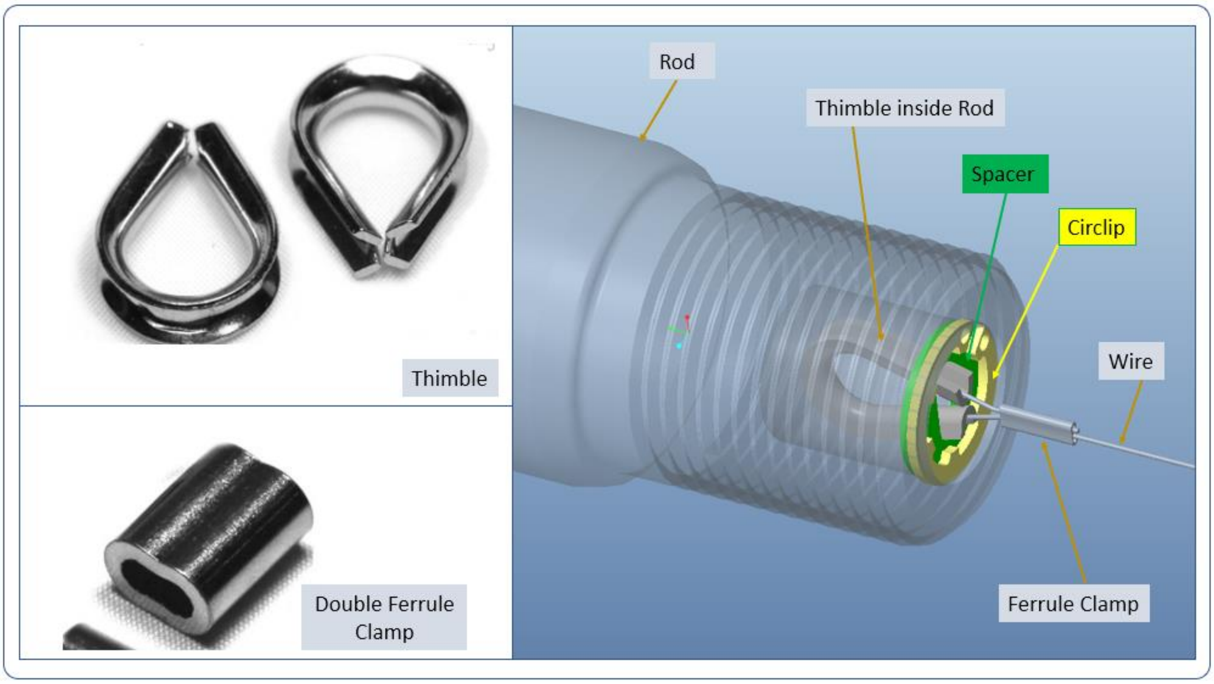


Figure 68 Wire Connection using a thimble

This connection is more suited for hooking directly onto equipment and it took up a lot of space. One solution was to put the thimble inside the rod. This required a lot of machining to open a bore hole large enough for clearance to hold the thimble, which weakened the rod structure.

To simplify the connection for assembly, building length and cost, a lock screw method was designed in CAD. For this method it would involve getting a M6 grub screw and drilling a small hole in one side to accommodate the wire with 0.3mm clearance other side there was a Ø3mm clearance hole added, that would hold a clamped ferrule. This can be seen in Figure 69.

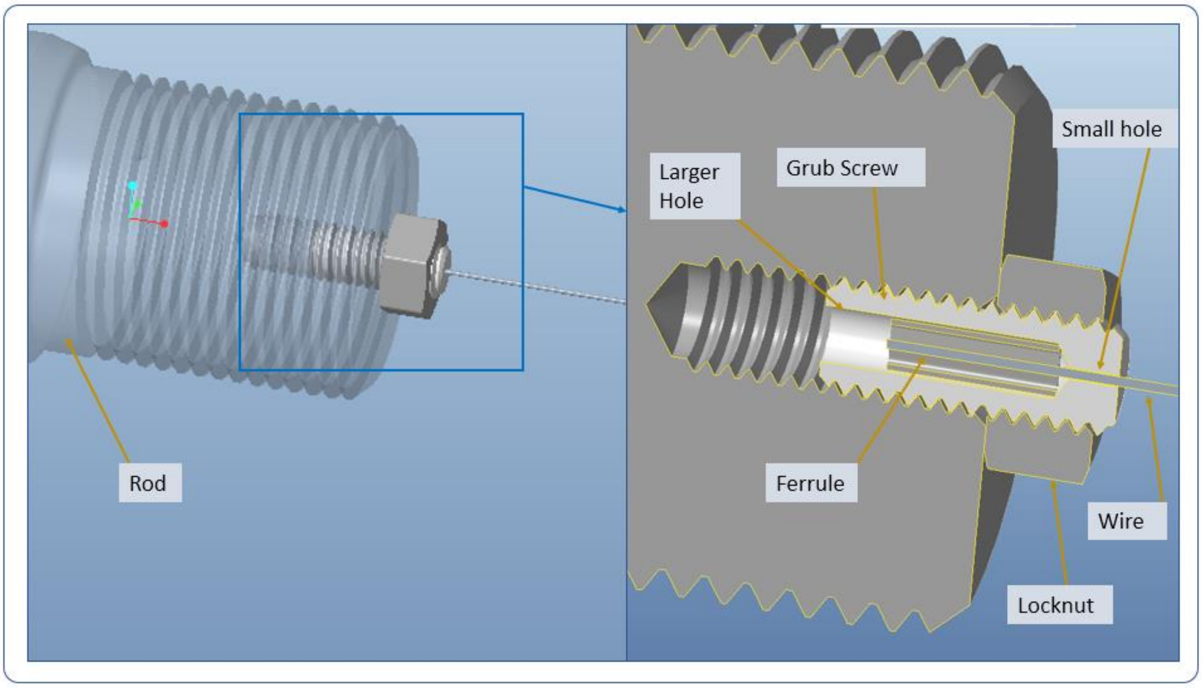


Figure 69 Retaining with lock screw

The ferrule needed to be long enough to grip comfortably, so it would resist the pulling force of the coil spring. The ferrule also needed to be able to rotate freely inside the grub so there was no twisting or binding of the wire during assembly. The screw is assembled into the rod about halfway. A locknut nut is then torqued behind to prevent loosening.

To overcome the possibilities of the screw going inside the rod and ability to be assembled easily a one-piece screw was designed. This can be seen in Figure 69. Final torqueing of the nut can be done with an open-ended spanner. This would allow for quick assembly, be a reliable joint because of ability to torque properly. This solution was deemed best to proceed with for the initial prototype design.

4.2 CAD design of assembly and parts

4.2.1 Overview of Assembly

The first assembly can be seen in Figure 70. The working principle is that the wire screw is connected to the piston rod of the hydraulic cylinder. The aluminium body and surrounding assembly are connected to the tube barrel of the cylinder like shown in Figure 20 on page 46.

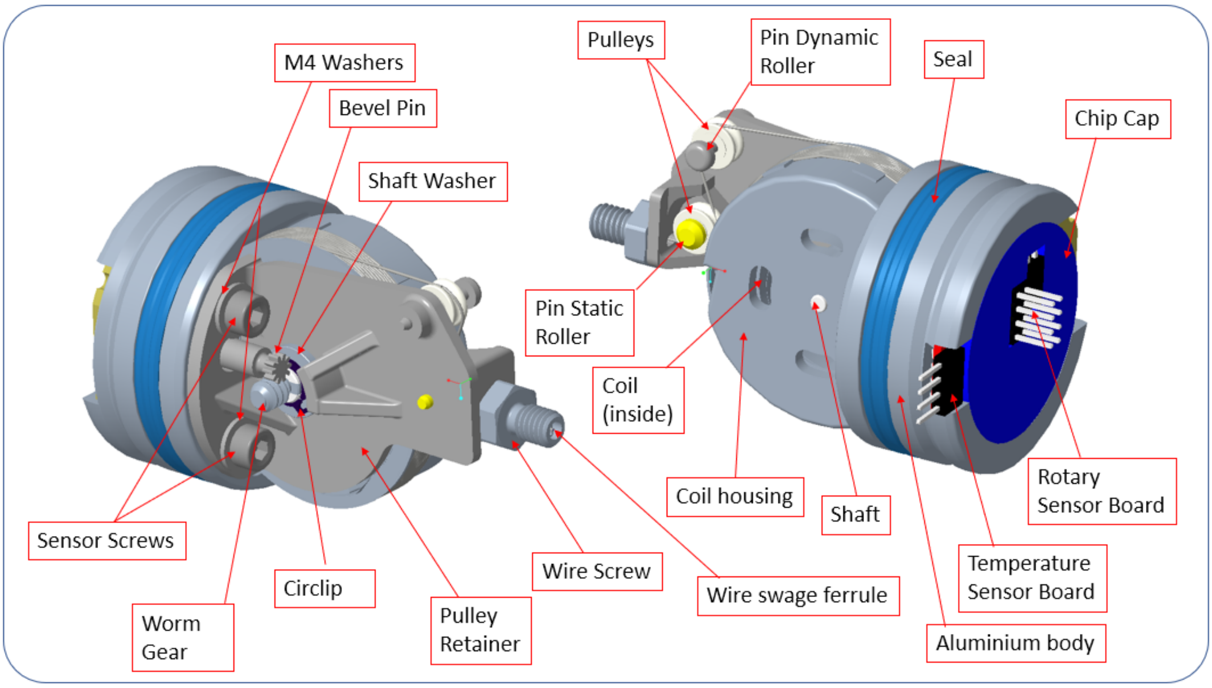


Figure 70 First designed assembly labelled

As the rod extends it pulls the wire screw along with it. This pulls the wire, which is guided around the pulleys. The wire is wrapped around the coil housing so as the wire is pulled out it turns the coil housing. The shaft and the worm gear are connected to the coil housing and turns at the same time.

Assembled at ninety degrees is the bevel pin which has gears on the end which meshes together to translate rotational movement by ninety degrees. The bevel gears hold the magnet which converts rotational movement of the magnet over the rotary sensor to generate a varying electrical output.

When the piston rod is returning the coil, spring has built up energy, so it winds the wire back in as the piston assembly is retracting. This means the rotational movement of the magnet over the rotary sensor happens in both directions and gives positional feedback of the piston head in the cylinder

4.2.2 Coil Housing

The coil housing has many functions. It is used to retain the coil spring inside, used to secure and guide wire rope around the outside and secure one end so it cannot come loose on the outside. It is also used to drive the shaft.

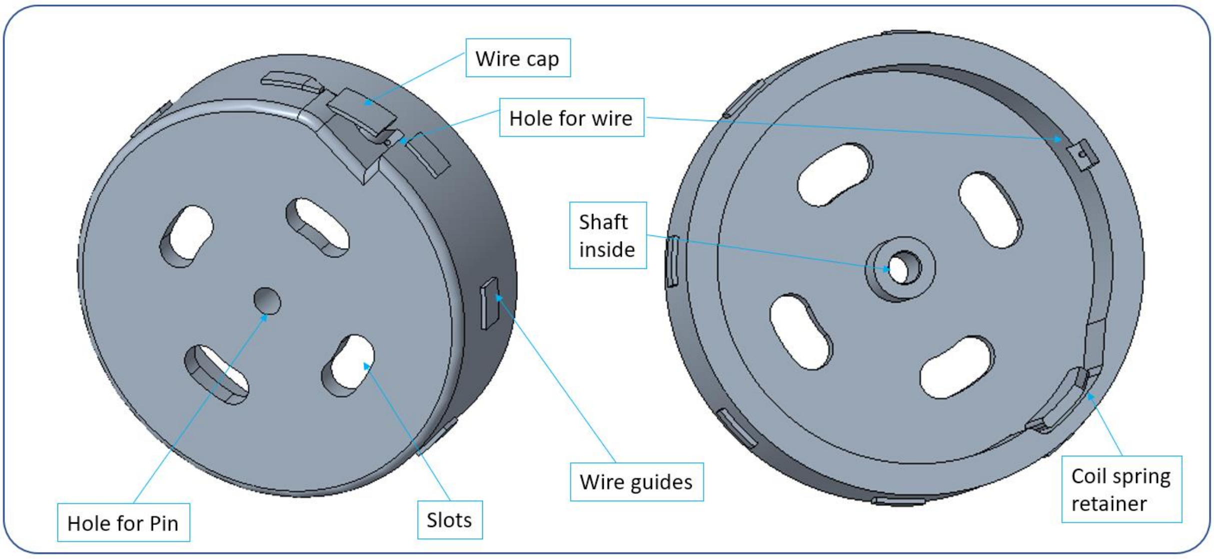


Figure 71 Coil Housing

There is a hole for the wire where it can pass through and be secured. The inside of the coil housing has a retaining lip for the coil spring retainer as shown in Figure 71. There is a hole in the centre for the shaft to pass through. There is also a shaft inside to extend the guidance length for the shaft. The hole is smaller than the shaft and would be a press fit.

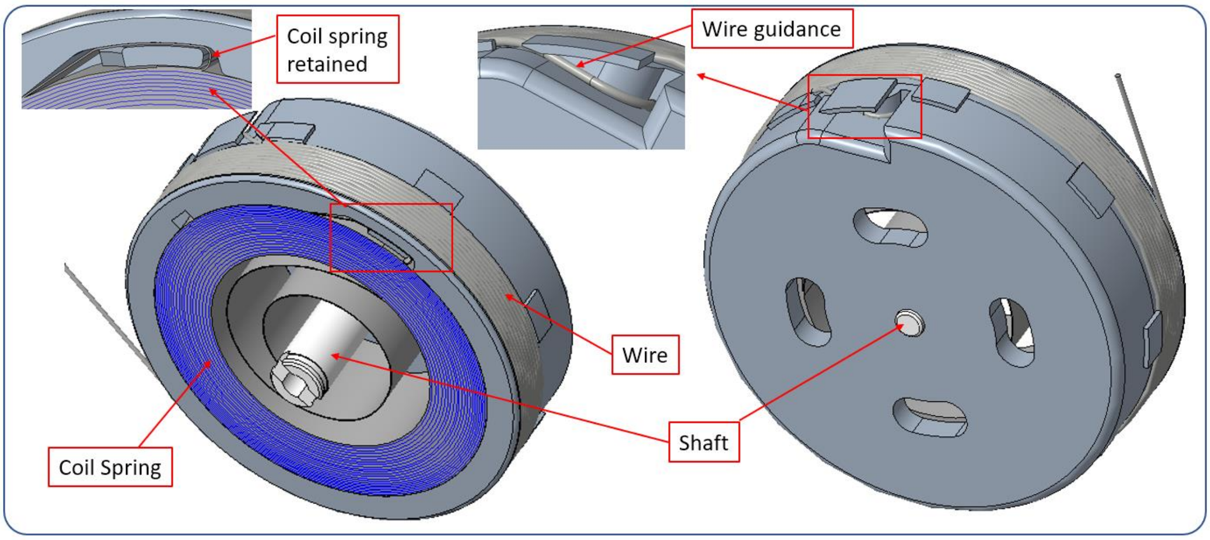


Figure 72 Coil Housing and Assembled parts

In Figure 72, the immediate surrounding parts are shown. The wire is fed through the hole and secured with a swage ferrule. It is then guided out underneath the wire cap and wound around the outside of the housing. The wire guides (rectangular steps) act to support the wire as it goes around and gives a definitive starting point.

The coil spring retainer was just a protruding oval lip to secure one end of the coil spring. It was long to give strength in the direction of tension from the spring. A small gap is left on the inside to wrap the coil spring around to be secure. As the coil spring is wound into the coil housing this gives additional strength support in this area as the loop is secured with the next revolution of the coil spring.

When the pin was push fitted inside the coil housing the interference and guidance, performance of the coil proved unsatisfactory. Therefore, it was decided to add a web on the outside of the coil housing as shown in Figure 73.

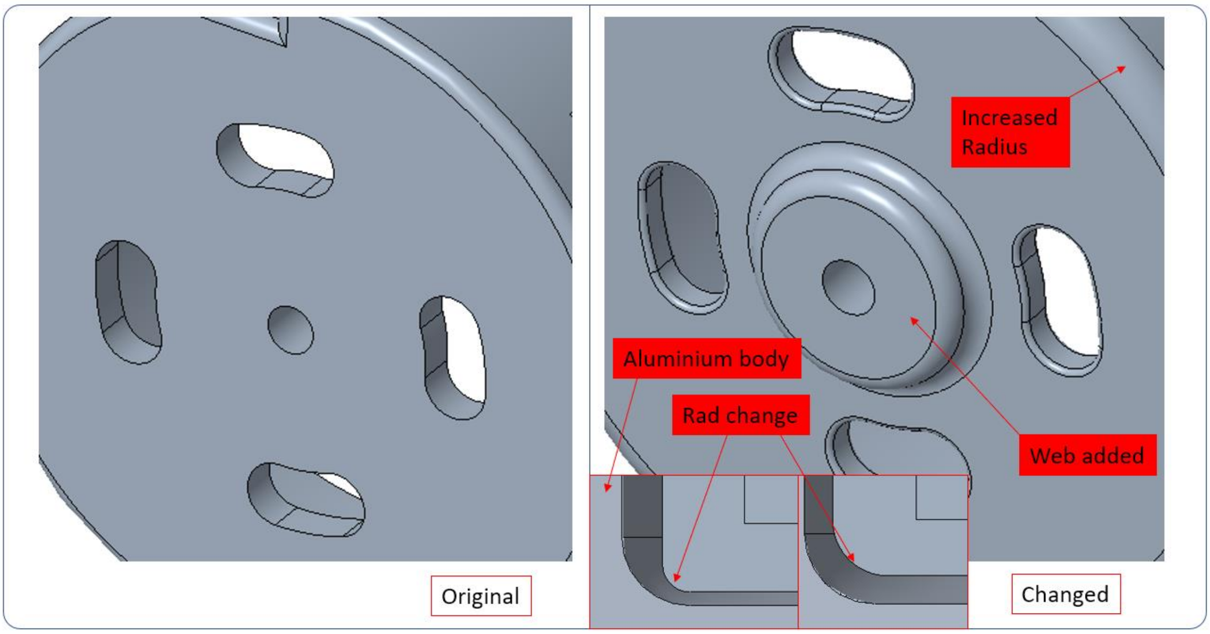


Figure 73 Web and increased radius

When the coil housing was running inside the aluminium body it was felt that the clearance would be increased to match the radius on the inside of the aluminium body. The radius on the coil housing was increased from R1mm (radius) to R2mm.

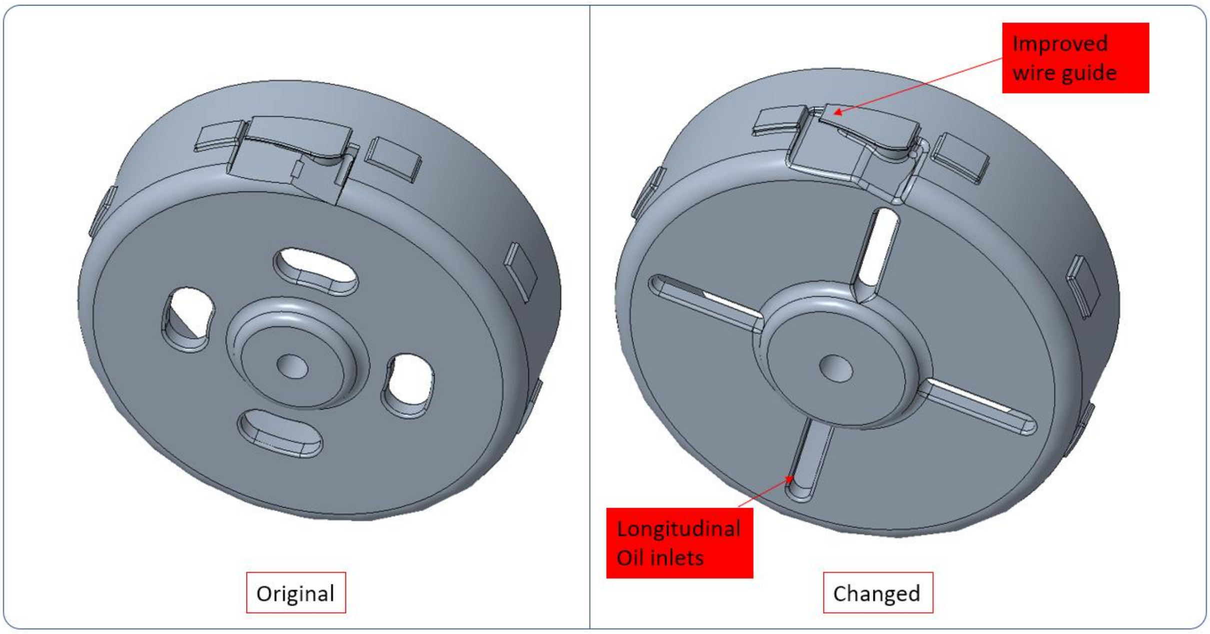


Figure 74 Oil inlet and wire guide

It was also decided to change the shape of the oil inlets to allow better oil distribution as the oil passed around the coil spring during the winding phase.

The gaps, widths and clearances of wire guides were optimised during physical tests on first printed 3-D models to get the most appropriate design.

Figure 75 Raised spigot for coil

In Figure 75, the raised spigot to catch the coil spring on the outside can be seen in green and labelled as raised spigot for coil. The coil is wrapped around the outside of this piece as the coil is rotating and being pulled towards the inside of the shaft so that it cannot come loose. The gap was too small here with the gap closing in the printing process with the result that the coil would not be fitted. If the gap was made large, it weakened the raised spigot and there was a possibility it would break off during assembly or during the working cycle. Both events occurred during initial prototyping, until the optimum size was realised in terms of allowing a gap that would not close but was not weak enough to break off under tension.

4.2.3 Gearing

To get a 90˚ connection a gearing system was necessary. As space was tight the gearing system had to be small to fit within allowed constraints which was decided in section 3.5.7 on page 71. The system as designed can be seen in Figure 76. The magnet was retained in one end of the bevel pin with a push in interference fit. The bevel pin gear was located on the other end. This meshed with a worm gear which was connected to a shaft. The shaft turned and the gears meshed together. The bevel pin would rotate more slowly than the shaft.

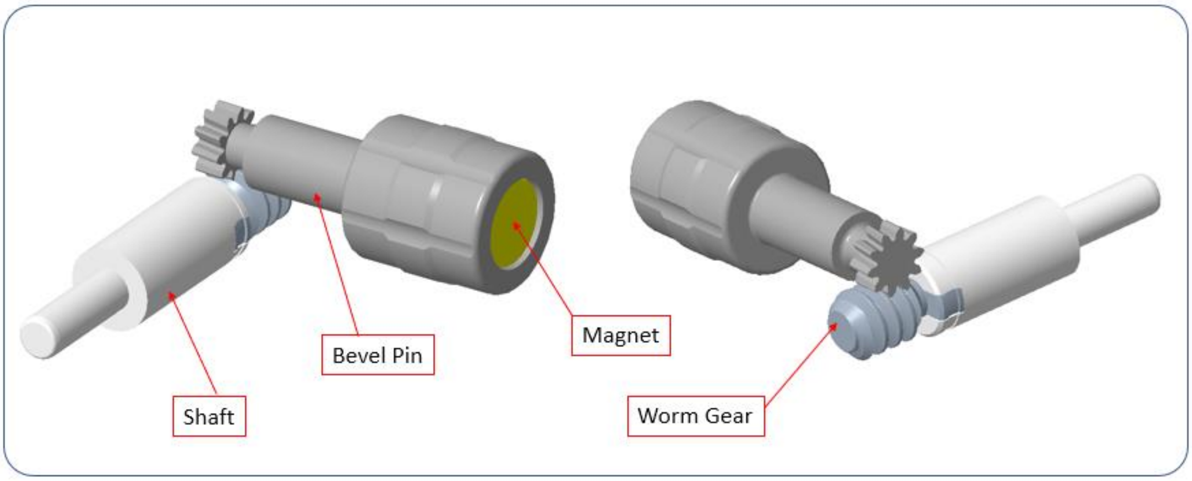


Figure 76 Gearing system

When the gearing was looked at with respect to the space available, there was a minimum number of gears that would be meshed together to ensure continuity between the mating gears and to always have gears in contact. This can be seen in Figure 77. With six gear teeth and eight gear teeth on the wheel it was not possible to get next gear tooth started before previous one had left mesh. Therefore, ten gears were chosen as the optimum gearing for this project as it eliminated this problem in the transmission.

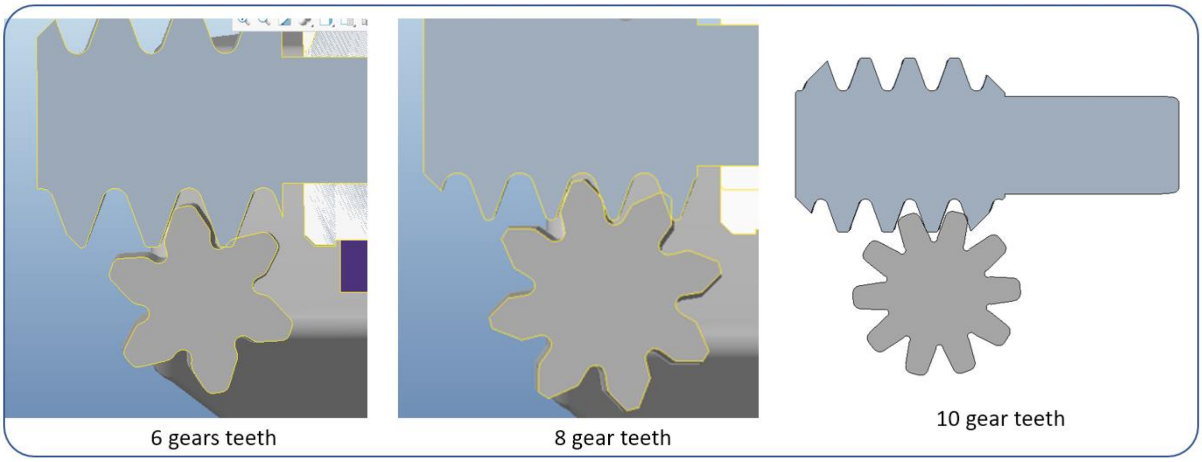


Figure 77 Evaluating number of gear teeth

From looking at the gear ratios in Table 16 on page 188, a lower gear ratio of about 7.5 or 8:1 would have suited 1000mm stroke better to give a finer resolution, but 10:1 was still appropriate and would allow up to 1300mm stroke if needed in the future for longer cylinders without creating an overlap of one turn of the magnet over the encoder. 10:1 gear ratio would allow a change in output every 0.68mm of cylinder stroke.

4.2.4 Pulley Retainer

The pulley retainer forms parts of the main structure for the sensor. It has two main faces at ninety degrees. One face is to bolt to the aluminium body. The other face is to attach on mating parts.

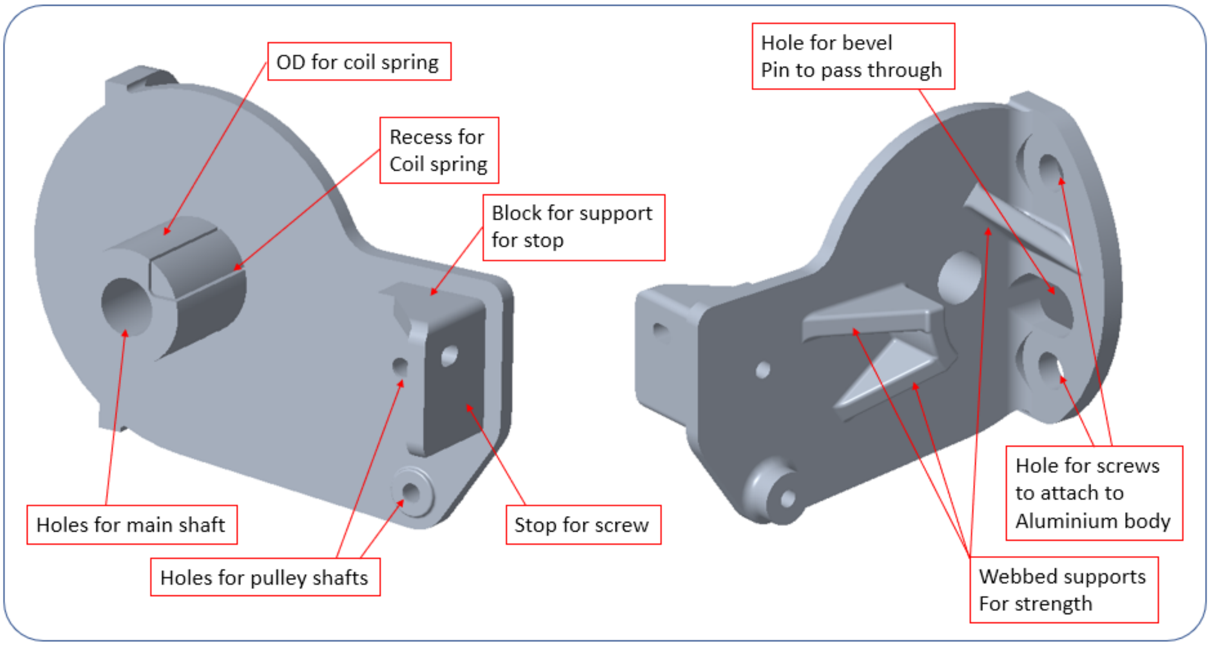


Figure 78 Pulley Retainer

In Figure 78, the OD can be seen which the coil spring would be wrapped around. There was a recess to attach the coil spring to, so it was secured on the inside so tension can be created on the coil spring. There was a stop for the screw to give a defined stop position for the screw when fully retracted. There was a hole for the main shaft to rotate about when in operation. This fit would be running clearance between the mating parts.

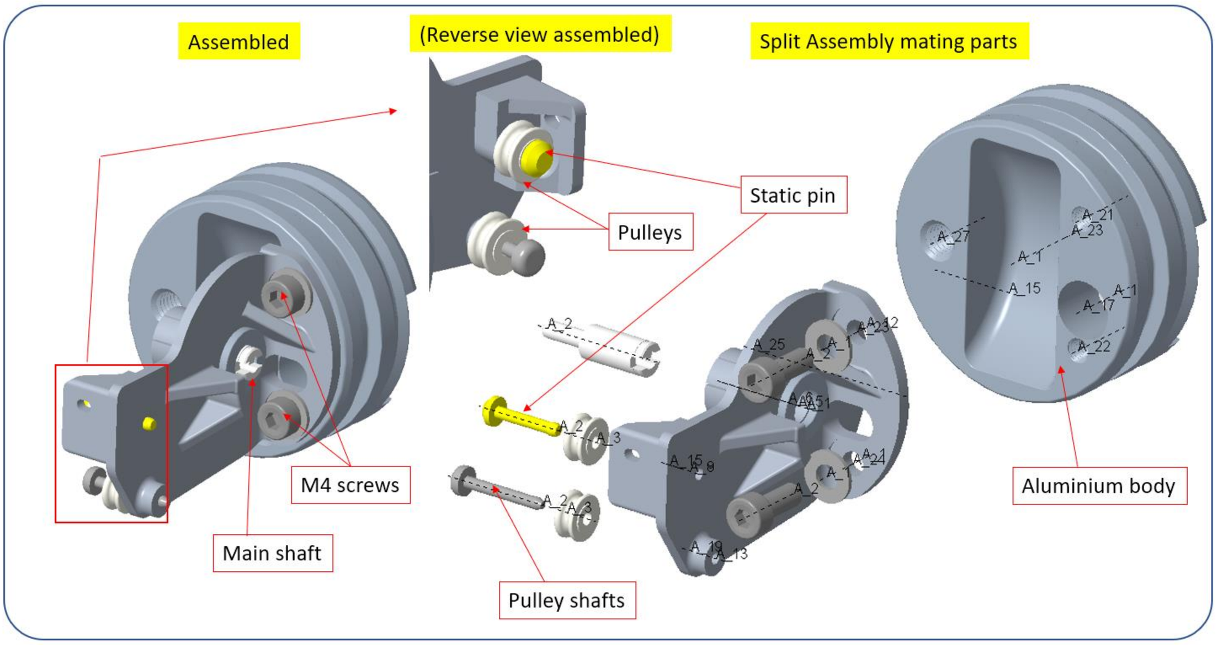


Figure 79 Pulley retainer and mating parts

In Figure 79, the mating parts can be seen. The pulleys are clearance fit running on the pulley shafts. The pulley shafts are push in interference fit through the pulley retainer. The pulley, as shown with the yellow pin (static pin), was not allowed to move laterally only rotate. The second shaft was slightly longer. This allows the pulley to rotate and move across to follow the line of the wire as it is pulled back around the coil housing by the coil spring.

4.2.5 Aluminium body

The aluminium body was used as the break between the pressure of the cylinder and the non-pressurised side where the electronics are situated. In Figure 80, the various machining details can be seen. There are two M4 holes to allow the pulley retainer to be bolted on.

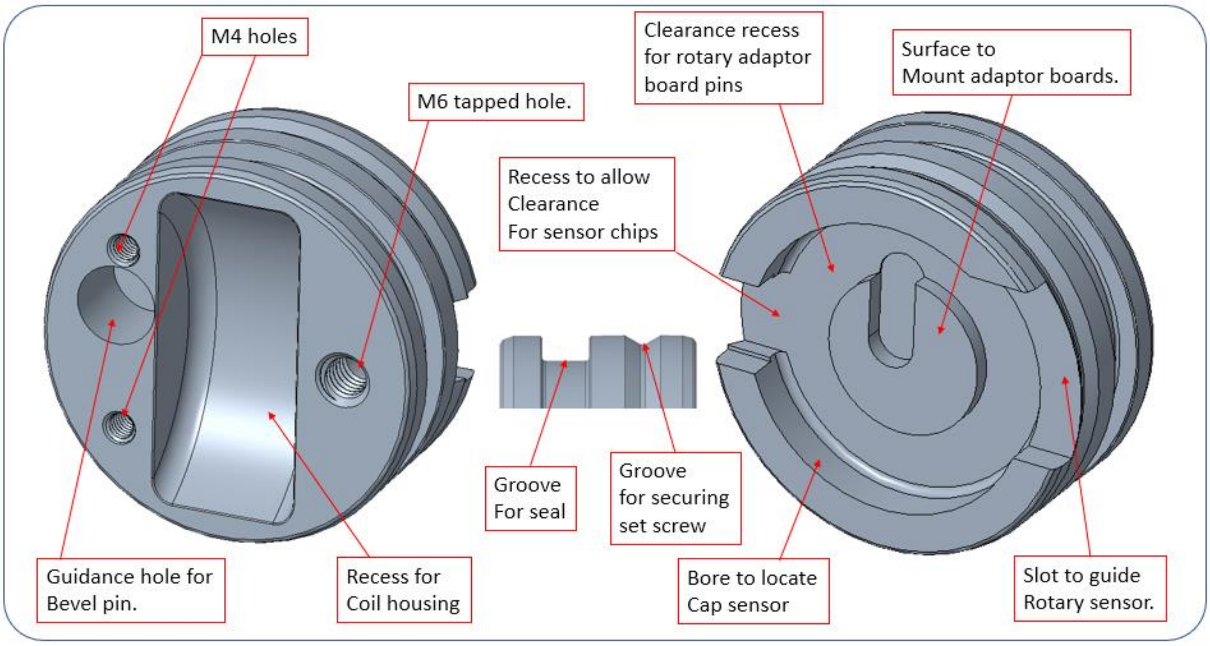


Figure 80 Aluminium body

There was a recess which allows the coil housing to be accommodated and save on building length needed for the sensor to be incorporated within the cylinder. On the outside diameter there are two grooves. One groove was to accommodate the pressure seal. The second groove was to catch the point of the grub screw so the sensor cannot be pulled out of the housing when mounted in the cylinder.

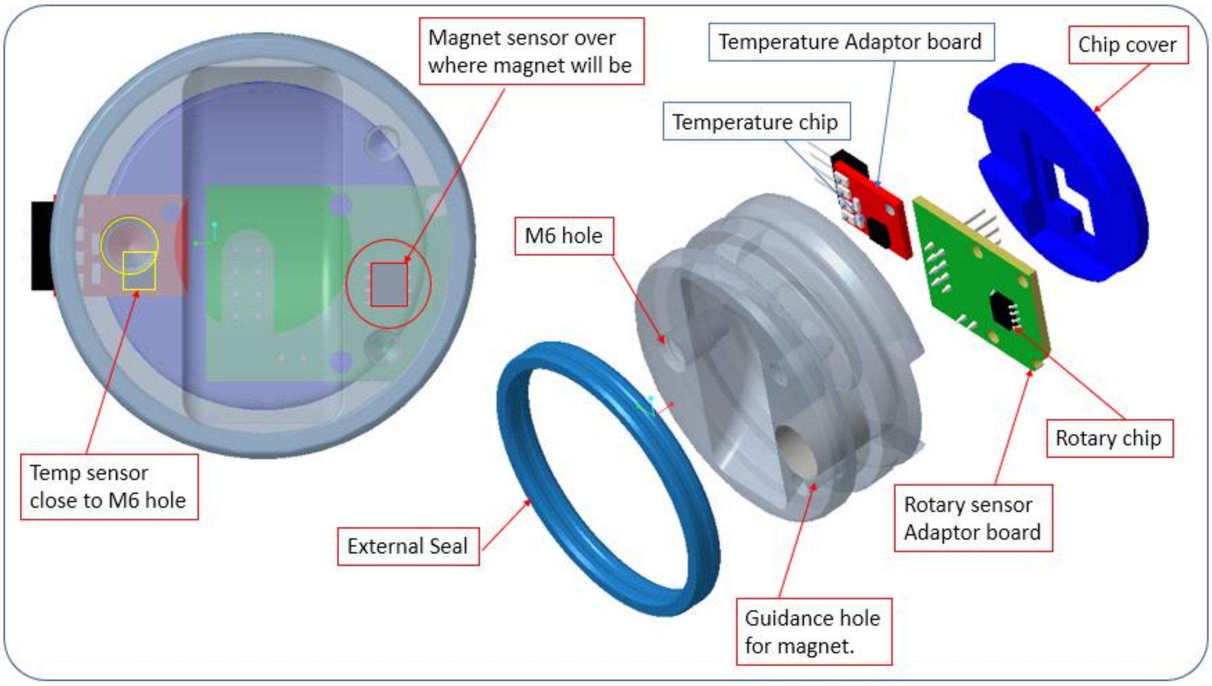


Figure 81 Aluminium body mating parts

In Figure 81, the surrounding chip components are seen. The chip cover has a cut out to allow the pins and surrounding plastic cover of rotary sensor adaptor board to come through and locates the rotary chip directly over centre of the magnet guidance hole. This assures best accuracy for the working of the rotary sensor. The temperature chip position was not so important for function as the surrounding area heats up to match oil temperature but was just in front of M6 hole to allow for optimum response to changes in cylinder oil temperature.

4.2.6 Pulleys and Pulley Shafts

The pulleys guide the wire between the screw which was connected to the cylinder and to guide the wire back to the outside of the coil housing efficiently. The fixed pulley can only rotate and was fixed directly in line with the centre of the cylinder. The variable pulley is free to rotate but also free to move along shaft. When the cylinder was fully extended all the wire was nearly fully unwound from the coil housing. The two pulleys would be in line with the centre of the cylinder.

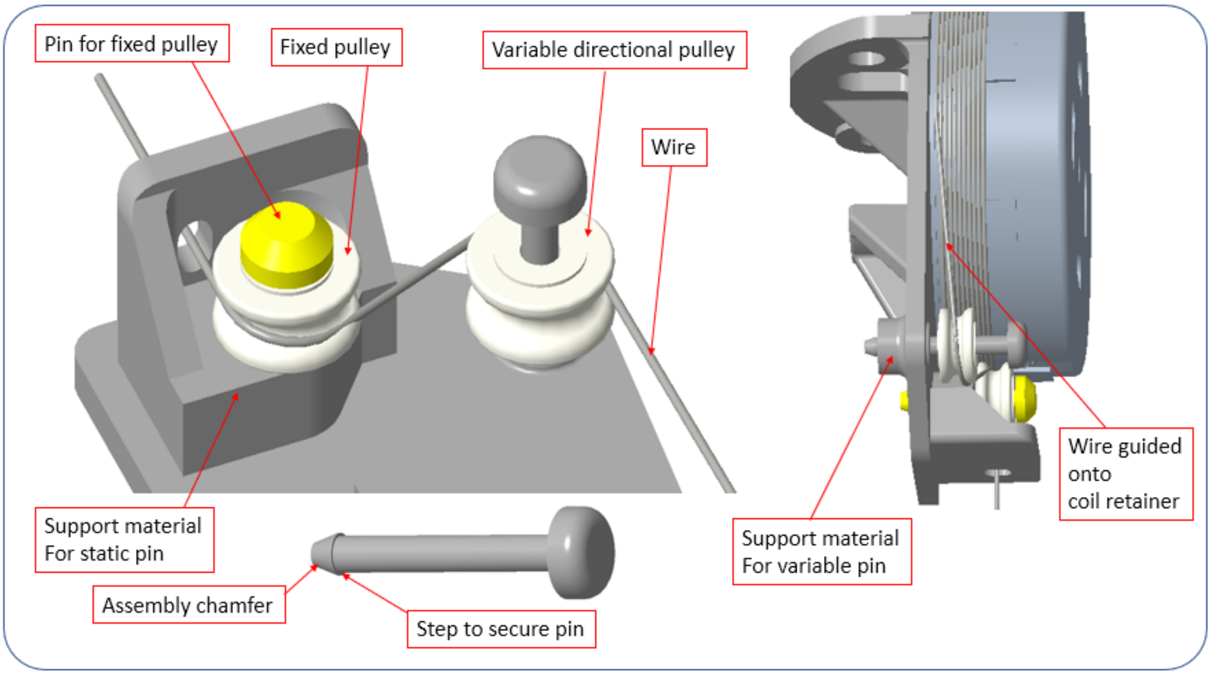


Figure 82 Pulleys and Pins

As the cylinder retracts the wire would be wound back onto the coil housing. The natural curvature of the wire helps to guide the wire beside the previous row as it was being wound in.

The variable pulley moves across to act as a smooth transition as more wire builds up on the coil housing. This minimises the risk of wire overlap on the outside which would result in different speed of rotation of the pulley retainer and an inaccurate positional reading back to the encoder.

5. BUILD

5.1 Sourcing Parts

The initial assembly can be seen in Figure 83. The items are listed with a balloon number to link drawing to the parts list. In Table 5 the part name and material are listed.

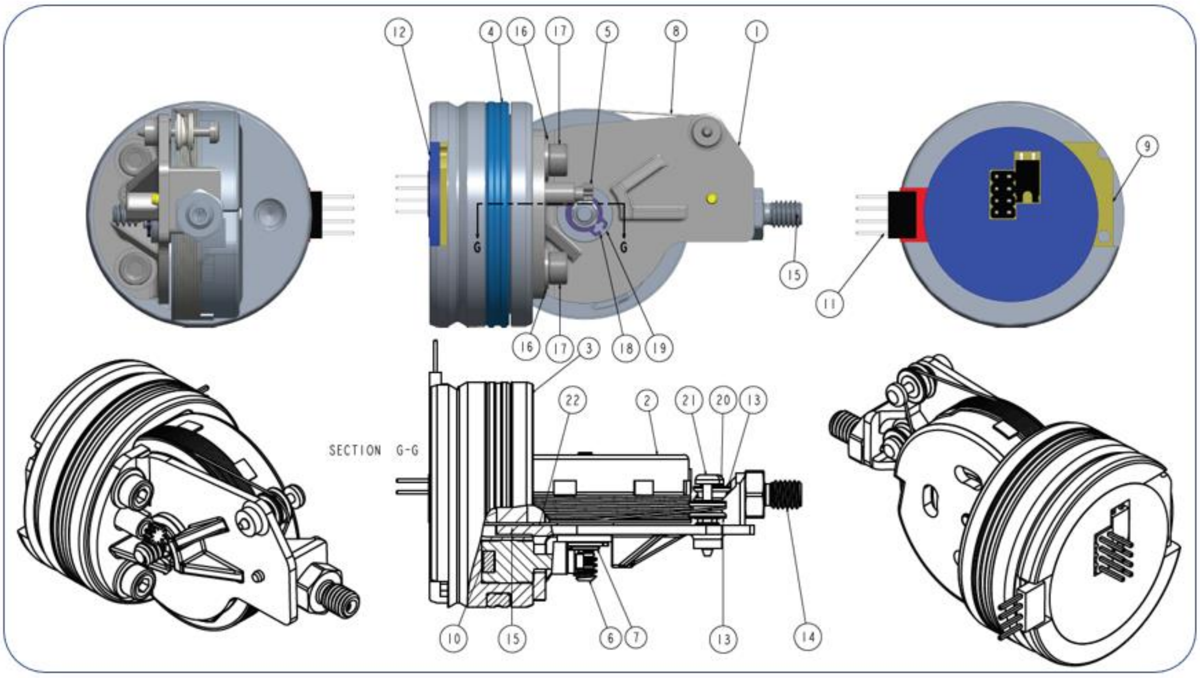


Figure 83 First assembly

Part	Name	Process	Material	Qty per Assy
1	Pulley Retainer	3-D Print	PLA	1
2	Coil Housing	3-D Print	PLA	1
3	Aluminium body	Turn & Mill	6082 T6-551 Aluminium	1
4	Seal (AT042048)	Purchase Part	Polyurethane	1
5	Bevel Pin	3-D Print	Crystal	1
6	Worm Gear	3-D Print	Crystal	1
7	Sensor Shaft	Turn & Mill	Ø6mm Stainless 303S31	1
8	Ø0.5mm Wire	Purchase Part	304 Stainless 49 strand	1
9	AS5601 Dev Board	Purchase Part	Electronic component	1
10	Rotary Magnet	Purchase Part	Commodity Component	1
11	Temperature Dev board	Purchase Part	Electronic component	1
12	Chip Retainer	3-D Print	PLA	1
13	Pulley for wire	Machine	Polyacetal	2
14	Hex Screw to join cyl	Machine	Free cutting hex bar 10 A/F	1
15	Swage Ferrule	Purchase Part	Aluminium	2
16	M4 Washer	Purchase Part	Steel	2
17	M4 x 10 screw (Din 912)	Purchase Part	Steel	2
18	6mm Circlip D1400	Purchase Part	Steel	1
19	Washer M6 x Ø12mm x 1.6mm	Purchase Part	Din 125A BN 670 Stainless	2
20	Static Pin for Roller	Turned Part	Ø5mm Stainless bar	1
21	Dynamic Pin for roller	Turned Part	Ø5mm Stainless bar	1
22	Coil Spring	Coil Sping Maker	Spring Steel	1
			Total	27

Table 5 Parts List

5.1.1 Pulley Retainer

This part was printed in Burnside on a Robo 3-D printer using PLA material. It took time to get the settings right to ensure functional quality. Generally fine settings were needed, and it took about 7-8 hours to print. The printer working and the finished part can be seen in Figure 84.

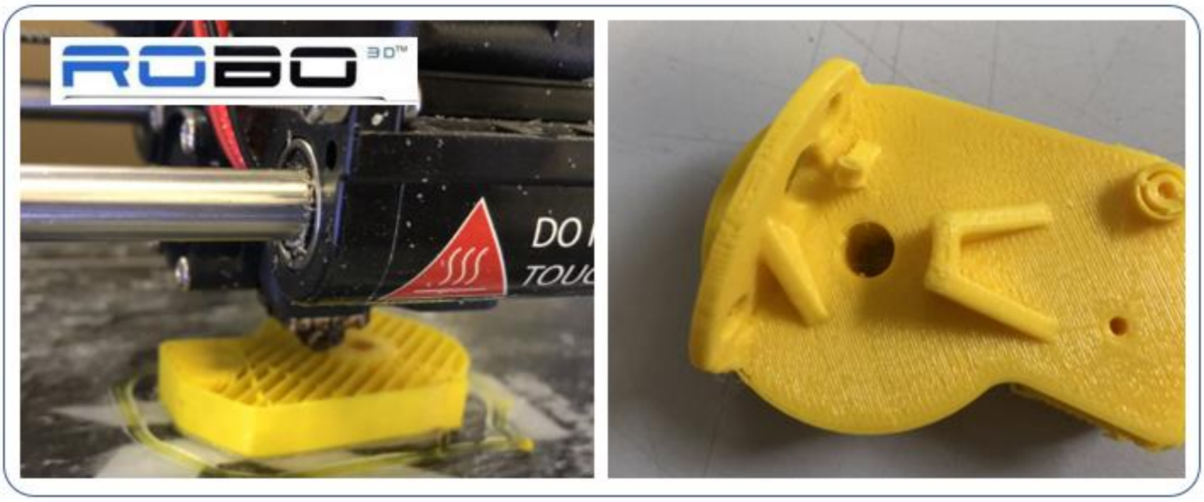


Figure 84 Pulley Retainer 3-D Print

5.1.2 Coil Housing

The coil housing was 3-D printed in Burnside, yellow printed part, and in IT Carlow on an Ultimaker 3 3-D printer with the white printed part. The settings were set as fine to get good quality prints and 100% fill. Parts were sufficient quality to be able to carry out initial functional tests.

Figure 85 Coil Housing prints

5.1.3 Aluminium body

The aluminium body was complex in that it needed to be machined. It has specialised machining that required specialised milling machining equipment. A link up was done between Andrew Keppel, a lecturer in IT Carlow and a French intern student Solène Bouchet from Seatech University in Toulon over for the summer of 2018.

First the parts were turned to get parts to the right length and grooves in the back face were turned to get as much material removed in the turning phase as seen in Figure 86. The parts were turned in Burnside on a CNC lathe and the milling were done in IT Carlow.

Figure 86 Turned aluminium body

Jigs and fixtures required to be constructed to be able to clamp the turned shape in a fixed pattern when the part was being machining to ensure correct machined orientation between machined faces. The fixtures can be seen in Figure 87.

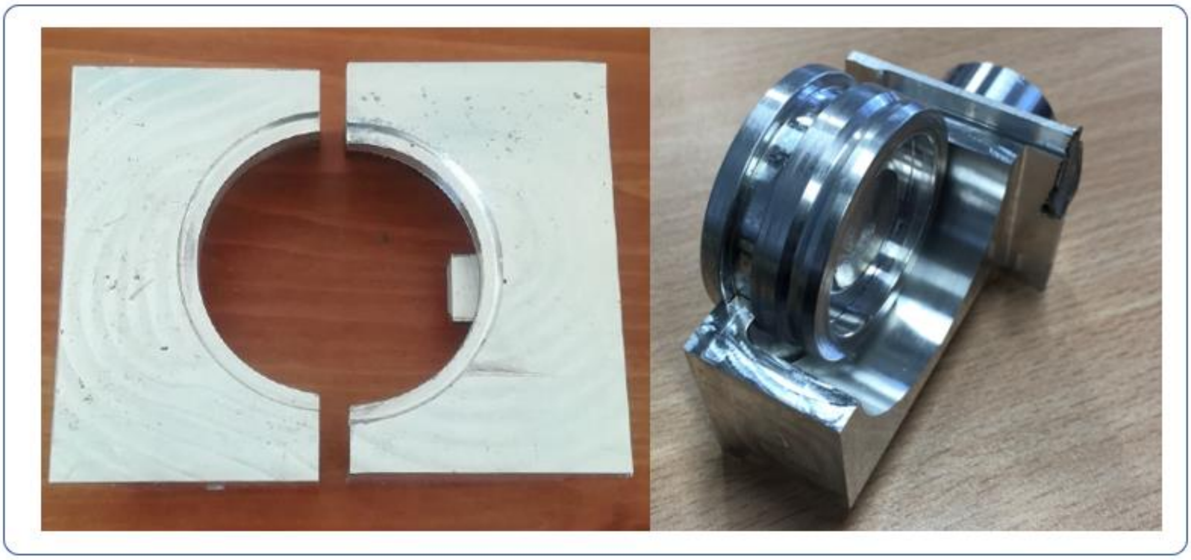


Figure 87 Fixture to secure turned part

The machining was done in a Hurco 5 axis machining centre and the Cad Cam was done on HSM Works.

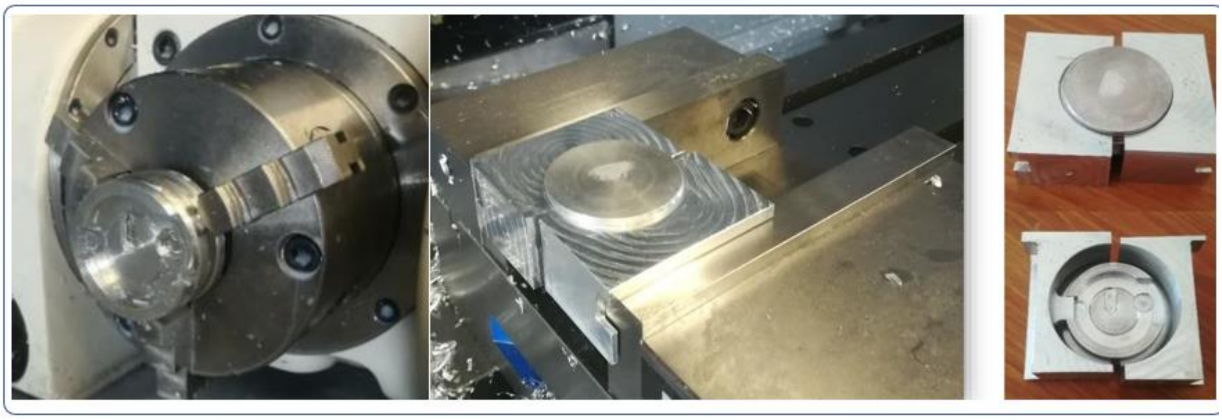


Figure 88 Milling of Aluminium Housing

In Figure 88 the machined parts can be seen inside the fixtures used to hold them for machining. The parts turned out well and were ready to use when received.

5.1.4 Pins for Rollers and Sensor shaft

The pins were small precision machined items and would not be machined in Burnside lathes so were outsourced to a local specialised supplier. The material used was stainless steel for strength and to prevent corrosion. Basic drawing dimensions can be seen in Figure 89.

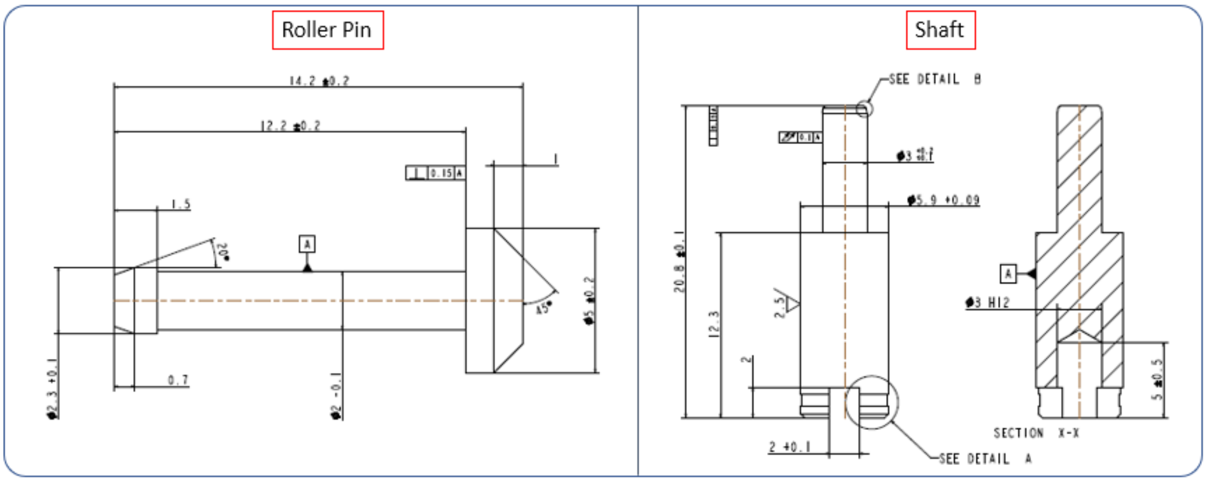


Figure 89 Pin for Roller and shaft

5.1.5 Worm Gear and bevel Pin.

Initially these parts were printed on Robo 3-D in Burnside, but the quality was poor, and the parts could not be used. Parts were then printed on an Ultimaker 2 printer. However, it was found that the print although was better, was still not up to the accuracy required for these parts. The setup and supports can be seen in Figure 90, along with the parts as printed with supports still connected. The parts were outsourced to a company in Galway called 3-D Technology and were printed on an MJP 2500 with a special melt away wax support, so no manual removal of support was needed. The quality of these prints was good enough for practical tests on the assembly.

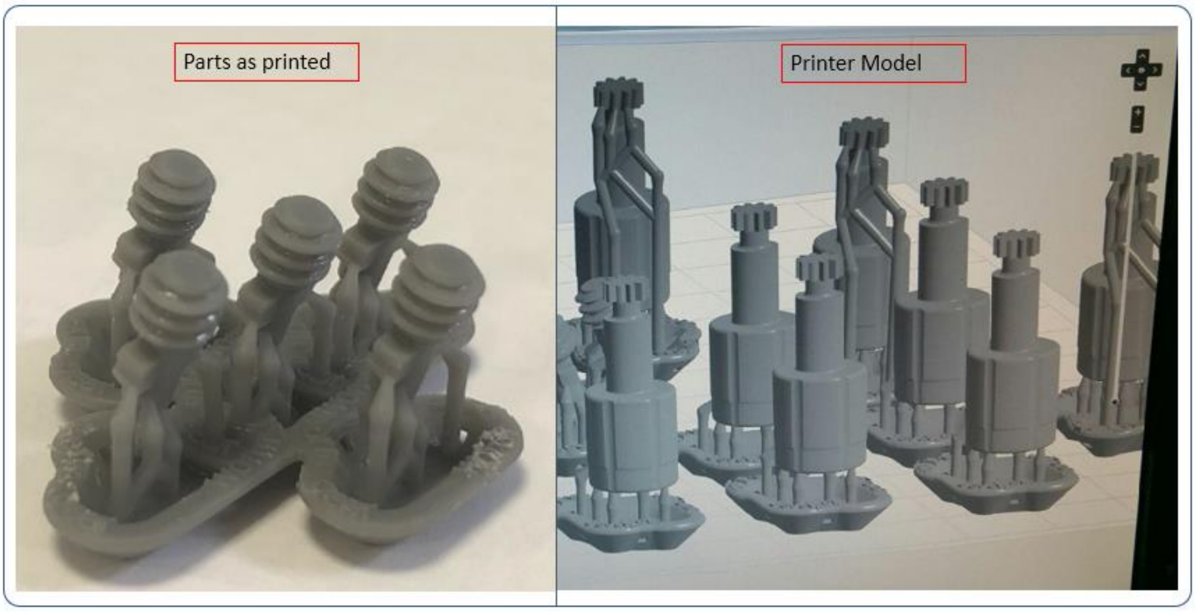


Figure 90 Ultimaker 2 parts as made and in setup for 3-D print.

5.1.6 Hex screw

A standard M6 x 8mm long hex screw was used to join the wire to the cylinder. It was modified with a 0.8mm hole to allow the wire to pass through. There was a Ø3mm clearance drilling added to allow the swage ring to fit inside also. The modification can be seen in Figure 91.

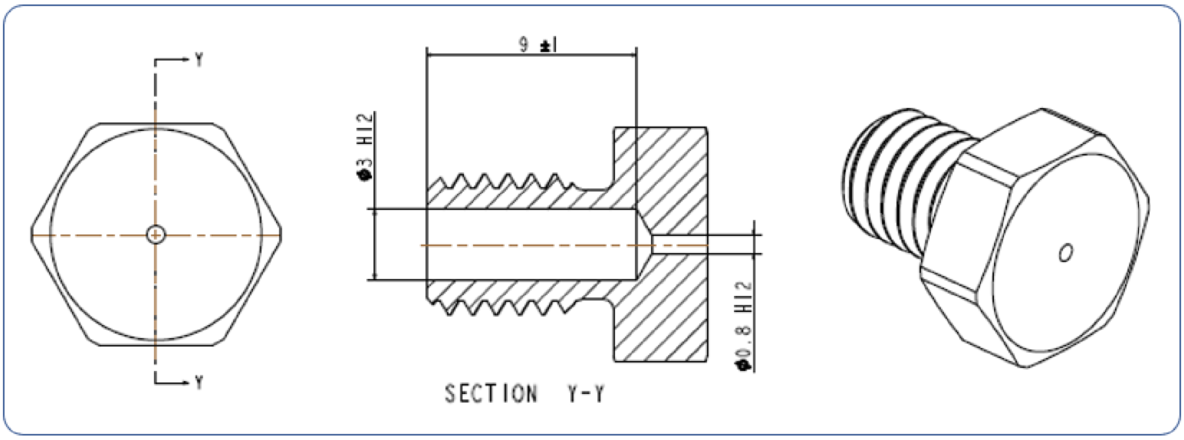


Figure 91 Screw for connection to cylinder

5.1.7 Chip Retainer

The chip retainer was printed on Burnsides 3-D printer. The inside of the chip retainer has precise shapes to position the two adaptor boards in the correct position.

5.1.8 Coil Spring.

The coil spring cavity void was maximised during design to allow for the largest coil spring that would be used in terms of number of coils and width of coil. There was consultation with various coil companies to get the best solution and a good company to work with. Kern-Lieber's in the UK was chosen as the company to work with for prototypes.

A standard bending shape was chosen based on similar designs they use today in a seat belt application like shown in Figure 92, and the coil housing and pulley retainer were designed around these connection shapes.

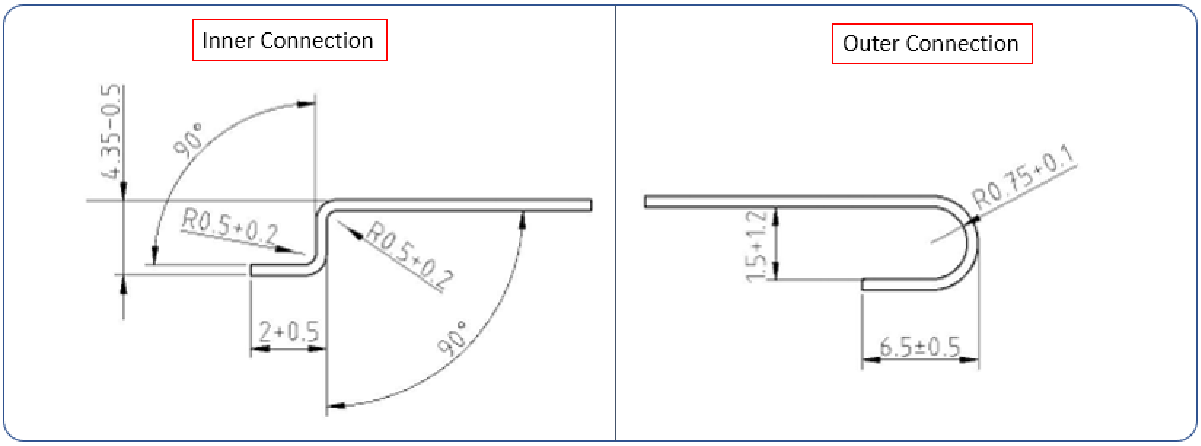


Figure 92 Coil Spring connections

The size chosen was 12mm wide x 0.165mm thick. The full unrolled length of the coil was 3000mm. The material was a texture rolled carbon steel strip. The ID that the coil was wound around was Ø12mm and the outside diameter inside the coil housing Ø38mm. This allowed for a 48% fill factor.

The total number of active turns based on above was 17 turns. The distribution was planned at 5 turns for preload, up to 10 active turns and the remaining 2 turns left as reserve. For production Kern-Lieber's would fit the spring directly into the coil housing.

Figure 93 Coil Springs as delivered.

In this case for samples the coil springs were sent wrapped in a cable tie and insulation tape wrapped around for security, as loose springs unwinding have lots of potential energy. The springs as delivered can be seen in Figure 93.

5.1.9 Electronic components

The two main electronic parts were bought connected to an adaptor board. The rotary encoder adaptor board in Figure 94 was made by AMS and came complete with a magnet. The magnet came as part of the adaptor board package properly selected in strength to work with the AMS rotary encoder.

The temperature chip was sourced from closed cube also as part of an adaptor board with an operating temperature range from – 40° C to +125°C. Both chips had I^2C outputs to work with Arduino programming module as shown in Figure 94. The data sheet for the temperature sensor can be seen on Figure 160.

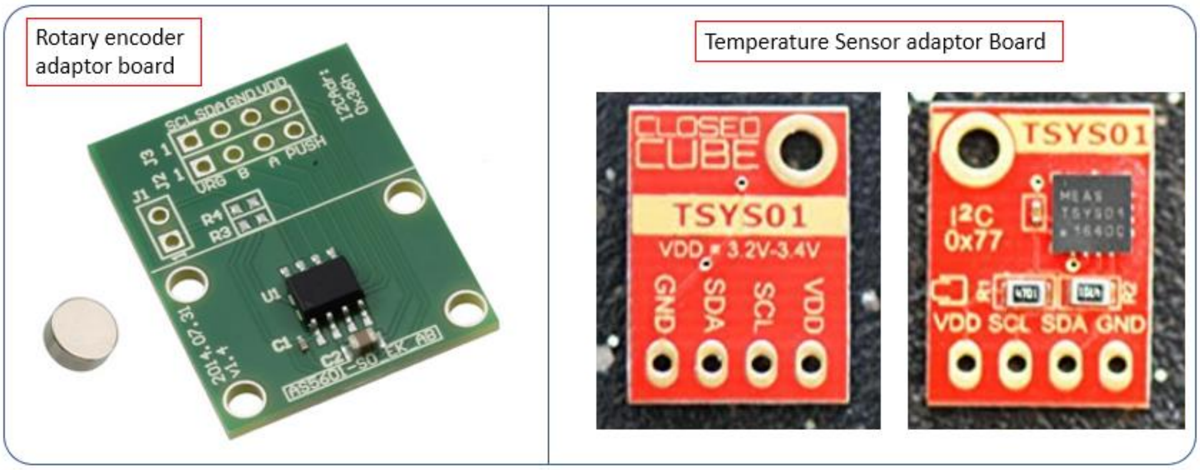


Figure 94 Rotary Encoder and Adaptor Board

5.1.10 Pulleys, Swage Ferrule and Stainless wire

Small commodity pulleys were found. These were spindle pulleys to fit a 2mm RC Motor drive shaft. The inside dimension was 2mm, so were suitable for the pin for rollers. The pulleys can be seen in Figure 95.

The wire selected was 0.5mm. The grade of stainless was 7x7 49 strand 18/8 Inox Surgical wire. The material was 304 stainless stock to avoid corrosion with a breaking load of 14Kg.

The swage ferrule was also bought as a standard part. They were sold based on wire size. 1mm was the smallest available size which was selected. The material was aluminium to allow for easy crimping and good grip on the wire.

Figure 95 Pulleys and Swage Ferrule

5.1.11 Static seal

The seal selected was a polyurethane static seal from Gapi seals. A backup ring and an O ring would have been used but the static seal is good for all pressures up to 400 bar and most types of hydraulic fluid. The risk of using an O ring with a back-up ring is they would be fitted the wrong way around. Also, the rubber O ring is not advised for use with some of the newer synthetic oils used in hydraulic cylinders today where Polyurethane is okay to use, (Heney, 2016).

5.1.12 Washers, circlips and M4 screws.

For the washers and the M4 screws standard off the shelf parts were chosen. However stainless-steel material was used to avoiding potential corrosion issues in storage prior to usage.
The circlip was also made from stainless steel. It was Din 471 (D1400) circlip with 2 x lugs for mounting and dismounting.

Figure 96 Stainless Steel Components

5.2 Building test unit

For the first few tests the output display from the sensor was displayed on a laptop. However, it was decided a portable standalone test unit was needed to display the outputs for the sensor. The main reason was to free up the laptop for other uses during testing and to ensure the laptop did not get damaged in the workshop.

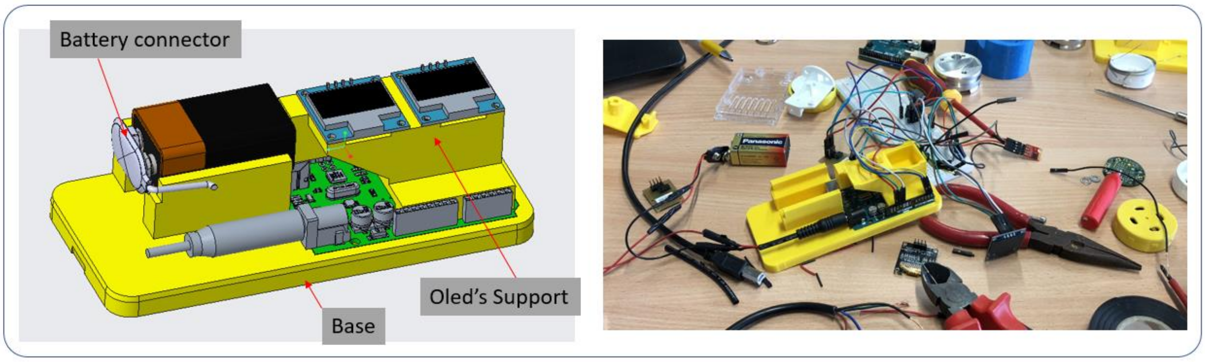


Figure 97 Test unit design

In Figure 97, the internal design can be seen. Initially a base was designed to accept the Arduino board. Then the battery holder was added so the device would be used as a standalone item. To keep the unit compact, a raised OLED support was added above the Arduino board to hold them in position.

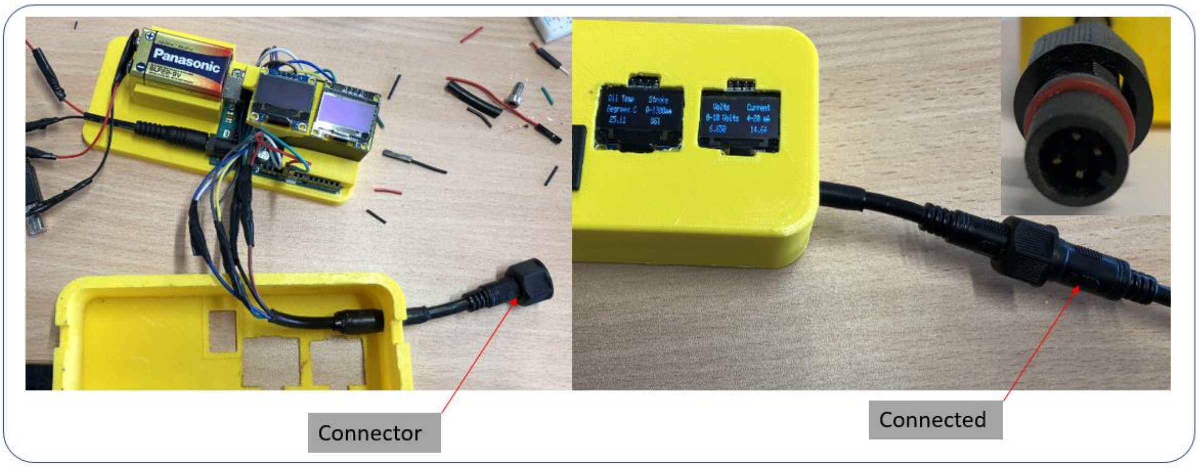


Figure 98 Connection

A 9-volt battery connector was included to power the Arduino. This was routed through an on-off toggle switch so the unit would be turned on and off.

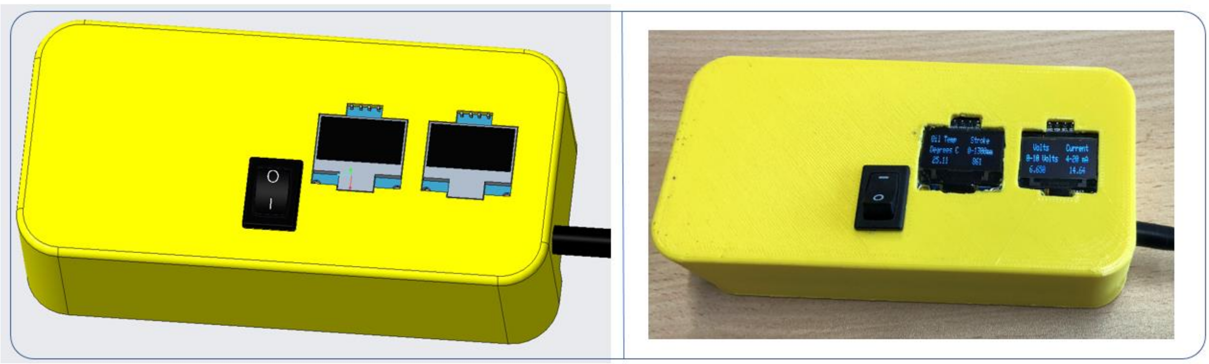


Figure 99 Completed test unit

The cover had a slot taken away to allow the OLEDs to be seen and a recess for the switch to be pushed through. This can be seen in Figure 99, with the designed CAD model on the left-hand side and actual unit on the right side. This unit was printed in Burnside Autocyl. The output from the sensor would also be visualised as a rolling display on a laptop as seen in Figure 100.

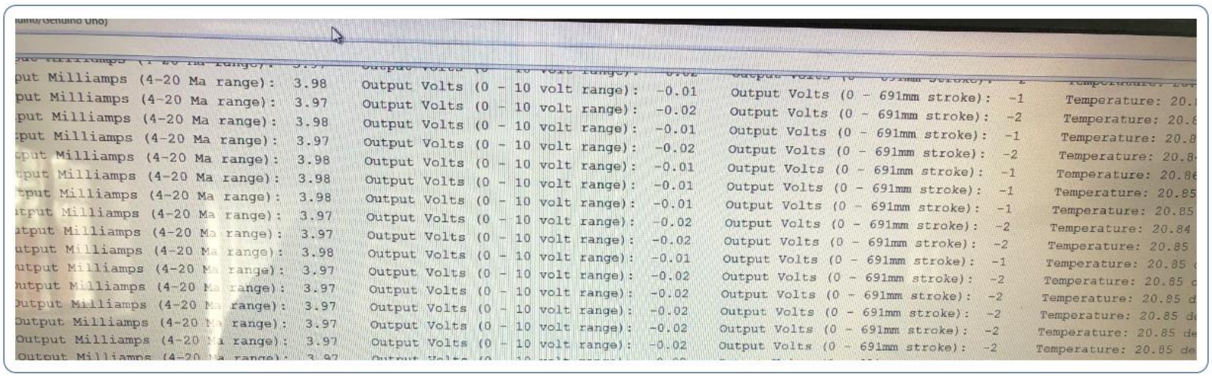


Figure 100 Display on laptop

5.3 Building Sensor

5.3.1 Pulley Retainer

When the pulley retainer was printed there were small variances depending on the printer and the material used. To allow for this, small machining allowances were left on the inside of the holes to allow for uniformity.

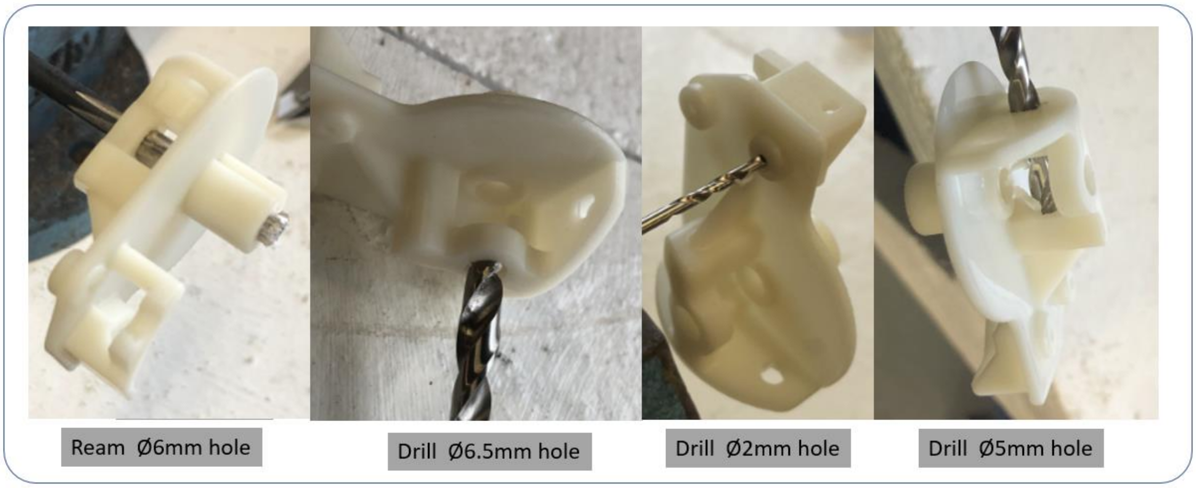


Figure 101 Machining pulley retainer

The machining operations used can be seen in Figure 101. For the sample process, the guidance length was varied by drilling the hole deeper until a rotational running fit was present when assembled to the aluminium body.

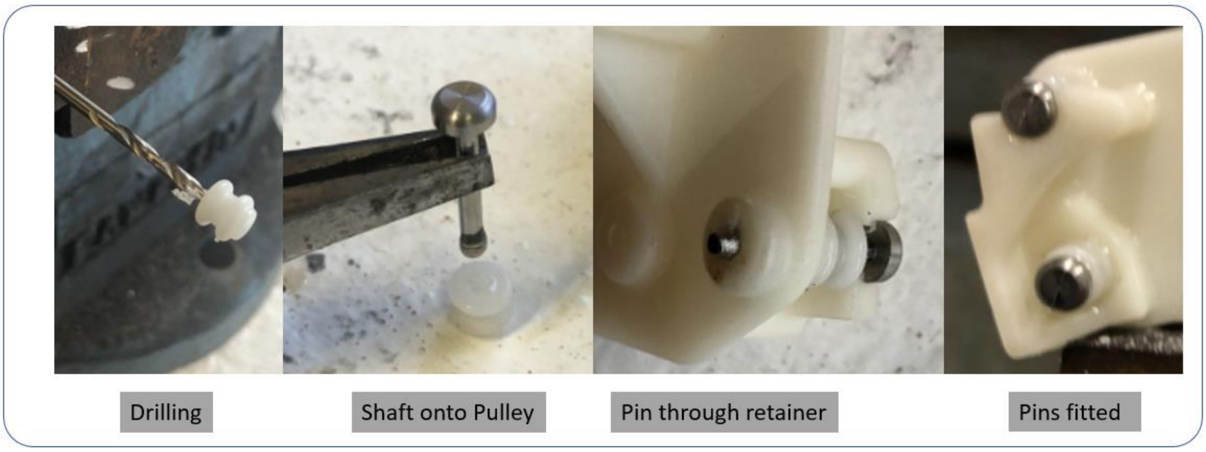


Figure 102 Fitting pins into retainer

In Figure 102, the various stages of fitting the pins can be observed. The end of the shafts was a little big and were cracking the pulley when passing through so the OD of the lip of the pin was reduced slightly.

The end of shaft and inside of pulley was oiled. The pin was gripped with a pliers and tapped through the pulley. The pins were then tapped through the pulley retainer and when fitted pulleys were a good rotational fit on the pin shaft with no frictional resistance.

5.3.2 Coil Housing

Long term for production it would be envisaged that the coil housing would be sent to the coil company and the coil would be fitted by them.

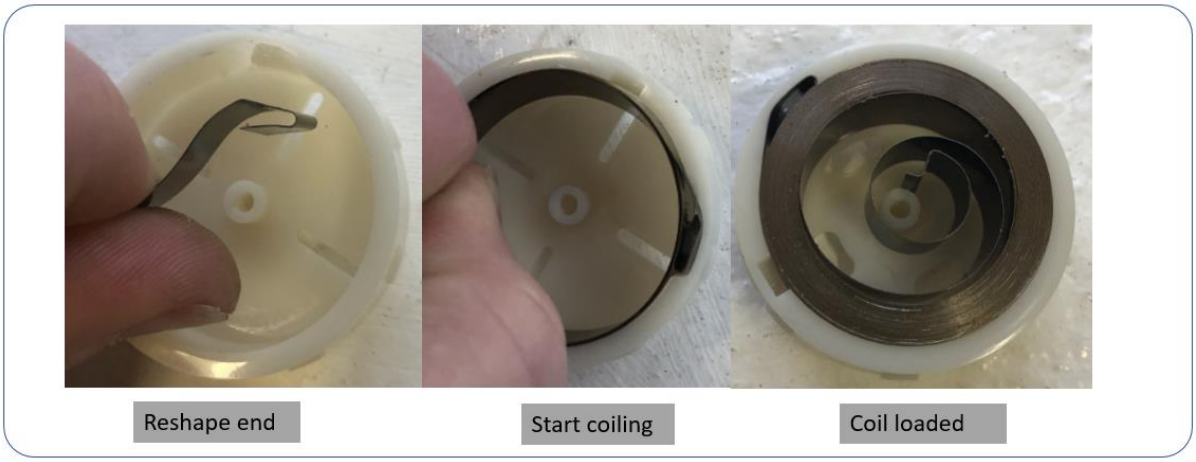


Figure 103 Loading coil

In Figure 103, the various stages can be seen. Initially the end of the coil was slightly reshaped to match the profile of the coil housing. The longitudinal shape of this spigot was strong in one direction. This was needed during working but not in the other direction, where it was thin.

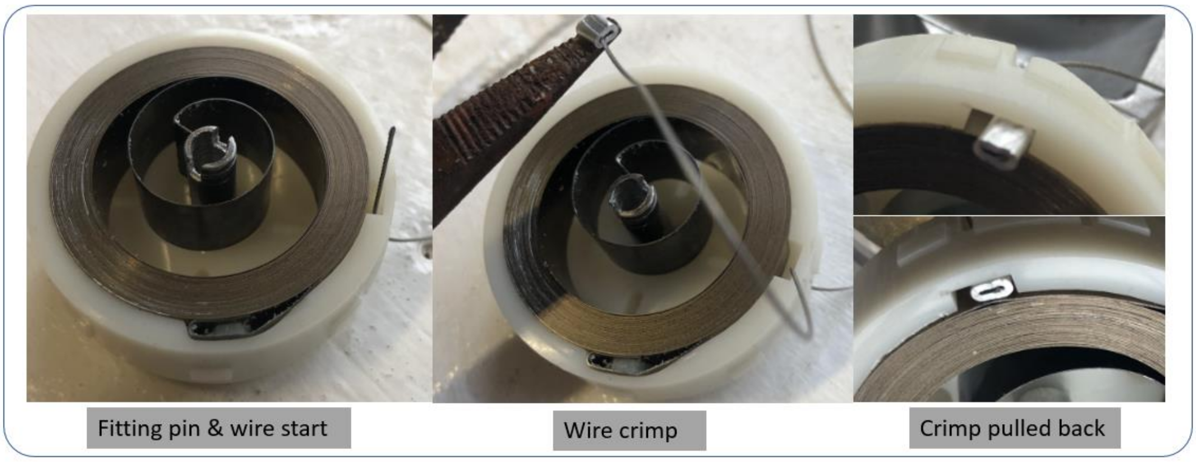


Figure 104 Fitting Pin and wire

In Figure 104, the pin can be seen fitted. This joint was an interference fit. The process of how the wire was retained inside the coil housing is also shown in Figure 104. Then a wire crimp is added to the end of the wire. When crimped the wire was pulled back through until it hit internal stop, this ensured wire would not come off outside of coil housing.

5.3.3 Joining coil housing and pulley retainer

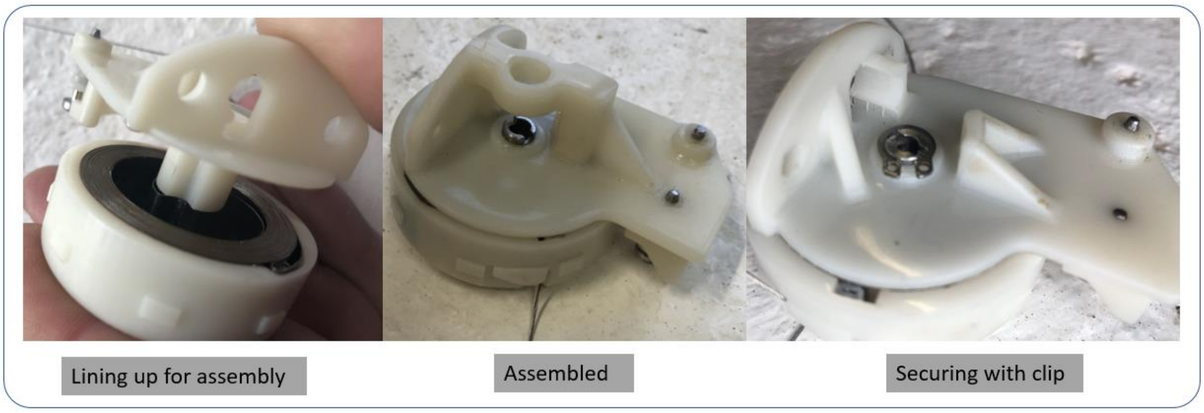


Figure 105 Joining

In Figure 105, the mating process can be seen. Once assembled it was checked to ensure it was running freely. The circlip was fitted at this point to ensure the parts stay together as the coil was being energised.

5.3.4 Fitting wire to outside of coil retainer.

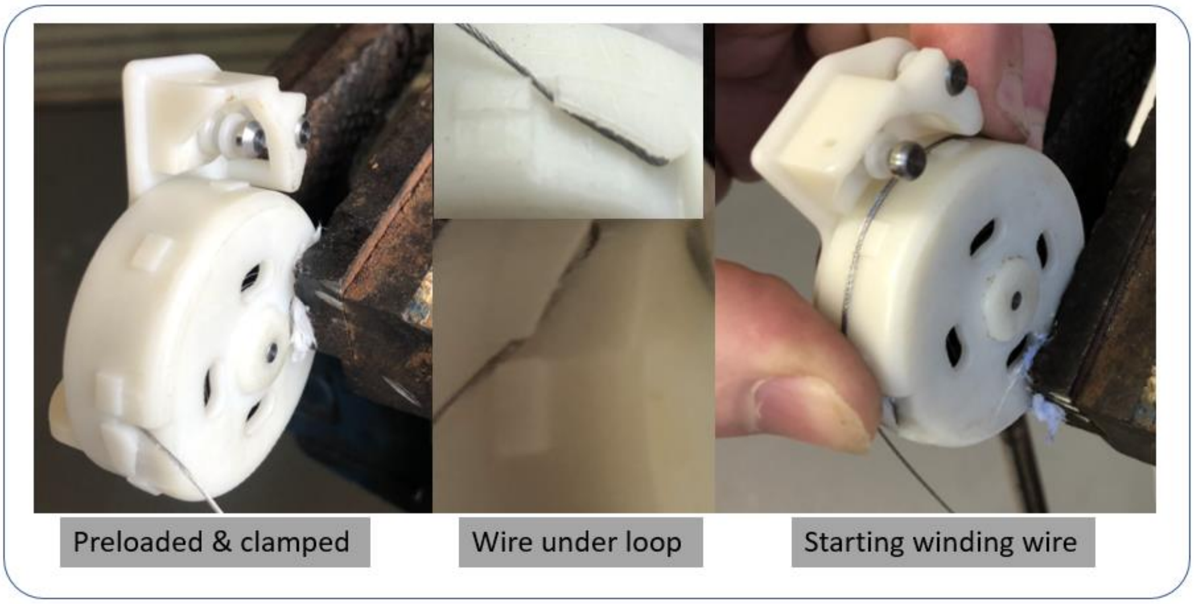


Figure 106 Getting wire started

In Figure 106, the initial steps can be seen. The wire is looped underneath the wire cap. After preloading the coil, and for ease of winding the wire, the two parts were clamped lightly in a vice.

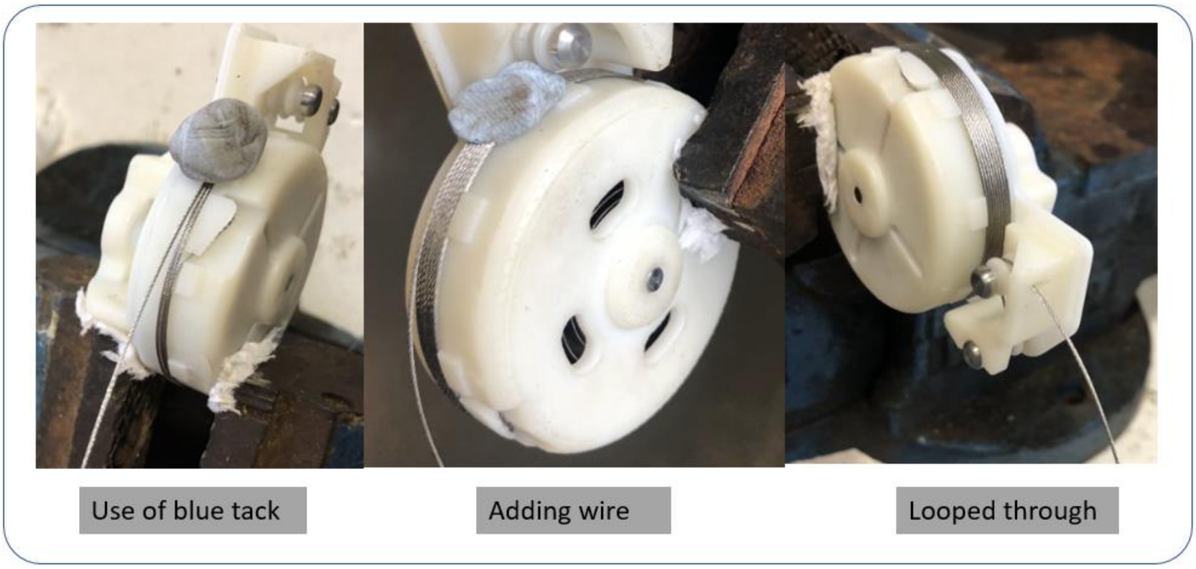


Figure 107 Adding wire

In Figure 107, the wire adding process can be seen. It was found that by adding blue tack to hold the wire in place after each added layer helped the wire stay secure on the coil housing. Without this the wire tended to come loose due to there being no tension in it.
When the correct number of revolutions for the stroke were added the wire was looped around both pulleys and out through the hole in the block support. It was then ready to add the second wire swage ring. Some extra wire was also allowed for the assembly process in the cylinder where the wire would be pulled out past the maximum stroke.

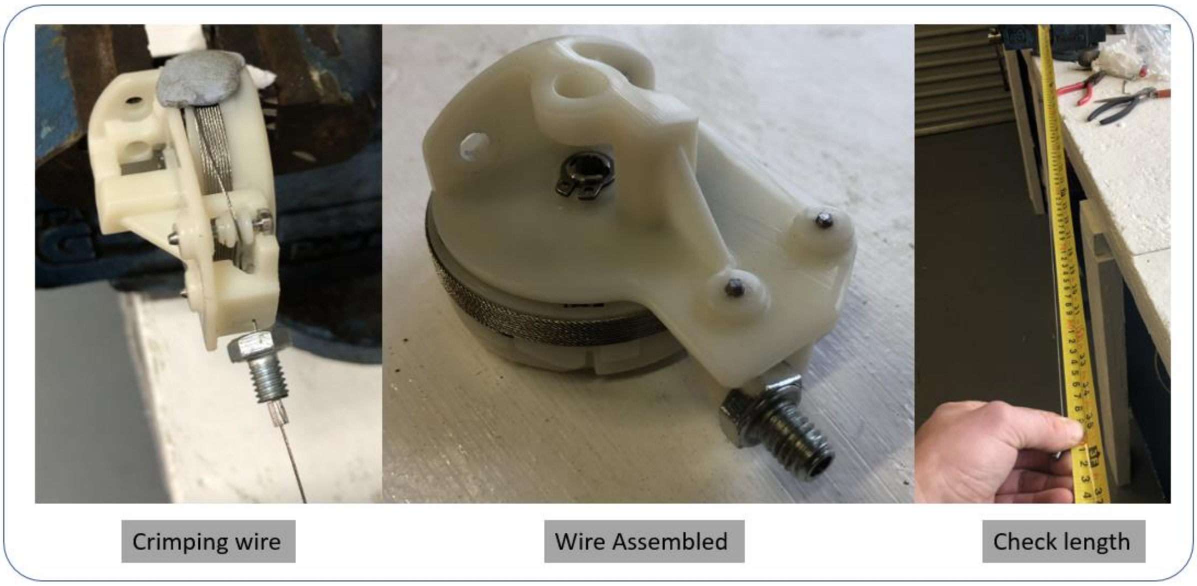


Figure 108 Adding nut

In Figure 108, the final process for securing the other end of the wire can be seen. The nut, with the drilled hole, is passed through the wire and a swage ring is added behind and crimped with a pliers. The end of the wire was then cut near the crimp. The crimped joint can be checked by pulling on the screw firmly to ensure the crimp was gripping the wire sufficiently.

The assembly can then be removed from the vice. It took about five full extension and retraction strokes for the wire to find equilibrium, run smoothly and for the twists and turns in the wire to be removed. When operating the wire always went back in side by side formation and ran smoothly with no wire overlaps on the coil housing. This was important for accuracy of the sensor output signal. The stroke length of the sensor can also be checked and verified at this stage.

5.3.5 Assembling Gears

At this stage the gears would be assembled into the unit. First the bevel pin was inserted into the assembly. It was then positioned so a gap was left for the cross over position where the worm gear would be passing over it. This can be seen in Figure 109.

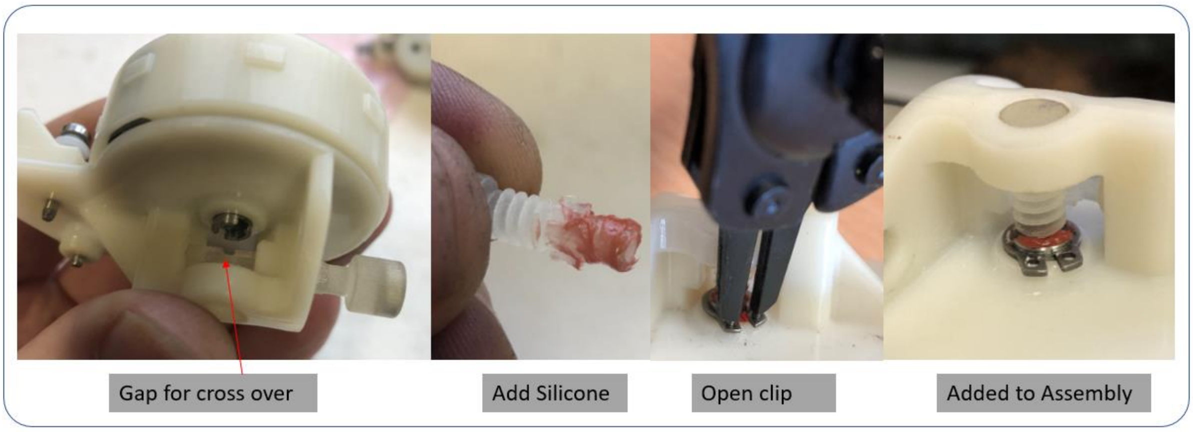


Figure 109 Adding gears

The worm gear was secured with the circlip as the primary mode of retention. As an additional security, heat resistance silicone was added to the end of the worn gear prior to assembly. For the final engagement a pinch of a circlip pliers was needed to open the circlip on shaft to allow the worm gear to slide through and engage with the groove on worm gear.

5.3.6 Joining to Aluminium body

The washer and the screw can be seen in Figure 110. The screws were lightly tightened by hand with an Allen key to get a firm grip equally each side, and then finished off by torqueing both screws to 8Nm. This would ensure consistency between the various assemblies.

Figure 110 Fasteners

In Figure 111, the assembly can be seen completed. Having it joined together also made it easier to hold and to pull the wire for checking to ensure final running was smooth and the gears were running correctly with no visual play. At this point some lubrication oil was added to the joints of the running parts to ensure no premature wear. When mounted in the cylinder these moving parts would be lubricated all the time from the hydraulic oil.

Figure 111 Joined to Aluminium body

5.3.7 Adding electrical components

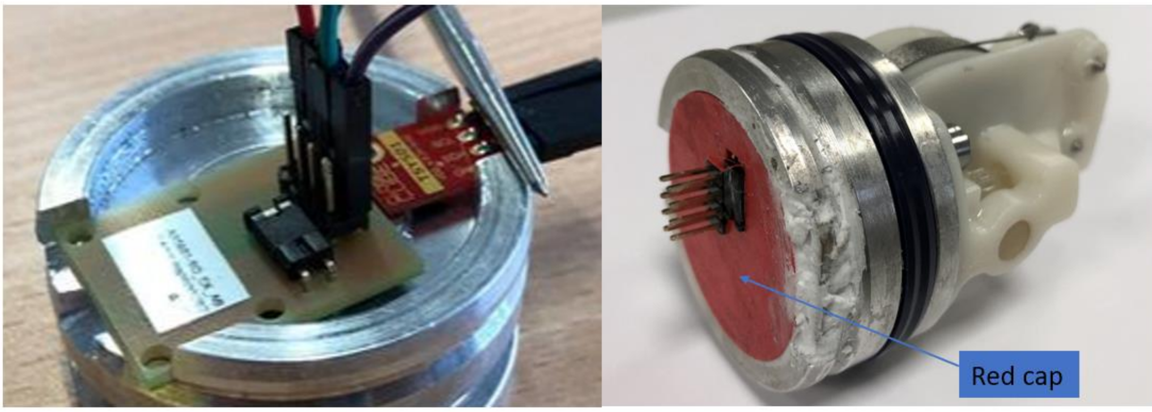


Figure 112 Electrical components

In Figure 112, the position where the electrical components would be situated can be seen. The aluminium body had a slot and a face to get an accurate sliding position in two fixed axes, with the final position being fixed with the sealing cap shown labelled red cap.

The board for the magnetic encoder was sealed with silicone to fix it firmly and negate any issues that would be presented in terms of vibration whilst working inside the hydraulic cylinder. There was also a recess without silicone to allow for the temperature sensor to be inserted after positioning the sensor inside the cylinder base.

The hydraulic seal can also be added during this time. The seal chosen was a one-piece polyurethane static seal that meets modern demands in terms of aggressive biodegradable hydraulic oils present in the mobile hydraulic market today, (Heney, 2016).

5.4 Building of Test Cylinders

5.4.1 Dry operating Prototype

To test the sensor in a similar working environment to that in a hydraulic cylinder, a dry test cylinder was designed and constructed. To ensure free moving of parts by hand, the seals were left off.

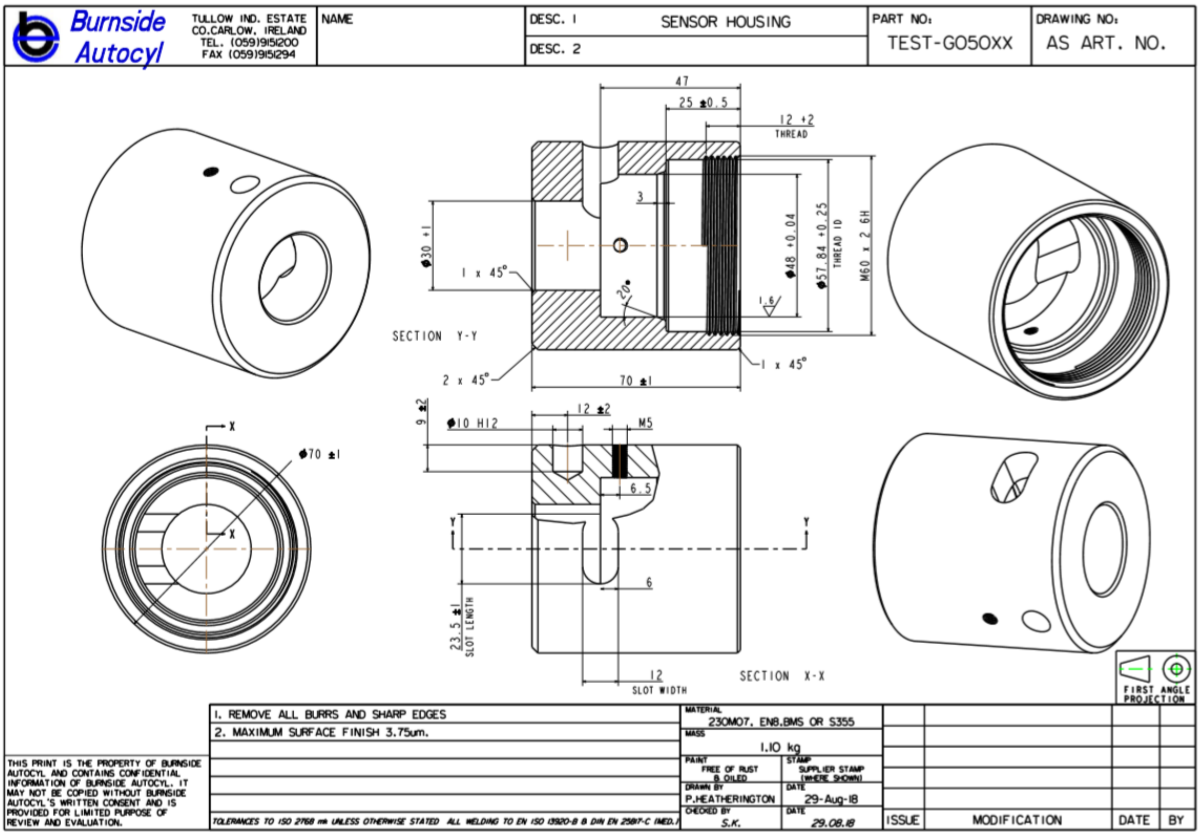


Figure 113 End Cap

The first cylinder part used was the end cap in Figure 113 to accommodate the sensor assembly. There was a 12mm slot machined into the side 23.5mm long. This was to allow the temperature sensor to be slid in from side once the sensor was inside the end cap.

To connect to this end cap, a tube was machined. The machining can be seen in Figure 114. The idea was to test the sensor in the smallest possible tube, that the sensor would fit inside, which was Ø50mm bore tube, to prove it would work. Some extra machining was needed on the inside of the tube to take a wire ring and a spacer to act as a stop so the piston head would not impact upon the sensor.

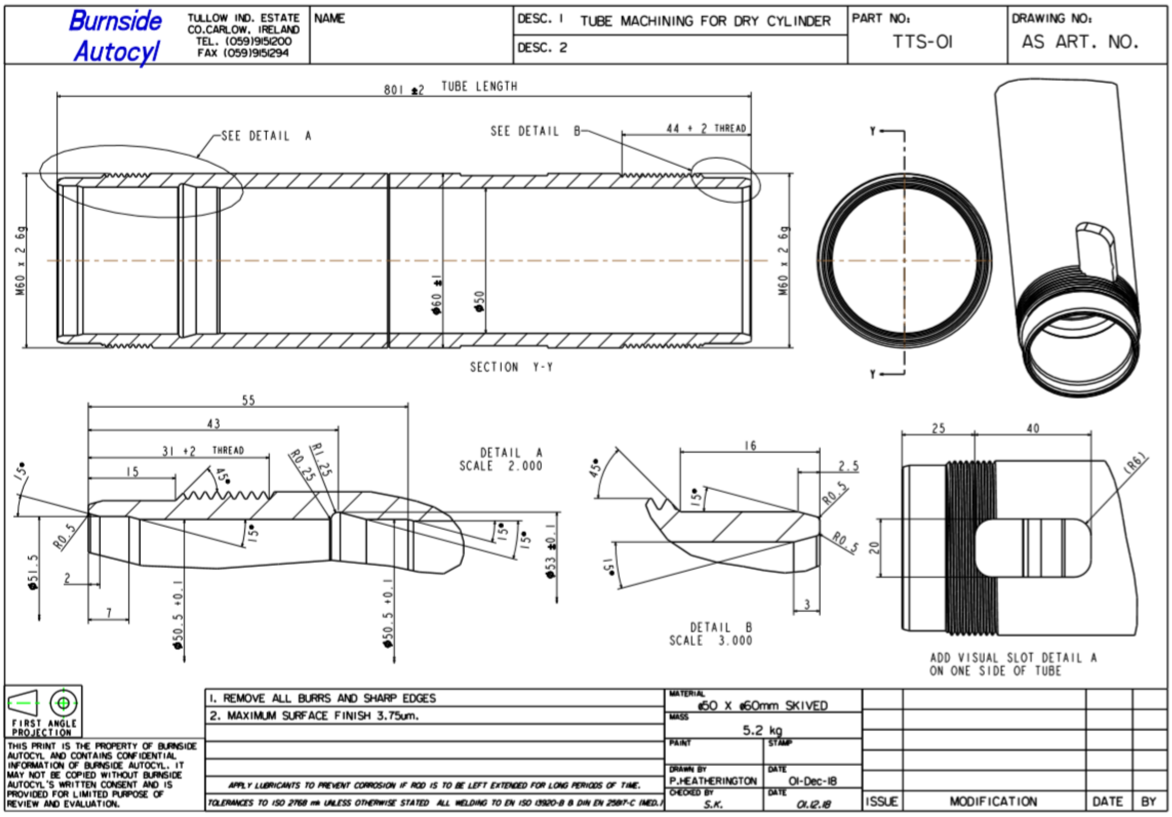


Figure 114 Tube machining

The rod was machined as shown in Figure 115. The end sticking outside the cylinder was just chamfered to remove the edges. The other end was machined to receive a piston head. The piston head locks on the front shoulder in 42mm as dimensioned in Figure 115.

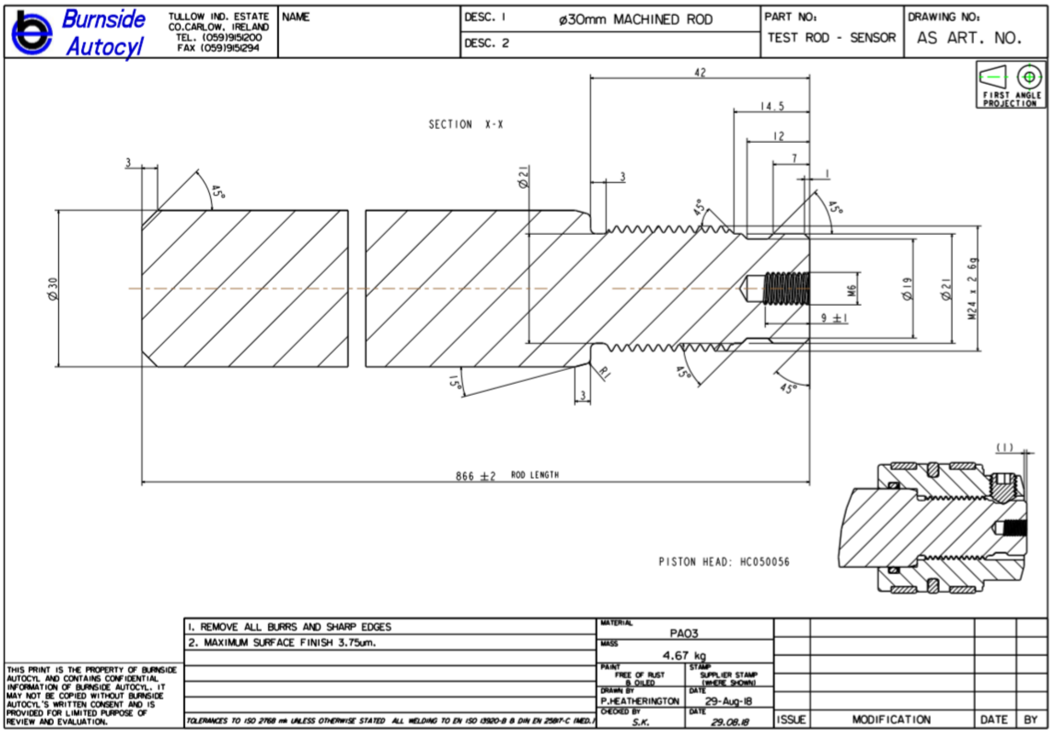


Figure 115 Rod machining

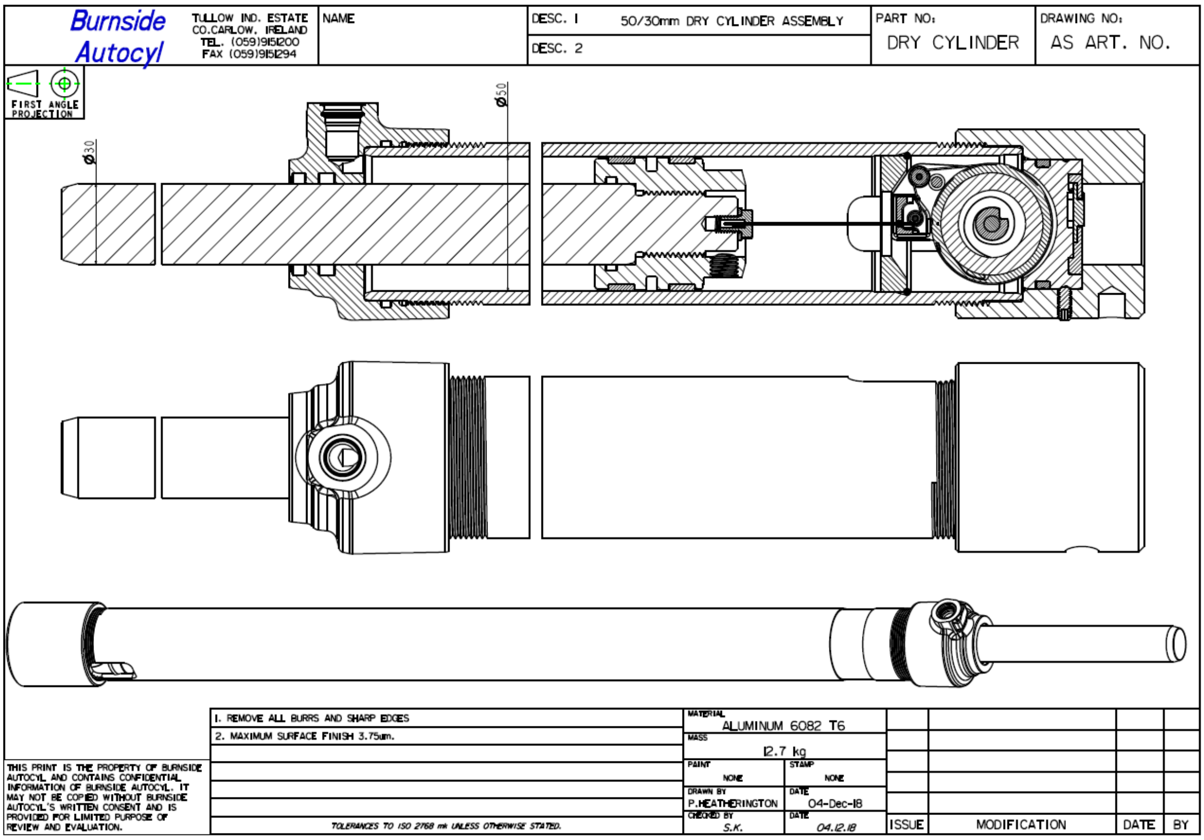


Figure 116 Dry Cylinder assembled

The dry cylinder assembly can be seen in Figure 116. To attach the screw on the end of the sensor to the rod assembly the rod was tapped internally M6. For the gland and piston head standard components were taken from stock in Burnside.

To allow free movement of the rod by hand no seals were fitted to the gland. For the piston head only the wear rings were fitted to provide guidance, but no piston seal. This ensured easy movement by hand so tests would be conducted easily.

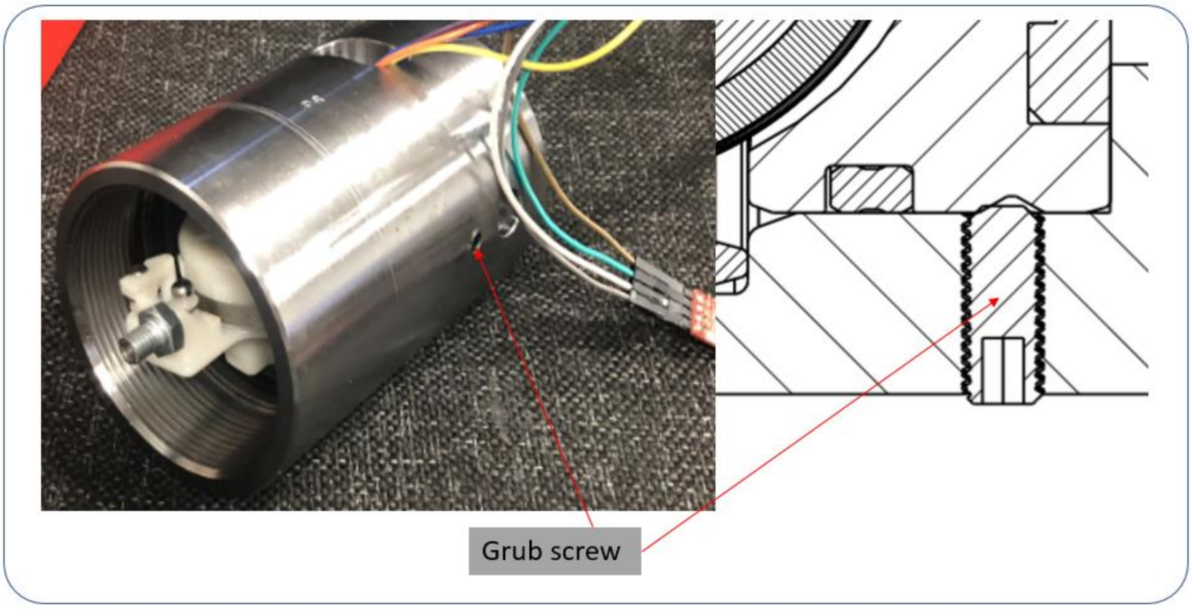


Figure 117 Sensor into base

For first assembly the sensor was inserted into the base and wires were fed in through the slot on the side. The sensor was then secured with a grub screw in the base so the sensor would not rotate or come out. The screw was a M5 Din 913 screw and was torqued to 5Nm. This is shown in Figure 117.

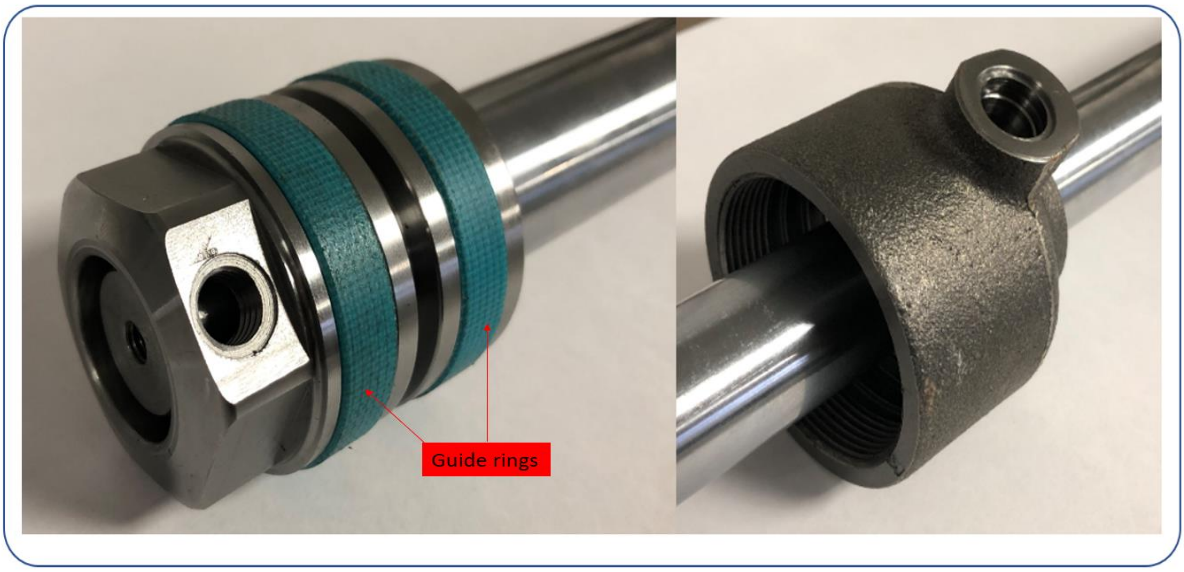


Figure 118 Assembling Gland and Piston

Then the piston head was fitted with two bearing rings as shown in Figure 118,the guide rings labelled.

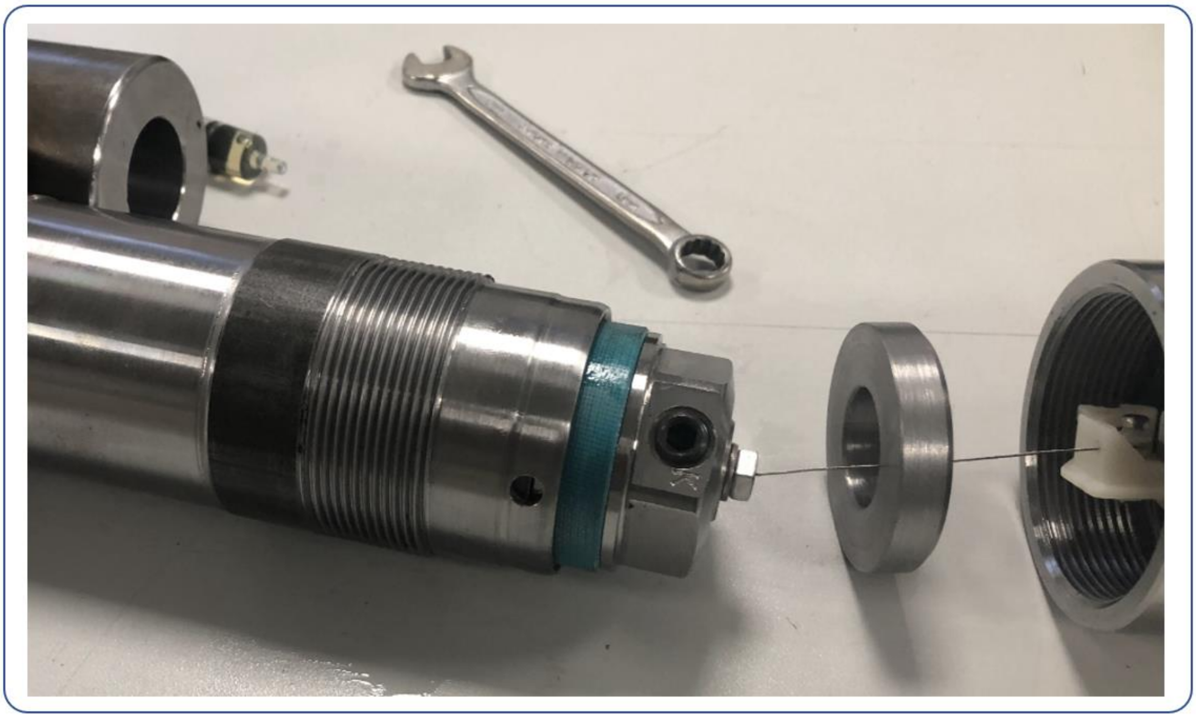


Figure 119 Assembling sensor

For initial assembly, the sensor was placed beside the cylinder as shown in Figure 119. The piston head was moved just outside the tube and the wire pulled out of the sensor. The M6 screw with washer was then attached to the back of the rod. Loxeal 24-18 was applied to the screw to prevent it coming loose during operation.

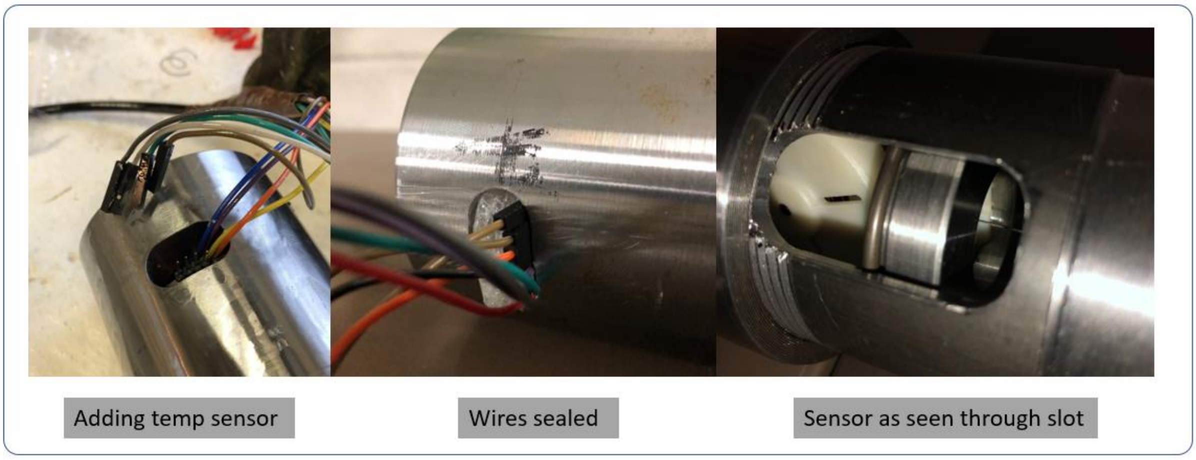


Figure 120 Adding temperature sensor

The end cap was screwed onto the outside of the tube. Care was taken to twist the rod assembly at roughly the same rotational speed as the end cap was being twisted onto the outside of the tube to avoid twisting of the wire of the sensor. The temperature sensor was fitted inside the sensor assembly through the slot. For these basic functional tests, the wires were held in place with some bubble wrap.

The viewing window can be seen in Figure 120 on the right. This offered a full visual window when the sensor was operating to ensure all the moving parts were operating as required.

Figure 121 Sensor and dry operating cylinder assembly complete

The complete sensor assembly and test unit can be seen in Figure 121.

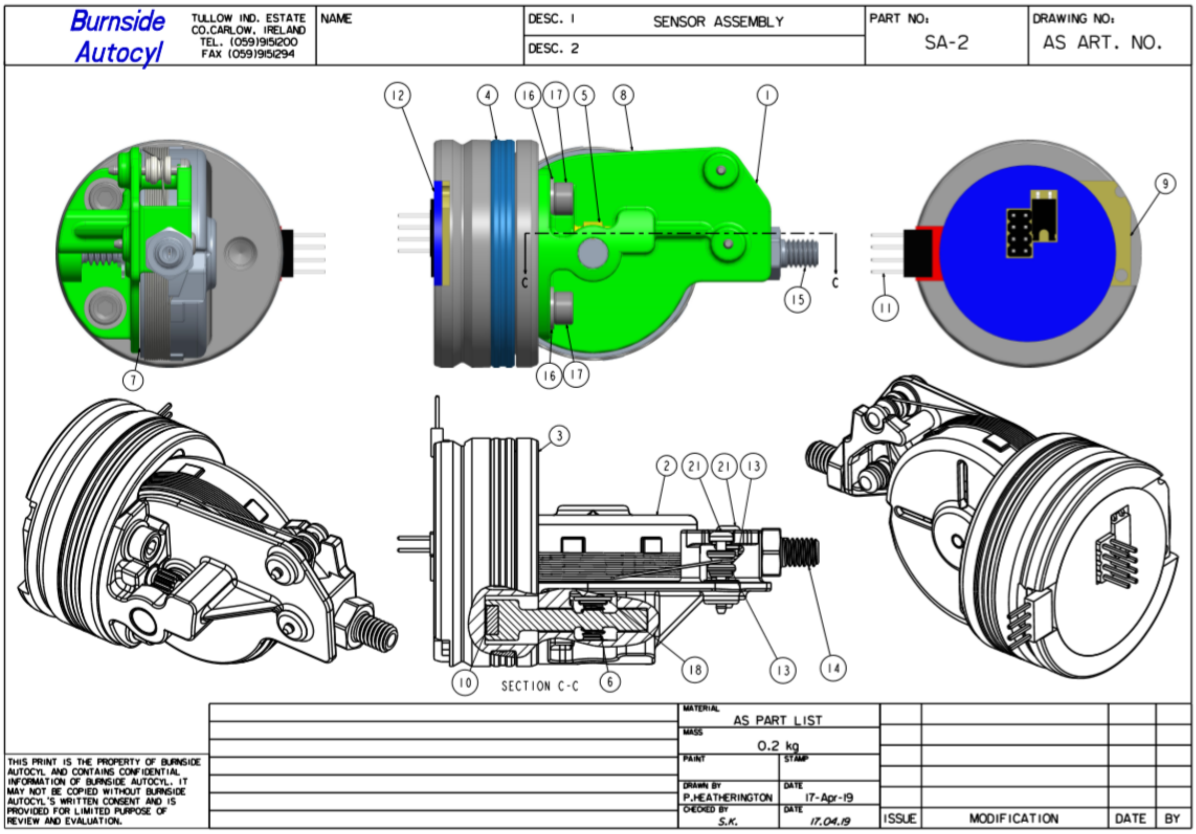


Figure 122 Final sensor assembled

In Figure 122, the final assembly drawing can be seen with all the parts assembled together.

5.4.2 Pressurised working cylinder

For the pressurised cylinder version, it was decided to build a longer cylinder with a 1000mm stroke. The tube was machined as before, but this time was longer and didn't have a viewing slot in the side of the tube. The cylinder assembly also needed to have all the hydraulic seals in place in the components and pressurised ports on each end to allow cylinder to be operated by hydraulic oil. The machining drawing for the longer tube can be seen in Figure 123.

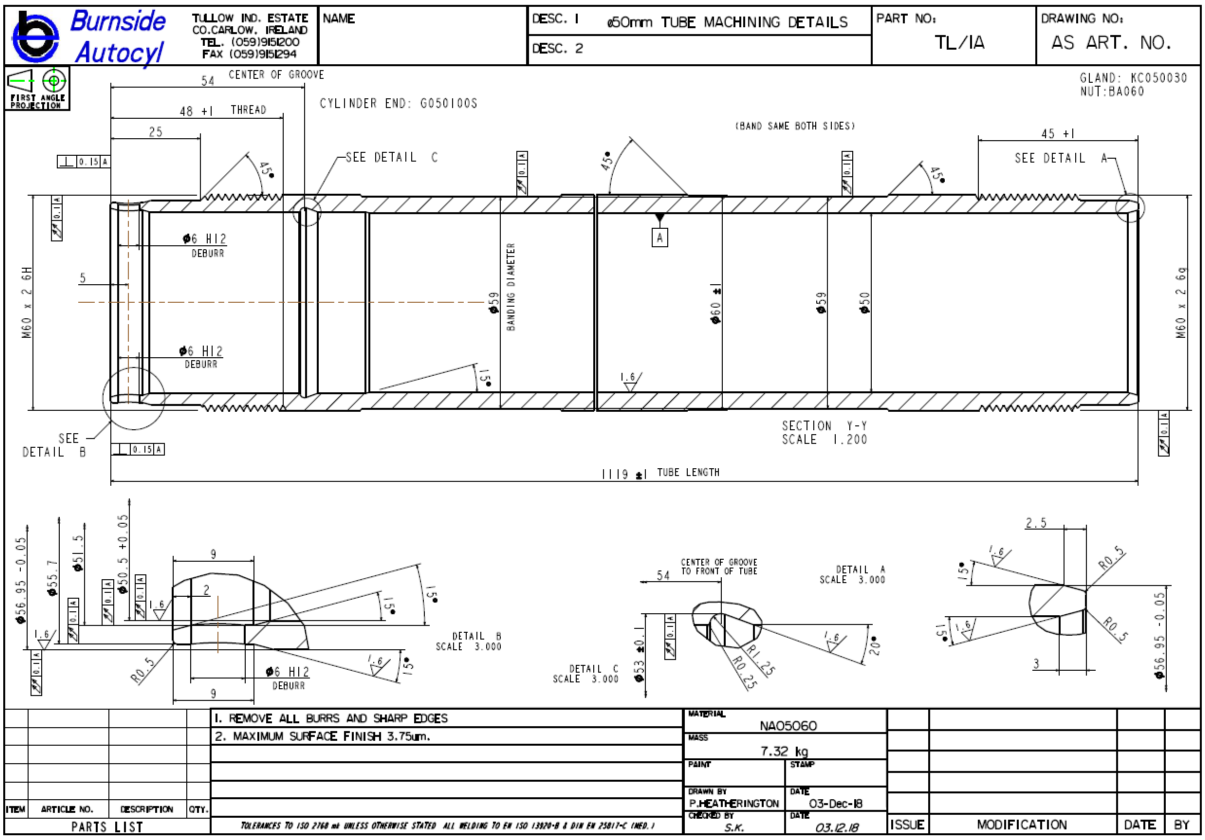


Figure 123 Long machined tube

Two Ø6mm holes were drilled in the tube to power out the cylinder with hydraulic oil. There was a port welded to the screwed cylinder end. There was a gap all around the circumference of the tube to allow oil in through the hole of the tube no matter where the cylinder end ended up when fully tightened. For first instance as a random outcome the hole lined up with each other as shown in Figure 124.

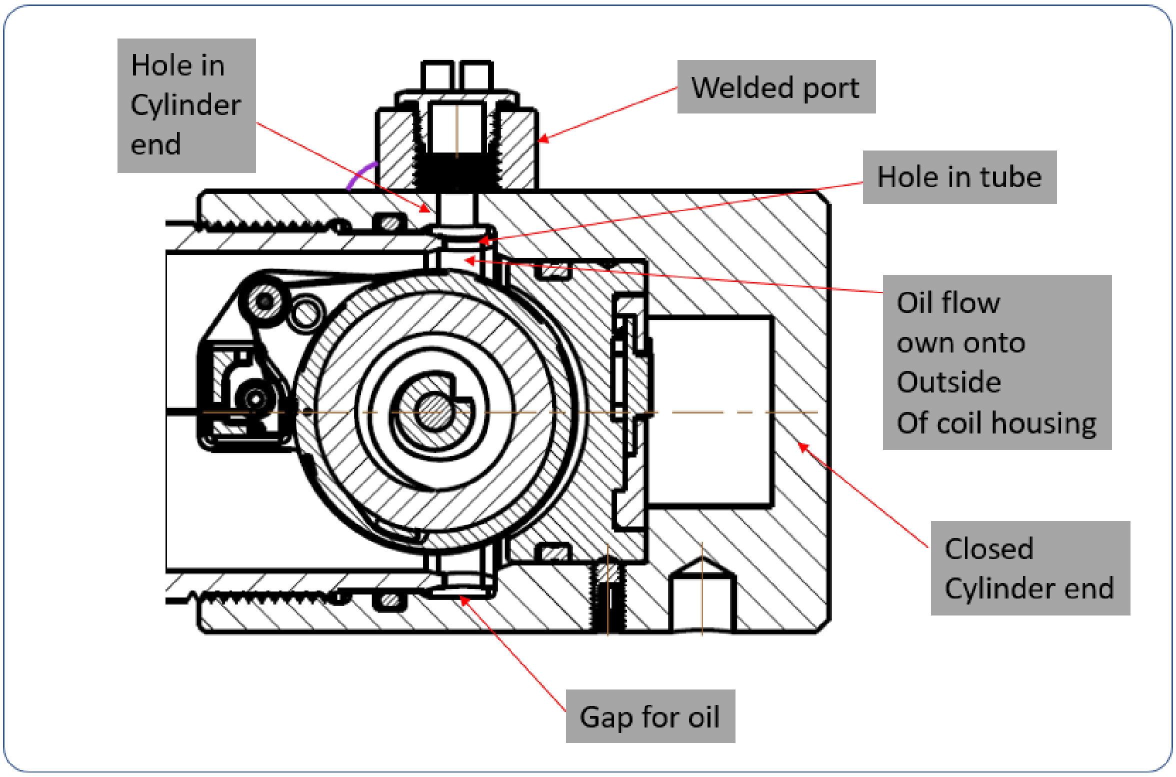


Figure 124 Cylinder end features

The rod was made the same as before only longer, this time the overall length was 1180mm over previous 866mm long and there was a 7mm long x 15° chamfer added to aid loading rod seal onto the rod. The assembly drawing as was planned is shown in Figure 125, sheet 1 of 2. The stroke of 1000mm can be seen along with all the hydraulic sealing to contain hydraulic pressure within the cylinder.

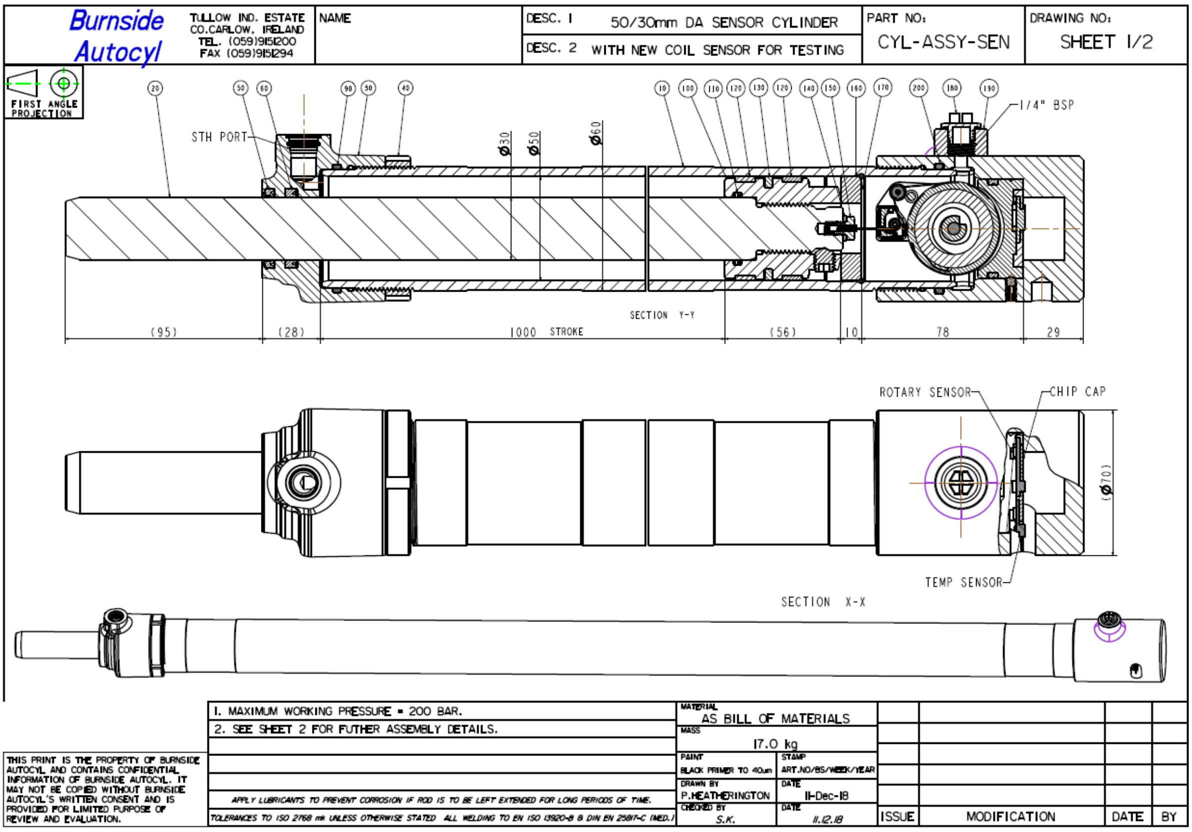


Figure 125 Assembly Pressurised Cylinder

There were some assembly instructions created showing the correct procedure on how to assemble the end cap containing the sensor into the tube assembly. The assembly instructions can be seen in Figure 126. This would make it easier to conduct repeat assembly for future assemblies and avoid potential omissions or incorrect sequence of assembly.

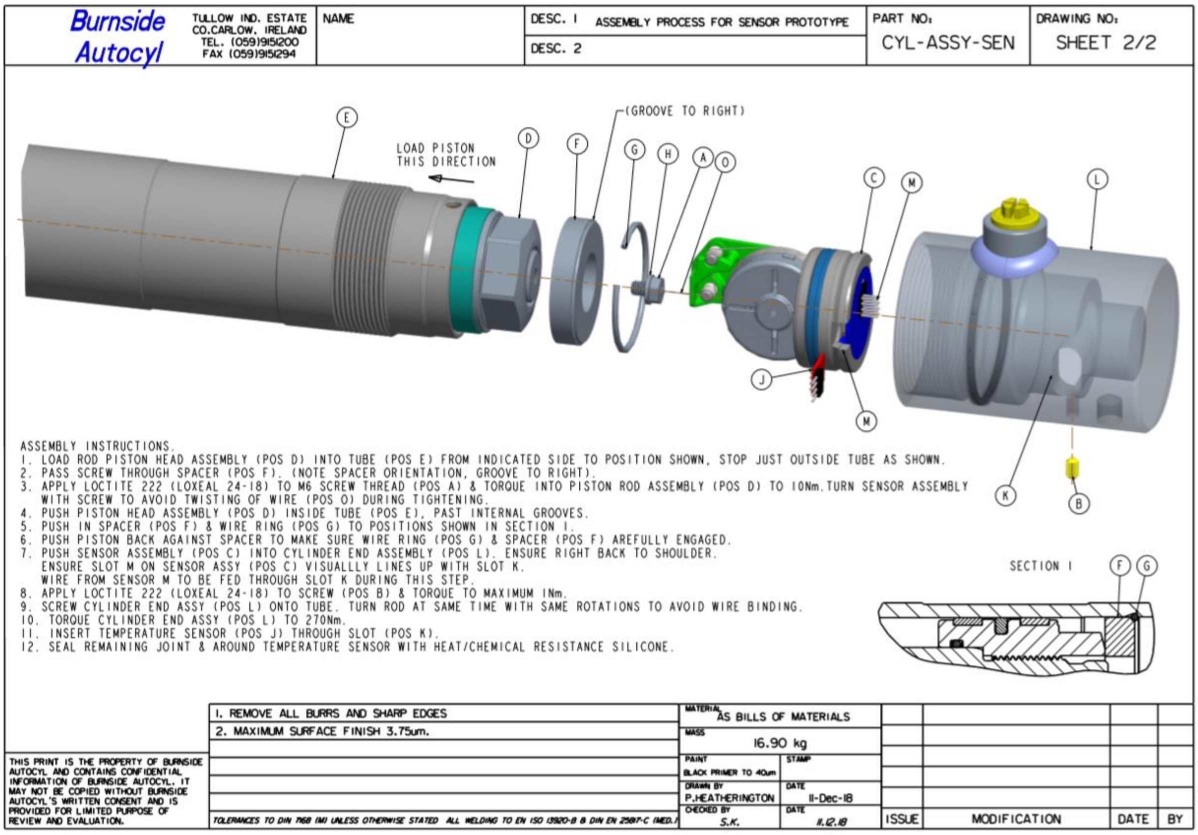


Figure 126 Assembly Instructions

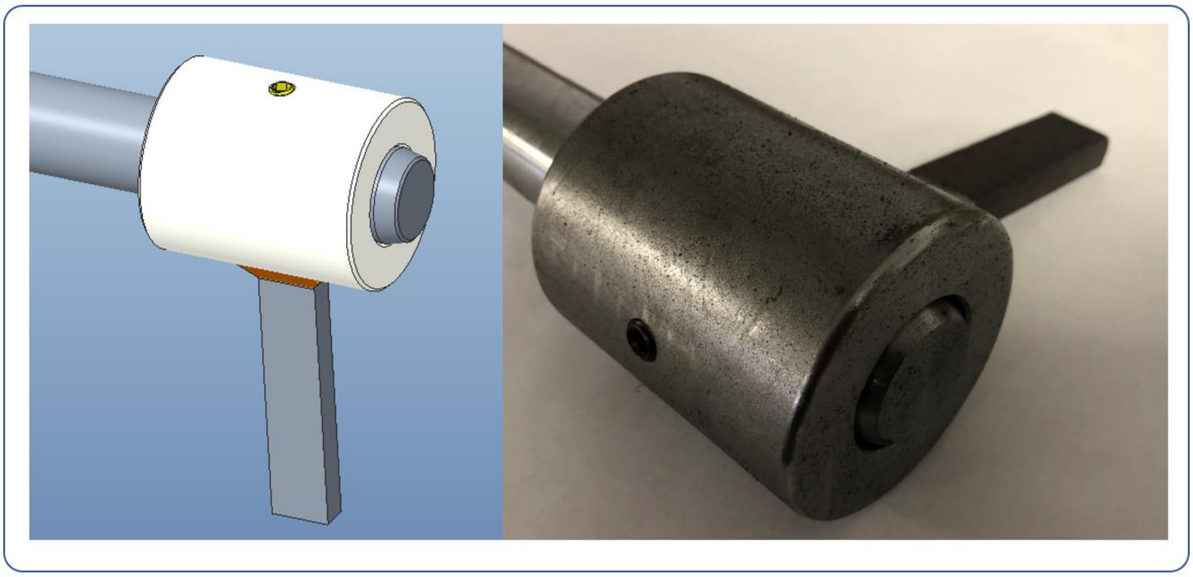


Figure 127 Adding spacer to rod

The natural tendency is for a rod to turn when operating inside a hydraulic cylinder when unconstrained. Normally a cylinder would have a weld on eye connected to the machine to prevent the cylinder rod from rotating. In this case the cylinder would be operating freely. To avoid rotation of rod and possible binding of the wire in sensor a spacer with offset a weight was added. This was secured to the rod with a grub screw. The weight would be facing down and prevent the rod from unwanted rotation.

5.5 Streamlining assembly process.

During the first few assemblies the assistance of two other people was required to assemble the cylinder. This was because it was tricky to screw on the end of the sensor attached to the rod and ensuring the wire did not recoil or lose preload tension during the assembly process.

To simplify, the assembly operation a modified spanner was made to hold the screw secure. There was a slot cut out to allow the wire to pass inside the spanner. At the back a welded stop was added. This would allow the hexagon of the screw to be held inside for tightening. The stop meant that the wire would be pulled with on with one hand and attached to the end of the rod easily.

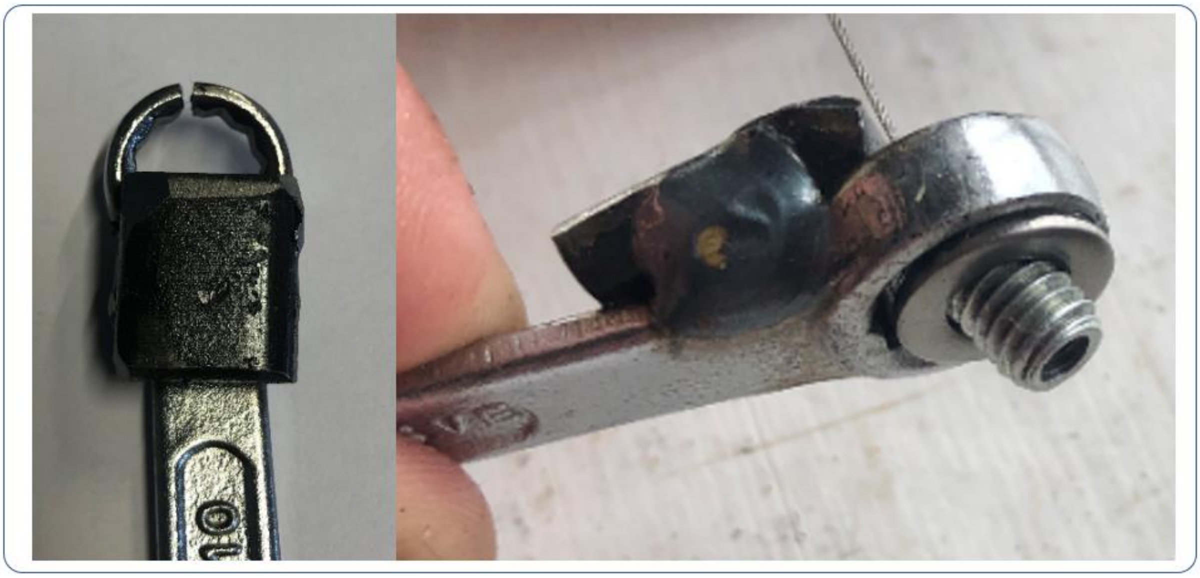


Figure 128 Modified Spanner

The second issue was the assembly process setup as shown in Figure 119. It was tricky to get the piston head to the end of the tube and attached all the bits with a one-person assembly process. A new way was needed. The new streamlined way is shown in Figure 129.

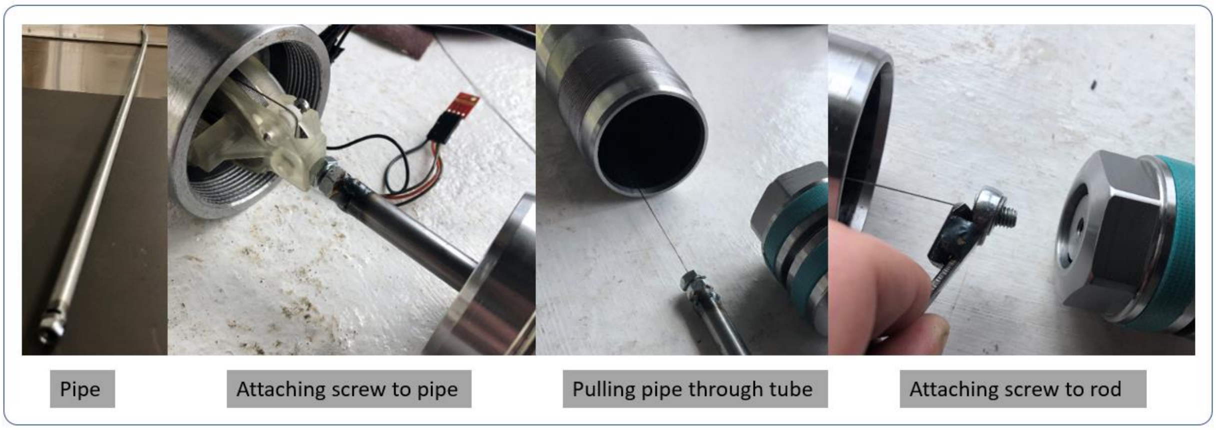


Figure 129 Pull through tool

A long pipe was made to pass all the way through the tube. At one end of the pipe a nut was welded for connection of the sensor screw. Then the pipe was pulled all the way through the tube until the screw and nut was visible. The modified spanner would be attached behind the screw and loosened from the pipe. The piston head was located just in front and would now be attached easily.

6. TESTING

6.1 Dry operating prototype

Movement by hand was quite easy and smooth with no jerky operation. The test unit would easily be connected and disconnected from the cylinder with the 4 quick release pin connection. Once the programme was uploaded to the Arduino inside the test unit it would be turned off with the switch when the test unit was not in use. When switched back on the Arduino would upload the programme in memory and was operational within a few seconds.

When the gears were tested for the first time it was not possible to get them to mesh accurately. The level on concentricity required on the bevel pin was not present. The OD of the bevel pin was guided inside the aluminium body, but this was not giving the guidance necessary to function as intended.

It was thought that by adding a support web on the opposite side of the gear this would allow for better guidance and the concentricity required to allow gears to mesh properly. This can be seen in Figure 130. There was also a raised plinth added to give more stability around the shaft area. This was added as an alternative to the washer in front of the circlip.

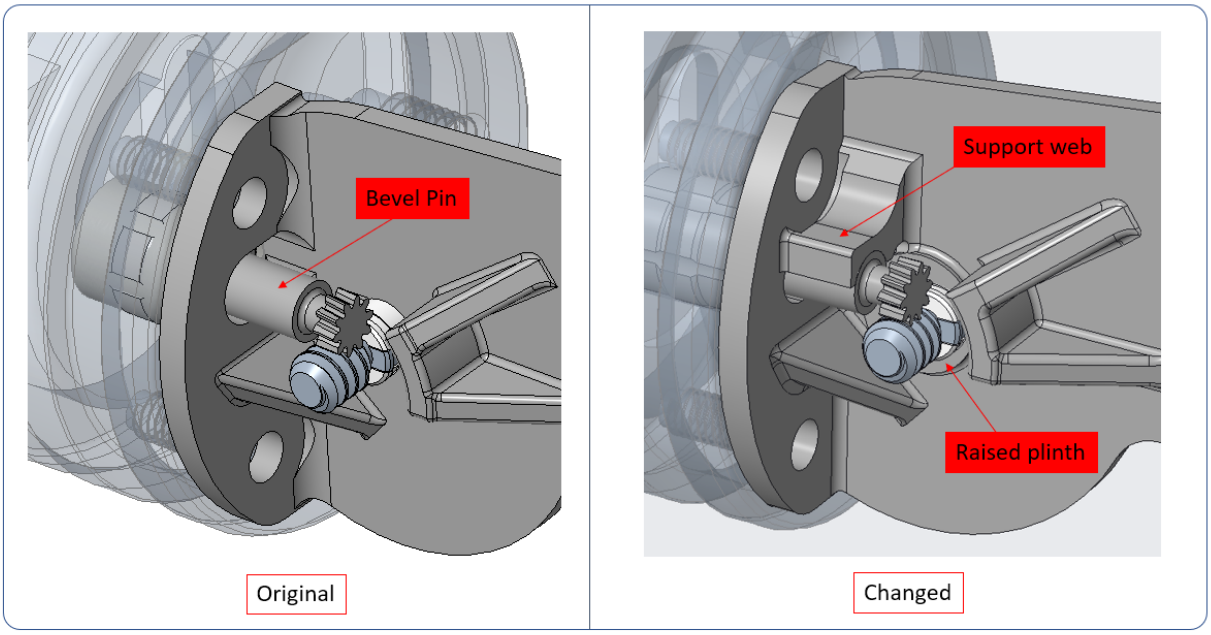


Figure 130 Guidance added for pin

It was found that even after modification, this support did not offer the guidance required so a major overhaul was required. There were problems getting the gear joined to the pin running concentric. It was decided to remove guidance off the bevel pin as from within the aluminium housing and make this a clearance fit so there was no contact on the diameters.

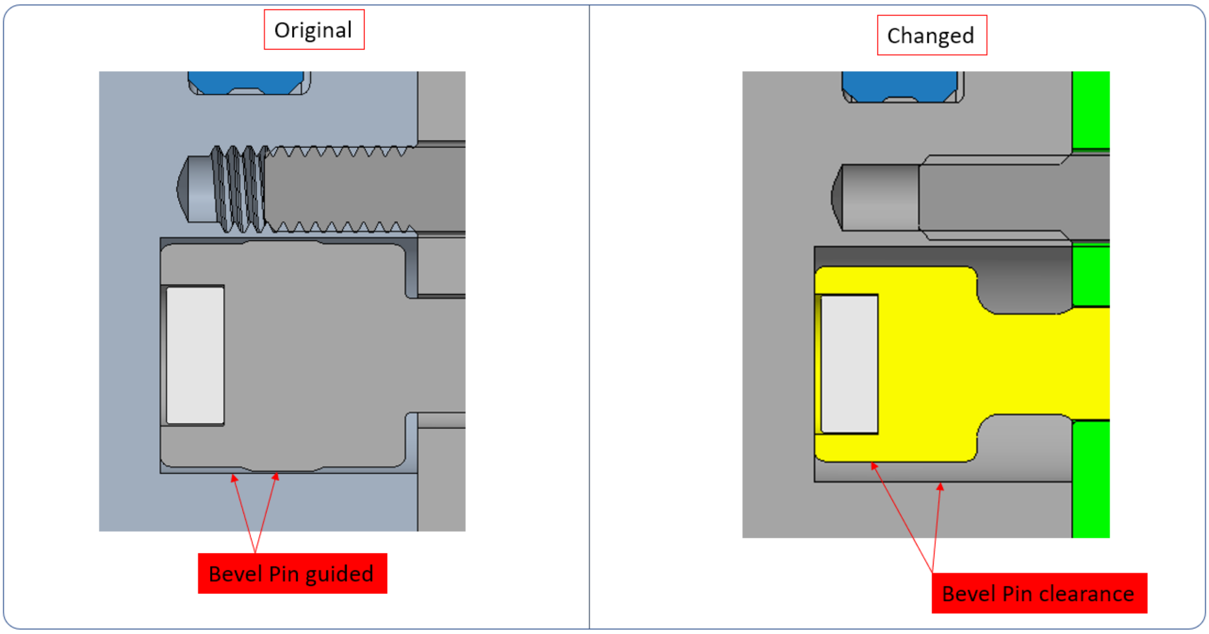


Figure 131 Guidance of bevel pin

The change can be seen in Figure 131, showing guidance inside the aluminium block and showing the clearance added. In the original design guidance was by the aluminium housing. This meant the pulley retainer had to be precisely located by hand to ensure that the gears meshed properly yet, even with proper care and attention, accurate meshing would not be achieved. The clearance would allow gears to be guided purely by one part the pulley retainer. It was decided both worm gear and bevel pin would need guiding on both sides of the meshing gears within the one part to ensure repeatability and concentric running of both parts.

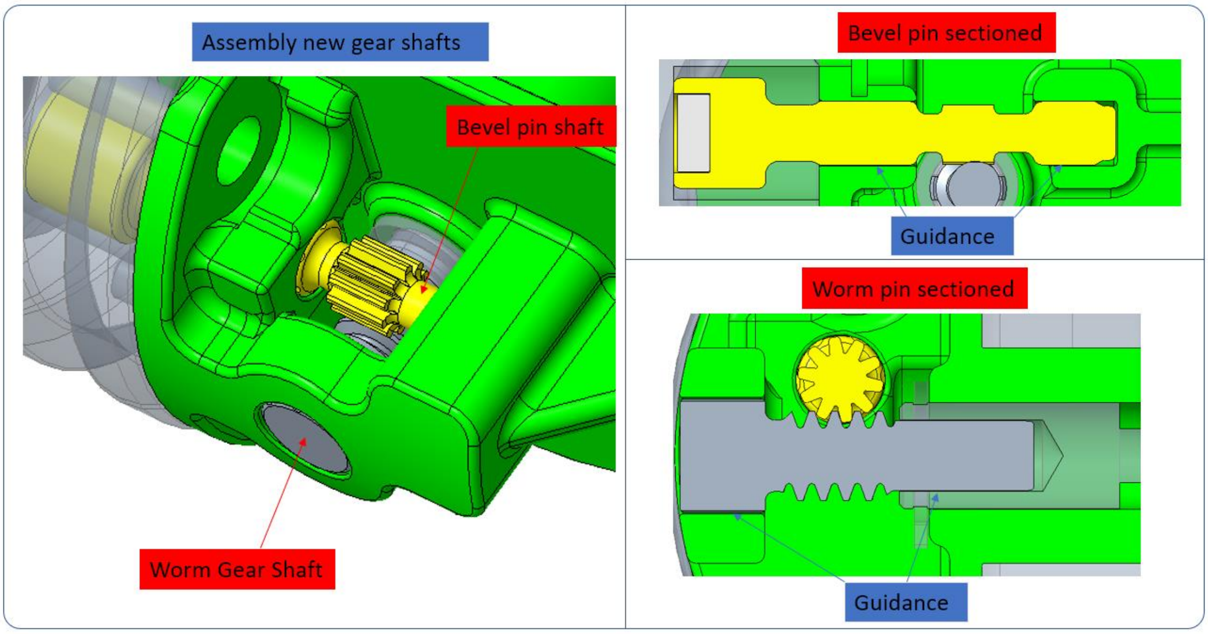


Figure 132 New gear shafts

In Figure 132, the newly designed gear shaft assembly can be seen. The design required the pulley retainer to be changed. This would allow full guidance of both shafts at both sides and allow for precise positioning of gears when meshing together.

For the assembly, the bevel pin would be inserted before it was attached to the aluminium housing. There would need to be a dead stop on the coil housing to position the bevel pin longitudinally and would be controlled with the machined depth of the hole in the aluminium housing.

For the worm gear, one end of the pin would be positioned inside the shaft. The other end would be guided in a diameter inside the pulley retainer. The worm gear would be retained by a partial circlip groove shared with the shaft groove. Additional security and retention for the worm gear would be with heat resistance silicone where it mated inside the shaft.

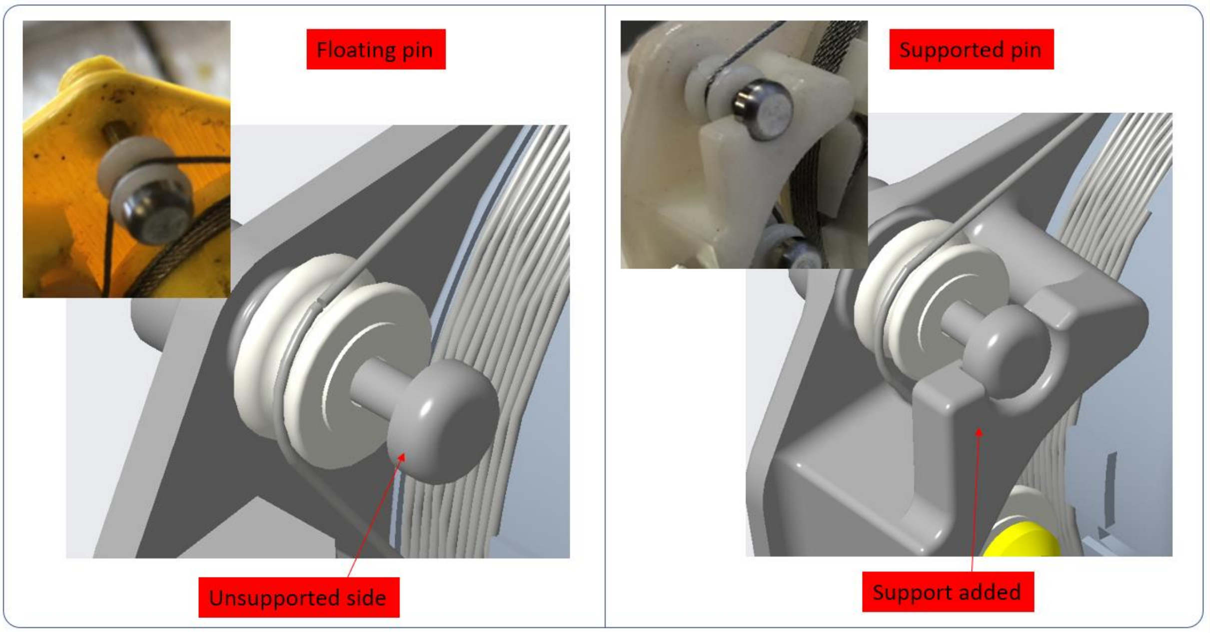


Figure 133 Floating pin redesign

In Figure 133, the floating pin was left unsupported. It was thought that if a good guiding length on a bore inside coil housing, along with a lip to prevent the pin coming out would be good enough to support the floating pulley. However, upon building it was found that the coil spring pulling on the wire dragged the pulley inwards and therefore the pulley did not run smoothly.

To prevent this from happening a support was designed onto the pulley retainer. This additional feature absorbed the side load and made sure the pin remained square with pulley retainer and pulley travelled across smoothly with the wire to guide wire repeatedly onto the outside of the coil housing. The redesign was successful.

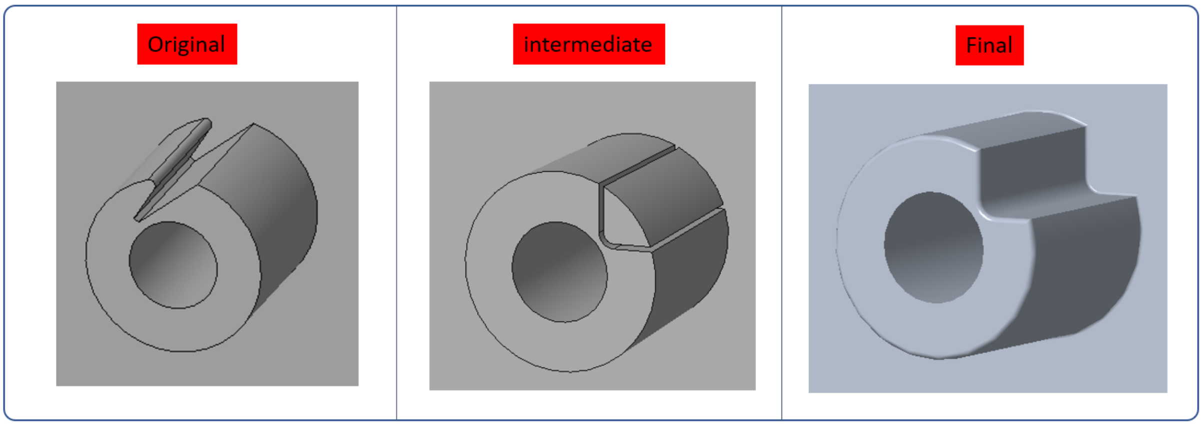


Figure 134 Coil pickup Internal

From testing dry prototype, it was necessary to improve the guiding of the gear components in relation to one another. The difference between the original gears and the newly designed ones can be seen in Figure 135.

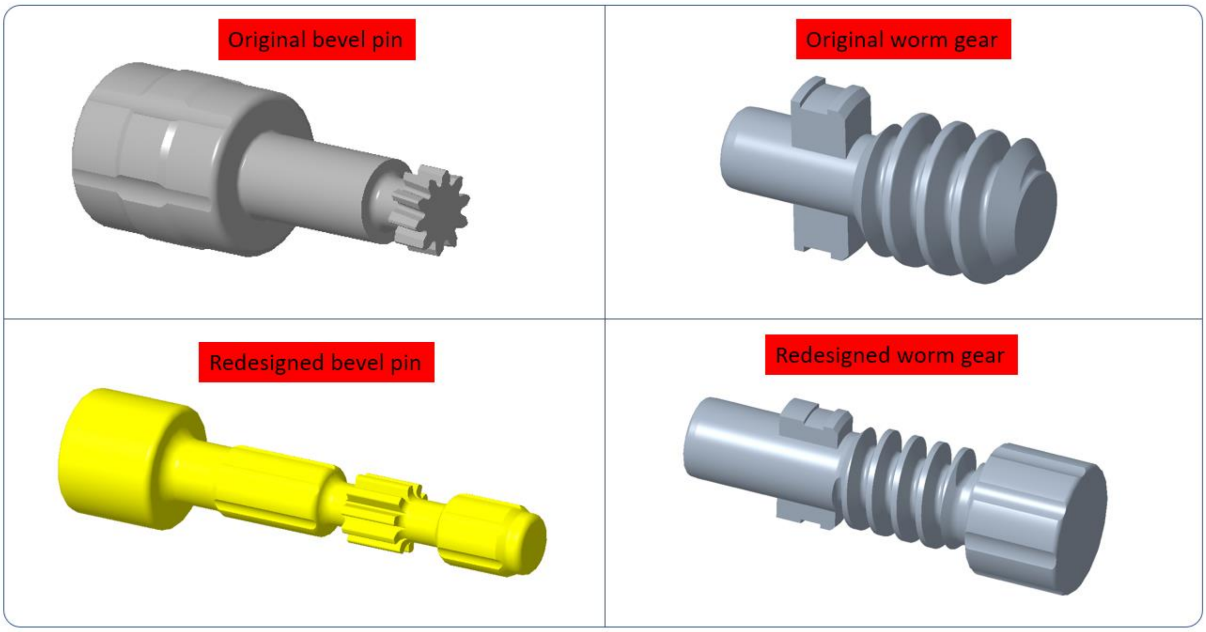


Figure 135 Gear redesign

The design and meshing intent remained the same as originally envisaged, just the guidance elements changed. The new design worked very well.

The circlip securing feature can be seen on the outside of the worm gear. This ensures once positioned in the assembly, it was secured, and not able to move out. It was important that the fit in the mating parts was free running and the length of the bevel pin was such that there was no linear motion only rotational motion. Long term it was envisaged to get these parts either injection moulded or machined from stainless steel.

When initially assembled and the programme was uploaded there was random outputs given on the display for the stroke, voltage and current outputs, so the sensor had to be calibrated to give actual required outputs. Long term this would be done by a dedicated programming tool. For prototyping the programming features of the Arduino were used to simplify and to allow infinite reprogramming for calibration as required. The AS5061 chip only allowed 3 times for zero positioning when done directly through the chip which would be fine for production purposes.

Figure 136 Measuring Cylinder

6.2 Pressurised working cylinder

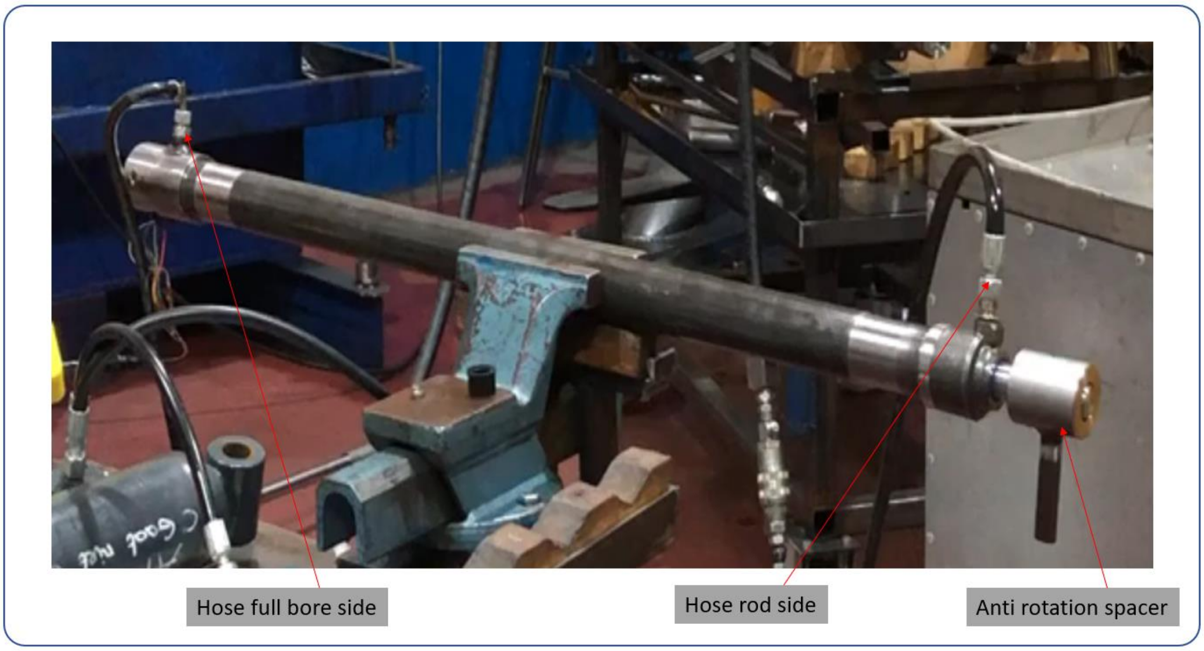


Figure 137 Cylinder mounted for testing

When the cylinder was assembled it was brought out to the R&D area and connected hydraulically to a power pack, one hose for each side as shown in Figure 137. The power pack would be worked manually to hydraulically move the rod in and out or set to cycle automatically so when the cylinder reached end of stroke, the power pack sensed a build-up of pressure and switched over to move the cylinder in the opposite direction. This was achieved using a hydraulic change over valve.

There were many failures initially and it was hard to pinpoint the actual cause of the failures. What was happening was the wire was being pulled out of the swage inside the nut connected to the rod. This happened a few times after a few cycles. Two of the failures when dismantled can be seen in Figure 138.

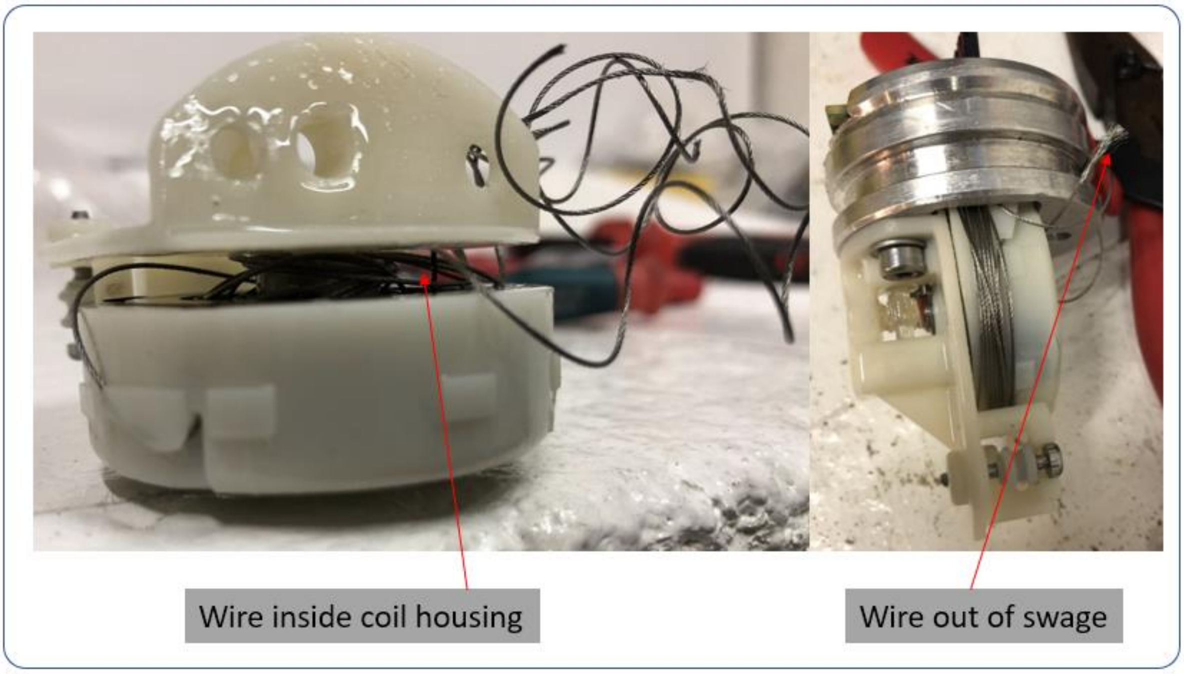


Figure 138 Wire failures inside cylinder

Initially thoughts were that the swage for the ring was not strong enough to take the load which might be higher due to oil circulating around the coil. Various solutions were tried to fix the issue as shown in Figure 139.

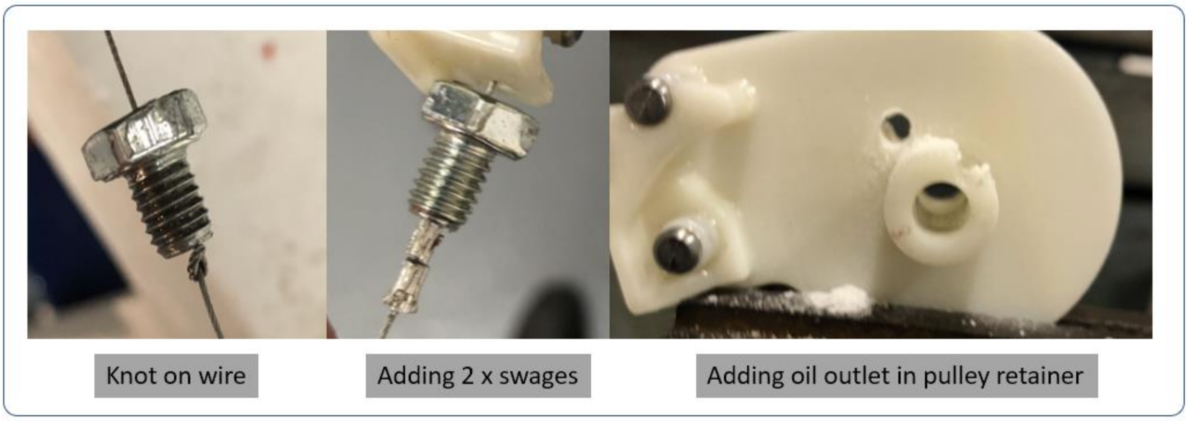


Figure 139 Various solutions tested

First a knot was added to the wire and tested again but the knot was sheared off and wire was inside the coil housing. Then two swage rings were tried and crimped on extra securely but with the same failure, the wire broke at the swage rings. Then it was thought that, maybe, oil was getting trapped inside coil housing, so a hole was drilled in the pulley retainer near the inside to allow an outlet for the oil, but again the wire failed. So, another idea had to be considered. Looking at how everything lined up inside, the oil flow was coming directly onto wire as shown in Figure 124 on page 139. It was decided to weld another port at 90° on the screwed cylinder end so oil was not coming down directly on top of the wire. It was considered a possibility that the oil flow was pushing the wire off the side of the coil housing and getting jammed between that and the pulley retainer.

Figure 140 Oil flow direction changed

So as not to change too many variables at once it was decided to add an extra test port to the side of the screwed cylinder end. The original port was blocked off with a steel blanking cap and a new test port added at 90° orientation to the original. The sensor was left at the same position inside as shown in Figure 140. This time the test was successful, and the wire did not separate from the swage inside the nut. This confirmed that oil flow was a factor in contributing to the failure. However, for production this would happen, so a fix was needed for this possible scenario.

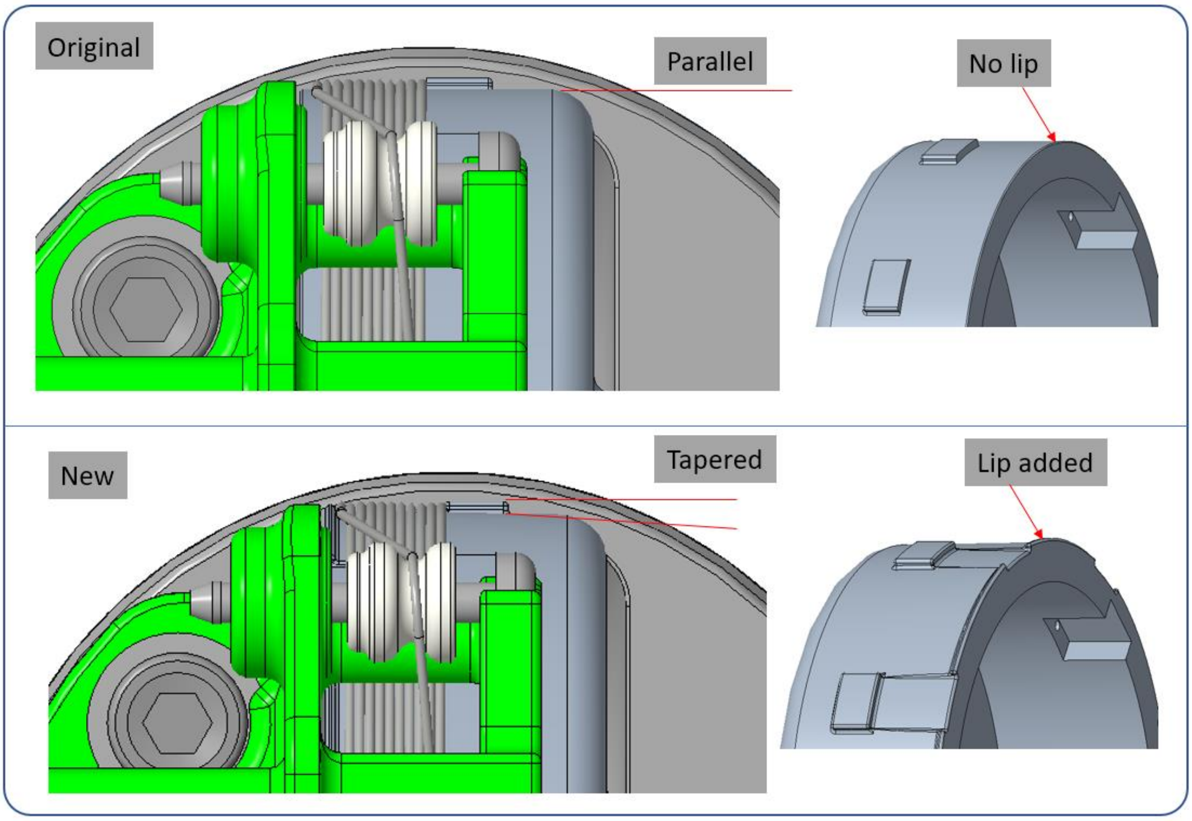


Figure 141 Redesign of coil housing

For the fix it was decided to add two features to prevent this from happening. First feature was to add a taper to the outside of the coil housing to pull the wire in towards central stop. This would help pull coils of wire in tighter together and reduce the chance of oil flow pushing the wire off the outside of coil housing. Second feature added as an additional security was to add a lip to the outside of the coil housing. The worst-case scenario the wire would only be pushed to this lip and then be stopped.

At this stage the outside of the coil housing was also prepared for the injection moulded process as tapers were needed for joint separation in tooling. Therefore, in front of the stops in the centre the taper must go in the opposite direction and there were no stops at these points. These taper details are shown in Figure 142.

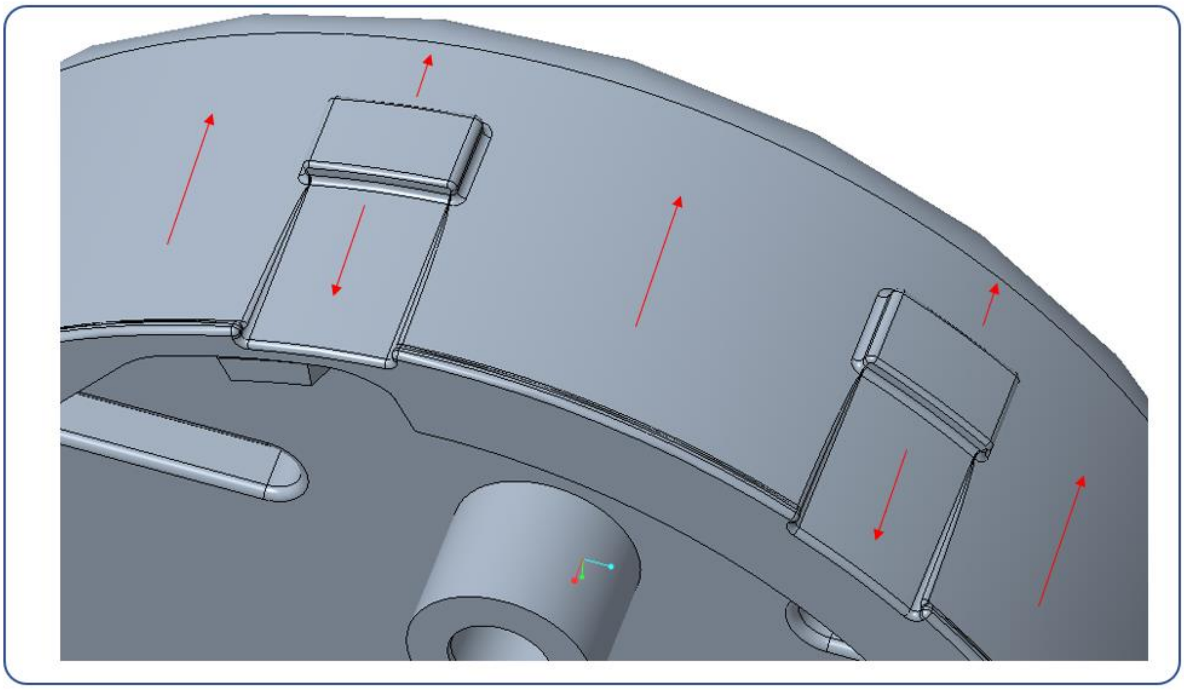


Figure 142 Tapers added

This sensor was assembled again and worked well with the oil being fed in though both ports in individual tests at full flow. The redesign was a success.

7. RESULTS

7.1 Dry operating Prototype

The process for calibration involved measuring the cylinder when closed and open to know the actual limits of the physical cylinder. This was compared to the outputs from the Arduino. For this prototype dry cylinder, the measured stroke was 691mm.

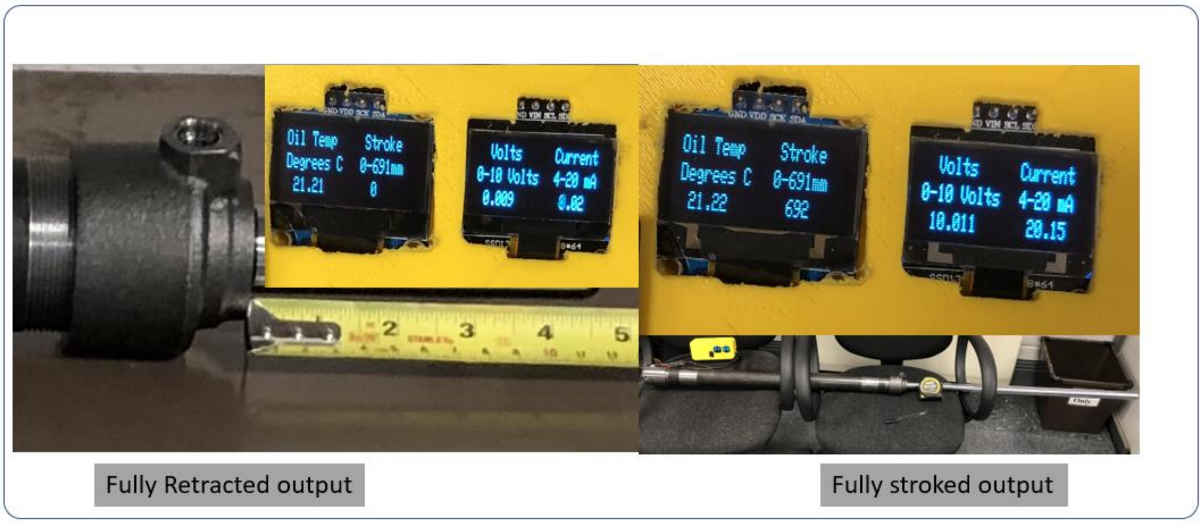


Figure 143 Outputs from sensor

The output from the sensor can be seen in Figure 143. When the cylinder was retracted all displays were showing approximately base valves. For the oil temperature it was just showing room temperature, in this case 21°C. For the stroke fully retracted it was showing 0 in the 0 to 691mm scale. For the voltage we were using a scale from 0 to 10 volts. It was showing 0.009 volts. For the current it was showing 4.02 mA on the 4-20 mA scale.

When extended it was showing the same temperature, 692mm on the 0-691mm scale, 10.011 volts on the 0 to 10-volt scale and 20.15Ma on the 4-20 mA scale. Output was stable in stationery positions and was linear in fashion. Overall the output was as expected.

When extended it was showing the same temperature, 692mm on the 0-691mm scale, 10.011 volts on the 0 to 10-volt scale and 20.15mA on the 4-20 mA scale. Output was stable in stationery positions and was linear in fashion. Overall the output was as expected. The results are summarised in Table 6.

	Oil Temp °C	Stroke (0-691mm)	Volts (0-10 volts)	Current (4-20mA)
Retracted	21.21	0	0.009	4.02
Extended	21.22	692	10.011	20.15

Table 6 Results of outputs at end limits

The sensor assembly was left in Burnside for about 2-weeks to show employees who had an interest in the workings of the sensor. Every time the Arduino Uno started without fail for demonstration purposes and the output gave the exact position of the cylinder stroke even if the cylinder rod was repositioned when the sensor was turned off.

The results from the dry testing were validated by observing the upper and lower displayed limits of the sensor once calibrated to ensure they remained consistent over the test period. Over the two-week period the outputted results were very consistent varying by about 2-3mm maximum on the upper and lower limits from start to finish of test with estimated double strokes of about 1000-1500 cycles. These initial results from dry testing gave confidence to move forward to the next planned stage of hydraulically testing of sensor.

7.2 Pressurised working cylinder

In the beginning the back play in the gears was nearly zero as there was no clearance between the gears. However, after a couple of 100 cycles there was increased clearance between the gears as wear took place between the mating parts. This change would be visibly seen on the output display as the upper and lower limits changed at the end of the strokes in and out.

The cylinder was dismantled after testing. It was found that the sensor was difficult to remove from the screwed cylinder end. The pulley retainer assembly was removed from the aluminium whilst still inside the cylinder end.

Figure 144 Dismantling of sensor

No special tools were available to pull the sensor from the screwed cylinder end. To get out easily a small hole was drilled behind the cylinder end to allow the housing to be tapped out. This is shown in Figure 144. There was some localised wear on one portion of the seal where it was directly over hole for the magnet retainer, but the seal did not leak oil during the test. The wear on the gear parts after disassembly were non-visible but the small increase in clearance was visible on the OLED display. Variation changed by 20mm of stroke at each end over 1000mm stroke, which was deemed too much wear on gear parts for a short test.

To reduce wear on the mating gears it was decided to change the material from plastic to metal. The parts were printed by 3-D hubs from 20ES stainless steel with a layer height of 20um. They were installed back inside the sensor assembly. The gears and assembly are seen in Figure 145. To allow for easier assembly and disassembly a small amount of material was sanded from the outside of the aluminium body. This allowed the body to be assembled and disassembled much easier inside the cylinder end.

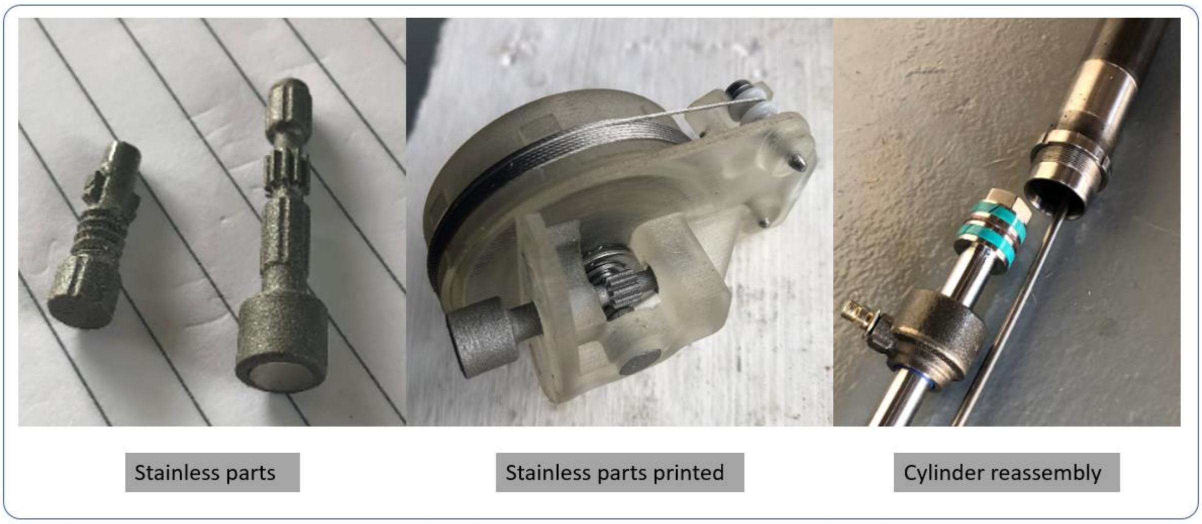


Figure 145 Stainless parts fitted

The cylinder was reassembled and calibrated again once assembled inside the cylinder. The recalibration was necessary as when the magnet is inserted inside the bevel pin, a random position is established in relation to the rotary encoder. The display from the OLED in fully retracted and fully extended positions can be seen in Figure 146.

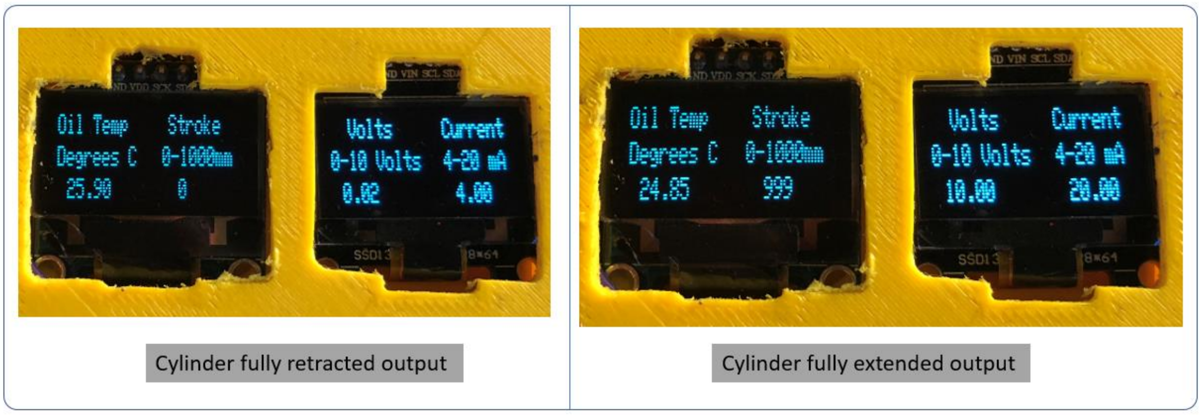


Figure 146 Display outputs

The cylinder with sensor was connected back to a hydraulic power pack in Burnside as shown in Figure 147. A short video of the sensor running can be viewed here https://www.youtube.com/watch?v=1D9GXD254S8 . The cylinder was slowed down to show the display more clearly. The cylinder was run over a period of 7 hours with a pressure spike of about 200 bars at the end of each stroke. The speed was around 0.5m/second. The changeover was setup to operate automatically by adjusting timers on the power pack display for. After about an hour the oil temperature maxed out at around 40°C and did not get hotter for the rest of the test. The resolution of the temperature sensor was excellent and adjusted quickly as the oil temperature increased inside the cylinder during testing.

At the end of the test it would be seen that the repeatability of the output was excellent with little variation between output at the end of the test and the beginning of the test. The repeatability was out by less than 0.3% (3mm on display), which was much better than expected and better than what the end user would typically need in outputted resolution. The cylinder was also pressurised for a time to 350 bars with the sensor inside and seal integrity was okay. At this point the design was verified to be operating as intended and the test was stopped. The final design as evolved was a success based on the consistent outputted displayed test results. For the final test the cylinder ran for about 5000 cycles.

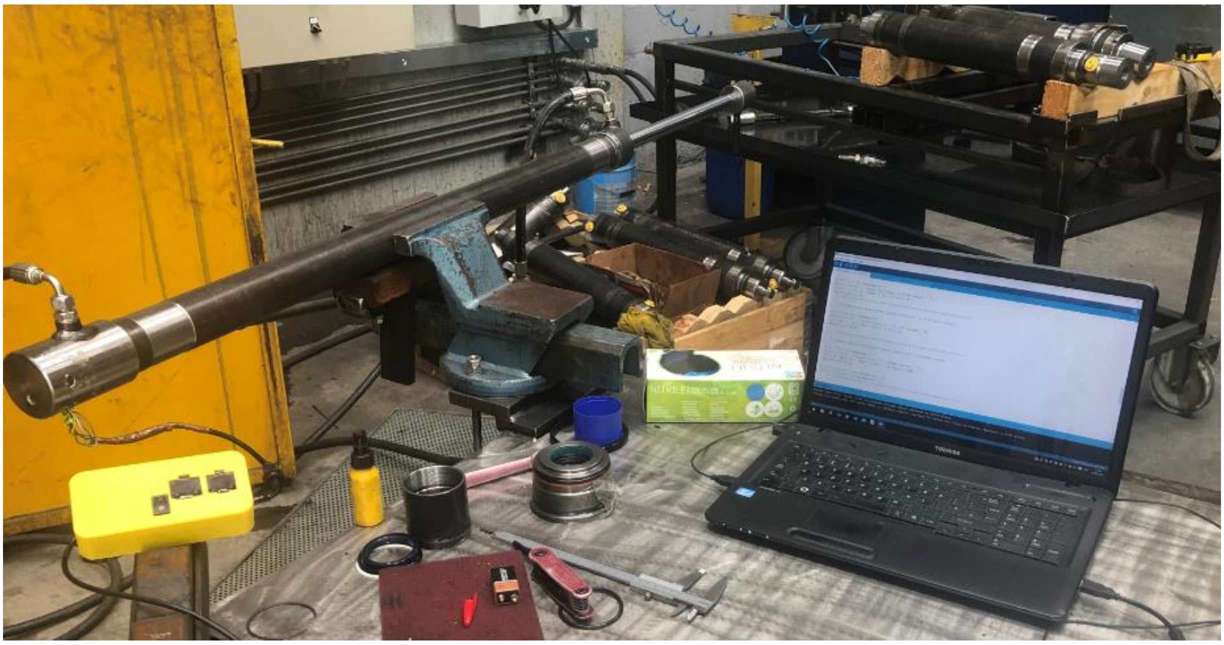


Figure 147 Final hydraulic retesting

All results along the outward and return stroke were as expected and were consistent over the full test duration. There was an offset of about 3mm shortly after start of test, but thereafter the outputted results stabilised and were consistent until the end of the test duration.

The measured stroke on cylinder when extending verses outputted stroke from sensor can be seen in Figure 148. The measured stroke on cylinder verses outputted voltage from sensor can be seen in Figure 149. The current output from the sensor verses stroke measured is shown in

Figure 150. It can be seen the comparison in linearity on all tables across the full stroke range was excellent. The difference in expected values towards actual values was out less than 0.3%.

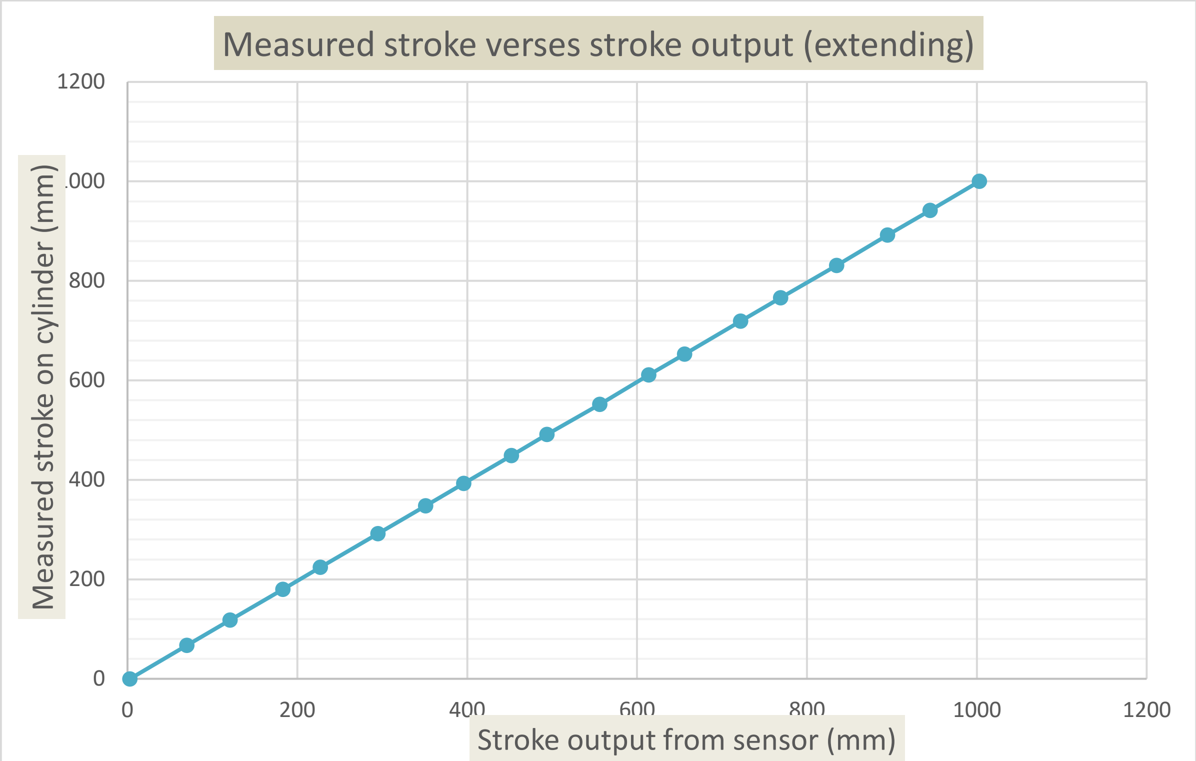


Figure 148 Measured stroke verses stroke output extending

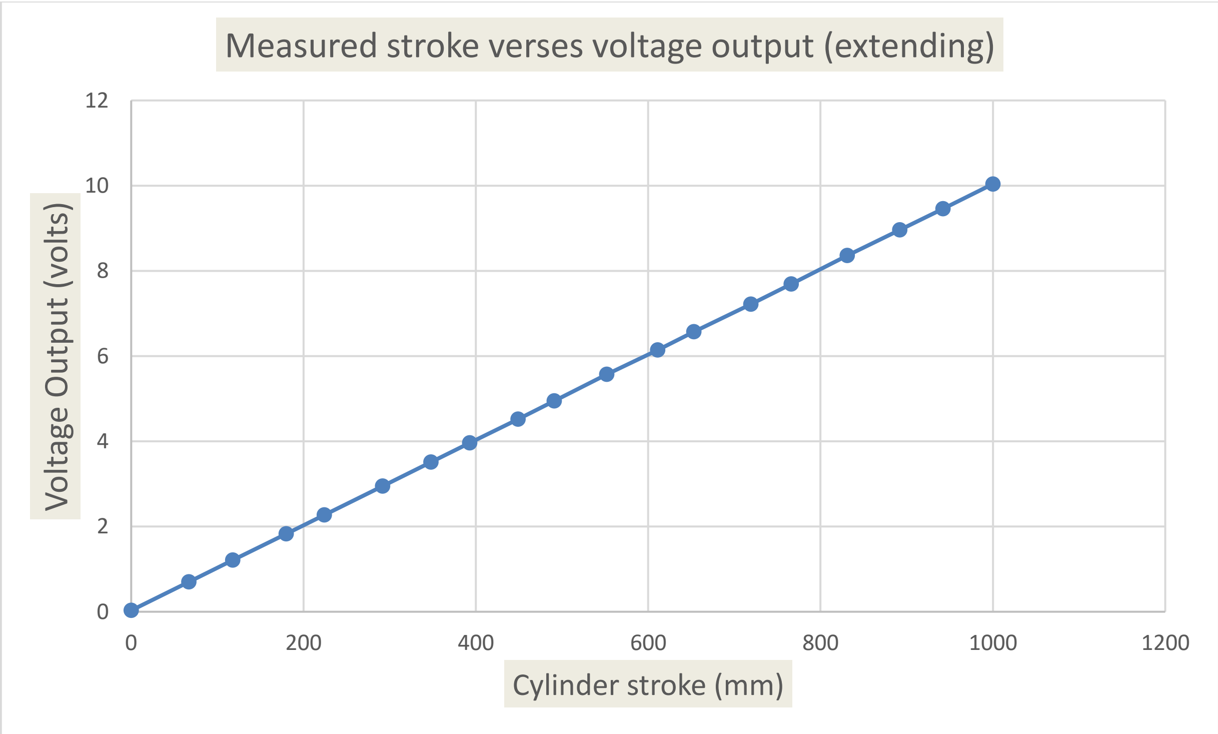


Figure 149 Measured stroke verses voltage output

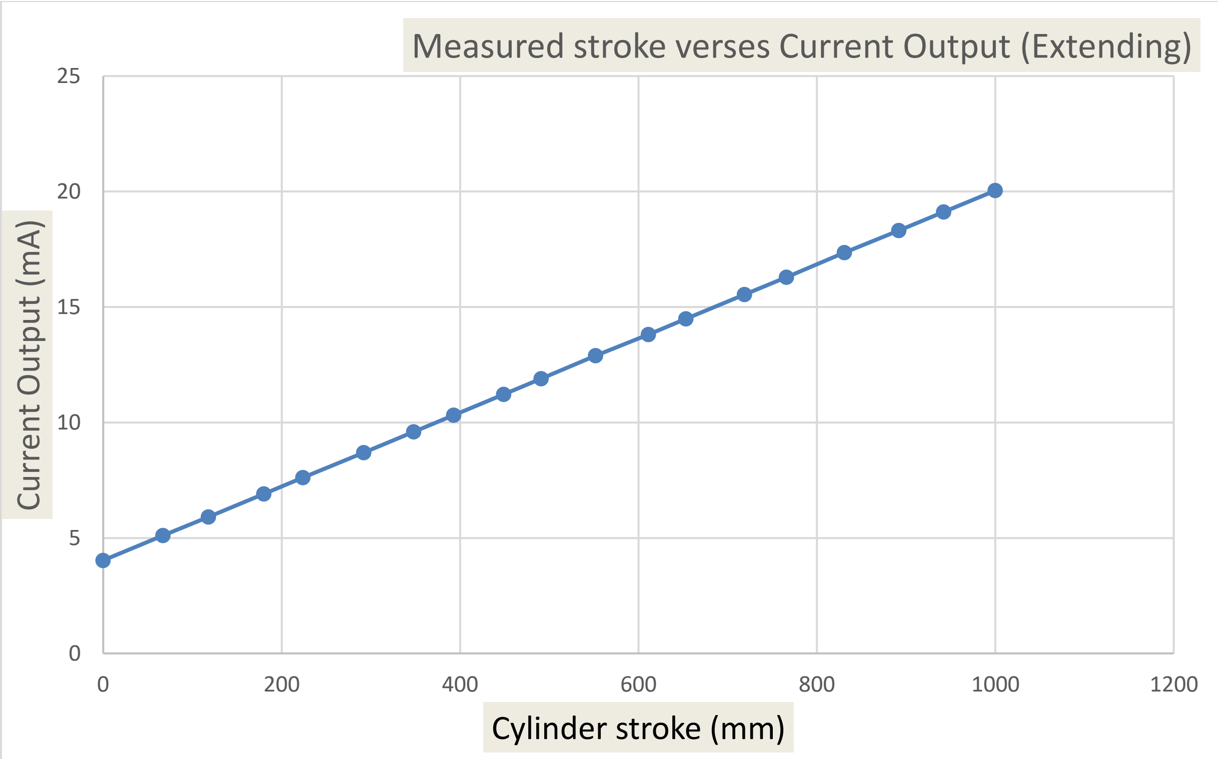


Figure 150 Measured stroke verses Current Output

The same measurements were done for the retraction stroke and are shown below in Figure 151, Figure 152 and Figure 153. The results were like the extending characteristics in reverse and were linear in nature.

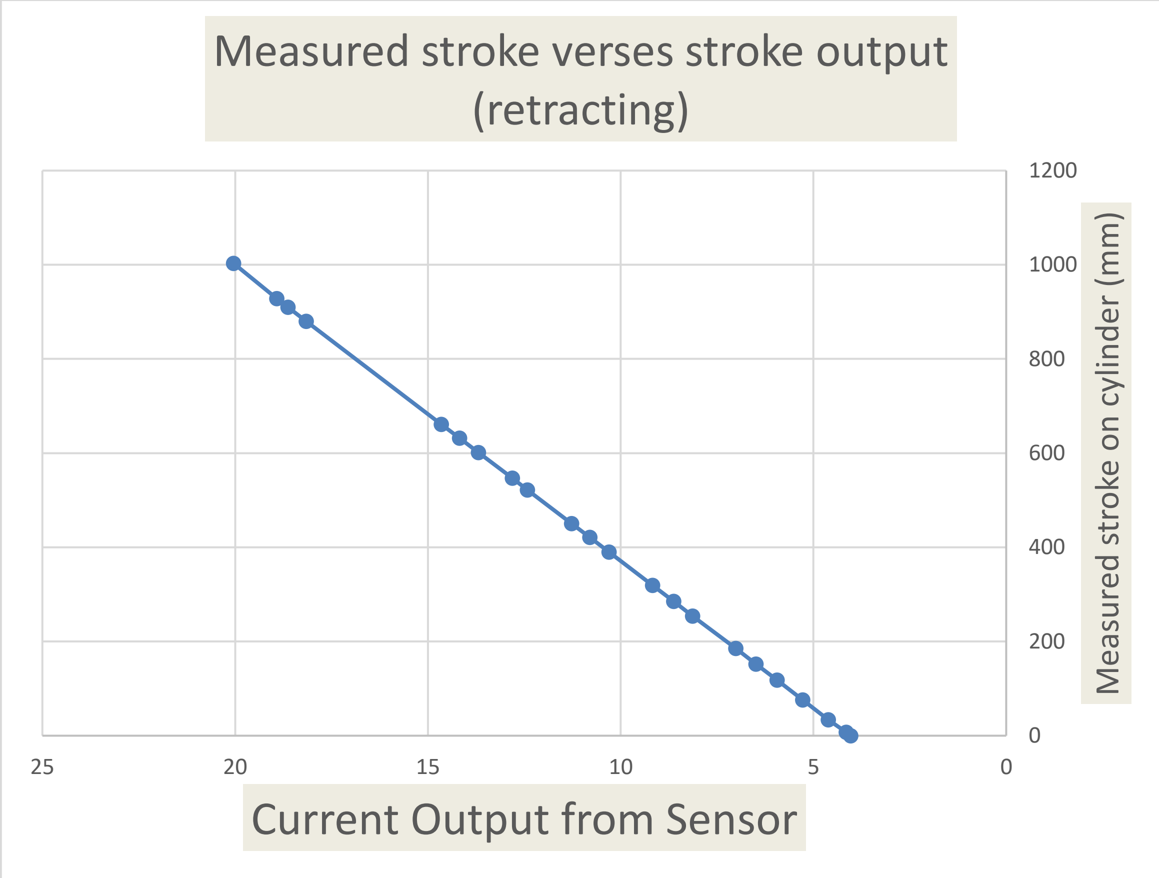


Figure 151 Measured stroke verses stroke output retracting

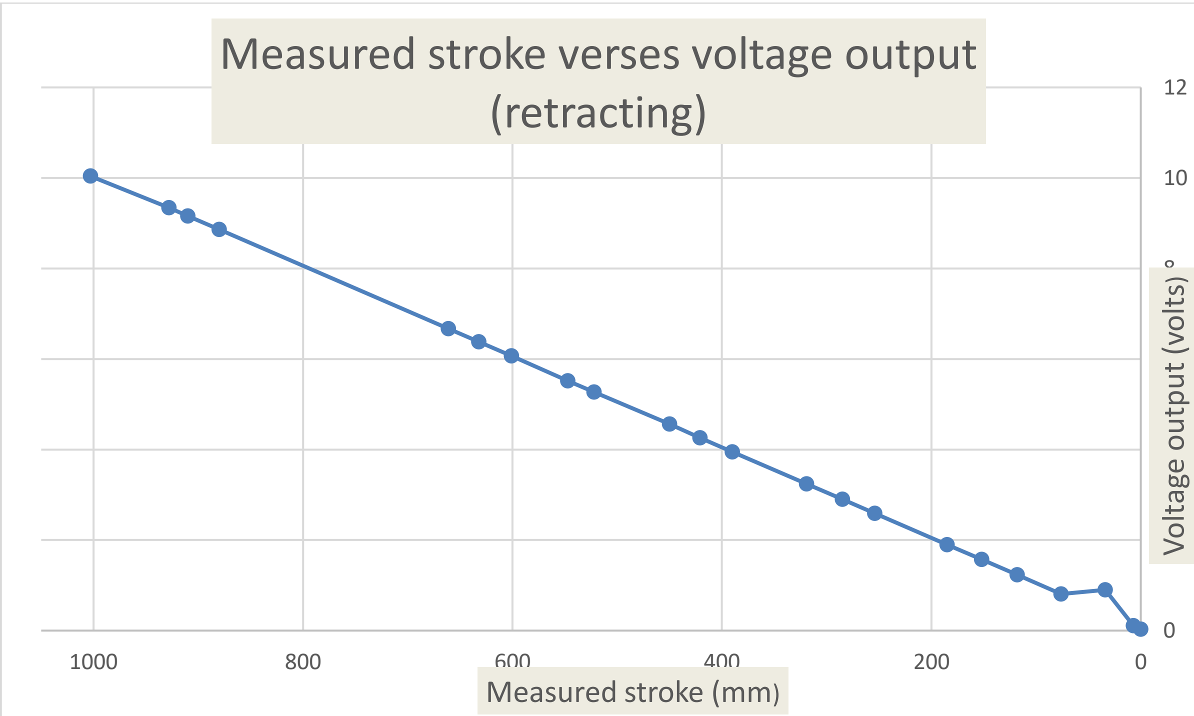


Figure 152 Voltage output verses measured stoke (retracting)

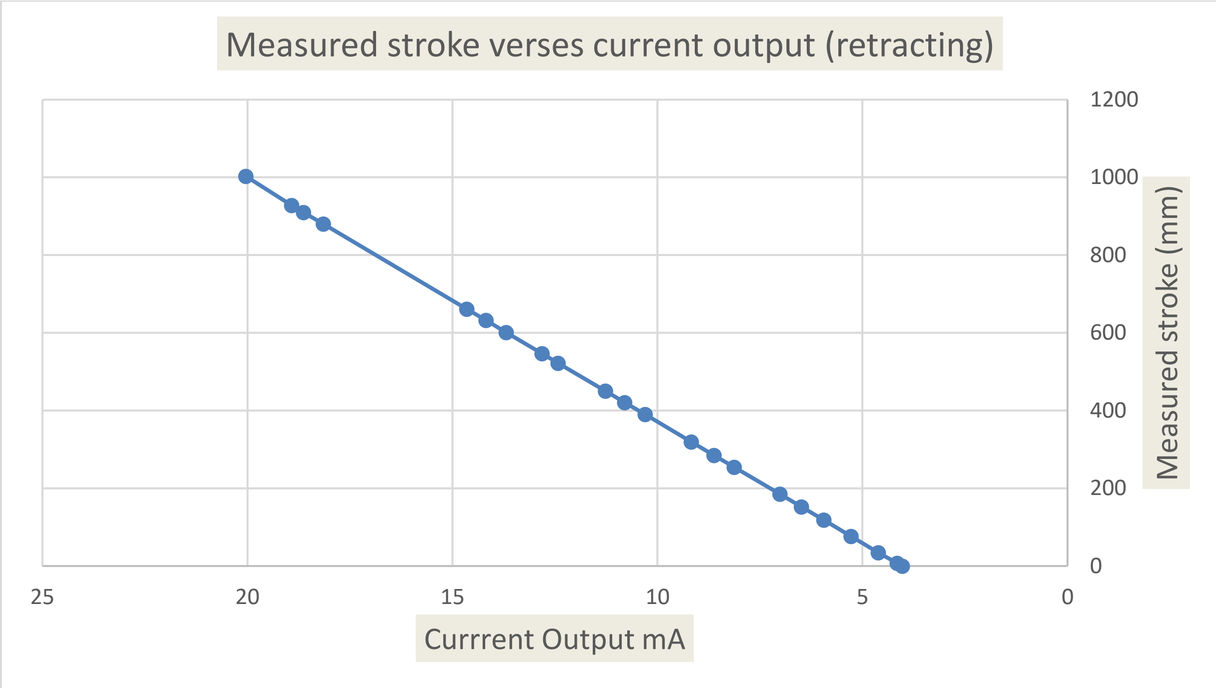


Figure 153 Measured stroke verses Current output (retracting)

To verify outputs were still consistent after testing was complete, the end positions and two mid positions were measured to ensure there was no change in the outputted results. This was found to be the case.

Figure 154 Examination of wearing parts

After testing was complete the cylinder was dismantled, and the wearing parts examined. There were no obvious signs of wear. Because the geared parts were 3-D printed the quality of the surfaces were not that good to start with, but there was no visible change from a new part and the part after testing. The static seal on the aluminium body showed no sign of extrusion and held up well. The design evolution to solve the problems were deemed to work. The wear parts after testing can be seen in Figure 154.

8. CONCLUSIONS AND FURTHER DEVELOPMENT

8.1 Conclusions

The research question was to examine and develop a new type of sensor that would be installed inside a hydraulic cylinder and incorporate some new feature not available inside a sensor solution currently available in the market. Overall the sensor development has been a success, the sensor is operating successfully inside a hydraulic cylinder and the temperature sensor is displaying oil temperature within the cylinder. Also, digital representative displays for voltage, current and actual stroke positions were successfully utilised which varied as the cylinder moved across the full stroke range. The sensor was fully customisable to be able to be adjusted by the initial setup by simple programming to suit any cylinder stroke length from short cylinders up to 1000mm stroke.

Initially all possible existing positional feedback options were evaluated to determine the best possible technology to pursue based on time frame, available resources and being able to offer something unique as part of a positional feedback package not currently available today. Various unique options were looked at and the decision to include a temperature sensor as part of the overall solution was decided upon.

Fixed position sensors and variable position technologies were looked at. Variable position sensing was determined to offer the most flexible options. Many advanced electronic and waveform technologies were examined but the resources and skills needed for this type of sensor were deemed outside the scope of this two-year research project. After careful consideration the sensor technology we decided upon was a wire-based encoder technology system that would work inside the hydraulic cylinder. The basic requirement established was the sensor needed to be able to work across multiple lengths and different bore sizes of cylinders. The sensor needed to be practically optimised in size to suit the widest range of stroke length and ideally be compact in overall envelope size. As hydraulic cylinders were cylindrical by nature the sensor would fit within a round envelope shape. The sensor needed to be reliable.

Some patent searches were done specifically on this wire sensor technology to see where some infringements potentially would occur. There were lots of examples of this technology being used outside cylinders but only a couple of examples were found that would operate inside a hydraulic cylinder. These dedicated in cylinder solutions were concentrated on in patent searches and it was found no infringements would occur.

One of the main objectives was low cost as this is where the biggest opportunities were envisaged, so simplicity of the overall design was important. A similar sensor was sourced and dismantled to understand it workings. This would form the basis of the start of the project. The project had two main working principles electrical and mechanical. Dave Allen offered electrical support and Paddy Buckley offered support on mechanical aspects of project.

For the basic working of the unit a rotary encoder would be needed, and a signal needed to pass through an aluminium body which would be pressure resistant. It was also determined the sensor needed to be able to display actual position upon start up even if power was cut to the sensor when the sensor was operating.

It was decided to pass a magnetic signal through an aluminium body so the pressurised cylinder and electronic components would be separated. A specific rotary encoder type was decided upon based on the output resolution needed for the cylinder output, and tests were conducted to establish the effects of different working gaps through air and passing through the aluminium body. The goal was to achieve a balance between reliable signal through the aluminium body by being close enough and to ensure there was enough thickness of material in the aluminium body to withstand the hydraulic pressure.

The evaluations for the gaps and material thickness were done by a variety of methods. One of the methods used was by practical testing between air gaps. A small test rig was constructed to vary the gaps between the rotary encoder. A programme was downloaded to drive the rotary encoder through Arduino and sub programmes were written to convert angular output to voltage and current outputs. Tests were done with different magnet types and the results monitored to find acceptable limits. Additional research to confirm optimised dimensions was done by manual calculations and by using Creo CAD Simulation software.

Some research was done on best methods of connecting the sensor to the rod, different types and sizes of connecting wire based on similar applications and theoretically gearing needed to allow for most refined stroke outputs for the longest cylinder envisaged.

The first assembly was constructed in CAD to contain all the main parts needed using information from initial research. The assembly of parts in CAD was done concurrently and the parts modified to get best fit within the available space. The aluminium body was recessed to allow coil housing to fit in place. The gears were designed to be in contact and allow rotational movement so as the wire was being pulled out by the cylinder. The magnet was rotated over the magnetic encoder thus giving proportional outputs from the sensor used to determine the cylinder stroked position. The size of sensor was optimised to allow it to fit within a commonly used small cylinder in Burnside.

Some of the parts designed had various functions and emphasis was made on keeping overall design simplified as much as possible and optimising the balance between the functional various elements and needed of constant adjusting of part shapes to make room for others until initial design proposal was complete.

Once the initial design was finalised in CAD, a prototype sensor needed to be constructed to see would it function as intended. This involved 3-D printing for some parts. This 3-D printing was done in three locations Burnside, IT Carlow and IT Athlone. Some material allowances were allowed for machining internal holes on machined parts, by printing undersize and machining after. This allowed for consistency in mating tolerances along with good ovality and surface finishes.

The main aluminium body was machined in IT Carlow which took lots of work in building jigs and getting set up for CAD CAM. Some of the small precision parts were outsourced to specialist suppliers. The coil spring was designed in conjunction with a UK company who specialised in this manufacturing technology. The commodity electrical components, nuts, bolts, washers were sourced through local commodity suppliers.

Various issues were encountered along the way, changes made in CAD, parts redesigned and remade. The biggest design issue encountered along the way was the alignment and meshing of gears. Without adequate support and guidance, the gears never meshed together properly.

To fix this issue, major redesign of both gear mating parts, and pulley retainer was required. This redesign proved to be successful and allowed basic functional tests to be conducted. To be able to display output properly a dedicated test unit had to be designed, built and tested.

The test unit involved being able to run two individual OLED screens and display four different outputs. The test unit was designed to be self-sufficient so when programme was uploaded to the Arduino, it would operate independently powered by a 9-volt battery. A quick release electrical fitting was added to allow it to be used across multiple cylinders.

To enable the initial sensor to be tested properly a dry cylinder was built with a medium stroke. The smallest bore cylinder was used to prove it would work for this size. The ends were customised to be able to accept the sensor and a viewing window was machined away in the tube to allow sensor to be seen whilst working. Any seals or friction elements normally used in a hydraulic cylinder were omitted to allow the rod to be moved freely by hand.

The cylinder and sensor were assembled with the test unit connected and the sensor was initially calibrated by a PC so start and end positions were displayed correctly. The sensor was turned on and off randomly and operated successfully over a two-week period in Burnside, thus proving the dry prototype testing was a success.

The results from the dry testing were validated by observing the upper limits of the sensor once calibrated to ensure they remained consistent over the test period. Over the two-week period the outputted results were very consistent varying by about 2-3mm on the upper and lower limits from start to finish of test with estimated double strokes of about 1000-1500 cycles. This gave confidence to consider hydraulic testing of the sensor.

Once this dry testing was complete a new cylinder had to be designed and constructed to operate under hydraulic pressure. The longest cylinder, as planned, was built at 1,000mm and the appropriate sealings added to make the cylinder pressure tight. Initially it was difficult to assemble and took three people, so some customised tools were made to simplify the process and allowed assembly by one person.

The hydraulic testing was conducted in Burnside Autocyl. No special rigs were required, only vice clamps and hydraulic power packs. An anti-rotation spacer was added to stop the rod turning during operation. There were some failures of the sensor unit and the cylinder had to drained of oil, dismantled, sensor rebuilt, and cylinder reassembled between failures.

Initial thoughts were that swage rings were not strong enough, so this area was strengthened and retested. However, these retests were not successful after strengthening this area. Looking at the sensor orientation and wire position it was thought maybe oil inflow was pushing the wire off the coil housing and locking wire between pulley retainer and coil housing. To test the theory, the cylinder was redesigned to allow the oil flow to come in from a different position.

The cylinder was retested and operated successfully. However, a redesign was needed to ensure wire would not be displaced from any random oil inflow direction. There was a slight taper added to the outside of the coil housing and an extra security lip also added. The cylinder was retested with different oil inflow directions and proved successful in all cases.

Running the cylinder for an hour or so there was a noticeable visible change in repeatability of the output of the sensor. This was due to wear in the plastic 3-D printed gears. It was decided to get the gears 3-D printed in metal and the test run again. The test was run for a period of 4 hours and there was no change in output repeatability. The output at the beginning of the test was the same as the output at the end of the test. For the final test the cylinder ran for about 5000-6000 cycles.

At this point the complete sensor development was deemed a success. The development process was long and was done over various incremental stages. Initial technologies were researched and decided upon. Various iterations of designs were designed and tested in dry mock-up and pressurised cylinders until a successful solution was found and successfully tested.

8.2 Further Developments

To make the next step to commercial level for the sensor proper injection moulded parts would need to be invested in. The pulley retainer would be split into one main body and two push in caps to simplify overlays for the injection moulding process.

An investment would be needed to develop the electronics side of the sensor with temperature and rotary sensor on its own dedicated circuit board. Not having the slot cut away in the aluminium body for adding the temperature sensor would further strengthen this body part and give support where wear sometimes appears in outer sealing element. A contact has been established in Ireland with an electronic board development company who would be working to develop this circuit board.

Machining the worm gear from stainless steel and joining this with sensor shaft as one part would be recommended to strengthen the main shaft through the middle and improve the surface finish on the gear surfaces. This would mean a circlip would be required and assembled over the shaft from the opposite side, but entirely possible.

Once invested in and permanent parts built, endurance testing over longer periods and under varying conditions such as cold start-ups and inflated temperatures would be needed but a good solid working base in terms of design and test results is now done to justify this investment.

BIBLIOGRAPHY

Ametek, 2013. *Company History.* [Online]

Available at: https://www.solartronmetrology.com/about-us/companyhistory

AMS, 2018. https://www.mouser.com/datasheet/2/588/AS5601_DS000395_3-00-1512703.pdf. p. 34.

AMS-5601, 2016. *AMS.* [Online]

Available at: https://ams.com/as5601

Balluff, 2017. *Comparision of postion sensing options for hydraulic cylinders.* [Online]

Available at: https://m.balluff.com/fileadmin/user_upload/PDF/basics/015_Continuous-vs-End-Stroke_V1_EN.pdf

Balluff, 2018. *External Position feedback for hydraulic sensors.* [Online]

Available at: https://automation-insights.blog/tag/hydraulic-cylinders/

Baluff, 2018. *Overview of sensors.* [Online]

Available at: https://app01.balluff.com/image-fit/996-373/fileadmin/user_upload/products/sensors/magnetostrictive-sensors/overview_sensors_magnetostrictive-transducers.jpg

Banner, E., 2017. *Ultrasonic sensors.* [Online]

Available at: https://www.bannerengineering.com/in/en/company/expert-insights/ultrasonic-sensors-101.html

Besch, B., 2016. *Smart sensors reduced operational cost.* [Online]

Available at: http://blog.parker.com/smart-cylinders-reduce-operational-costs

Burnside, A., 2018. *Burnside Autocyl.* [Online]

Available at: https://burnsideautocyl.com/

Byrne, P., 2018. *Sensor Incorporation* [Interview] 2018.

C&S, M., 2010. *Spiral Spring Solutions.* [Online]

Available at: http://www.spiral-spring.com/about_power_springs.html

Calin, M., 2011. Temperature influence on magnetic characteristics of NdFeB permanent magnets. *IEEE Explore.*

Control, C., 2017. *Linear position transducers.* [Online]

Available at: https://www.cpi-nj.com/linear-position-sensors

Cosford, J., 2015. *Mobile hydraulic tips.* [Online]

Available at: http://www.mobilehydraulictips.com/trends-in-construction-machinery-hydraulics/

Cranes, K., 2018. *Kone Cranes.* [Online]
Available at: http://www.konecranes.com/equipment/lift-trucks/fork-lift-trucks
Decker, K., 2016. *Slow Electricity: The Return of DC Power?.* [Online]
Available at: http://www.lowtechmagazine.com/2016/04/slow-electricity-the-return-of-low-voltage-dc-power.html
Eitel, E., 2014. *Machine Design.* [Online]
Available at: http://www.machinedesign.com/sensors/basics-rotary-encoders-overview-and-new-technologies-0
Engineering, R., 2019. *Rota Engineering.* [Online]
Available at: https://www.rota-eng.com/linear-position-sensors
Greyline, 2018. *Greyline.* [Online]
Available at: http://www.greyline.com/pdf/TwoTechnologies.pdf
Group, F., 2018. *Flodraulic G.* [Online]
Available at: https://www.flodraulic.com/tech-tips/electro-hydraulic-feedback-cylinders-0
Hankinson, M., 2009. *Sensor Performance and Longevity in Wood cutting application.* [Online]
Available at:
http://www.mtssensors.com/fileadmin/media/pdfs/MTS714_High_Vibration_Wood_Industry.pdf
Heney, P., 2015. [Online]
Available at: https://www.fluidpowerworld.com/hydraulic-actuator-trends-sensing-in-harsh-environments/
Heney, P., 2016. *hydraulic fluid compatibility.* [Online]
Available at: https://www.sealingandcontaminationtips.com/hydraulic-fluid-compatibility-important-seals/
Herceg, E., 2013. *Fluid Power Journal.* [Online]
Available at: https://fluidpowerjournal.com/position-sensor/
Herceg, E., 2013. *Position Sensor Technology Comparision.* [Online]
Available at: http://alliancesensors.com/sites/default/files/pdfs/FPJMJ13_Sensors.pdf
Herceg, E., 2018. *Comparing Position Sensors for Hydraulic Cylinder Feedback.* [Online]
Available at: https://www.machinedesign.com/motion-control/comparing-position-sensors-hydraulic-cylinder-feedback

Hitchcox, A., 2013. *Hydraulics & Pneumatics.* [Online]
Available at: http://www.hydraulicspneumatics.com/cylinders-amp-actuators/smart-cylinders-stabilize-cranes
Hostick, C., 2013. *Moisture Protection Of Electronics.* [Online]
Available at: https://www.efficientplantmag.com/2013/09/moisture-protection-of-electronics/
Howard, M., 2017. *Measuring position in harsh environments.* [Online]
Available at: https://www.zettlex.com/articles/measuring-position-speed-harsh-environments/
Howard, M., 2018. *Incremental versus Absolute Sensors.* [Online]
Available at: http://www.zettlex.com/articles/incremental-versus-absolute-sensors/
Howard, M., 2018. *Potentiometers.* [Online]
Available at: http://www.zettlex.com/articles/engineers-dislike-potentiometers/
Hydadmin, 2009. *How do hydraulic cylinders work.* [Online]
Available at: https://www.hydrauliconline.com/hydraulic-cylinders/how-do-hydraulic-cylinders-work/
Hydraulics, A., 2016. *Purpose Built: Engineering for the application.* [Online]
Available at: https://www.aggressivehydraulics.com/blog/purpose-built-engineering-for-the-application/
Jones, D., 2009. Biomedical Sensors. In: s.l.:Momentum Press, p. ix.
Kocis, S., 1996. Ultrasonic Measurements and Technologies. In: Slovak Republic: Chapman & Hall, pp. 78-79.
Lee, B., 2014. *Hydraproducts.* [Online]
Available at: https://www.hydraproducts.co.uk/blog/postid/87/how-do-hydraulic-cylinders-work.aspx
Lesjöfors, S., 2018. *Constant Force Springs.* [Online]
Available at: http://www.lesjofors.us/products.htm
Lesurf, J., 2017. *Ranging Radar.* [Online]
Available at: https://www.st-andrews.ac.uk/~www_pa/Scots_Guide/RadCom/part15/page1.html
Liebherr, 2017. *Liebherr.* [Online]
Available at: https://www.liebherr.com/shared/media/components/documents/control-

technology-and-electronics/sensor-technology/liebherr-liview-intelligent-position-transducer-hydraulic-cylinder-product-feature-en-web.pdf
LVDT, 2015. *Linear variable Differential Transformer.* [Online]
Available at: http://www.lvdt.co.uk/how-lvdts-work/
McIntyre, T., 2016. *Eaton Hydraulics.* [Online]
Available at:
http://www.eaton.com/ecm/groups/public/@pub/@eaton/@hyd/documents/content/pct_2867430.pdf
Meyerhoefer, R., 2010. *Hydraulic cylinders under pressure.* [Online]
Available at: https://www.mobilehydraulictips.com/hydraulic-cylinders-under-pressure/
MTS, 2017. *Magnetostriction Basic Physical Elements.* [Online]
Available at:
http://www.mtssensors.de/fileadmin/medien/download/mts_measuringprinciple.pdf
MTS, 2019. *MTS Sensors.* [Online]
Available at: http://www.mtssensors.com/products/
Nyce, D., 2001. *Sizing and Applying Magnetostrictive Linear Position Sensors.* [Online]
Available at: http://www.machinedesign.com/technologies/sizing-and-applying-magnetostrictive-linear-position-sensors
Omega, 2016. *LVDT White paper.* [Online]
Available at: https://www.omega.co.uk/technical-learning/linear-variable-displacement-transducers.html
Parker, 2018. *Parker Hydraulics Position switches.* [Online]
Available at:
https://www.parker.com/literature/Industrial%20Cylinder/cylinder/cat/english/HY08-1132-5_NA_Switch.pdf
Reddy, B., 2016. *Reed switch working principle.* [Online]
Available at: https://instrumentationtools.com/reed-switch-working-principle/#.WmD_TTfLjcs
Relais, C., 2013. *Magnetic Proximity Sensor.* [Online]
Available at: http://www.celduc-relais.com/wp-content/PDF/pta50010.pdf
Scienceclarified, 2018. *Ultrasonics.* [Online]
Available at: http://www.scienceclarified.com/everyday/Real-Life-Chemistry-Vol-5/Ultrasonics.html

Seco, F., Martín, J., Ruiz, A. & Calderón , L., 2005. A high accuracy magnetostrictive linear position sensor. *Sciencedirect,* pp. 216-233.
Sensors, B., 2019. *Balluff Sensors.* [Online]
Available at: https://www.balluff.com/en/de/products/sensors/magnetostrictiv-sensors/
Sharpley, N., 2014. *Wind Power Engineering.* [Online]
Available at: http://www.windpowerengineering.com/electrical/parker-launches-smart-cylinders-integrated-intellinder-absolute-position-sensor/
Siko, 2017. *Position Sensors for Hydraulic Cylinders.* [Online]
Available at: https://www.siko-global.com/adbimage/27897/asset_original/flyer-sgh10.pdf
Siko, 2017. *SGH10 Wire actuated encoder.* [Online]
Available at: https://www.siko-global.com/adbimage/28056/asset_original/data-sheet-sgh10.pdf
Siko, 2018. *Siko Sensors.* [Online]
Available at: https://www.siko-global.com/en-hr/products/linearline-wire-actuated-encoders/wire-actuated-encoders
Spaceagecontrol, 2018. *String Potentiometer and String Encoder Engineering Guide.* [Online]
Available at: https://www.spaceagecontrol.com/s054b.htm
Spring, L., 2018. *Contant force Springs.* [Online]
Available at: http://springipedia.com/constant-force-about.asp
TE, 2017. *String Potentiometer.* [Online]
Available at: http://www.te.com/usa-en/products/sensors/position-sensors/cable-actuated-position-sensors/what-is-a-string-pot.html
Ullrich, G., 2015. Automated Guided Vehicle Systems: A Primer with Practical Application. In: s.l.:Springer, p. 90.
Vázqueza, C. & Freidovich, L., 2016. *Robust position control design for a cylinder in mobile hydraulics applications.* [Online]
Available at: https://www.sciencedirect.com/science/article/pii/S0967066117302009
Waycon, 2016. *Series SX200 Draw wire sensor.* [Online]
Available at:
http://www.waycon.biz/fileadmin/waycon/dateien/products/draw_wire_sensors/Draw_Wire_Sensor_SX200.pdf

Womack, 1988. *Cushioning and Decelerating Methods for Cylinders.* [Online]
Available at: http://www.womackmachine.com/engineering-toolbox/data-sheets/cushioning-and-decelerating-methods-for-cylinders/

Wright, A., 2017. *Rota-Eng.* [Online]
Available at: http://rota-eng.com/public_docs/mobile-brochure.pdf

Zhang, X. & Ning, C., 2018. *Study of the Hydraulic synchronous circuit.* [Online]
Available at:
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.819.2642&rep=rep1&type=pdf

Zieseri, M., 2015. *Using Magnetic Sensor ICs In Highly Magnetic Environments.* [Online]
Available at: https://www.fierceelectronics.com/components/using-magnetic-sensor-ics-highly-magnetic-environments

9. APPENDICES

No.	Keywords used			Relevant notes from search		
	Title	Number of results	Year	Patent number	Overview	Notes
1	Wire actuated	77				No Relevant results
2	Wire encoder	26	2016	EP2653428	Wire-actuated linear encoder (used externally)	Cable sensor used to measure distance boom of crane has been extended. Also used a eddy current brake.
3	Wire sensor	1635				Too many returns to check
4	Wire sensor hydraulic	5				No Relevant results
5	Encoder cylinder	22	1996	US6393963	Hydraulic cylinder with position encoder	Uses hall effect sensors
6	Absolute cylinder encoder	0				
7	Wire position sensor	41				No Relevant results
8	Cable sensor	1549				Too many returns to check
9	Cable sensor hydraulic	3	2012	DE102012209715	Cable length transmitter for working cylinder for detecting number of revolutions	A rotatable cable drum for winding a cable and a detection device to measure number of revolutions. Somwhat similar but vague on specific details.
10	In cylinder wire sensor	1				No Relevant results
11	Linear sensor measurement	62				No Relevant results
12	stroke measurement hydraulic cylinders	0				No Results
13	string pot hydraulic cylinder	0				No Results

Table 7 Title search patent results

No.	Title or abstract	Number of results	Year	Patent number	Overview	Notes
1	string pot hydraulic cylinder	1				No Relevant results
2	stroke measurement hydraulic cylinder	99	2014	CN204082748	Oil cylinder with built-in sensor	Uses a pull wire sensor which enters the oil and is connected to the piston head. The wire outlet is provided with hydraulic seals and sensor can bear pressure to a certain degree.
3	drum position measurement	648				Too many returns to review efficiently
4	drum position measurement pressure	65				No Relevant results
5	precision sensor hydraulic cylinder	4	2001	US2001018861	Uses a sensor mountable in a hydraulic sensor. Uses a flexible connector between converting element and piston.	Looks to be using a big bulky coil spring and reel for pulling in the wire, but somewhat same principle used as proposed sensor type selected to pursue
6	precision sensor wire	2125				Too many returns to check
7	precision sensor wire measurement	568	2014	CN204007495	Stay wire displacement sensor	A steel strand wound around a rotational wire hub. There are gears and a circuit board with an angle sensor. Looks to be an external wire transducer.

Table 8 Title or Abstract results 1-7

No.	Title or abstract	Number of results	Year	Patent number	Overview	Notes
7	precision sensor wire measurement	568	2006	CN202770388	Tensile cable type linear displacement sensor	Uses an automatic plastic angle displacement sensor. It uses the angle sensor to convert to distance measurement. (Non-hydraulic sensor)
8	cylinder stroke measurement	452	2016	CN205260492	Hydro - cylinder displacement detection device and changer	Uses a connection between the piston rod of the hydraulic cylinder and a universal coupling. Linear motion converted into rotary motion and therefore displacement of piston measured.
9	cylinder stroke measurement	568	2015	KR20150134146	Device for stroke measurement of a hydraulic cylinder	Connects a sensor body to one side of cylinder. Uses a magnetic plate to convert linear motion into rotary motion.
10	sensing convert wire	63				No Relevant results

Table 9 Title or Abstract results 7-10

No.	Title or abstract	Number of results	Year	Patent number	Overview	Notes
11	sensor convert wire	224	2013	CN102997829	Micro-displacement sensor	A steel wire rope is wound on a disc wheel and is drawn to convert linear displacement motion into rotation of the acceleration mechanism. Reed switch generates pulse signal, so displacement is computed according to pulse data. Difference appears to be how the rotary data is converted to displacement using reed rather than angular sensor.
12	wire pull displacement	417		CN105547123	Displacement measurement device and displacement measurement method by adopting displacement measurement device	Contains a winding assembly and a pull wire and through calculation on the pulse signals, the displacement generated by the measured workpiece is acquired

Table 10 Title or Abstract results 11-12

No.	Title or abstract	Number of results	Year	Patent number	Overview	Notes
13	Not used		2009	DE202009015774	measurement cable distance sensor for pressurised systems	Draw Wire Sensor is designed for an installation directly in the head of a hydraulic cylinder. The sensor reliably determines the exact position of the cylinders piston and emits an equivalent output signal by its sensor element. The draw wire mechanics gets installed in the pressurised area whereas the sensor element is attached at the outside of the cylinder.
14	Linear wire drum	356				No Relevant results
15	rotary encoder position	4618				Too many returns to check
16	rotary encoder position linear	358				No Relevant results
17	wire hydraulic linear	272				No Relevant results

Table 11 Title or Abstract results 13-17

AS5601

12-Bit Programmable Contactless Encoder

General Description

The AS5601 is an easy-to-program magnetic rotary position sensor with incremental quadrature (A/B) and 12-bit digital outputs. Additionally, the PUSH output indicates fast airgap changes between the AS5601 and magnet which can be used to implement a contactless pushbutton function in which the knob can be pressed to move the magnet toward the AS5601.

This AS5601 is designed for contactless encoder applications, and its robust design rejects the influence of any homogenous external stray magnetic fields.

Based on planar Hall sensor technology, this device measures the orthogonal component of the flux density (Bz) from an external magnet.

The industry-standard I^2C interface supports user programming of non-volatile parameters in the AS5601 without requiring a dedicated programmer.

The AS5601 also provides a smart low-power mode which automatically reduces power consumption

Ordering Information and Content Guide appear at end of datasheet.

Key Benefits & Features

The benefits and features of AS5601, 12-bit Programmable Contactless Encoder are listed below:

Figure 1:
Added Value of Using AS5601

Benefits	Features
• Highest reliability and durability	• Contactless angle measurement insensitive to dust and dirt
• Simple programming	• Simple user-programmable zero position and device configuration
• Flexible choice of the number of A/B pulses per revolution	• Quadrature output configurable from 8 up to 2048 positions
• Contactless pushbutton functionality	• Pushbutton output by detecting sudden airgap changes
• Low power consumption	• Automatic entry into low-power mode
• Easy setup	• Automatic magnet detection
• Small form factor	• SOIC-8 package
• Robust environmental tolerance	• Wide temperature range: -40°C to 125°C

Figure 155 AS5601 Rotary Position Sensor

AS5161

12-Bit Magnetic Angle Position Sensor

The AS5161 is a contactless magnetic angle position sensor for accurate angular measurement over a full turn of 360°. A sub range can be programmed to achieve the best resolution for the application. It is a system-on-chip, combining integrated Hall elements, analog front end, digital signal processing and best in class automotive protection features in a single device.

To measure the angle, only a simple two-pole magnet, rotating over the center of the chip, is required. The magnet may be placed above or below the IC.

The absolute angle measurement provides instant indication of the magnet's angular position with a resolution of 0.022° = 16384 positions per revolution. According to this resolution the adjustment of the application specific mechanical positions are possible. The angular output data is available over a 12 bit pulse width modulated (PWM) output.

The AS5161 operates at a supply voltage of 5V and the supply and output pins are protected against overvoltage up to +20V. In addition the supply pins are protected against reverse polarity up to –20V.

Figure 1:
Typical Arrangement of AS5161 and Magnet

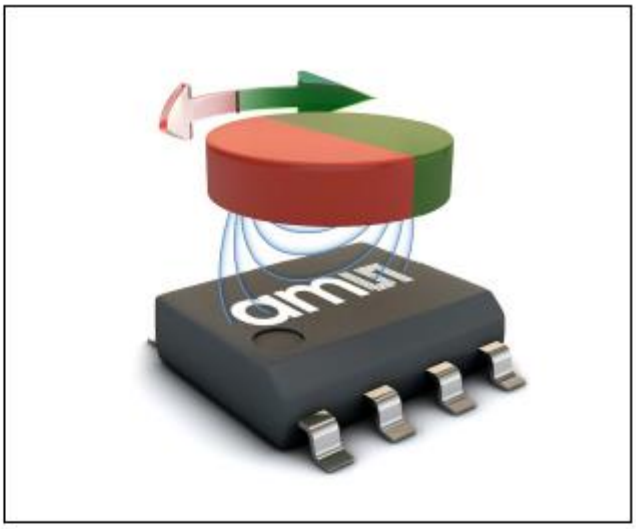


Figure 156 AS5161 Magnetic Position Sensor

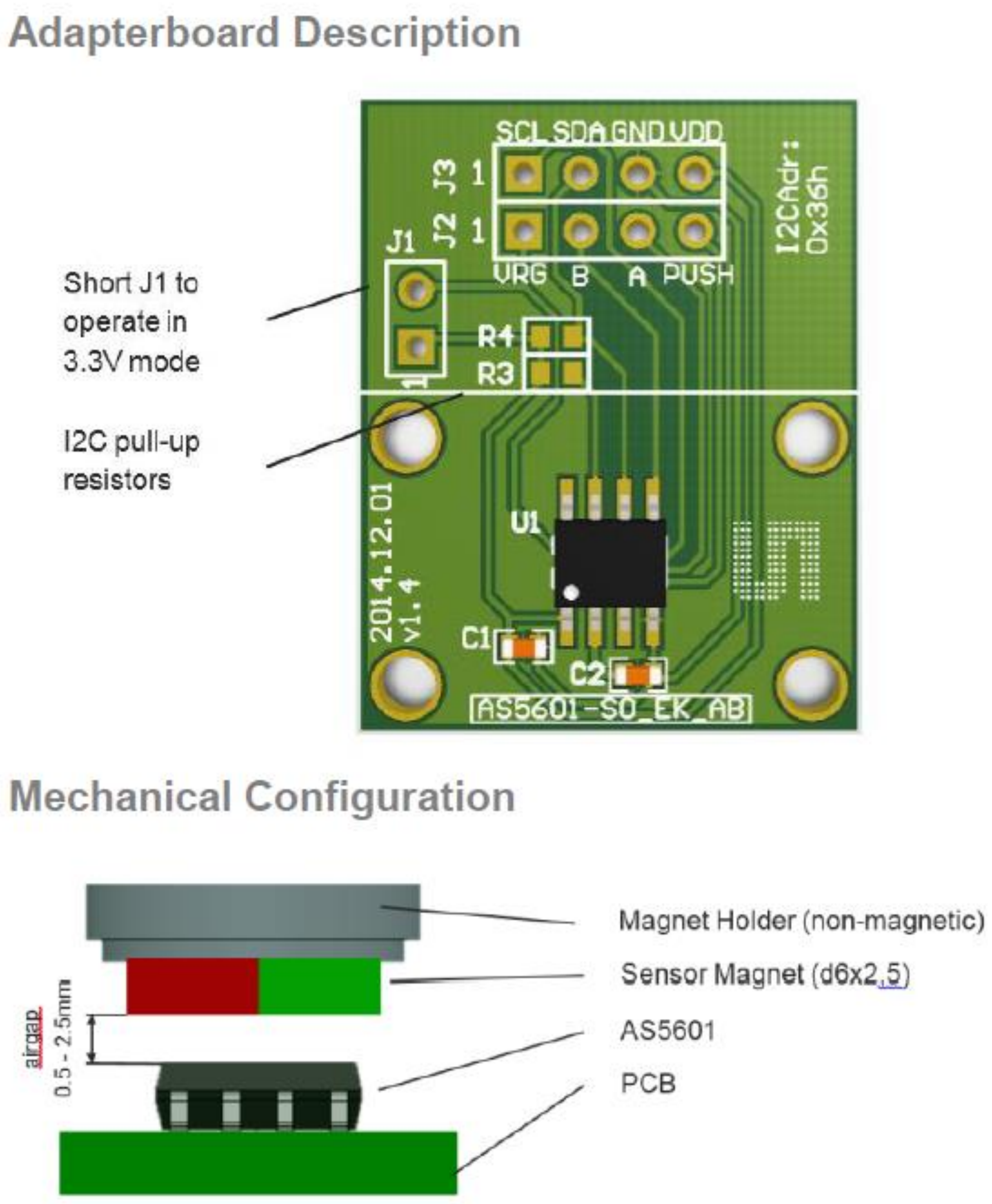


Figure 157 AS5601 Adaptor Board

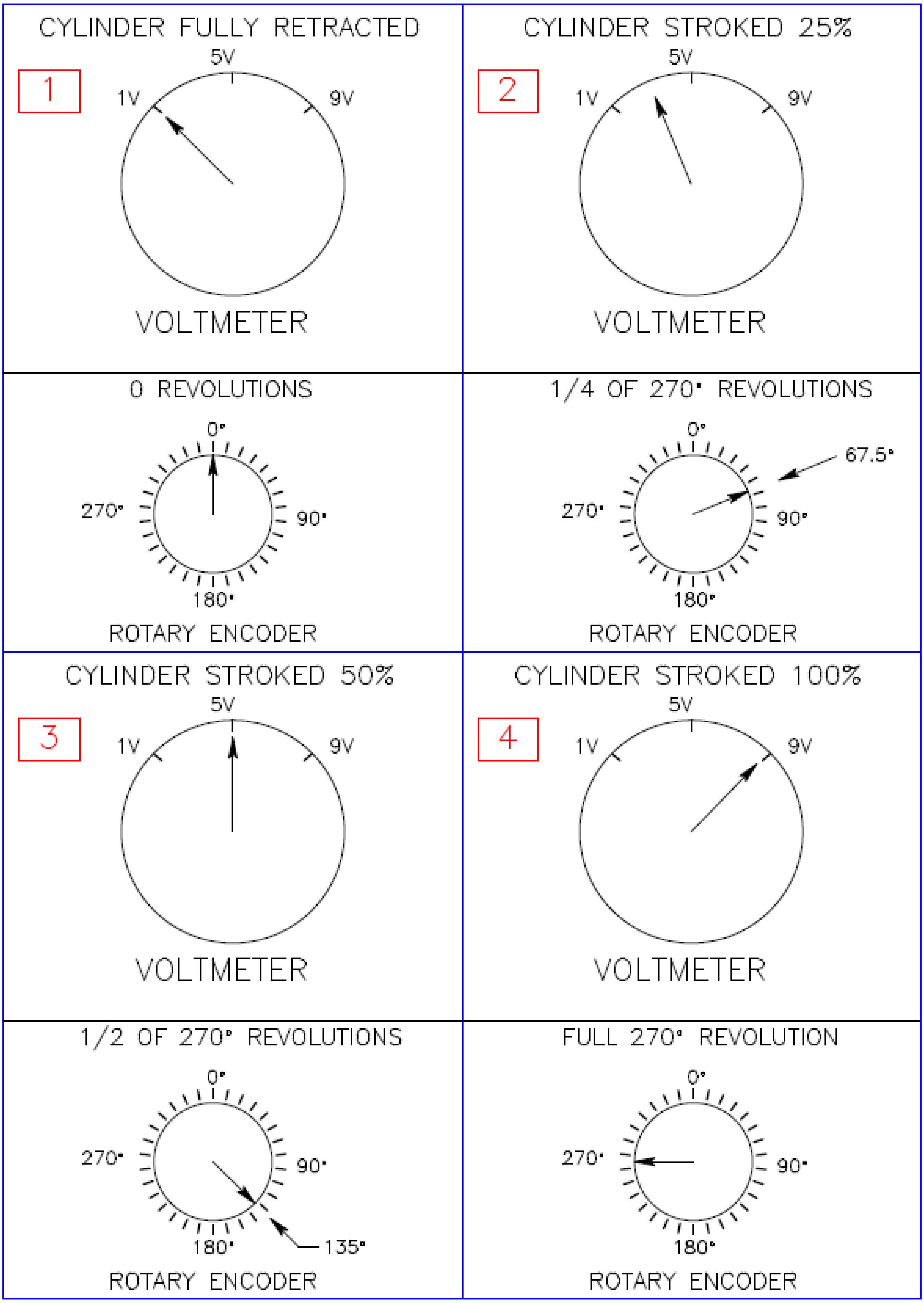


Figure 158 Single encoder to measure cylinder stroke

Magnet		AMS supplied		
Dimension		Ø6mm X 2.5mm Solid (35BH)		
Board		AS5601 Adaptor Board		
Frame		Plastic Frame		
Medium		Air		
Temperature		20°C		
Gap	AGC (0-255 scale)	Working	Fluxation of angular units static position 0-2048 divisions)	Effective angular error °
1mm	81	ok	0	0
1.5mm	105	ok	0	0
2mm	153	ok	0	0
2.5mm	255	ok	0	0
3mm	255	ok	0	0
3.5mm	255	ok	0	0
4mm	255	ok	0	0
4.5mm	255	ok	0	0
5mm	255	ok	0	0
5.5mm	255	ok	0	0
6mm	255	ok	0	0
6.5mm	255	ok	0	0
7mm	255	ok	0	0
7.5mm	255	ok	0	0
8mm	255	ok	0	0
8.5mm	255	ok	0	0
9mm	255	ok	0	0
9.5mm	255	ok	0	0
10mm	255	ok	0	0
10.5mm	255	ok	0	0
11mm	255	ok	1	0.18
11.5mm	255	ok	1	0.18
12mm	255	ok	1	0.18
12.5mm	255	ok	1	0.18
13mm	255	ok	1	0.18
14mm	255	ok	1	0.18
15mm	255	ok	1	0.18
16mm	255	ok	1	0.18
17mm	255	ok	7	1.23
18mm	255	ok	10	1.76
19mm	255	ok	14	2.46
20mm	255	ok	20	3.52

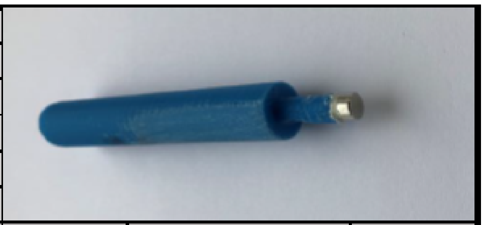
Table 12 Ø6 x 3mm Magnet Plastic Frame

Magnet	AMS supplied	
Magent Dimension	Ø6mm X Ø3mm Ring x 5mm	
Board	AS5601 Adaptor Board	
Frame	Aluminum Frame	
Medium	Air	
Temperature	20°C	

Air gap Bottom	Aluminum Gap	Air Gap Top	**Total Gap**	**AGC (0-255 scale)**	Working	Fluxation of angular units static position 0-2048 divisions)	Effective angular error °
0.5mm	3.5mm	0mm	4mm	255	ok	0	0
0.5mm	3.5mm	0.5mm	4.5mm	255	ok	0	0
0.5mm	3.5mm	1mm	5mm	255	ok	0	0
0.5mm	3.5mm	1.5mm	5.5mm	255	ok	0	0
0.5mm	3.5mm	2mm	6mm	255	ok	0	0
0.5mm	3.5mm	2.5mm	6.5mm	255	ok	0	0
0.5mm	3.5mm	3mm	7mm	255	ok	0	0
0.5mm	3.5mm	3.5mm	7.5mm	255	ok	0	0
0.5mm	3.5mm	4mm	8mm	255	ok	0	0
0.5mm	3.5mm	4.5mm	8.5mm	255	ok	0	0
0.5mm	3.5mm	5mm	9mm	255	ok	1	0.18
0.5mm	3.5mm	5.5mm	9.5mm	255	ok	1	0.18
0.5mm	3.5mm	6mm	10mm	255	ok	2	0.35
0.5mm	3.5mm	6.5mm	10.5mm	255	ok	3	0.53
0.5mm	3.5mm	7mm	11mm	255	ok	4	0.70
0.5mm	3.5mm	7.5mm	11.5mm	255	ok	4	0.70
0.5mm	3.5mm	8mm	12mm	255	ok	4	0.70
0.5mm	3.5mm	8.5mm	12.5mm	255	ok	4	0.70
0.5mm	3.5mm	9mm	13mm	255	ok	5	0.88
0.5mm	3.5mm	9.5mm	13.5mm	255	ok	5	0.88
0.5mm	3.5mm	10mm	14mm	255	ok	8	1.41
0.5mm	3.5mm	10.5mm	14.5mm	255	ok	8	1.41
0.5mm	3.5mm	11mm	15mm	255	ok	9	1.58
0.5mm	3.5mm	11.5mm	15.5mm	255	ok	10	1.76
0.5mm	3.5mm	12mm	16mm	255	ok	10	1.76
0.5mm	3.5mm	12.5mm	16.5mm	255	ok	11	1.93
0.5mm	3.5mm	13mm	17mm	255	ok	12	2.11
0.5mm	3.5mm	14mm	17.5mm	255	ok	13	2.29

Table 13 Results Ø6mm x Ø3mm x 5mm long Ring (Aluminium block)

Magnet	AMS supplied
Dimension	Ø6mm X 2.5mm Solid (35BH)
Board	AS5601 Adaptor Board
Frame	Aluminum Frame
Medium	Air
Temperature	20°C



Air gap Bottom	Aluminum Gap	Air Gap Top	**Total Gap**	**AGC (0-255 scale)**	Working	Fluxation of angular units static position 0-2048 divisions)	Effective angular error °
0.5mm	3.5mm	0mm	4mm	255 (too high)	ok	0	0
0.5mm	3.5mm	0.5mm	4.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	1mm	5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	1.5mm	5.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	2mm	6mm	255 (too high)	ok	0	0
0.5mm	3.5mm	2.5mm	6.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	3mm	7mm	255 (too high)	ok	0	0
0.5mm	3.5mm	3.5mm	7.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	4mm	8mm	255 (too high)	ok	0	0
0.5mm	3.5mm	4.5mm	8.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	5mm	9mm	255 (too high)	ok	0	0
0.5mm	3.5mm	5.5mm	9.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	6mm	10mm	255 (too high)	ok	0	0
0.5mm	3.5mm	6.5mm	10.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	7mm	11mm	255 (too high)	ok	0	0
0.5mm	3.5mm	7.5mm	11.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	8mm	12mm	255 (too high)	ok	0	0
0.5mm	3.5mm	8.5mm	12.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	9mm	13mm	255 (too high)	ok	0	0
0.5mm	3.5mm	9.5mm	13.5mm	255 (too high)	ok	0	0
0.5mm	3.5mm	10mm	14mm	255 (too high)	ok	1	0.18
0.5mm	3.5mm	10.5mm	14.5mm	255 (too high)	ok	1	0.18
0.5mm	3.5mm	11mm	15mm	255 (too high)	ok	1	0.18
0.5mm	3.5mm	11.5mm	15.5mm	255 (too high)	ok	7	1.23
0.5mm	3.5mm	12mm	16mm	255 (too high)	ok	13	2.29
0.5mm	3.5mm	12.5mm	16.5mm	255 (too high)	ok	17	2.99
0.5mm	3.5mm	13mm	17mm	255 (too high)	ok	22	3.87

Table 14 Results Ø6mm x Ø3mm Solid (Aluminium block)

Inputs				Results			
Hole size (mm)	Pressure (bar)	Yield Strength (N/mm^2)	Shear Thickness	Loading N/mm^2	Shear area (mm^2)	Yielding Force	Safety Factor SF/1
7	400	100	3.5	1539	77	20	5.00
8	400	100	3.5	2011	88	23	4.4
9	400	100	3.5	2545	99	25.7	3.9
10	400	100	3.5	3142	110	28.6	3.5
7	400	100	4	1539	88	17.5	5.7
8	400	100	4	2011	101	20	5.0
9	400	100	4	2545	113	22.5	4.4
10	400	100	4	3142	126	25.0	4
7	400	100	4.5	1539	99	15.6	6.4
8	400	100	4.5	2011	113	18	5.6
9	400	100	4.5	2545	127	20.0	5.0
10	400	100	4.5	3142	141	22.2	4.5
7	400	100	5	1539	110	14.0	7.1
8	400	100	5	2011	126	16	6.3
9	400	100	5	2545	141	18.0	5.6
10	400	100	5	3142	157	20.0	5

Table 15 Shear results

Inputs						Results						
Housing OD	Wire section	Effective PCD	Wire Travel one revolution	No of wire revolutions on housing	Gear Ratio selected :1	Total stroke available	Angle Magnetic encoder used of 360°	Resolution encoder	Available encoder angle used	resolution of encoder used	Resultant resolution stroke	voltage steps
44	0.5	44.5	139.80	11	11.2	1538	354	2048	98.2%	2011.4	0.76	0.0038
44	0.5	44.5	139.80	10.5	11	1468	344	2048	95.5%	1954.9	0.75	0.0038
44	0.5	44.5	139.80	10	10.5	1398	343	2048	95.2%	1950.5	0.72	0.0037
44	0.5	44.5	139.80	9.5	10	1328	342	2048	95.0%	1945.6	0.68	0.0035
44	0.5	44.5	139.80	9	9.5	1258	341	2048	94.7%	1940.2	0.65	0.0033
44	0.5	44.5	139.80	8.5	9	1188	340	2048	94.4%	1934.2	0.61	0.0032
44	0.5	44.5	139.80	8	8.5	1118	339	2048	94.1%	1927.5	0.58	0.0030
44	0.5	44.5	139.80	7.5	8	1049	338	2048	93.8%	1920.0	0.55	0.0028
44	0.5	44.5	139.80	7.25	7.5	1014	348	2048	96.7%	1979.7	0.51	0.0026
44	0.5	44.5	139.80	6.5	6.75	909	347	2049	96.3%	1973.1	0.46	0.0023
44	0.5	44.5	139.80	6	6.5	839	332	2050	92.3%	1892.3	0.44	0.0023
44	0.5	44.5	139.80	5.5	6	769	330	2051	91.7%	1880.1	0.41	0.0022
44	0.5	44.5	139.80	5	5.5	699	327	2052	90.9%	1865.5	0.37	0.0020
44	0.5	44.5	139.80	4.5	5	629	324	2053	90.0%	1847.7	0.34	0.0018

Table 16 Evaluating Gearing

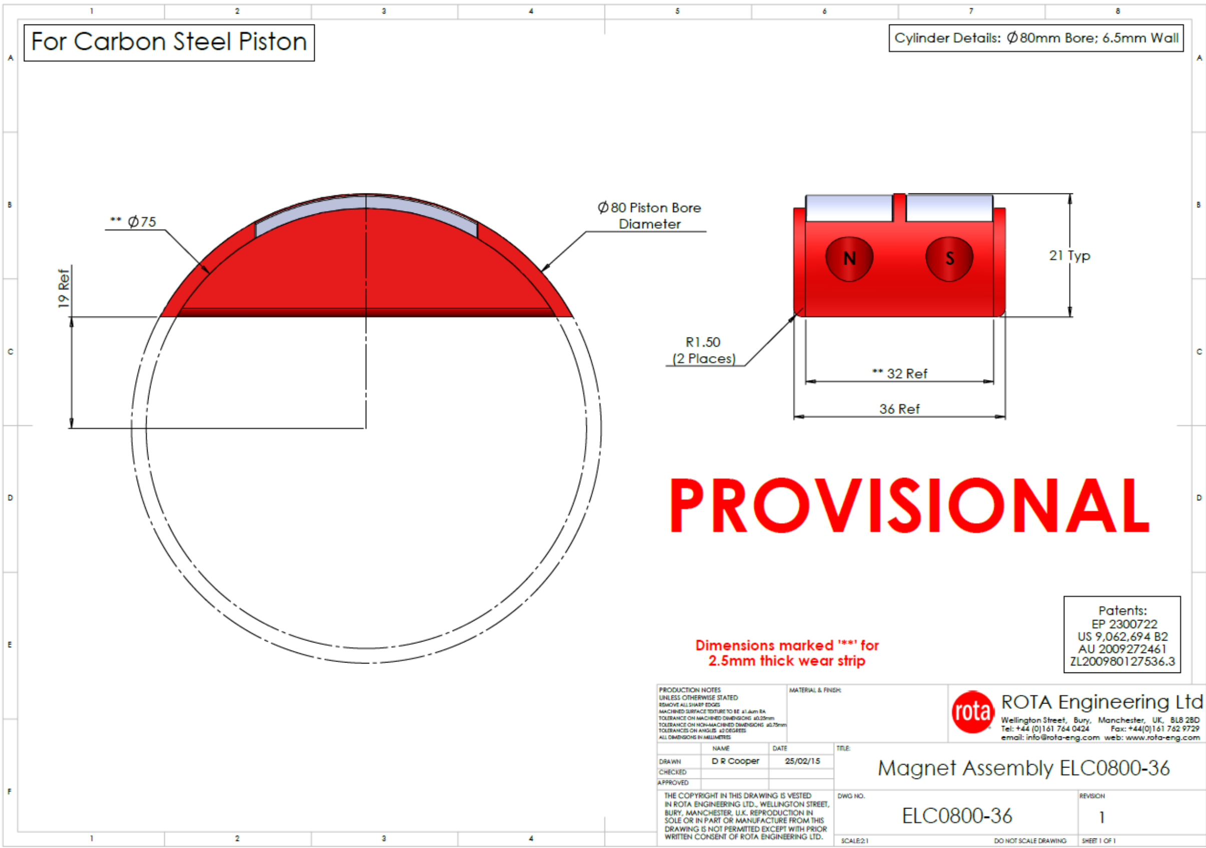


Figure 159 Piston magnet

TSYS01
Digital Temperature Sensor

FEATURES

High Accuracy ±0.1°C @ Temp.: -5°C … +50°C
Adjustment of high accuracy temp. range on request
Low Current, <12.5 µA (standby < 0.14 µA)
SPI / I²C Interface
Small Package: QFN16
Operating Temperature Range: -40°C … +125°C

APPLICATIONS

Industrial Control
Replacement of Thermistors and NTCs
Heating / Cooling Systems
HVAC

ABSOLUTE MAXIMUM RATINGS

Absolute maximum ratings are limiting values of permitted operation and should never be exceeded under the worst possible conditions either initially or consequently. If exceeded by even the smallest amount, instantaneous catastrophic failure can occur. And even if the device continues to operate satisfactorily, its life may be considerably shortened.

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
Supply Voltage	VDD		-0.3		+3.6	V
Operating Temperature	Top		-40		+125	°C
Storage temperature	Tstor		-55		+150	°C
ESD rating	ESD	Human Body Model (HBM) pin to pin incl. VDD & GND	-4		+4	kV
Humidity	Hum		Non condensing			

OPERATING CONDITIONS

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
Operating Supply Voltage	V_{DD}	stabilized	2.2		3.6	V
High Accuracy Supply Voltage	V_{DD}	To achieve Acc1	3.2		3.4	V
Supply Current	I_{DD}	1 sample per second			12.5	µA
Standby current	IS	No conversion, VDD = 3V T = 25°C T = 85°C		0.02 0.70	0.14 1.40	µA µA
Peak Supply Current	I_{DD}	During conversion		1.4		mA
Conversion time	T_{CONV}		7.40	8.22	9.04	ms
Serial Data Clock SPI	F_{SCLK}				20	MHz
Serial Data Clock I²C	F_{SCL}				400	kHz
VDD Capacitor		Place close to the chip	100nF			

Figure 160 TSYS01 Temperature sensor data sheet