Integration and Commercialisation of Tube Measuring Devices

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Bernard James Huggins

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Abstract

Failure of plant equipment in the hydrocarbon processing industry can lead to significant financial, environmental, and health and safety consequences. Therefore, the equipment is subject to ongoing routine inspections, which often involve significant labour and financial resources.

Methanex is a methanol producing company operating plants at six sites globally, including in New Zealand. The production of methanol involves the use of steam-methane reformers, which house hundreds of process-carrying vertically hung reformer tubes in a large gas fired furnace box. The heat and pressure of the process places the metal used for the tubes under high stresses, which results in the creep strain phenomenon exhibited as diametric growth in the tube. As the growth increases, the tube becomes weaker, and eventually fails. Methanex has developed a device for inspecting the reformer tubes and detecting this growth, called the Economole, thus helping to predict remaining tube life. However, the Economole device is not capable of inspecting the other part of the reformer, also at risk of creep strain, the pigtail collection pipes. These pipes are used to collect the gas at the bottom of the reformer tubes, and are smaller in diameter. Normal practice is to manually externally inspect these pipes, costing in excess of 100 000 NZD for Methanex New Zealand’s three reformers.

The research performed during this thesis was initiated to address the gap in internal, automated, reformer inspection at Methanex, by integrating the field proven Economole tube measuring device, with a laboratory tested prototype, the Minimole. Commercialisation of the Minimole concept was carried out, to provide a fit for purpose device, and integration of mechanical, electrical, communication and control systems was subsequently completed.

The final outcome of the project was the MXmole device. It consists of an improved Economole system, integrated with the Minimole system.. The MXmole is able to measure the full reformer tube, as well the top section of the reformer pigtail, during one inspection. Real time feedback is provided on the condition of the pigtail, with instantaneous critical warnings, indicating near end of life of the pigtail. This feedback can initiate immediate necessary replacement. Inspection coverage for Methanex’s reformer equipment has increased as a result of this research. This increase has provided them with additional data necessary to assess the life expectancy of their reformer equipment, including pigtails, without the need for costly and laborious manual external inspection. The outcome of this research may be adapted to other plants and processes in industry, allowing further economical inspection of equipment vulnerable to creep strain, and the overall safer and more reliable operation of high pressure and temperature plant equipment in industry.

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Chapter 1. Introduction

1.1 Overview

This research was carried out to address a gap in high pressure and temperature equipment inspections. The research was initiated by Peter Tait, who is a global expert in static equipment, for *Methanex New Zealand Limited* (Methanex), where the project has been based.

Methanex is a methanol producer, which entails the operation of plant equipment at temperatures and pressures lending themselves to excessive stresses and potential rupture over time. This occurs due to a highly researched mode of failure, which reveals itself as a permanent growth in the dimensions of metal process components over time.

To mitigate the risk of catastrophic plant failure, Methanex currently inspect the main section of their higher risk plant at regular intervals. Using a University of Canterbury developed inspection instrument, the plant equipment is inspected for signs of imminent failure, typically exhibited as diametric growth in cylindrical parts. This is standard industry practice, which Methanex take one step further, utilising the data for asset management. This avoids in-service failures and maximises the life of each part. The developed tools are integral in achieving this. However, the tools are currently unable to gain the inspection coverage that Methanex desires.

This research project was raised with the aim of capitalizing on a lab tested piece of instrumentation, called the *Minimole.* This instrument has been designed to address the gap in the testing which Methanex requires. The objectives of the project are outlined in the project execution plan (Appendix 1) with the successful completion of the project stated therein as:

> "Full mechanical, electronic, and software integration of Minimole probe with Economole System [existing], resulting in an all in one system that is readily manufacturable for deployment globally. The system will provide low-cost, low-impact maintenance inspection of reformer tube equipment [currently covered], including the upper section of the pigtail [the extent of the coverage desired]."

1.2 Methanex

Methanex is a global methanol production and supply company. The company is the world's largest producer and supplier of methanol, producing methanol at six sites globally, and distributing worldwide via a dedicated tanker fleet of 17 vessels (Methanex Corporation, 2015a).

Methanol is a form of alcohol with uses, among others, in transportation fuel, as a key component in the production of synthetic and bio fuels, and as a chemical feedstock (Methanol Institute, 2011).

The two Methanex sites operating in New Zealand are Motunui and Waitara Valley, both in Taranaki. The Motunui plants were commissioned in 1985, built and operated by the New Zealand government as part of the ‘think big’ energy and infrastructure projects of the time (Naidu, 2014). The Motunui plant was originally built for natural gas to methanol to gasoline production, the first production plant in the world to do so, while Waitara Valley was used to produce methanol for the export market, with the overall theme being to “put the Maui and Kapuni natural gas fields to good use” (Naidu, 2014; Greg & Walrond, 2012; Stace, 1990). From 1989 to 1993 Fletcher Challenge Limited took over ownership and operation of the two sites, as the government of the day lost the appetite for the inherent risk involved with energy asset ownership (Naidu, 2014; Gas Industry Company Limited, 2013). From 1993 to 1994 Methanex took up ownership and operation of the two plants, eventually stopping gas to gasoline production on the Motunui plant in 1996. The gas to gasoline plant equipment was eventually sold for scrap metal in 2004 (Naidu, 2014; Methanex Corporation, 2015b). Over the next seven years activity fluctuated according to varying market conditions and gas supply issues. Both plants have now been consistently operational since 2013 (Naidu, 2014; Methanex Corporation, 2015b).

1.3 Steam-Methane Reforming

Steam-methane reforming is the predominant method used in the production of methanol on an industrial scale (Methanex Corporation, 2015c). This begins with mixing steam and a hydrocarbon feedstock together in a *reformer* to create *synthesis gas*. Natural gas is considered the cheapest hydrocarbon feedstock in this process (Speight, 2011); at Methanex, steam is mixed with natural gas from the nearby Pohokura gas field. The synthesis gas is then converted and distilled to create pure methanol (Methanex Corporation, 2015c).

The creation of synthesis gas is an endothermic process (Speight, 2011), meaning that heat input is required in order to facilitate the necessary reaction. The reaction requires heating the gas mixture to around 815 °C, before passing it over a specific catalyst to engage the desired reaction (Speight, 2011). The reformers at Methanex facilitate this with catalyst filled tubes hanging vertically in a furnace box. A depiction of this set up is shown in Figure 1. The process mixture of steam and natural gas is fed into the top, heated while passing over the catalyst, and exits as synthesis gas. This process has a limited conversion rate, which is mitigated by recycling excess carbon dioxide that is taken out in the downstream purification process (Speight, 2011).

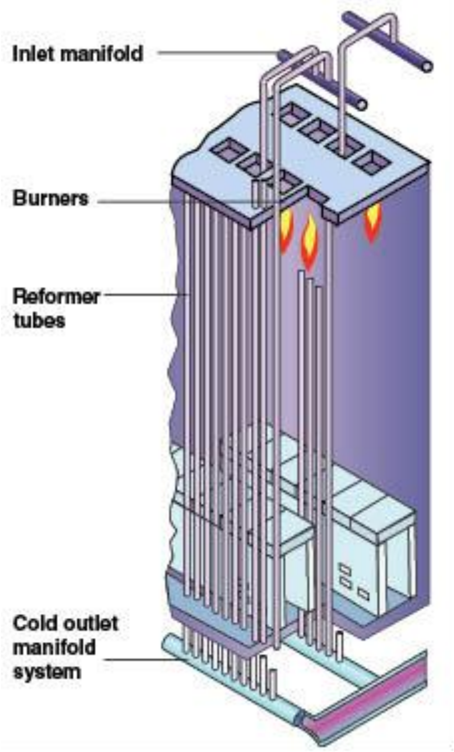

Figure 1: Typical vertical tube reformer set up (Gumilar, 2010)

Of particular interest in this research are the reformer *tubes* and *pigtails*. The tubes run the height of the reformer (at 15 m each), are heated via external firing, and contain the catalyst necessary for the reaction. The pigtails are of a reduced diameter, collecting the gas at the bottom of the tube, and piping it to a common collection manifold.

1.4 In-Service Inspections of Pressure Equipment

In New Zealand, most pressure equipment must be inspected according to the Ministry of Business, Innovation and Employment's Approved Code of Practice for Pressure Equipment (Excluding Boilers) (Department of Labour, 2001), in order to comply with the Health and Safety in Employment Act (1992). The code states that the objectives of inspection are to comply with legislation, and to protect people, assets, and the environment. Steam-methanol reformers are a type of fired heater pressure equipment, and fall under this requirement.

The code of practice specifies that in-service inspections shall be carried out. In-service inspections are those which are carried out post design, installation, and commissioning, when the vessel is in service. Carrying out effective in-service inspections, in order to comply with the code necessitates "verifying that pressure equipment is safe and fit for service under the specified operating conditions until the next planned inspection" (Department of Labour, 2001). The code requires that the inspections are carried out at intervals set with regards to "generally accepted industry practice, AS/NZS 3788 and this code" (Department of Labour, 2001).

AS/NZS 3788 is the Australian/New Zealand Standard titled "Pressure equipment – In-service inspection" (2006), falling under the parent code AS/NZS 1200 for pressure equipment (2000). There is some room for interpretation in the code, when selecting the time interval for a specific piece of plant; however, whether a reformer is considered a steam pressure vessel, fired heater, or convection bank under AS/NZS 3788, or a catalyst containing reactor vessel under the code, the internal inspection interval is set at four years. Taking the conservative approach, as the reformer is effectively a catalyst filled reactor, *external* inspection must be carried out yearly according to the code, or two yearly when the controller has a sufficient inspection management system. Methanex had a leading hand in the recognition of risk based assessment as part of a sufficient management system, leading to this being included in the code (Malcolm Kelsen, personal communication, January 28, 2016).

1.5 Pressure Equipment Design Life

Pressure equipment, like modern houses, bridges, and power transmission lines, is designed with a pre-defined service life. Design life is observed to be typically engineered based on eventual expected failures from things such as corrosion, cyclical stresses, wear, and from required useful life span, derived, for example, from gas field life expectancy. Therefore, it is the prerogative of the owner/designer to set the reformer tube life (Peter Tait, personal communication, January 14, 2016).

Peter Tait (January 14, 2016), the global expert in static equipment for Methanex New Zealand Limited, says:

> "The actual life is heavily influenced by the operating conditions and is to a large extent manageable. However the nature of the equipment and components means that there is a large spread in actual life and the key to meeting life and production requirements is in identifying the outliers."

IPENZ Practice Note 19 (2013) has recommended a design life of new pressure vessels of 25 years, as per the Australian standard AS 1210:2010 requirement. As this standard comes under the parent AS/NZS 1200 standard, this must be followed according to the Approved Code of Practice for Pressure Equipment. Equipment designed and built before or not following such requirements simply carries with it a life expectancy based on the design and predicted operating conditions.

Design life is directly affected by the ability to assess defects that lead to failure. For example, the amount of corrosion a high pressure pipeline may experience before becoming too thin and unable to hold design pressure. Therefore, it is necessary to monitor the engineering factors contributing to design life. These factors must take into account the margin of uncertainty around any inspection technique being used to gather data (Grote & Antonsson, 2009).

1.6 Scope of Research

The scope of the research is to derive a solution to measuring small bore pipe diameters, in the context of large scale fired industrial plant equipment. This will require measurement to an accuracy appropriate for discerning predicted end of life of the measured pipe. This will be achieved by integrating the existing main inspection device that Methanex uses, the *Economole*, with the lab tested Minimole prototype.

Not included in the scope of research is the development of other measuring principles not used in the Minimole prototype. The scope is set as such in order to ensure focus and the timely delivery of a useable device at the end of the project period.

1.7 Problems and Challenges

The Minimole probe, introduced earlier in this chapter, was received in an unfinished lab tested state. This presents the challenge of developing and testing the probe for deployment into a field environment which is the aim of this master's thesis research.

The aim of integrating two separately developed pieces of equipment presents challenges in mechanical, electrical, and software design and engineering. Each part must interface seamlessly.

The entire assembly must operate in the field as one unit, without failure. This environment may be dusty, and involve knocking and rough handling.

Existing literature on the systems is not readily available. Discerning exactly the manner in which each separate piece was originally designed, and how it operates, will require finding and compiling resources, and detailed survey and investigation.

1.8 Research Topics

To achieve the final goal of this research, there are a number of major research topics, which are mentioned in brief here.

Data communications technology will be investigated. It will be necessary to determine a suitable method for transmitting data between the Minimole and Economole, and measurements to the user.

Measurement technologies will be investigated to ensure that the project outcome will be fit for purpose. This will mean providing stable displacement measurements that meet accuracy requirements in determining excessive pipe growth.

Analogue signal processing will be researched, in order to design electronics to process sensor data appropriately.

Calibration practices will be investigated. This will be necessary in order to provide a sound calibration technique for the Minimole probe.

Power delivery and energy storage will be researched. The Minimole probe will require power to take measurements and either store or transmit the data.

Fabrication and prototyping techniques will be investigated. These will utilised to best suit the project needs, largely in terms of practicality and ease of rapid development.

Project management and execution strategies will be researched. This will ensure that the project is kept to an agreed schedule, and will achieve a successful outcome for all stakeholders.

1.9 Organisation of thesis

The organisation of the thesis is laid out in this section to help the reader, starting after the current introduction chapter.

Chapter 2. Literature Review. This chapter begins by covering the failure modes of steam-methane reformer equipment, mainly through a summary and analysis of papers published on instances of failures. Life expectancy requirements according to codes and standards are then discussed, along with life prediction techniques. This leads to an investigation of inspection techniques for reformers, including Methanex's methods, before arriving finally at "The Opportunity" – the gap in the current research and techniques.

Chapter 3. Research and Methods. This chapter opens with a clear description of the objective of the research. Next, an overview of the proposed design is given, including assessment of the measurement, power, and communication principles to be used. Methodologies are then covered for the mechanical, electrical, and soft system design, and for testing and validation. Lastly, the execution strategy for the project is discussed, which covers how and why the project was conducted as it was.

Chapter 4. System Development and Integration. The main body of work is covered in this chapter. The mechanical, electronic, and software sub systems' design parameters are defined, and concepts developed. Detailed design of the final concepts is exhibited, leading to fabrication and testing. Integration and testing of the system as a whole is covered, before briefly covering the build of an entire modified Economole system from start to finish.

Chapter 5. Results and Discussion. This chapter discusses the results of the research and development, in regards to the success of the outcome and the way in which the project was conducted. Although in many instances this chapter would be the main body of work, in this case the work is based on a research and development project for a specific project. Hence there is not a large amount of data to be interpreted and processed, and the former chapters cover the more pertinent points of the project.

Chapter 6. Conclusions. The thesis ends with this chapter, drawing conclusions from the work completed. These are in terms of the specific project objectives, and the wider implications for the research and development completed. Potential for future work is also covered briefly in this chapter,

Chapter 2. Literature Review

2.1 Failure Mode of Reformer Tubes and Pigtails

Reformer tubes undergo prolonged exposure to high temperature and pressure, over the course of years of service. Although they are designed to operate under these conditions for a number of years, the length of operational service lends itself to opportunity for mishap and chronic fatigue mechanisms. Inspection of Fired Boilers and Heaters, also known as API 573 (2013), is the recommended practice document published by the American Petroleum Institute (API) for the inspection of such plant. This contains known deterioration mechanisms for catalytic reformers, listed as: Creep; Hydrogen attack; Metal dusting; and spheroidization. The known causes of these failures are also listed, and are generally common to high temperature, high pressure, abnormal operation, low process flow, and flame impingement.

Analysis carried out on failed reformer tubes and pigtails reveals that creep strain resulting in rupture is the primary mode of failure presented (as found by Ray et al., 2002; Roberts and Brightling, 2005; and Maharaj, Clement and Dear, 2007). Creep strain is a well known phenomenon defined succinctly by Nayler (1996) as "a slow plastic deformation of a metal under stress especially at high temperature". This is identified by Ray et al in one instance as being caused by a partial blockage of the tubes, by damaged catalyst. This catalyst stems the flow of the process gas, reducing the efficiency of endothermic reaction in the process. This means that without a good flow of gas, the process cannot absorb enough heat, resulting in increasing tube temperature outside the normal operating parameters, subsequently reducing the stress tolerance of the metal. Roberts and Brightling cite cases of burner impingement and mal-distribution of flue gases, resulting in tube failure. Maharaj, Clement and Dear recognise that the undetected non-uniform distribution of heat in the reformer is the cause of failure in their case study.

Although the study by Ray et al identifies the cause of failure as being damaged catalyst causing a blockage in the reformer tube, no mention is made of the potential for this to occur in the pigtail section. This would appear to be a possible scenario; when the extent of catalyst damage is not quantified, it may be presumed that there is potential for small enough particles to accumulate past any holder in the main tube, and cause increased stress in the pigtail section. This is, however, considered unlikely due to increase in gas velocity, as a result of the smaller pigtail diameter. Spyrou et al (2014) report excessive pigtail deformation after seven years of service. This is less than the generally accepted design life of reformer tube assemblies of 11 years (Roberts and Brightling, 2005); it would be desirable from an operator point of view to have tube and pigtail lives match. Spyrou et al (2014) elaborate on main contributing factors to failure, being operating temperature, thickness reduction, external stresses, and grain size of the alloy. However, no rupture or resulting life expectancy was reported in the paper.

API 573 contains a section that specifically discusses the deterioration of steam methane reformers. Creep strain resulting in stress rupture in the tubes and pigtails is the primary focus of the discussion. Identified is the progressive rise in temperature caused by the endothermic catalytic reaction subsiding as the reactants are consumed and the gas absorbing sensible heat, a concept that was not found in the other literature reviewed. The process gas is at its hottest exiting the tube and entering the pigtail, on the way to the collection manifold. Therefore, this is the most likely place to see rupture. Failures at the bottom of the tube are observed in photos shown in the research carried out by Ray et al. (2002) and Roberts and Brightling (2005); one example is shown below (Figure 2).

Figure 2: Failed reformer tubes, showing rupture at the lower end where the pigtail exits (Grote & Antonsson, 2008)

Roumeau (2010) has stated that pigtail failure can occur as early as three years into operation. These failures are, however, reported to be linked directly to the cold working of the pipe during fabrication. This cause of failure is linked closely to the grain size of the metal, in which material selection is an important factor. Therefore, careful material selection and manufacturing processes (hot bending) appear to be the best defence against the fastest cause of failure in the pigtails. The next fastest reported failure found is four years (Ray et al, 2011), due again to catalyst blockage, causing elevated temperature and accelerated creep strain.

Methanex (2012) presents pigtail failures due to creep, embrittlement, and nitriding, as early as 4 years. Figure 3 shows images from the presentation relating to these three failure modes. The extent of bulging that can occur leading to rupture is the most readily observable.

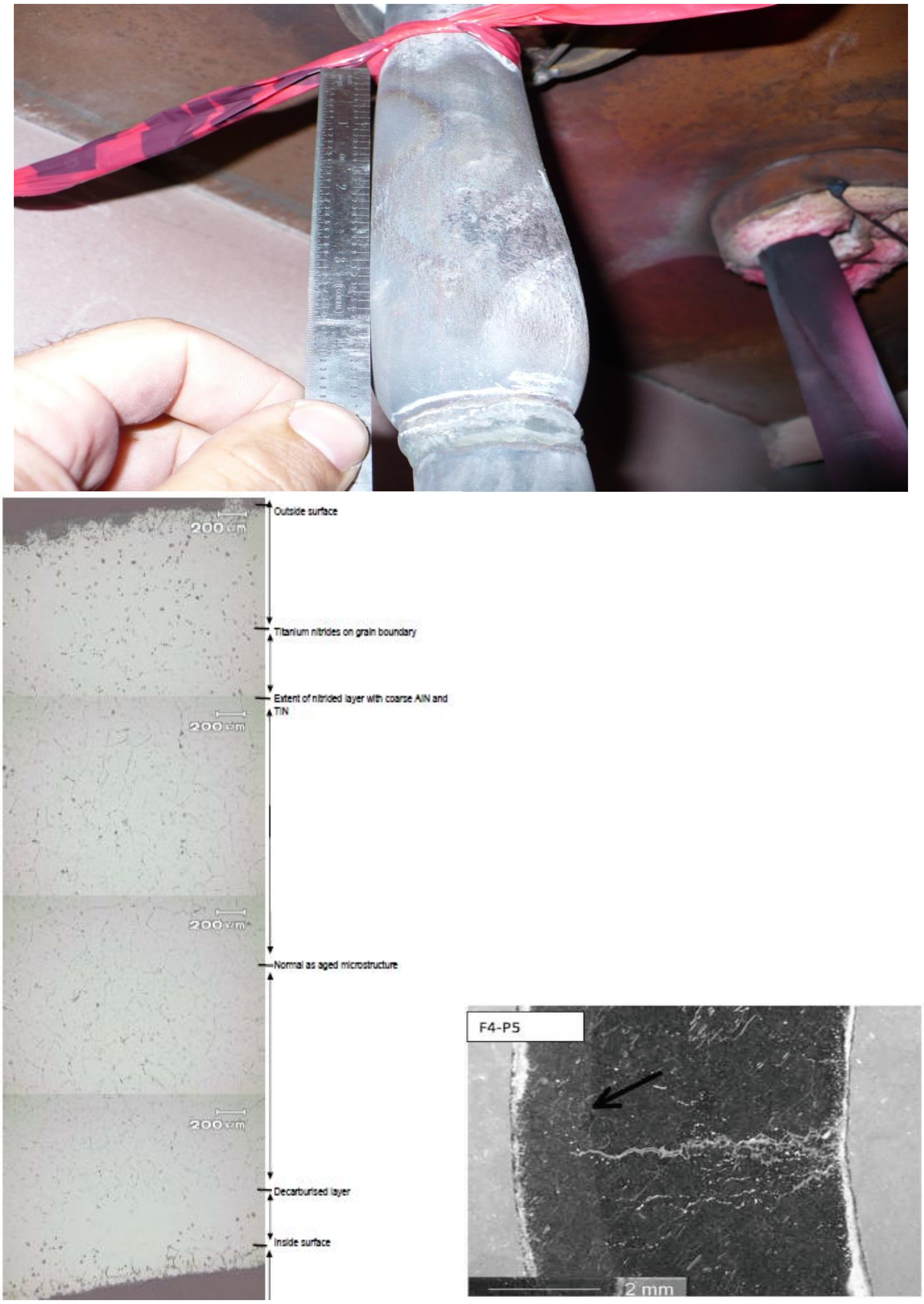

Figure 3: Pigtails failures, clockwise from top: photo of pigtail bulging due to creep strain – original diameter in bottom of photo, bulge in top; microscopic images of cracking due embrittlement from a sample of failed pigtail; microscopic image of nitriding evidence from a sample of failed pigtail (Methanex, 2012).

Of these mechanisms, creep is observed to be the only failure mode that can be identified without the use of destructive material sampling. The Methanex presentation goes on to mention the installation of real time temperature monitoring, to mitigate against over-temperature operation.

The question manifests of how such significant and potentially hazardous pieces of equipment have been designed and built such that failure has occurred so regularly, that it has indeed become an area of prevalent research. This raises questions as to whether the industry companies and associated institutes and societies are doing anything to address the problem at the design and build phase. In an interview with Peter Tait (December 24, 2015), Global Expert – Static Equipment, Methanex New Zealand Limited, it was noted that current practice is to design reformer tubes to API 530 (2015), Calculation of Heater-tube Thickness in Petroleum Refineries. For pigtails, a combination of allowable stress values from API 530 and methods from power piping code ASME B31.3 (2014) is currently used. Peter considers that these references are regarded by the industry as the most up to date and relevant available. This is evident in that industrial standards are constantly revised, and in recognising the recent revision dates of the aforementioned standards. Peter is a contributor to a standard being developed by API, specifically to address the design of mechanical reformer components.

The reviewed information suggests that appropriate manufacturing techniques and material selection, real time process monitoring and data collection, and finite element analysis may all be reliable defences against premature reformer tube failure. However, there are many reformers in service that were commissioned before the published information was known. There may be little or no available historical data, making finite element analysis less useable. Furthermore, materials have already been selected and put in use, and there will be a desire to gain a return on their investment before replacement. There may also be modes and means of failure that have yet to be experienced or recorded. Therefore, regular ongoing inspection is a critical exercise in the operation of reformer plant, in order to provide reliable data on the present and predicted condition, and life expectancy, of reformer tubes.

2.2 Reformer Life Expectancy Requirements and Techniques

Jelwan, Chowdhury and Pearce (2011) assess a range of current and well known techniques used in high temperature component life prediction, in their paper *Creep Life Design Criterion and its Applications to Pressure Vessel Codes*. They discuss the problem that the existing theories and calculations appear to deviate from experimental fact. In support of their assertion, they carry out experiments on thick walled tube similar to that of a reformer. In exploring a new method of life prediction, they discover that the error in the calculated life when compared to experimental data varies as little as 0.8% (in their calculation), up to as much as 186%.

However, it appears that limited sample size and variation was used in the experimental data gathered for the research. Calculations that the researchers made comparing the well established methods generally varied by the same order, and often on the non-conservative side of safety.

A clear picture begins to emerge that failure due to creep strain is not uncommon, and that results from existing design and life expectancy techniques vary significantly. Limited experimental data gathered by Jelwan, Chowdhury and Pearce (2011) suggests that many techniques produce answers that would create the inherently non-conservative design and operation of reformers. Inspection appears to be the robust answer to ensuring the continued safe operation and life management of the set of tubes which is vulnerable to types of failure not yet completely understood by the engineering and science community.

AS/NZS 3788 (2006) explains that external inspection is carried out in order to gather information on the condition of externally visible parts of pressure equipment. Corrosion, leaks, or other signs of failure are looked for. The code goes on to say that internal inspection is generally carried out with the aim of identifying the same things as external inspection, except from the inside. As the tubes in reformers are internal to the equipment, these fall under the internal inspection category. The code states that the objectives referred to above are also achieved by “assessing remaining safe life of the pressure equipment.”

Grote and Antonsson (2008) state that fitness-for-service design is becoming increasingly prevalent. This is explained in their book *Springer Handbook of Mechanical Engineering* as the practice of designing components for a well-defined service period, within which any defect will not become critical. They also state that the assumption of a maximum undetectable defect is necessary in taking this approach to design. This ensures that the design does not encroach upon the margin at which an imminent failure would occur. Therefore, fitness for service checking can be carried out to assess the remaining safe life of plant equipment, and ensure that failure before next inspection is not likely.

According to Ray et al (2002), visual inspection of failed reformer tubes provides no evidence of pre-failure indicators. It is stated that the expansion in the outer diameter of the tube for two test pieces is not significant. However, measurement data provided in the paper shows circumferential growth in the failed section of between two and four percent. This is a significant measurable growth. Furthermore, the bulging already shown in the Methanex pigtail failure in the previous section is obvious to the naked eye.

Jaske and Finneran (2013) have recognised the need for reformer tube and collection manifold life expectancy predictions. By using historical reformer data on operating temperature, pressure, and up time, they have carried out finite element analysis on reformer collection manifolds to predict existing creep strain damage, and predict remaining life until the damage becomes critical. It should be noted that data used in Jaske and Finnerans predictions would be subject to any assumptions made on temperature data completeness and quality. From the study stems the notion that the data used in this type of analysis must be reliable and robust. Maharaj, Imbert and Dear note in their 2007 paper that individual temperature monitoring of tubes is critical, due to occurrences of distributed temperature monitoring not capturing temperature excursions on individual pigtails. This subsequently led to a number of failures; after only six years of service in one case. As mentioned in the previous section, Methanex have installed such devices in their plant.

It becomes apparent that internal inspection, as mandated by AS/NZS 3788 (2006), is an important and robust step in the prediction of remaining reformer life. In fact, ASME B31.1-(2014), which is one of the American Society of Mechanical Engineers codes for pressure piping, explains that it is the responsibility of the operating company to develop a programme of data collection and evaluation, when using material operating in the known creep range.

2.3 Reformer Inspection Techniques

Creep prior to failure in tubes manifests as a bulge according to API 573 (2013). The recommended practice document for the inspection of fired heaters and boilers suggests a number of reformer tube inspection techniques, which are discussed as follows:

- In-situ metallography using non-destructive testing such as ultrasonic, magnetic particle, and liquid penetrant. These techniques are typically performed external to the tube wall, by specialist personnel. Pigtails and tubes are austenitic, meaning magnetic particle testing is not possible (low magnetic permeability); stainless steels are known to attenuate ultrasonic making it ineffective; creep is a mid wall phenomenon, making dye penetrant unusable. For these reasons in-situ metallography is not a good solution;
- Laser profilometry. API 573 describes this technique as taking a large number of diametrical dimensions down the tube, with the use of a distance measuring laser. This produces a 3D model of the entire tube interior. This is a worthwhile procedure, effectively capturing the necessary data for determining life expectancy of tubes. However, it is not practicable in the reduced diameter of the pigtails;
- Ultrasonic measurement, which has been developed in two streams: one derives fissuring occurring in the tube wall, depending on transmission attenuation of response; the other detects flaws with are already present at the tube wall, using time of flight diffraction. Both methods require specialist equipment and operators to interpret the results. The latter will not effectively detect creep strain, being a mid-wall phenomenon, undetectable through surface inspection;

- Radiographic inspection, which can show cracks on the tube wall. However, API 573 states that this method is sensitive to the apparatus being normal to the apparent face of the crack. Ultrasonic is recommended over this technique;
- Eddy current inspection, which API 573 explains as using changes in magnetic flux density down through the tube wall as indicative of crack presence. Slight material difference contributing to magnetic permeability is identified as a problem in using this technique.

Overall, API 573 suggests a combination of techniques in order to gain a comparative picture and build a full assessment of reformer tube condition relative to one another.

The section on pigtail inspection in API 573 is much shorter. In situ metallography as suggested above is carried over to pigtail recommendations, although abridged to only dye penetrant inspection. To elaborate on the common recommended metallograpy technique, dye penetrant testing is carried out by first ensuring that the surface of the metal is uniformly smooth in appearance, after which it is covered in a crack-seeking dye. Dye accumulation is followed up by focused inspection and evaluation of that area. Thomas and Smillie (2011) also mention this technique for use in pigtail inspections; however, they correctly identify that cracks due to creep occur at the inside of the tube wall first.

The one other recommendation in API 573 is to use callipers on the outer diameter of the pigtail, in order to make manual measurements and assess any growth. Thomas and Smillie (2011) also identify manual measurement of the external diameter of pigtail tubes as a viable option. While this second technique gathers information that should be present before cracks appear, there can be hundreds of tubes and therefore pigtails per reformer, in all manners of orientation and position. The manual measurement of these tubes would be laborious and potentially hazardous. External measurements made on these tubes would typically require the installation of scaffolding and the removal of insulating lagging and possibly other support structures.

Thomas and Smillie (2011) go on to mention that radiography has been used on line through insulation, on pigtails. However, no assessment is made of the success, and no mention of the limit of being normal to the crack.

2.3.1 Risk-based engineering assessment

In the most recent edition, AS/NZS 3788 (2006) makes provision for risk-based engineering assessment. This allows inspection intervals to be adjusted based on thorough and competent assessment of the engineering variables, whereas they were previously explicitly prescribed. The intention is stated as “to allow the efficient use of integrity management programs by large scale industry”. In New Zealand, government approval is required for methods of analysis in assessing risk in this manner, which Methanex have gained (Sam Tait, personal communication, November 26, 2015).

To this end, Methanex New Zealand Limited have nominated a five yearly internal reformer tube inspection interval. This is one year longer than the interval prescribed by the code of practice, when risk-based engineering is not implemented.

2.3.2 Currently marketed inspection services.

Three main companies appear to dominate the reformer inspection market: *QuestIntegrity, US Thermal Technolgy & Magnetische Prüfanlagen* and *‘H’Scan International*. They operate both independently and as sub-contractors through other companies. In fact, all inspections services offered for reformers by other companies, lead back to one of these three.

QuestIntegrity (2016) use two separate devices in their inspections, one running external to the reformer tube and one running internal. Between the two devices, a combination of laser profiling, eddy current sensors and other proximity sensors is used. Advertised services provide data on cracking, major bulging due to creep strain, and internal tube diameter profiling. A full tube inspection can be carried out “on a single tube in as little as three minutes”. Neither the diameter nor length of that tube is specified. Assessments are advertised in “levels”, for example if the level one assessment flags certain concerns, the purchase of a level 2 assessment is likely imminent. No mention is made of pigtail inspection.

‘H’Scan International (2010) appears to utilise ultrasonic and eddy current methods to assess strain measurement (diametric) and tube wall thickness. “The inspections are carried out in a single, simultaneous scan, with custom-designed hardware and software”, reports the webpage. Photos on the page show a bulky apparatus surrounded by an array of parts and wires, being operated by a man in a white lab coat. Jargon and elitism appear to be the marketing theme. The page additionally offers “tube remaining like assessment” software, which utilises finite element analysis and the assessed current tube condition. Although it is advertised, it is not clear how the pigtail inspection works, or what is required in order to facilitate the inspection of the pigtails or otherwise.

US Thermal Technolgy and Magnetische Prüfanlagen (2016) offer testing, and evaluation, of reformer tubes and pigtails. The external tube inspection involves using in-house developed eddy current sensors, alongside laser measurement of the outer diameter. Internal tube inspection consists of laser measurement. External pigtail inspection is achieved by means of a two axis device which is clamped over the tube. No details are given on the technology. However, by looking at the advertisement pictures, some sort of contact measurement appears to be used, while moving the device along the pipe manually. The two axes provide compensation for out-of roundness in the bent sections of the pipe. The company also advertises remaining life calculations, in a product know as “TUBELIFE”. The sold advantage in pigtail measurement is that it is faster and more repeatable than a manual gauge. However, an insulating lagging will still require removal, which is a far more significant task than manual versus electronic gauge.

2.4 The Methanex Solution

When contracted services have been procured by Methanex to inspect the reformer tubes, this has cost in excess of 100 000 NZD for one reformer (Peter Tait, May 21, 2015). This means a cost of a least 300 000 NZD to cover all three Methanex New Zealand Limited reformers every inspection. Methanex operates six sites globally with ten steam reformers, and so the cost to the business begins to grow. Peter also reported that disagreements were experienced over ownership of inspection data. The pigtail inspection services being offered involved the removal of lagging, scaffolding the underside of the reformer, and manual measurement of the outer diameter. The cost of pigtail inspection on three reformers very rapidly exceeds 100 000 NZD. The driver for an in house inspection tool was strong, and so the Economole began development in 2008.

2.4.1 Reformer tube inspection.

The Economole was first developed in 2008, with the goal of providing in house reformer tube inpection. It was refined in 2012, which is the configuration still being used - the main device shown in Figure 4. This system has successfully provided baseline data on new tubes, mapped growth rates in new and existing tubes, and provided data which has been used to assess and facilitate reformer tube retirement outlook and planning. This has enabled the safe and continued operation of the Motunui and Waitara Valley reformers.

Figure 4: Economole device as a stand-alone inspection instrument

2.4.1.1 User interface.

Reformer tube analysis is achieved by first lowering the Economole device into an opened and cooled reformer tube. This is done via a custom made winch set up, lowering the device at the end of a Kevlar sheathed Ethernet cable. A photo showing the winch fixed over the top of the hole, and inspection staff in attendance, is shown below (Figure 5).

Figure 5: Inspection of a reformer tube during plant shutdown.

The device is connected to a host PC at the site of inspection, providing feedback on tube condition after each tube run (around 3 minutes). This allows critical decisions on tube replacement to be made at the time of inspection.

2.4.1.2 Measurement concept

A laser in the lowered device projects a ring of light, via a conical mirror, onto the inner wall of the tube. A camera inside the device captures a monochrome image stream. Images from this stream are saved by the host PC, at times based on the winch encoder (every 25 mm). An example of one of these images is shown below (Figure 6).

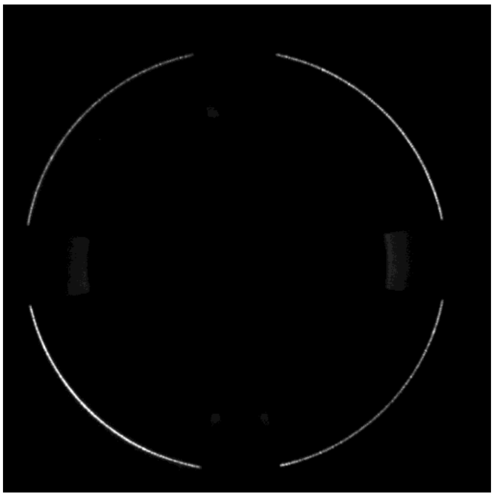

Figure 6: Typical image of ring of reflected laser light seen by the Economole camera

The program on the host PC then calculates the internal diameter of the tube, based on the number of pixels, ie a wider ring will have more light pixels resulting in a larger calculated diameter. This concept has proven accurate to a tolerance of ±0.2 mm (Rees, Hussey, and Dixon, 2012).

2.4.1.3 Power and data

The cable used for lowering provides power and communications via *Power over Ethernet* (PoE). PoE is a term used to describe technology which transmits power over the same 4-pair Ethernet cable used for communication, allowing network devices to be powered by the same cable used for transmitting data (Netgear, 2016).

The camera uses both the data, for sending image information, and power, necessary for running the camera. The power is also used to power the laser via a linear regulator.

2.4.2 Pigtail inspection

The current method of assessing pigtail condition at Methanex is by scaffolding the under side of the reformer, removing lagging and support structures, and running a mechanical feeler gauge over the outer diameter (OD) of the pipe. An excess OD indicates imminent pipe failure. Pigtail inspection and remaining life assessment remains a gap in the automated testing regime.

The Minimole probe was developed in 2013 with the aim of providing Methanex with a device capable of detecting damage to their 28 mm internal diameter pipes, due to creep (Turner & Zin, 2013). At this time, the device was developed to a state where the probe body was fabricated, the electronics powered from a lab power supply, and the raw measurement signal read with a lab type data acquisition card, before being processed in two separate PC programs. Integration with the Economole tube measuring system was flagged by the 2013 developers as the next step to be undertaken.

In 2014, the Minimole was taken on by another developer, with the aim of creating a standalone system (Allom, 2014). The probe was incorporated into a large device that would be lowered to the bottom of the reformer tube, before extending the Minimole into the pipe with a lead screw. The overall assembly became bigger than the Economole, and required a lab type power supply and specialised engineering software (*MATLAB*) to operate. Dimensions were taken to outer limits in terms of fitting down the tube, and unsuitable materials were used. This was not in line with the development of a commercialised product, and ultimately, did not satisfy Methanex requirements.

The Minimole probe device itself converts physical measurements into electrical signals for processing. Two arms pivot about a point, each with a rolling contact surface (bearing) on one end, and an electronic transducer at the other. As the bearing moves in and out along the wall of the pigtail the arm pivots, acting on the transducer, which in turn varies the electronic output signal. The physical concept is shown below (Figure 7). The arms are measuring inward in the left image, and outward in the right. Note that the arms are sprung outward.

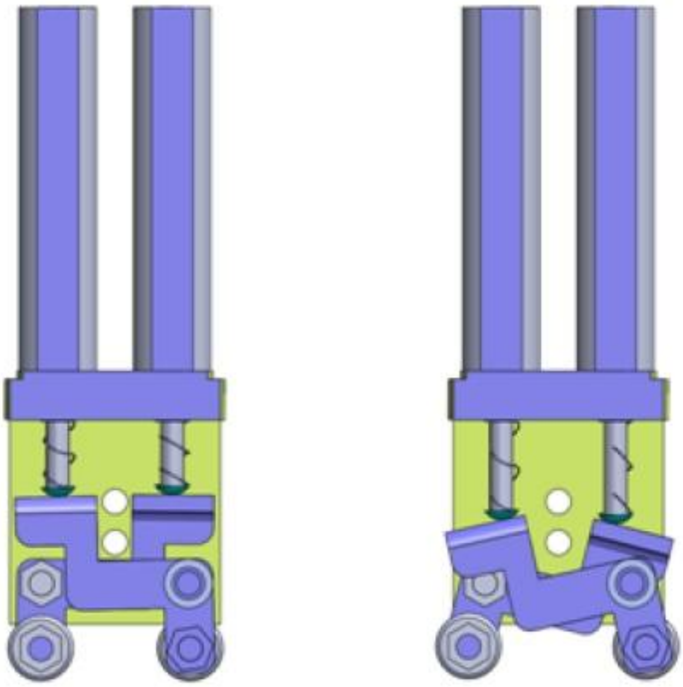

Figure 7: Minimole measurement arm movement concept (Turner & Zin, 2013)

2.5 The Opportunity

Reformer tubes and pigtails are subject to creep-strain which results in catastrophic failure endangering people, the environment, and leading to lost production and revenue. Though catastrophes are unlikely with the end of life failures that the Economole and Minimole are designed to manage, regular inspections of reformers are a legislative requirement, and are an important technique in mitigating the likelihood of these failures.

As Methanex is a principal producer of methanol, operating steam-methanol reformers at six sites globally, staff have identified the risks associated with a dependency on costly, inconvenient, and incomplete inspection services. Hence, they have endeavoured to develop their own in house inspection and life expectancy prediction systems.

The current system Methanex operates for inspection of their reformer tubes has proved reliable after years of service. A probe for inspecting the pigtails has been lab tested and is waiting to be developed for the field. This provides an opportunity to develop the lab tested probe, and integrate it with the existing system, resulting in one overall system, capable of inspecting the reformer tube and into the pigtail.

This will be the first inspection system in the world capable of providing real time quantitative analysis of reformer tube and pigtail condition concurrently, and from inside the tube. The solution will eliminate the need for using separate inspection systems; processing data ex-situ; and mobilizing significant resources for lagging removal and manual measurement. These inspections are part of the critical path for a turnaround, so the time saved is directly linked to restarting production. The data analysis will immediately notify of any urgent or upcoming pigtail replacements required, thereby averting expensive in-service failures or major catastrophe.

The integrated solution will provide direct and accurate data on the condition and life expectancy of reformer tubes. This will be a key tool in preventing or eliminating incidents and shutdowns due to reformer tube and pipe failure. Inspections will be carried out by Methanex staff using their own equipment. The result will be savings through in-house testing and continued production, a reduction in spurious plant shutdowns, a safer workplace, and less effort required in meeting legislative requirements.

If successful, integrated solution could be extrapolated on to meet other industries’ needs. In New Zealand this could be reformer plant at hydrogen peroxide plants, or in fertilizer manufacture, or heaters in refineries.

Chapter 3 Research and Methods

3.1 Objective

The research objective was to develop a system for gathering data on reformer pigtails. This data would be used during plant shutdowns to instantaneously identify pigtails at or near end of service life, facilitating non-wasteful replacement. The obtained data could also be used to predict end of life for each specific pigtail.

The aim would be fulfilled by developing the lab-tested Minimole pigtail probe to a field ready state, and integrating it with the in-use Economole reformer tube measuring system.

Specific objectives were agreed upon prior to the start of research proper. In the first stages of research, these were refined and finalised. They are detailed in the Project Execution Plan (Appendix 1), and listed as follows:

1. Assess and design methods of power and data communication to/from the Minimole probe which are compatible with the existing Economole system:
    a. Investigate viable power delivery to Minimole probe electronic systems;
    b. Investigate current Economole data transmission method, and others;
    c. Investigate viable Linear Variable Differential Transformer (LVDT) compatible with Economole;
    d. Design sub systems for power and data around the most viable options.
2. Integrate Human Machine Interface (HMI) Software:
    a. Evaluate current software;
    b. Modify to incorporate Minimole;
    c. Provide high level pass/fail feedback alongside real time Economole measurements.
3. Design probe control and output evaluation software:
    a. Integrate with Economole position monitoring, to allow Minimole to measure the correct section of pipe (the pigtail);
    b. Store minimole data, following Methanex protocol.
4. Physical Integration:
    a. Mechanically integrate Minimole with Economole, to provide correct functionality as one unit;
    b. Test system in lab and in field service to verify correct functionality.

3.2 Proposed Design

The aim of the research was the integration of two pipe inspection devices: the field proven Economole, designed for reformer tubes, and the laboratory tested concept Minimole, for reformer pigtails. Therefore, the proposed design was to mechanically and electronically couple the devices, to provide feedback about the condition of the tubes and pigtails concurrently during inspection.

The proposal was to keep the Minimole measurement concept, which had been tested to produce satisfactory results prior to this research. However, the rest of the Minimole design would be deleted and replaced. This included electronics, mechanical mounting, and communication and control.

The Economole power and communication concept would be retained for the integrated system. This had proved reliable over years of service. The Minimole system would therefore be designed to be incorporated into this as seamlessly as possible.

3.2.1 Measurement technology

The sensors that are currently used in the Minimole were selected in a previous project. The review below has been conducted to check the assumption that these sensors are the best option moving forward. It discusses the selected sensors' principles of operation, technological application of these principles, and selected model. The sensors previously selected for the Minimole are found to be fit for purpose, and a strong choice.

Pigtail growth tolerance was set at 6% of original typical 28 mm internal diameter (Peter Tait, personal communication, May 21, 2015). This is the tolerance past which the pigtail is at the end of its serviceable life. An accuracy and repeatability target of ± 0.2 mm was set, in order to match the Economole capability. A survey of ten disused pigtails determined an average internal diameter of 29.28 mm. The set tolerance would therefore comfortably detect the 6% growth creep damage of a 28 mm pipe at a read out of 29.48 mm, which is greater than the average surveyed retired pigtail.

3.2.1.1 Electromagnetism principles

The current sensor configuration in the Minimole uses a pair LVDTs. The basis for the operation of these sensors is Faraday's law of electromagnetic induction. This law states that the induced electromotive force in any closed circuit is equal to the negative of the time rate of change of the magnetic flux enclosed by the circuit (Jordan and Balmain, 1968).

A good example of the use of this law is commonly seen in transformers. Figure 8 shows a step-up transformer, which is used to raise voltage. An alternating current is applied across the primary coil, inducing a time varying magnetic field, Φ_B, through the core. This field, in turn, induces an alternating current in the secondary coil.

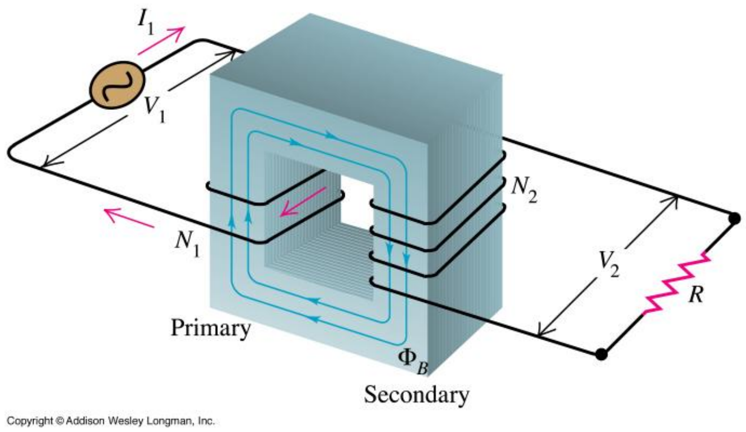

Figure 8: Step-up Transformer diagram (Stelmark, 2016)

The voltage V_2 in the above diagram is proportional to the input voltage, V_1, and the ratio of the number of turns in the secondary coil, N_2, to the number of turns in the primary coil, N_1. It is expressed as (Giancoli, 2009):

$$V_2 = V_1 \frac{N_2}{N_1}$$

(1)

The application of this principal to measurement requires the use of a straight core that may be moved linearly through two co-linear coils, as opposed to the looped core seen above. As the core is withdrawn from the secondary coil, fewer turns in the secondary winding are acted upon by the magnetic field. As the core is inserted into the secondary coil, more turns in the secondary winding are acted upon by the magnetic field. Hence it is possible to deduce a linear displacement which is proportional to the voltage across the secondary coil.

3.2.1.2 Linear Variable Differential Transformer – LVDT

An LVDT is a transformer with a variable voltage differential caused by Linear movement. LVDT's utilise two secondary coils positioned one either side of the primary. An example of this is depicted in Figure 9. This arrangement provides information on displacement either side of the primary coil, and direction of travel deduced from the phase of the output signal.

Figure 9: Diagram of a conventional LVDT, showing from left to right: Secondary Coil; Primary Coil; Tertiary Coil (Amtek, 2015a)

It is stated in the report 'The Minimole' from 2014 that: "Methanex desired that the existing LVDT sensors are to be used, as they are robust and reliable and the probe is already designed to accommodate the actuation of the LVDT cores" (Allom, 2014).

It is prudent to check the assumption that an LVDT is appropriate for the task in terms of cost, range, and accuracy. The graph below (Figure 10) is from a selection page on spaceagecontrol.com, which appears to be a reputable company, with ISO 9001 accreditation. An LVDT utilises inductive principals, so looking at the 'Inductive' line below, it is at the applicable end of range scale, desirable end of the accuracy scale, and in the middle of the cost range. The LVDT is therefore an appropriate choice.

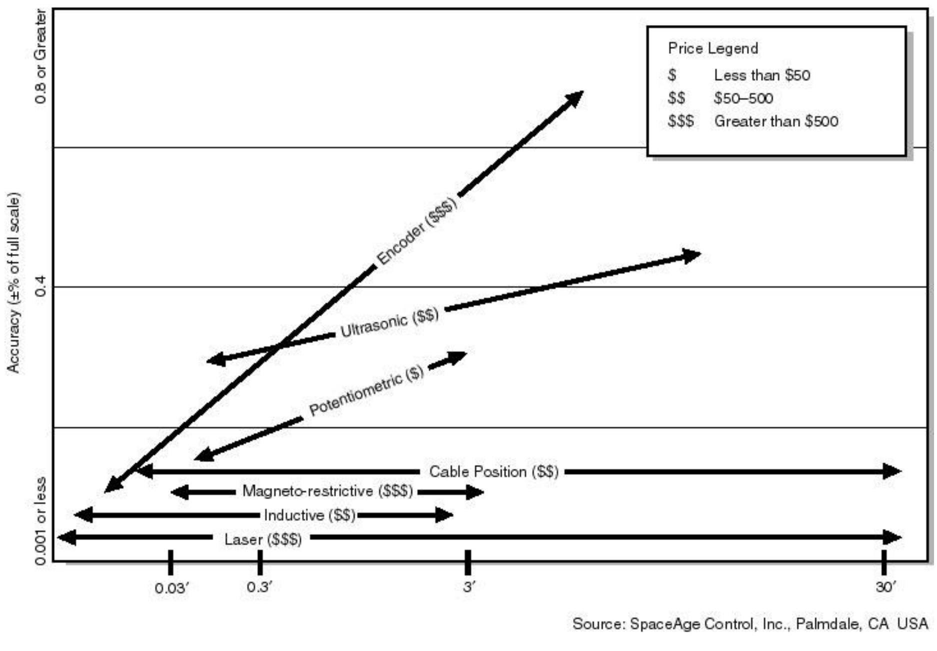

Figure 10: Graph of Sensor Range vs Accuracy, including cost (Space Age Control, 2015)

3.2.1.3 Solartron Metrology LVDT

The model that is currently selected for the Minimole is the Solartron Metrology MD5. Solartron Metrology is a UK based designer and manufacturer of precision sensors (Amtek, 2015b). Details taken from the manufacturer's datasheet for the MD5 model are as follows (Amtek, 2009):

- Product Type: MD Type, LVDT with Free Core
- Measurement Range: ±5 mm
- Resolution: Infinite (limited only by conditioning electronics)
- Body Diameter: 8 mm
- Body Length: 49 mm
- Body Material: 400 Stainless Steel
- Operating Temp.: -10 to +80 degC
- Energising Voltage: 1-10 Vrms
- Energising Current: 1 mA/V

To verify that this model is the best fit from this supplier, a comparison against the other two models available in the Solartron Metrology "Miniature" Range is provided below in Table 1. The most relevant parameters, where the models differ have been included and arranged in order from most important to least important.

Table 1: Comparison of Solartron Metrology Miniature LVDT Models

Model	**SM**	**MD**	**DF**
Body Diameter (mm):	9.52	6 – 8 ✓	19 ✗
Measurement Range (mm):	±1 - 3	±1 – 10 ✓	±1 - 5
Energising Voltage:	1 – 10 (Vrms)	1 – 10 (Vrms)	10 – 24 (VDC) ✓

Evidently, the MD model has the best diameter and range characteristics. While the DF model has the most convenient supply voltage, a 19 mm diameter body would be inconvenient to fit into a device that must operate inside a 28mm bore. Therefore, this is the best available model.

3.2.2 Power and communication technology

A key objective was integrating the Minimole *into* the Economole system, without disturbing the operation of the Economole. Therefore, the power and communication technology used in the Economole was used and will dictate key parameters of the Minimole design. The Economole, and now the integrated MXmole (Methanex mole - the integrated Economole and Minimole), utilises *Power over Ethernet.* An explanation and review of this technology is provided henceforth.

3.2.2 Ethernet

The Economole device communicates with the host PC over an *Ethernet* connection, specifically *IEEE 802.3 1000baseT*, commonly known as *Gigabit Ethernet* (Allied Vision Technologies, 2013). Ethernet is in layer two of the *OSI network model* – Figure 11 (Rakocevic, n.d.). This model lays out the layers in a modern PC or device network, from the application, such as processing streaming audio visual data for entertainment, down to the physical layer, where the physical electrical pulses representing ones and zeros exist. Ethernet fits into the physical or hardware connection between devices. Below this layer the electrical pulses are sent (ones and zeros), and above addressing and directing information happens in layer three, networking. Above further the data itself is arranged into frames, in layer four, transport.

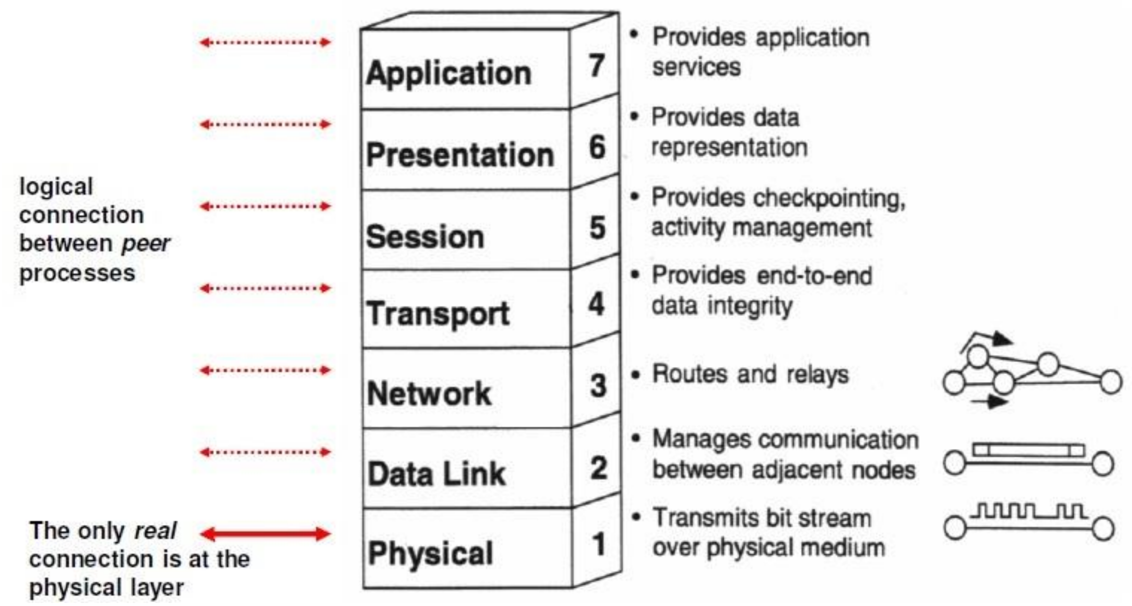

Figure 11: OSI Layered Network Model (Rakocevic, n.d.)

Ethernet, as defined in by IEEE 802.3, is the most widely used data communications technology in the world (Spurgeon & Zimmerman, 2014). Although it has been in existence since 1973, continued adaptation and progression has kept it firmly in use. It can be seen in all office spaces and all modern homes today, even adapting to wireless and fibre-optic requirements (Spurgeon & Zimmerman, 2014). The version used in the Economole is one version of Gigabit Ethernet, – 1000baseT. This version uses all four pairs of a Cat-5e, Cat-6, or Cat-6a twisted pair Ethernet cable to gain a data transfer rate of between 1000 and 10,000 bits per second, more commonly stated as 1 Gbps to 10 Gbps (How-To Geek, 2015).

3.2.2.2 Power over Ethernet

Power over Ethernet (PoE) is a technology used to transmit power over the same cable as data, using the four pair Ethernet cable. Cisco was one of the first companies in the world to use this technology extensively, in their internet protocol phones since 2000 (Cisco, n.d.). The IEEE standardised this technology three years later, with *IEEE 802.3af* (Eisen, 2009).

The version of PoE technology used in this device is the IEEE 802.3af 1000baseT specified implementation, providing 15.4W of power, and gigabit Ethernet data capability (Allied Telesis, 2008). This is achieved by feeding 48 Volts direct current (VDC) across the centre taps of the transformers of two of the four twisted pairs in the Ethernet cable (Eliteun, 2013). An example of this is shown in Figure 12.

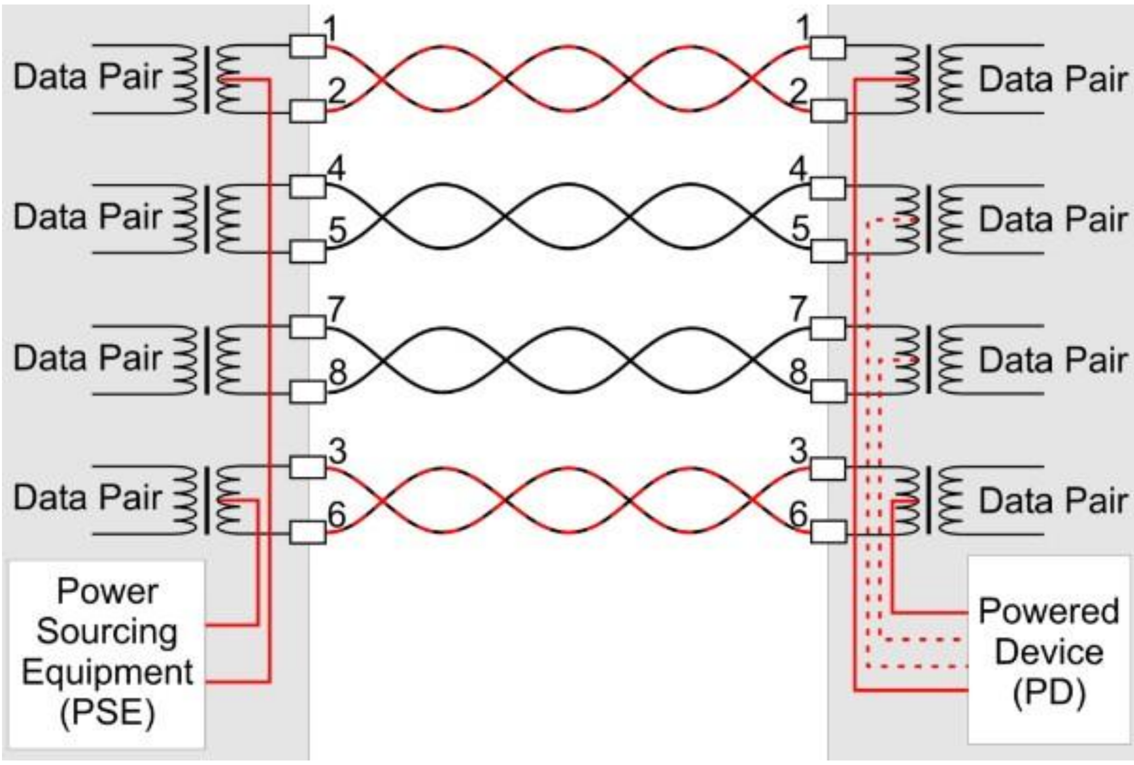

Figure 12: PoE implementation - ***Alternative A*** **(Fiberstore, 2014)**

This voltage simply offsets the alternating current (AC) signal used for data transmission on those pairs, not interfering with the high frequency transmissions on the two wires in each pair. At the receiving end the power is taken from the centre taps of the same two pairs' transformers.

3.3 Methodologies

Methods used throughout the project are discussed henceforth.

3.3.1 Mechanical design

The computer-aided design (CAD) program *SolidWorks* was the principal tool used in the evaluation and design of mechanical parts. SolidWorks is a well known program used by over 2.5 million engineers and designers in 220 thousand organisations worldwide (SolidWorks, 2016).

To start, 3D models were created in SolidWorks using relevant drawings for existing parts. Selection of drawings and correctness was confirmed by surveying existing parts, using electronic callipers. Photos taken during survey, such as those shown in Figure 13, also aided in confirming assembly details.

Once full 3D CAD models of the existing individual assemblies were made, constraints could be worked into drawings and design take place. This allowed known parameters such as the distance of pigtail penetration to be worked into drawings on the relevant plane, and the gaps or requirements in between to be detailed.

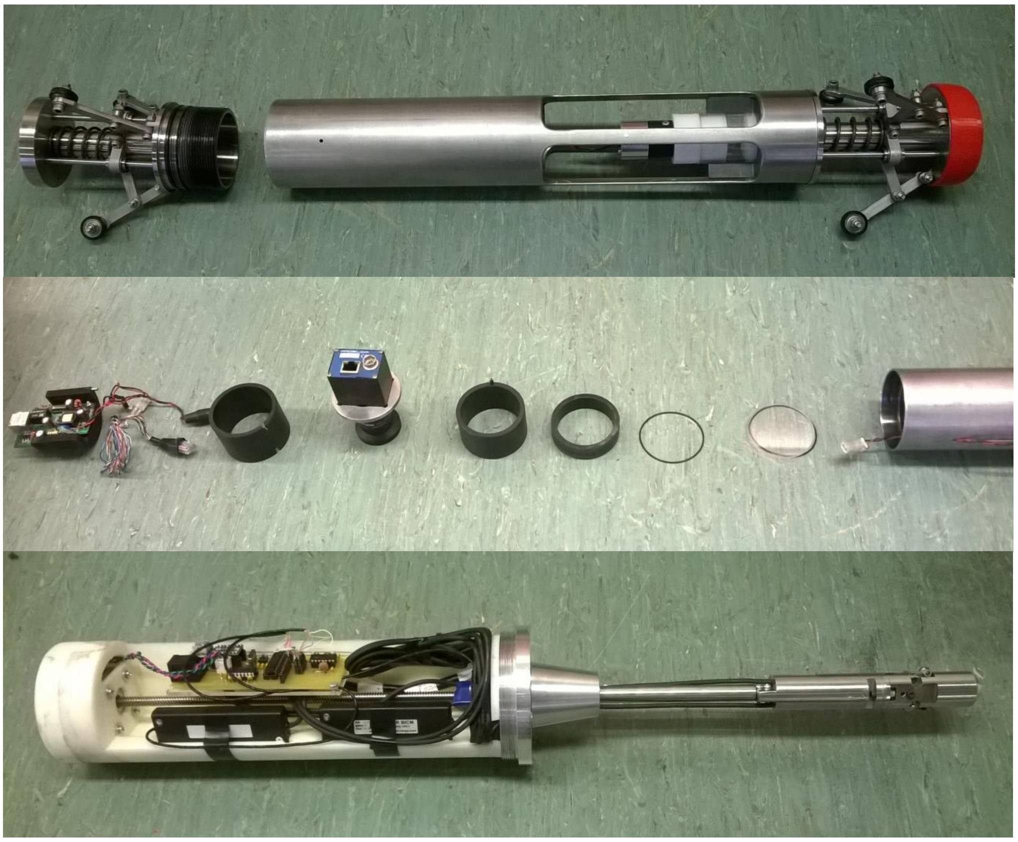

Figure 13: Inspection photos, from top to bottom: Economole; parts from top of Economole Chassis; Minimole with chassis cover removed.

Drawings and models were produced from designed parts to allow parts to be manufactured by manual machining, CNC milling, water jet cutting, hot wire cutting, and 3D printing. 3D printing was often used in its capacity for rapid prototyping where the fit and feel of some parts could be better designed after evaluating the physical pieces themselves.

3.3.2 Electronic design

Electronic design began with a detailed survey of the existing systems. Unlike mechanical design, a full understanding was not gained immediately by way of survey, or by reading the available literature.

To progress development and insight concurrent activity, a *black-box* approach was adopted to electronics and software investigation. At any given time, known details about the systems could be sketched out in, for example, a block diagram – as shown in Figure 14. In this way, areas for focus could be identified and followed through either by complete understanding of the system inside, or by empirical knowledge of the inputs and outputs to that system. These signals were obtained either by multi-meter or oscilloscope, as required.

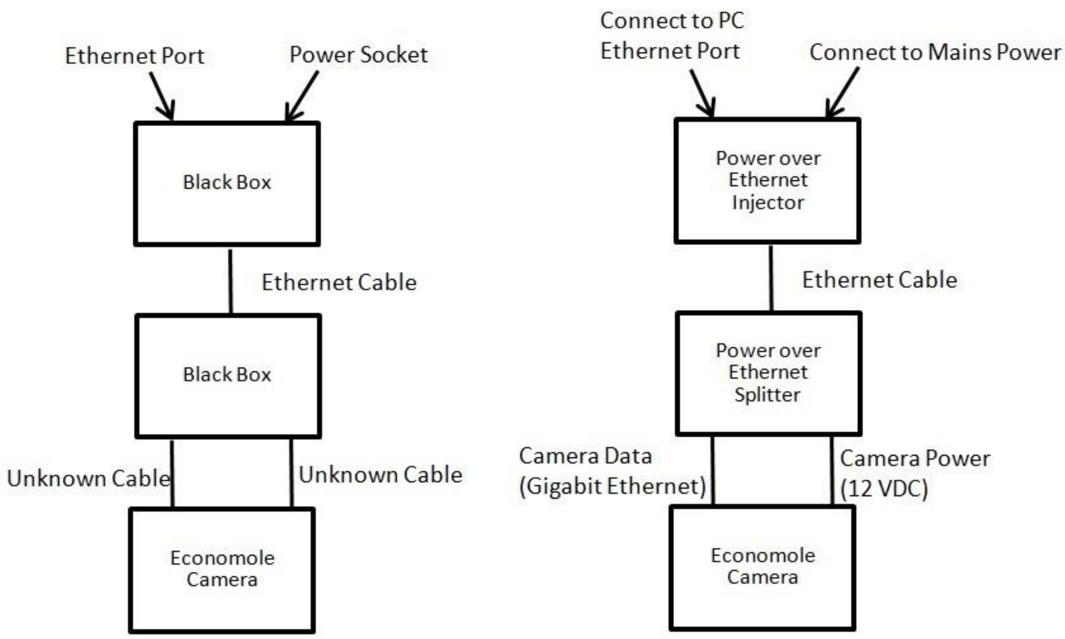

Figure 14: Black-box approach for Economole power and data set-up, showing initial knowledge on left, and final on right

Once the necessary information was gathered, design of the electronics was undertaken. This was achieved first by referring to empirical digital and analogue electronics information. A circuit was then sketched out and parts selected with the use of manufacturer data sheets. The circuits were then prototyped and debugged on a *breadboard,* which is a standard electronics prototyping tool. This allowed electronic components to be arranged in various configurations in quick succession.

After the electronics were finalised, the components were designed into a circuit in *Altium Designer*, a CAD program for designing printed circuit boards (PCBs). Altium Designer is an intuitive PCB design program, used by wellknown companies such as Agilent Technologies, Bosch, and SpaceX (Altium Limited, 2016). The program allows the user to design a circuit in a schematic format, and then assists in placing the components and tracks, or connections, onto a PCB design according to rules and the schematic that the user has designed. The resulting PCB design document can then be sent directly for manufacture. The schematic then generally helps in PCB assembly and debugging, as well as serving as a design record.

3.3.3 Software and firmware design

Development of the coded systems began with an investigation of the existing codes' functionality and structure, and the tools which were used to create and implement it.

In the case of the Economole, the code was written in *C++* using *Visual Studio.* C++ is a programming language originated in around 1983 (Cpluslus.com, 2015a). Visual Studio is an integrated development environment (IDE) released by Microsoft, that is "a free, fully featured, and extensible IDE for creating modern applications" (Microsoft, 2016). C++ has many features that allow for significant programming flexibility (Cpluslus.com, 2015b). However, a move to a more contemporary and user friendly language such as *C#* was desirable for effective current and future development (also available in Visual Studio). The main consideration in the language change was the main hardware interface – the Economoles gigabit camera. The camera manufacturer had recently released code examples and support for C#, and so program development in this language was selected as the goal for the software.

The existing software for the Minimole was written in MATLAB code, and the onboard microcontrollers' firmware written in *Arduino* and loaded onto an *ATMega328.* As the Minimole was to be integrated with the Economole, no separate software would be required. Arduino is an open-sourced electronics platform based on easy-to-use hardware and software (Arduino, 2016). The ATMEGA328 is a ubiquitous microcontroller, used extensively for in product development (Gibb, 2014). Due to previous experience, a *Teensy 2.0 USB development board* was selected, to be programmed in Arduino. The Teensy 2.0 is a complete USB-based microcontroller development system, encompassing all of the features of the ATMEGA328, in a package around half the size. In addition, the Teensy encompasses the mini USB port required for programming, whereas, the the ATMEGA328 must be removed and plugged into a programming board with a specialised socket.

3.3.4 Testing and validation

Preliminary testing of each sub-system was carried out during development. This provided assurance of the behaviour of each component, prior to full assembly. In some cases, the development of one system was necessary for testing the next. This was planned as much as possible. For example, in order to verify that software was working and that signals to the host PC were being received correctly, the electronics and firmware had to be developed and tested first.

Testing of the developed and integrated Minimole was completed on the bench, with the integrated system fully assembled. This consisted of running a length of pigtail pipe up and down the probe, checking for feedback on the host PC, and recording measurement data for system capability analysis. A photo of this testing procedure is shown in Figure 15.

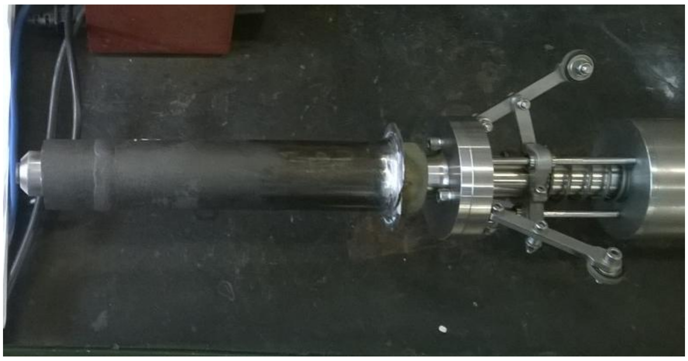

Figure 15: Bench testing integrated Minimole

Laboratory testing of the assembly was completed with the use of a test rig, fully simulating the field set up. This ensured pigtail entry without incident. This was an important step in ensuring and assuring that nothing untoward would happen upon field deployment. For example, an inspection tool stuck in a reformer tube on a critical turnaround would be detrimental to production schedule. This also provided data for assessing repeatability of measurements in a field simulated set-up.

Field testing of the entire integrated device was carried out at different stages in development. This verified parts and functions of the full device as proven in use during actual reformer inspections, as opportunities arose.

3.4 Execution Strategy

This research was carried out primarily in an industrial setting at Methanex. This allowed first hand supervision in by stakeholders from the company, and input from them and other involved staff. Input from these parties was intrinsic to defining a successful research outcome. The staff at Methanex understood best the problems to be addressed, and that they were of significant importance to the company. Because solving them as well as practicable in a one year project time frame was necessary, an execution strategy was required, ensuring a successful and timely outcome overall.

To begin with, the stake holders and other involved people were identified. Objectives were discussed with each of these people as appropriate, based on the original project scope provided by Methanex.

Once objectives were established, a *Gantt chart* was built; a tool used to graphically layout tasks and timings on a project timeline. This was key in identifying dependant and concurrent activities. For example, significant electronics development was seen as necessary prior to effective software/firmware development. Whereas some parts of the mechanical design could be developed more easily in parallel with other tasks, such as electronic development at the time of determining how much space would be required for electronic components.

The project Gantt chart was split into the following main sections, helping to build and organise the tasks involved:

1. Preliminary Work
2. Concept Development
3. Fabricate/Develop/Test
4. Refine & Improve
5. Thesis

The above listed sections followed five phases of the same name in the execution plan, with the exception being the last, called “Completion and Handover”. Each of the phases has identified deliverables. A deliverable in this context is something that is produced at the completion of a given phase, such as the Project Execution Plan for the first phase, being where the details outlined in this strategy are recorded (Appendix 1), or the completed integrated device at the end of the fifth phase, “Completion and Handover”. The deliverables would be used to justify completion of each of six identified milestones, at the end of each phase, plus one for thesis completion.

3.4.1 Assurance and changes

Near weekly informal communication was kept with the industry and university supervisor. Monthly progress reports were issued, to ensure alignment with research objectives. Changes and clarifications were confirmed by email or by minuted meeting, ensuring supervisor's agreement.

Chapter 4 System Development and Integration

4.1 Mechanical System Design and Prototyping

In this section design considerations are discussed, leading through to concept development. Prototyping is then covered, including assembly of the final designs.

4.1.1 Design parameters

The mechanical design of the system was carried out after an understanding was gained of the existing components, and any limiting factors to be considered. Research revolved around material considerations, spatial requirements, and fitting techniques.

4.1.1.1 Material considerations

The high temperatures inside the reformer tubes and pigtails during reformer operation (up to 900°C), bring about the risk of liquid metal embrittlement (LME) from residual metal tracings left behind by foreign objects, such as inspection probes. LME in Nickel alloys under these conditions occurs when other inter-metallics melt and precipitate between the host metals grain boundaries, reducing ductility (Briant & Banerji, 1983). Furthermore, Nickel alloys are stated in the referenced material as being extremely susceptible to embrittlement through this mechanism. Briant & Banerji (1983) also state that a number of residual metals have induced embrittlement and reduced creep life expectancy even at room temperature. LME can be avoided through the following, according to WebCorr Services (n.d.):

- Avoiding contact with known crack causing liquid metals, specific to the host metal;
- Not using low-melting point metals near their melting points;
- Using metallic coating or cladding as a barrier of protection.

The Minimole system as received included a large aluminium alloy main body. This is shown in Figure 16 with the stainless steel probe attached. All exisiting Economole exterior metal surfaces and components were constructed from stainless steel. Aluminium alloys melt at 463 - 671 °C, and stainless steel 1510°C (Engineering ToolBox, n.d.). Any residual aluminium alloy left in the reformer tubes or pigtails would be past its melting point once the reformer was operational; the stainless steel would not be. Stainless steel is not one of the known crack causing metals for Nickel alloys. For this reason, stainless steel was chosen as the metal for the exterior parts of the entire system.

Figure 16: Minimole as received

4.1.1.2 Spatial requirements

The probe of the Minimole as received (Figure 17, below), had an overall diameter of 27mm. The minimum diameter of the pipe to be measured was 28mm and so the external diameter of the probe design was suitable.

Figure 17: Minimole probe

The Minimole chassis as received was large and bulky at around 400 mm long and 100 mm diameter. This contained a large printed circuit board (PCB), vendor sensor signal conditioners, and a stepper motor and lead screw assembly for driving the probe out of the chassis and down the pigtail – all shown in Figure 18. The electronics were observed to be bulky, spread out, and with excess cabling throughout. The lead screw concept was complex and unnecessary.

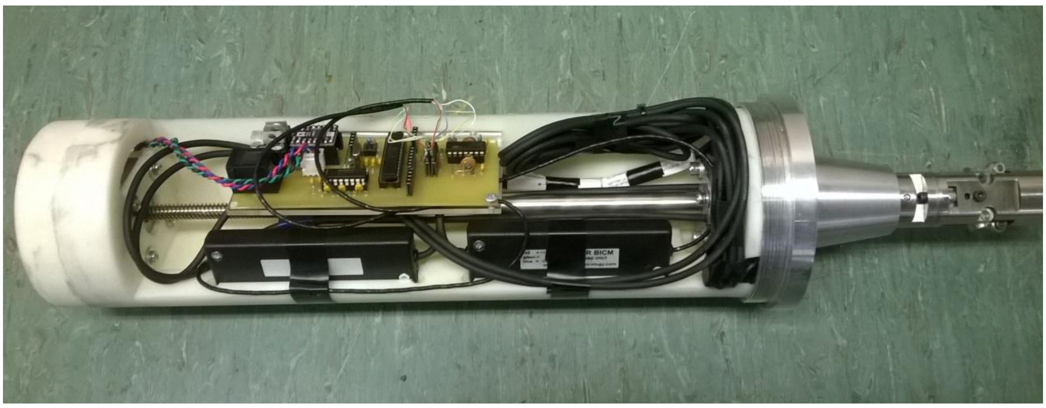

Figure 18: Minimole as received, chassis with cover off

During concurrent electronic testing and circuit design, it was asserted that the maximum space required for the electronics would be a 100mm extension to the Economoles 73mm OD chassis. For the length and complexity of the lead screw arrangement, an extension of the same length of screw protrusion could meet the same down hole test coverage while using the same overall length.

Overall, considering the existing winching arrangement for the Economole, in order to comfortably feed into and extract from the hole, the total length of the integrated assembly could be no longer than 1063 mm. This allowed for the 100mm electronics housing on top of the Economole Chassis, and a 271 overall protrusion of the Minimole probe, from the bottom of the Economole assembly.

4.1.1.3 Fitting techniques

The Economole system utilises a 68 mm thread to secure the main components of the system together. The male end of one of two of these fittings is shown on the right of the far left part in Figure 19. This is the upper wheel-set disconnected from the main chassis. The lower wheel set is shown connected on the right. The electronics and combined communication and power link for the Economole are located inside the chassis cavity where the wheel set is unscrewed from.

Figure 19: Economole with top wheel-set removed

The Minimole must be fitted to the bottom of the Economole (far right), and not impede the inspection coverage of the existing system. Any fitting to the main chassis should be done in line with the existing 68 mm thread, and anywhere else, bolted with socket head cap screws, in keeping with the existing philosophy.

4.1.2.4 Other considerations.

Following on from the above, some other criteria arise:

- The design should be modular and able to be appended to the Economole with little or no re-work of the existing Economole parts;
- The design should be as light weight as possible, whilst not compromising durability;
- Provision for two 3.5 mm OD LVDT cables from bottom of Economole to top;
- The wiring of the LVDT's is permanently attached at both ends, meaning a 49 mm long cylinder of 8 mm diameter must be able to be threaded from the top of the Economole to the bottom.

4.1.2 Concept development

Concepts for the various mechanical components were developed to meet the project objectives in line with the above parameters.

4.1.2.1 Electronics housing concept

A rendered image of a 3D model showing the intended position of the Minimole electronics housing is shown below (Figure 20). Changes from the original Economole design are the additional section shown in red, and the additional groove down the right hand side, in the far right image. The red section adds a total of 100 mm to the height of the Economole. The groove on the right is one of two additional grooves on opposite sides of the Economole chassis, with 8mm holes at either end, provisioning the LVDT install and cable run. The grooves are the sole modification required to the original Economole chassis required with this concept.

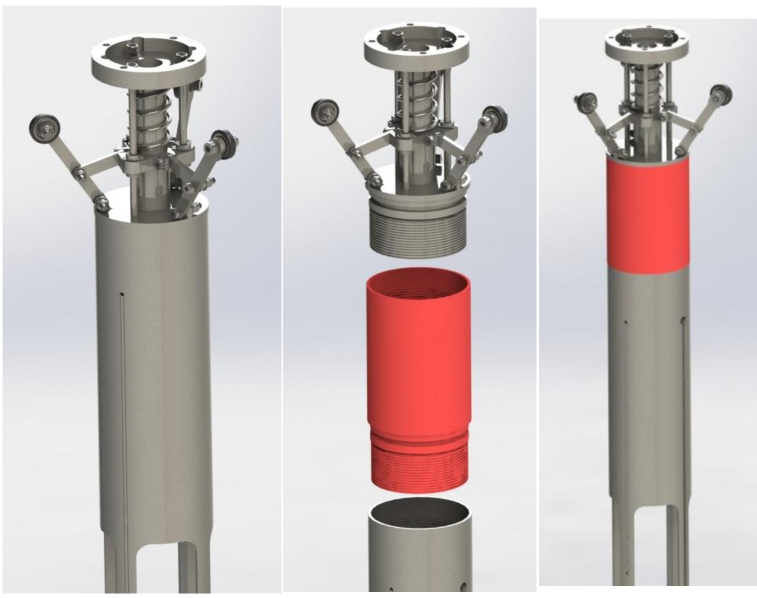

Figure 20: Economole electronics housing concept, to accommodate Minimole electronics

The electronics themselves would be mounted on an *electronics sledge* similar to the existing Economole electronics – Figure 21, below. Little more was known about the exact electronics design and configuration at the time of conceptualisation, and so further details were not developed initially.

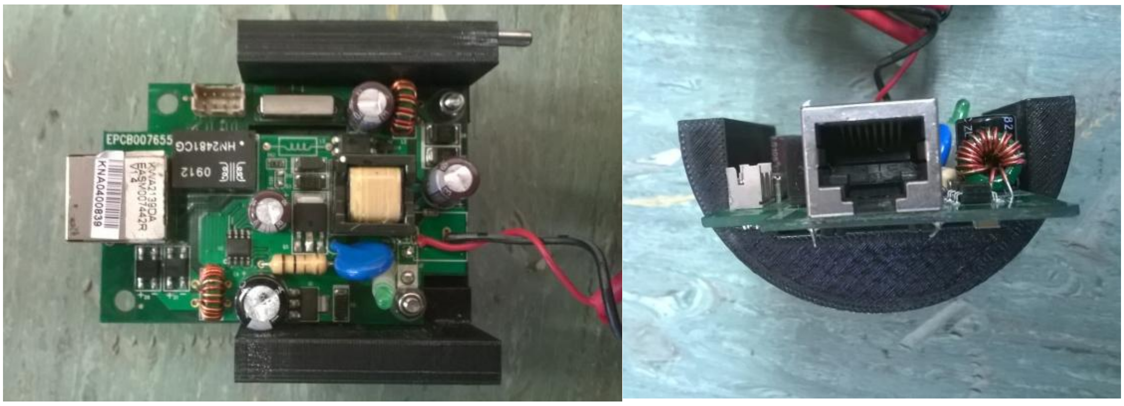

Figure 21: Original Economole electronics sledge, side view (left); top view (right)

4.1.2.2 Probe coupling concept

Coupling of the two probe assemblies is required to attach the top of the stripped back Minimole to the bottom of the Economole. Brief details of five concepts to achieve this are listed as follows:

- Concept M1 – Three thin solid cylindrical bars spaced 120 degrees apart about the centre, with the Minimole cable passing down the centre;
- Concept M2 – Two thin solid cylindrical bars spaced 180 degrees apart about the centre, with the Minimole cable passing down the centre;
- Concept M3 – A thin walled pipe section, with the Minimole cable passing down the centre;
- Concept M4 – Tightly wound cantilever spring, with the Minimole cable passing down the centre;
- Concept M5 – Steel cable, with the Minimole cable hanging in parallel;

Rendered images of 3D models of the mechanical components of each coupling concept are shown below (Figure 22).

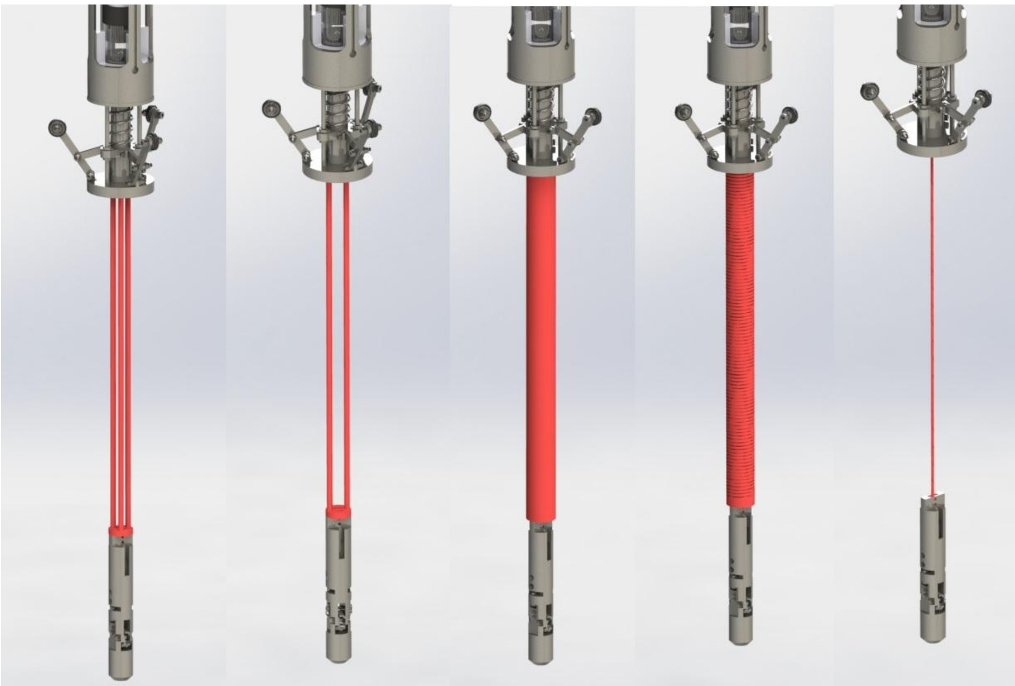

Figure 22: Probe coupling concepts M1 through to M5, from left to right.

A decision matrix was used to study the effectiveness of each concept – Table 2, below. All concepts are rated 1 to 5 against each of the tabulated criteria, which are derived from the previously discussed parameters. The concepts that best meet the criteria are given a 5, and others rated in comparison. Each of the criteria is viewed as equally important, and as such have no specific weighting.

Table 2: Mechanical concept decision matrix

Concept	Fabrication	Rework	Assembly/Modularity	Strength	Durability	Weight	Function	**Overall**
M1	3	3	3	5	4	4	4	26
M2	3	3	4	3	3	4	4	24
M3	4	5	5	4	5	3	4	30
M4	2	2	5	4	4	1	5	23
M5	5	2	5	2	1	5	1	21

Concept M3 was the resulting leader, when compared against the others. This is the concept that was taken through for detailed development.

4.1.2.3 Probe improvements

The main issue experienced during inspection of the Minimole probe was the entry of the probe given the spread of the measuring arms. Figure 23 shows the action of the arms. The contact surfaces are the round parts extended furthest from the body, which pivot around the anchor points, seen for the top arm as the point of attachment. This means that as the probe attempts to enter the pigtail, there is a good chance the arms will spread and deny entry.

Figure 23: Minimole close up, showing measurement arm assembly

To combat this spread issue, reversing the action of the measurement arms was considered. This was eventually discarded for fear of anchoring the device in the pigtail on any unexpected edges or burrs. Setting the spread to a maximum was then decided on, before finally an adjustable spread device concept was selected.

There was also potential for a reduction in length, and a simplified fixing design of the Minimole. The reduction in length would mean that the probe would be less susceptible to curves in the pipe, and also reduce its weight. The fixing would take advantage of two vertical screws that were already present, and make use the metal in the new end piece to accommodate tapped holes, instead of the nut previously used. This would then sandwich all three lower components of the probe along the same axis. Details of the developed prototype are shown in section 4.1.3.3, ‘Minimole modifications’.

4.1.3 Mechanical prototyping and assembly

CAD models of the new and modified parts were created, and drawings produced. In order to facilitate rapid project progression, professional services were employed to undertake the majority of fabrication.

Drawings and descriptions were provided to each contractor, requesting a quote and lead time on services to be provided. Where quotes were requested from multiple contractors, the least expensive that could deliver within the required time frame was awarded the work.

Stainless steel fabrication was carried out using manual mills and lathes, and computer numerically controlled (CNC) milling machines, lathes, water jet cutters and hot wire cutters. The particular technique to be used on each part was discussed with the contractor, to make use of the experience of the contractor and to ensure adequate consideration was given by each party, in terms of limitations, efficiency, and any negative effects of the processes used.

All received modified and new items were inspected for correctness according to the provided construction drawings and work descriptions. On occasion, where work was omitted or erroneous, the contractors were quick to make amends and supply the corrected part. Missing holes was one example of re work, that occurred repeatedly.

Plastic parts were prototyped at Massey University with the use of *fused filament* 3D printing. This is a form of rapid prototyping where a plastic filament is heated and extruded in layers, which on contact are fused together (3D Printing for Beginners, n.d.). Layers are stacked until the part is complete. This technology was used extensively in the rapid development of a set of parts in section 4.2.5.5 ‘Sledge design and fabrication’. .

4.1.3.1 Economole modifications

The modifications carried out on the Economole required machining to be done on three main parts, and complete re-design and manufacture of one. The development, fabrication, and assembly of the parts are covered in this section.

The Economole chassis required one groove to be machined up each side, with holes at the ends. The holes were necessary to facilitate the feeding of the Minimole sensors through during assembly, and the grooves for the cables to sit protected in during use. A 3D model of the original chassis was used in SolidWorks to ascertain the best position for the modifications. This detail is shown in Figure 24.

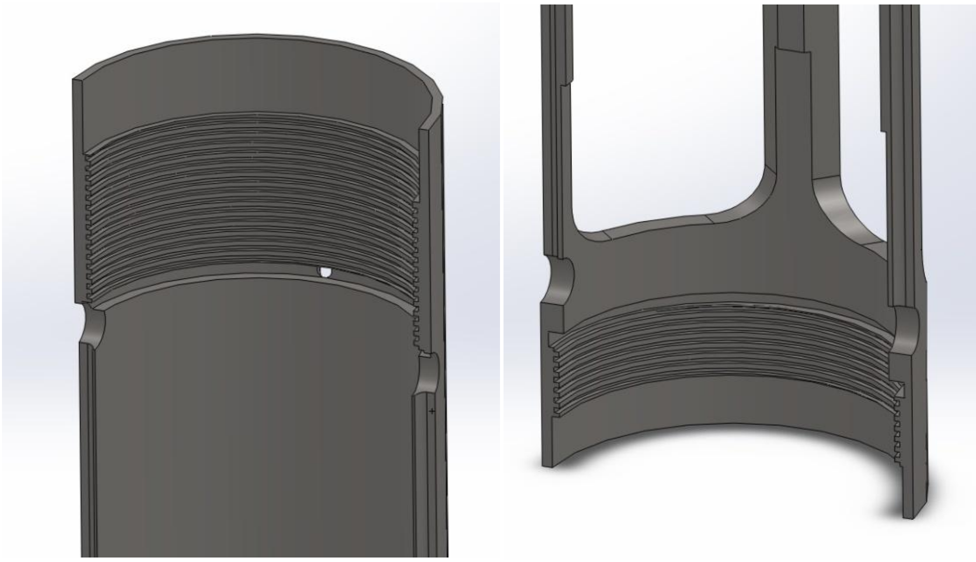

Figure 24: Section view of Economole chassis 3D CAD model, showing: upper hole and groove detail (left), and lower hole detail (right)

The upper holes are situated below the interference zone of the thread used to fix the top wheel-set – the capping piece of the Economole assembly, including preloaded positioning wheels. The lower holes were experimented with extensively in an attempt to facilitate sensor feed through without the need for removing the laser holder normally recessed there, along with the lower wheel-set which is fitted using the thread shown. A satisfactory angle of entry for the 8 by 49 mm sensor was not possible. In the end, modification of the *laser mount,* and *lower mount* of the bottom wheel assembly, was selected. The laser mount holds the laser assembly in the middle of the Economole, and the lower mount caps the end of the chassis and provides the mounting points for the lower wheel assembly. The holes in the chassis were positioned to suit, far enough away from the thread without getting too close to the fingered structure seen above to cause a weakening concern. The grooves were made 3.5 by 3.5 mm, round bottomed, to provide an interference fit for the 3.5 mm sensor cable.

The Chassis was milled and drilled according to the produced construction drawing, made using the CAD model. The chassis pre and post modification is shown below, in Figure 25. One of the two grooves and its upper and lower holes are shown.

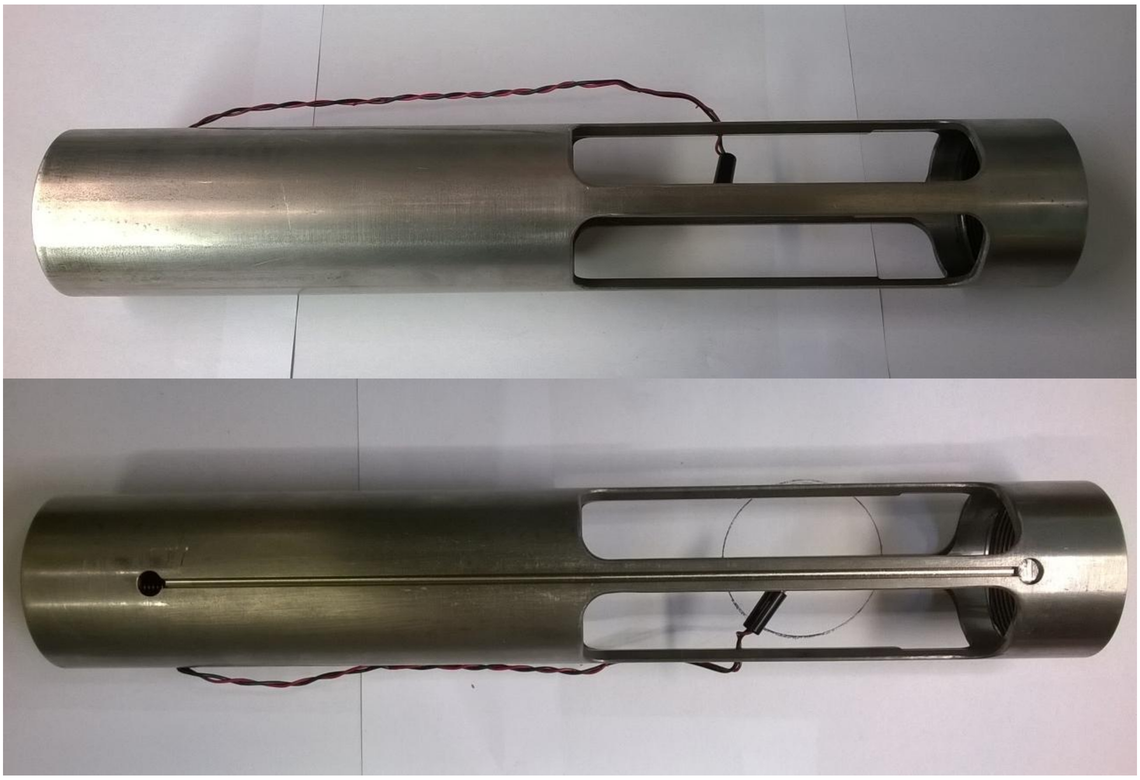

Figure 25: Economole chassis pre and post modification, showing one side with and without one of two sensor grooves and holes

The lower mount required modification as outlined above, to facilitate the fitting of the new sensors. A 3D model of the original lower mount is shown in red below, with the modified Chassis model – Figure 26. Clearly shown is the impingement of the lower holes by the skirt of the lower mount. The skirt in the original version is used to locate and retain the Laser Mount, against shoulders in the fingered parts of the Chassis.

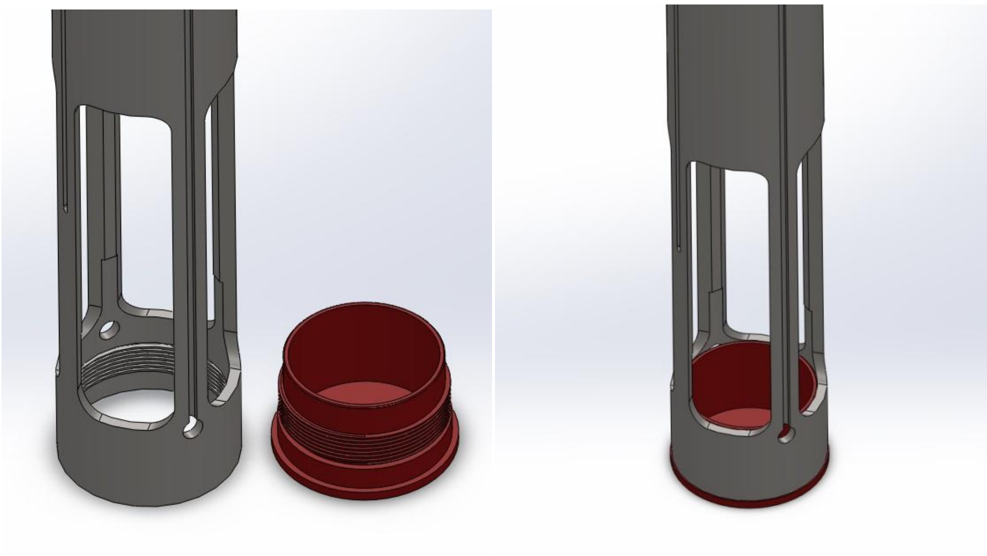

Figure 26: 3D model of modified Economole chassis with original lower mount, coloured red, adjacent (left), and fitted (right)

Taking the purpose of the skirt on the lower mount into consideration in the re-design of the Laser Mount allows this part to be reduced in length, so that the lower holes have a clear path straight through. The modified lower mount is shown in Figure 27. Just in view is the hole bored through in the lower mount, to enable the routing of the sensor cables down to the bottom of the Economole.

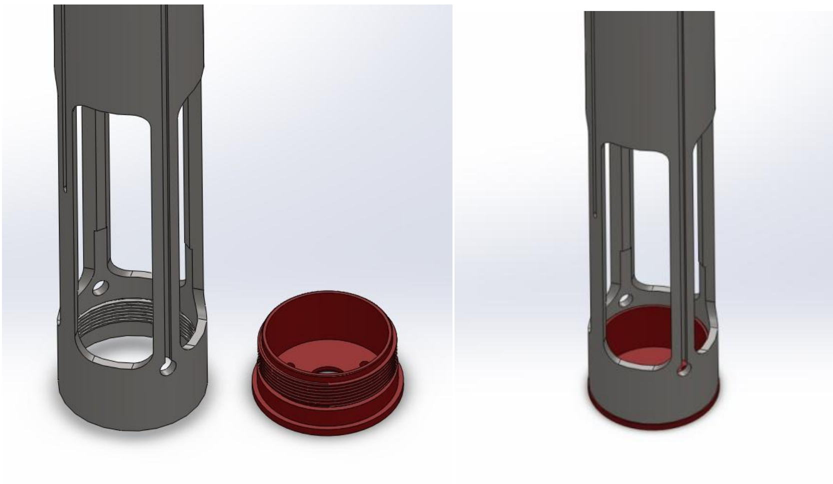

Figure 27: 3D model of modified Economole Chassis with modified Lower Mount, coloured red, adjacent (left), and fitted (right)

A construction drawing was created using the 3D model, showing details of 10 mm of the skirt being removed, and a 19.6 mm hole being bored through the centre. The lower mount was turned in a lathe to complete the work. The part pre and post modification is shown in Figure 28.

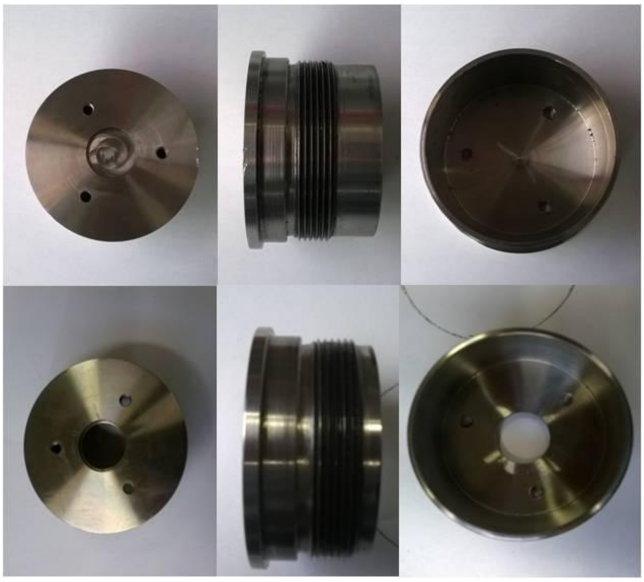

Figure 28: Economole Lower Mount pre modification (top row), and post modification (bottom row)

In order for the cables to make it to the very bottom of the Economole, the *bottom cap* also required punching through. The bottom cap sandwiches the lower wheel assembly together with the lower mount, providing the opposite end of fixing. A construction drawing was created and handed to a contractor for turning as with the lower mount. The part is shown before and after modification in Figure 29. Note also the additional three holes. These are designed to accommodate the fixing of the coupling to the Minimole. The holes are tapped to facilitate ease of assembly when the coupling is fitted. The fabrication of the coupling is covered in the next section.

Figure 29: Economole bottom cap pre modification (left), and post modification (right)

With the stainless steel requirements for cable fitting addressed, the new plastic laser mount could be designed. The driver behind the design is for it to be possible to assemble after the cables are fitted. This necessitated a way for the laser mount to pass by the sensors and cables on its way into place. Therefore, grooves were cut out of two fingers of the sensor. This is depicted in Figure 30, which shows the original design alongside the modified.

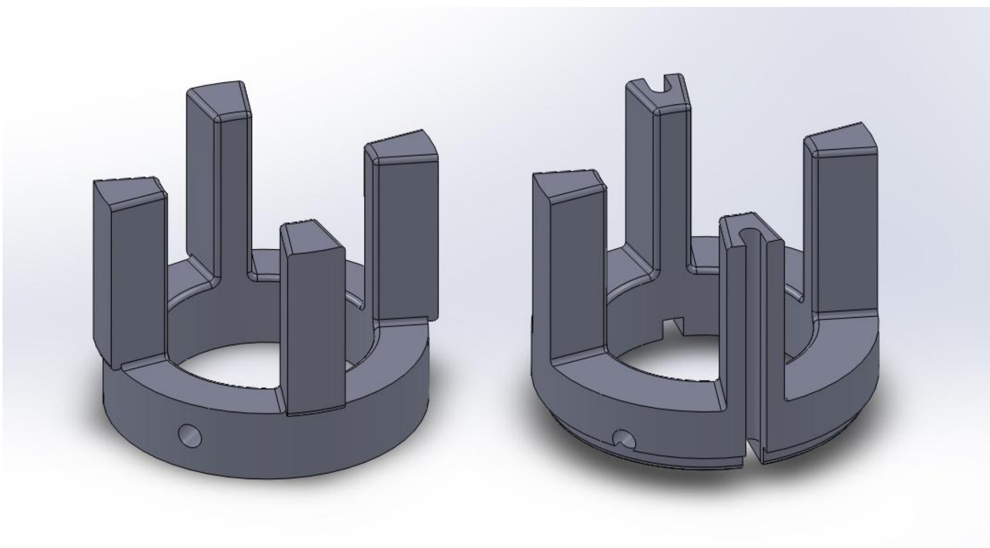

Figure 30: 3D models of original Economole Laser Mount (left) and new Laser Mount (right)

In the original laser mount, everything below the fingers forms part of the spigot. This spigot is used to locate the mount inside the lower mount. Because the skirt on the lower mount has been shortened to accommodate the sensor cables, the total outer diameter of the fingers has been modified to be retained as far as the bottom edge of the holes for the sensor cables. A clear path can be seen through from the chassis hole, down through the bottom of the modified lower mount, when fitted together with the new laser mount, as shown in Figure 31.

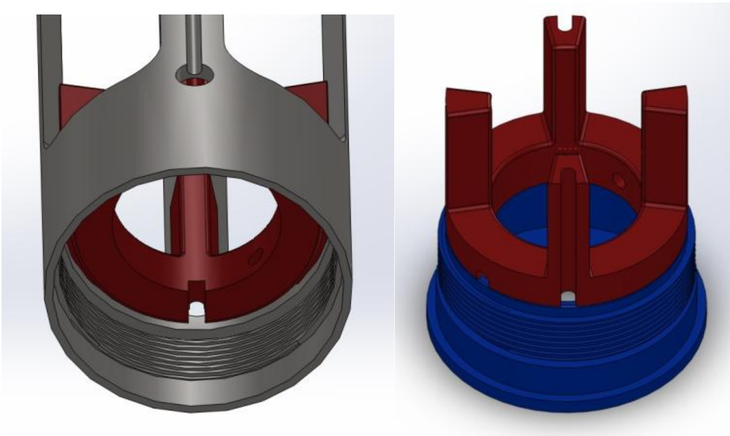

Figure 31: 3D model of new Laser Mount, red, inside modified Economole Chassis (left), and modified Lower Mount, blue (right)

In assembly of the system, the Minimole sensors are first passed through, before the Laser Mount is slid up into the Chassis, using the grooves passing by the loose end of the cables, and finally the Lower Mount is screwed in holding everything in place.

With the availability of rapid prototyping facilities at Massey University, and the relative ease with which they can be utilised when a 3D model has been created, it was decided to prototype the Laser Mount design using a 3D printer, prior to manufacture proper. To print a design in 3D, the model is first saved into an *STL* file format. STL is the defacto standard for 3D printing, basically converting the surfaces of the 3D model into a series of triangles (3D Systems, 2015). The STL version of the Laser Mount is shown below, on the left in Figure 32.

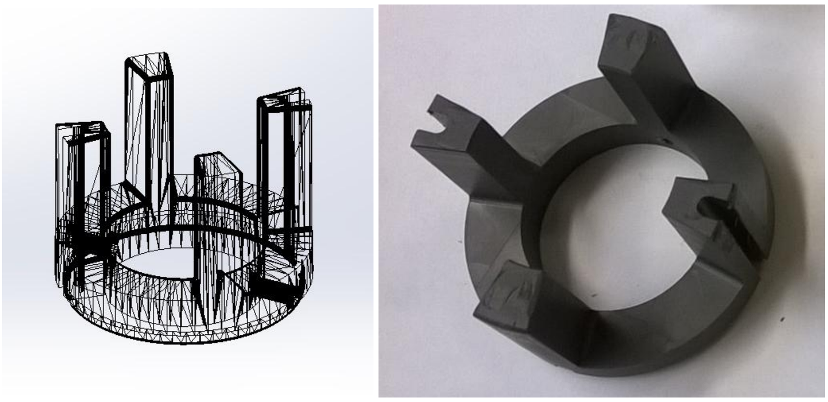

Figure 32: Laser Mount as an STL file (left); Finished new Laser Mount

The STL file can then be loaded into the 3D printer software. Before printing, one can set resolution, surface finish, and other quality settings. Plastic filament is then extruded in layers, building up in height until the model is complete. The 3D printed part lasted for a number of assembly trials, however, it eventually broke before a photo could be taken. Figure 32, above right, shows the final contractor manufactured piece, made of solid ABS plastic and considerably stronger. Punch marks are evident on the top surfaces from pressing it back out of the Economole Chassis during some fitting issues, attesting to its durability.

4.1.3.2 New parts

Two entirely new parts were required for integration of the Economole and Minimole. These were the Economole electronics housing extension, known as the Upper Economole Spacer, and the part linking the two devices together, the Minimole Coupling.

The Upper Economole Spacer was designed with three criteria: length to be 100 mm; threaded at the bottom to match Economole Chassis top thread; threaded at the top to match Economole top wheel-set cap, the Upper Mount. In this manner, the spacer part was able to be designed from existing drawings, modelled, and drawings to be produced for the contractor. There was no change or further detail in the design than that shown in the concept, in section 4.1.2.1, ‘Electronics housing concept’.

The upper spacer was manufactured and fitted without incident. Figure 33 shows the part as received from the contractor.

Figure 33: The newly manufactured Upper Economole Spacer

The Minimole coupling was designed to secure the Minimole to the bottom of the Economole, giving 100 mm of extension for the Minimole to fit to, providing for a measurement depth of 226 mm and a total overall length of the entire assembly of 1033 mm. In SolidWorks, the 3D model of the Bottom Cap was placed with the bottom face 271 mm away from the bottom of a 3D model of the Minimole assembly. This represented the comfortable working maximum height available when using the Economole winching system, of 1030 mm, leaving 30 mm of the total 1063 mm available for ease of movement. This is shown on the left of Figure 35, below.

The M3 concept, as described and selected previously in section 4.1.2.2, ‘Probe coupling concept’, uses a thin walled section of pipe to join the two devices together. A flange matching the outer diameter of the Bottom Cap was designed, with three holes, through which the coupling would be bolted to the Bottom Cap, and one large central hole, for the sensors and cables to pass through. In the bottom of the pipe, a tongue would be welded, where the Minimole would be fixed according to its existing mounting. The 3D model for this is shown below, in the centre of Figure 34. The assembly model is shown on the right of the figure.

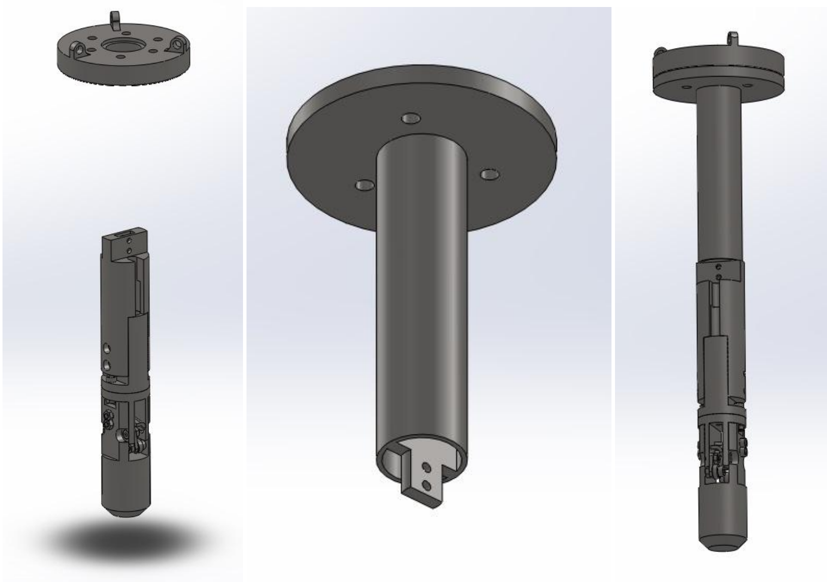

Figure 34: 3D model of coupling concept showing from left to right: spacing arrangement; Minimole Coupling; full assembly.

Upon issuing the construction drawing of the Minimole Coupling to the contractor for quotation, some suggestions were received on the manufacture and fitment of the part. It was suggested that turning the piece from one piece of stainless steel would be the fastest and most cost effective route. The contractor doing the work had more knowledge of his effort requirements and costs, so this was agreed. He was also suggested that a spigot for locating the coupling into the Bottom Cap should be included. This would aid in assembly of the parts, for the sake of a small lip on the top of the part already being turned, and so was considered a high value, low cost addition, and thus incorporated. The model was modified, and drawings updated to suit the contractors suggestions. The resulting part is shown below (Figure 35).

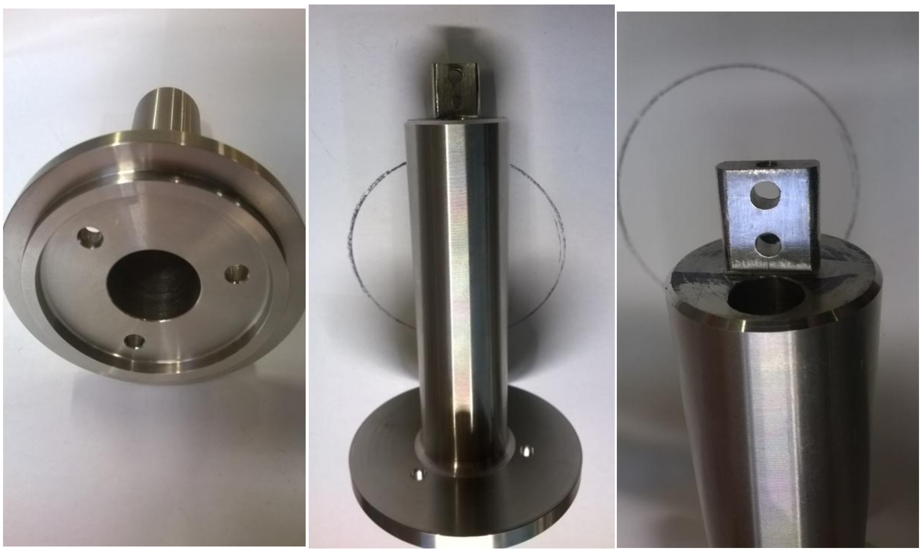

Figure 35: Minimole Coupling, from left to right: top view, showing spigot; side view; bottom detail showing sensor and cable holes.

4.1.3.3 Minimole modifications

The modifications carried out on the Minimole probe shortened the overall length of the probe, and addressed probe entry issues, by modification of the Bottom Case. A 3D model of the original design was created, and used as the basis for designing the modifications. The models, before and after modification, are shown in Figure 36. The length was reduced from 70 to 55 mm. A hole for an M8 bolt has been added in the bottom to facilitate pre-tensioning of the measurement arms. The two holes through the side of the old part, used for fixing to the upper part of the Mnimole, have been deleted; instead, a hole on each side at the top has been added, to be threaded for receiving the M3 bolt which held the upper two parts together. All unnecessary recesses have subsequently been removed. These improvements make both manufacture and assembly a much simpler process.

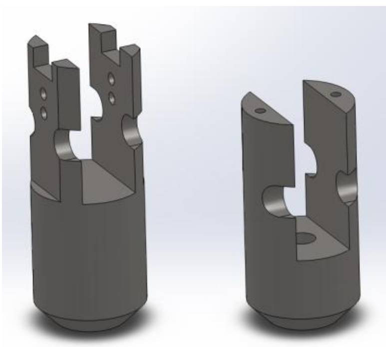

Figure 36: Mimimole Bottom Case, original (left) and modified (right)

A construction drawing was produced, and the manufacture of the part talked over with the contractor engaged. It was decided that a round bar would be turned down to the required diameter, including the lower bevel, before the slot would be milled, and finally the holes milled, drilled, and tapped.

The new design is shown alongside the old in Figure 37. It is lighter, more useful, and more to the point than the original design.

Figure 37: Original Minimole Bottom Case, alongside modified Bottom Case

During initial testing of pigtail entry with the above design, it was found that the Minimole measurement arms would catch on the pipe upon retraction of the device. As can be clearly seen in Figure 23, Section 4.1.2.3 ‘Probe improvements’, there is excess material protruding on each side of the device, above the rolling contact surfaces. This material served no purpose, and was ultimately removed, and a drawing produced for a new part template. The arms are made from a water jet cut section of stainless steel plate. Once the profile is cut, the lip for the sensor contact is folded, one hole drilled for the pivot, and another for the rolling contact or bearing. On changing the arms, it was decided to tap the holes where the bearings mounted, as then a low profile rose-head screw could be threaded directly into the arm, eliminating any interference caused by the nut or the head of the bolt rubbing down the inside of a small diameter pipe. Figure 38, below, shows the profile of the 3D model, alongside photos of the finished product.

Figure 38: Minimole arm inporvements showing left to right: 3D model; top view, assembled; view of threaded arm connection for bearing.

4.1.3.4 Assembly

With the exception some minor complications due to fabrication or drawing errors, which contractors were quick to rectify, the final assembly of all mechanical parts was seamless. The constituent parts of the overall assembly are shown in Figure 39. Note that this includes the Economole electronics which are installed within the Chassis, and the final version of the Minimole electronics, as above (right).

Figure 39: MXmole sub-assemblies (formerly known individually as Economole and Minimole)

The high quality of the machining in the Upper Economole Spacers threads resulted in smooth fitment of this part into the Economole Chassis, and of the Upper Mount into the Upper Economole Spacer. The Minimole Coupling was bolted to the Bottom Cap as designed. The spigot made the assembly easier, as intended. The new Minimole arms and Bottom Case were fitted, without issue. The entire assembly is shown in one piece, in Figure 40.

Figure 40: MXmole inspection device fully assembled

4.2 Electronic System Design and Testing

In this section the electronic system research and development is covered. This begins with thorough investigation and assessment of the existing systems and implemented technologies

4.2.1 Existing Economole electronic system

The Economole is connected to the laptop via a PoE (Power over Ethernet) injector. The power is split from the signal at the Economole, and used to power the camera and laser. The camera transmits image data in jumbo packets over Gigabit Ethernet to the laptop for processing. A block diagram of this system is shown below (Figure 41).

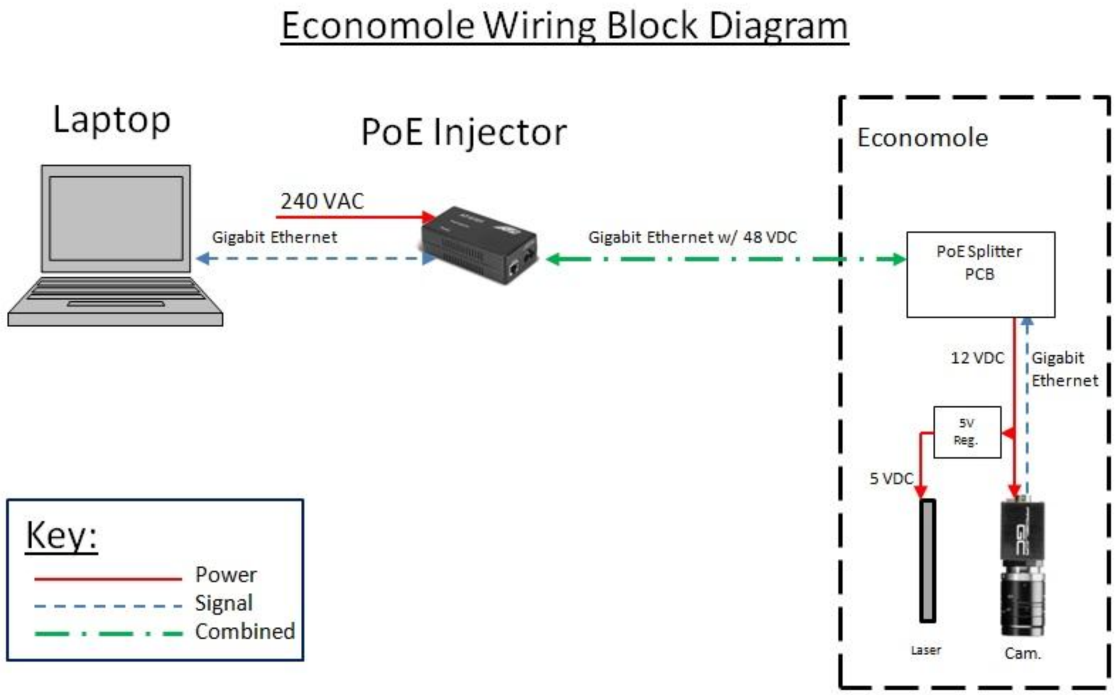

Figure 41: Economole data and power block diagram

It should be noted that the Gigabit Ethernet connection uses all four pairs of the Ethernet cable connecting the Economole to the laptop. Therefore when the camera is transmitting data over this line, there are no spare cores to use for other purposes.

The camera itself is a Prosilica GC1290, designed for industrial applications. It carries a range of *GPIO* (general purpose in-out, used for receiving and sending electrical signals), including RS-232. The RS-232 I/O is able to provide serial communication from peripheral devices near the camera. These communications are transmitted and received through the Ethernet connection to the host PC. During concept development, a test rig was set up for this, and RS-232 serial communications were successfully sent and received through the camera.

4.2.2 Existing Minimole electronics system

The Minimole design is connected to the laptop USB port and to a ±15 VDC power supply. The USB line connects through a USB to RS232 cable adapter, to a custom PCB. The power supply also comes in to the PCB. All external connections leave the board through an RJ45 jack into an Ethernet cable. At the Minimole, the power supply is fed to the BICMs (Boxed Inline Conditioning Modules) for the LVDTs, and a local micro controller. The LVDTs 0 – 15VDC output signal is attenuated to 0 – 5VDC, and fed into the microcontroller's analogue inputs. The microcontroller converts the LVDT output to RS-232 serial for transmission back to through the Ethernet cable to the laptop, via the RS232 to USB cable adapter. A block diagram of this is shown in Figure 42. It should be noted that unlike the combined power and signal line set up for the Economole, the Minimole uses separate cores of the same cable for its combined lines – a total of five cores.

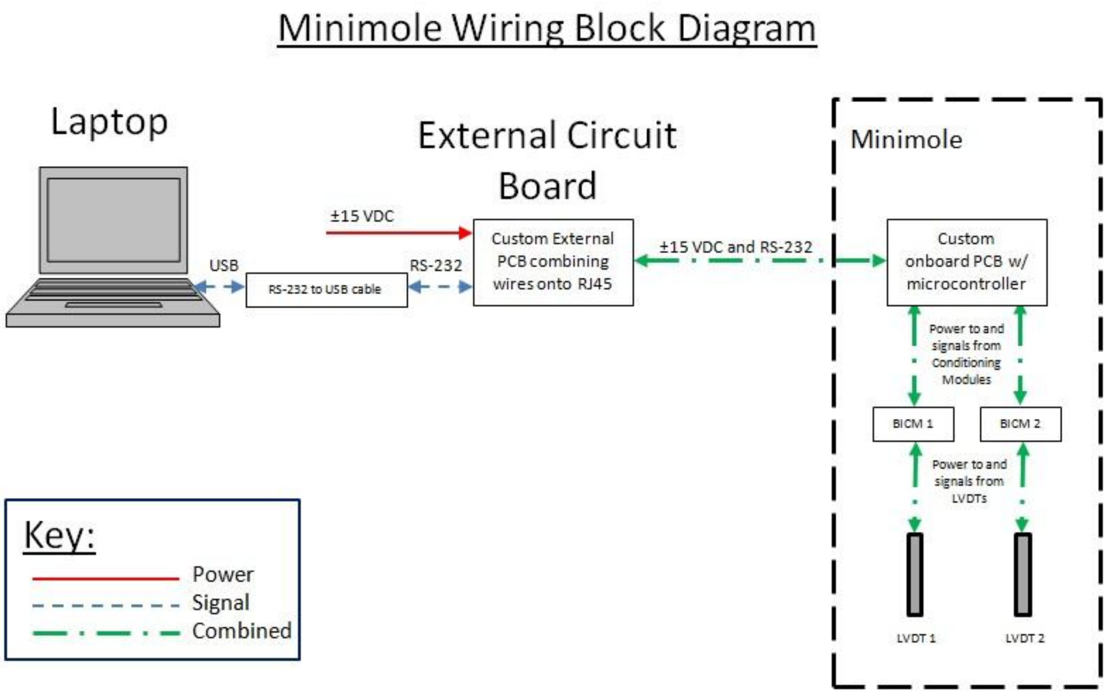

Figure 42: Minimole data and power block diagram

The existing onboard PCB from the Minimole assembly is housed in a large diameter tube chassis, which includes a stepper motor and threaded drive shaft, for driving the Minimole into the pigtail. Detailing this part of the existing design has been omitted from this section, as it deleted from further development. It is not an operationally feasible part of the existing design.

4.2.3 Electronic requirements

The Minimole must be electronically coupled to the Economole, without adversely affecting the existing Economole system.

Inspection carried out on the existing systems, together with project requirements, yielded a number of criteria to be met:

- The Minimole must receive sufficient power to the supply the LVDT's, and microcontroller and associated electronics;
- The design must permit data transmission to the laptop, in a manner that can be received by the laptop, and manipulated by the developed software;
- The design must be modular, and easily incorporated into the existing Economole system;
- The design must communicate down the reformer tube over the existing Economole Ethernet cable;
- The design should not interfere with the current measurement range of the Economole, down the tube.

4.2.4 Electronics concepts

The investigation of the existing systems and development of ideas around how to make them work together, led to three main concepts being developed.

The implementation of electrical systems carries a relatively high risk. It requires extensive testing and debugging of prototypes, and can also require the procurement of long lead items. As a result, a concerted effort has been made in developing the electrical concepts, in comparison to others.

These are detailed below, in chronological order, arriving at the final selected concept – E3.

4.2.4.1 Electronics concept E1

One issue with using the same cable, is that because all of the cores are currently used in the Economole design, there needs to be a way to switch modes and allow Minimole data transmission. To achieve this, the signal can be switched depending on what the Minimole is measuring. When the Minimoles measuring arms are wide open, the Minimole is not in the pigtail section and no measurement needs to be taken from it, so the data sent is from the Economole. When the Minimole enters the pigtail, the arms begin measuring and the signal sent is from the Minimole. This concept is shown in the diagram of Figure 43, below.

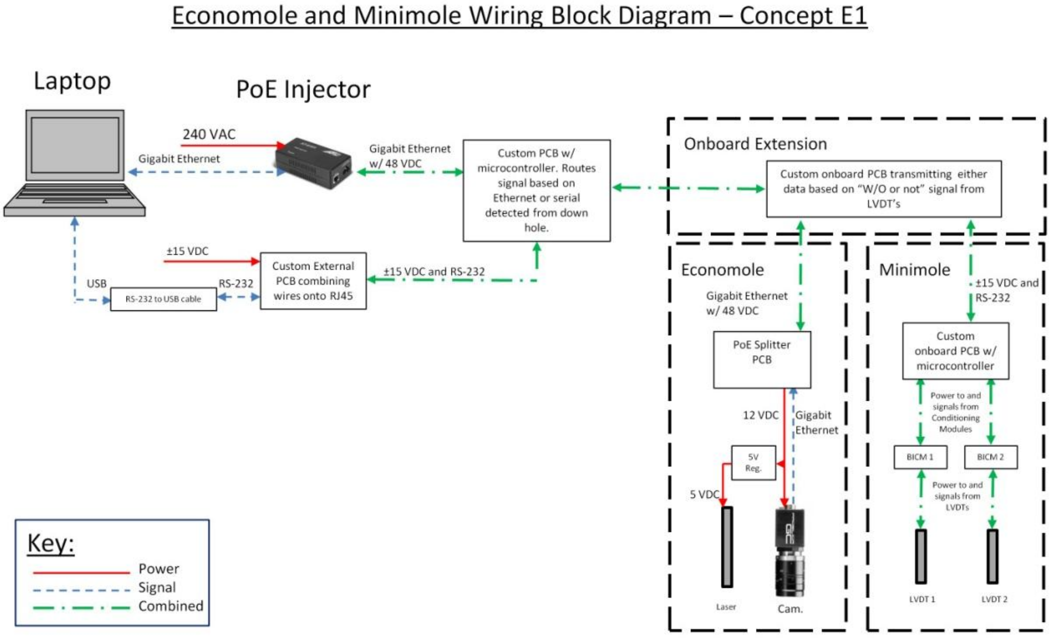

Figure 43: Concept E1

At the top of the reformer tube, a signal processing PCB routes the signal. This routing will vary based on what the signal is: Economole or Minimole data.

This concept presented a number of areas to be developed during a detailed design phase:

- It is possible that the power from the PoE may not be useable when the Ethernet is not connected under normal conditions. If the PoE is not able to be used to power the Minimole, an on-board power source would be required to keep the LVDT's operational when not receiving power from the top of the tube;
- There may be risks associated with un-synchronised signal switching top and bottom. These need to be addressed;
- If the Minimole is the sole transmitter for the section of travel which covers the pigtail, the data from the Economole will not be received over this distance. Some form of multiplexing would therefore need to be investigated.

4.2.4.2 Electronics concept E2

This concept was developed in an attempt to address complicated issues that present high risks with concept E1, as detailed above. The Minimole serial signal will be converted to Ethernet at the Economole. An Ethernet switch will be built in to the Economole to provide transmission of both Economole and Minimole data. This will leave signal processing and interpretation to software on the laptop. Figure 44 provides an overview of the layout of this design.

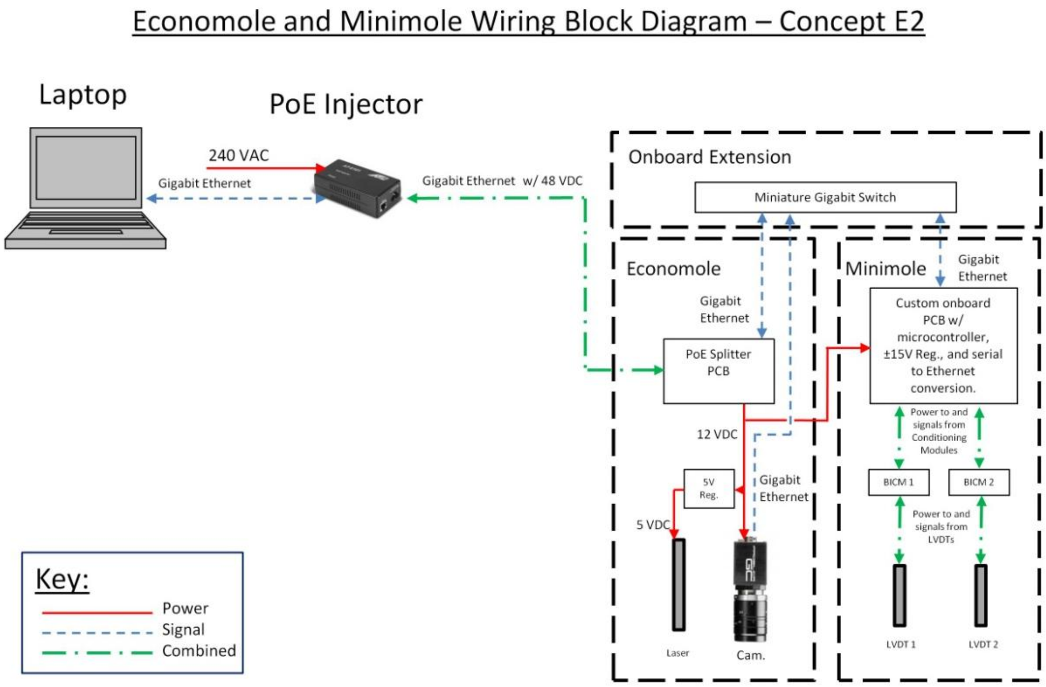

Figure 44: Concept E2

Serial to Ethernet converters are available as unenclosed PCB's, straight off the shelf. It is also possible to purchase relatively small gigabit Ethernet switches. This minimises the amount of bespoke electronics going in to the assembly, and hence reduces risk exposure in the development of those systems.

This concept may add significant length to the top of the Economole. This is required to fit the serial to Ethernet converter, and Ethernet switch, in addition to the existing Minimole electronics.

4.2.4.3 Electronics concept E3

It was discovered that the existing Economole camera has RS-232 serial communications capability. This was subsequently tested as successful, and resulted in the Concept E3 being developed.

This concept utilises the Economole camera RS-232 I/O to transmit Minimole data over the Economole Ethernet connection. The Minimole is powered via the Economole PoE splitter 12 VDC output. Figure 45 shows the concept.

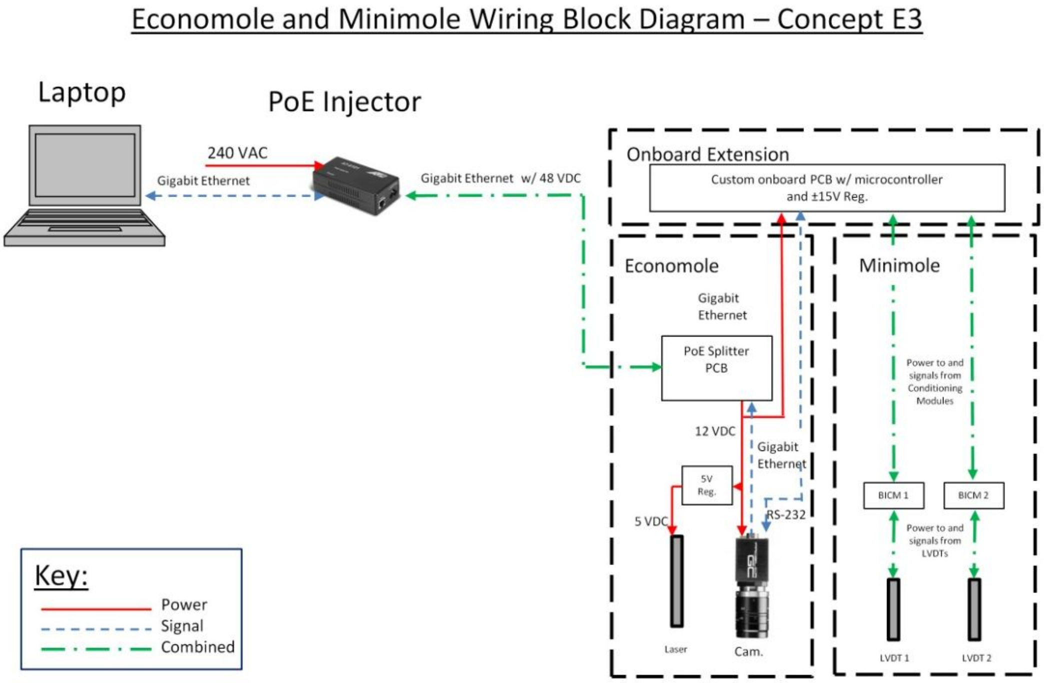

Figure 45: Concept E3

Receiving and processing of the Minimole signal at the laptop requires development of code in the same language and manner as the existing Economole code.

This concept meets fully the requirements set out in Section 4.3, while also addressing the issues arising in E1 and E2. It achieves this with a minimum of components, and low risk in development activities heading into the detailed design.

4.2.5 Electronics prototyping

Circuits were breadboarded in stages, ensuring that each part produced a satisfactory result, before progressing to the next.

4.2.5.1 Power supply

The first part to be tackled, to ensure the viability of concept E3 as detailed above, was the power supply for the Linear Variable Differential Transformers Boxed In-line Conditioning Modules – the LVDT BICM's. These required ±15 mA at ± 15 VDC. Power requirement for the BICM's is calculated as follows:

$$\begin{aligned} &P = VI \\ &V = 15\,VDC, \qquad I = 0.030\,A \\ &P = 15 * 0.03 \\ &= 0.45\,W \end{aligned} \tag{2}$$

With the goal of finding a compact solution for the limited space, a switch mode regulator was sought out. These are widely used because of savings in weight, cost, efficiency and performance (Poole, n.d.). A Dual In-Line Pin (DIP) packaged power supply was purchased from Texas Instruments' DCP02. The model purchased produces 2W of isolated, unregulated power at ±15 VDC from a 5 VDC power supply (Texas Instruments, 2006). Although a 1 W version was made, which would have covered the required 0.45 W, only the 2 W was readily available from the supplier. To begin with, the DCP02 was fed from a lab power supply, to check to output. An oscilloscope was used to verify output, as shown below (Figure 46).

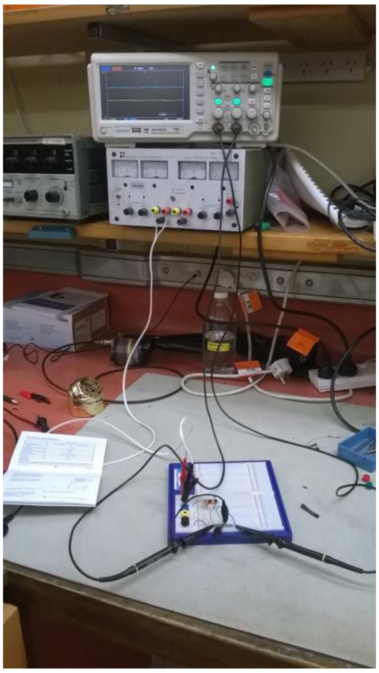

Figure 46: Testing sensor power supply output

The power supply produced ±23 VDC in open circuit. Resistors were added to simulate the load of the BICM's, resulting in a +16/-15.5 VDC output. The BICM's tolerate ±1.5 VDC, so this initial result was acceptable. However, a 500 mV peak-to-peak noise, at the regulators switching frequency of 400 kHz was observed. The LVDT BICM's were connected, and observed to produce stable readings on the oscilloscope.

The next step was ensuring that the DCP02 regulator could be powered from the existing Economole 5 VDC linear regulator, used to power the laser. This test was as above, except that the linear regulator was powered from the lab power supply, and the switch mode regulator supplied from the linear regulator. The circuit was not stable, cutting in and out, and sometimes not working at all. It was assumed that the connected BICM's were causing an *in-rush* current, interfering with correct linear regulator operation. An in-rush current is the sudden current draw of an electrical circuit during turn on, which may be many times more than the normal operating draw. Figure 47 shows the linear regulator as found in the Economole. It had been implemented without external bypass capacitors, which are recommended by the manufacturer for optimum stability and transient response (Texas Instruments, 2013). The regulator can be seen in the centre of the figure, above the Ethernet jack. It is hanging loose, soldered to loosely hanging wires. This position is precarious at best; the large metal surface seen is the heat sink which is also connected to the ground of the regulator. The heat sink gets extremely hot without being bolted to an appropriate dissipater, and could either melt nearby wiring or components, or cause a short by contacting anything on the circuit board below that is not a ground.

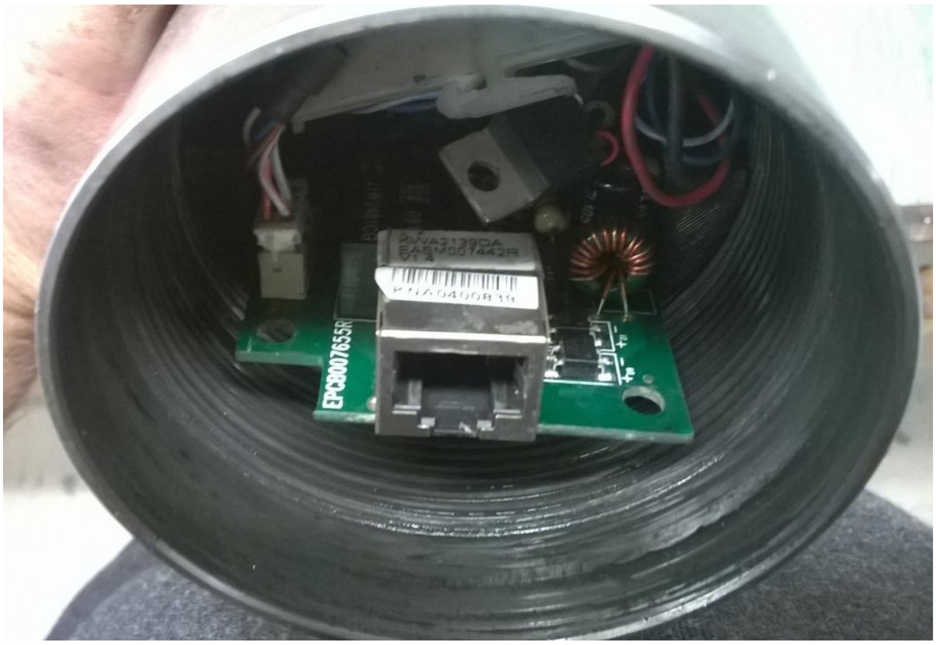

Figure 47: View inside the original Economole, showing linear regulator hanging loose above Ethernet jack

On the breadboard, bypass capacitors were fitted as per the manufacturer's recommendations. This immediately led to a functioning circuit.

The next step was to connect the power supply circuit to the Economole PoE splitter board. The PoE splitter provides a respectable 15.4 W at 12 VDC (Allied Telesis Inc, 2008). The splitter was set to output 12 VDC. This was used to power the camera directly, and the laser via the 5 V linear regulator. Power availability was calculated as follows:

$$p_{laser} = 0.9\ mW$$
$$p_{camera} = 3\ W$$
$$p_{splitter} = 15.4\ W$$

$$P_{available} = p_{splitter} - p_{laser} - p_{camera}$$
$$= 15.4 - 0.0009 - 3$$
$$= 12.4\ W$$

(3)

The circuit was successfully powered from the PoE board. This included powering the camera directly, the 5 V regulator, which powered the laser and the ±15 VDC regulator. The ±15 VDC regulator subsequently powered the BICM’s for the LVDT’s.

During the later development of the physical layout of the circuitry, and how it would fit in to the Economole, it was found that the heat generated by the linear 5 V regulator was so significant that it would require a large heat sink to dissipate effectively. Space requiring, heat generating components are not ideal for this application, thus a switch mode regulator for the 5 VDC supply was investigated. A Recom branded R-78B5.0-1.5 model switching regulator was selected for testing, taking in 6.5 to 18 VDC, and outputting 5 VDC ±0.15 VDC (Recom Power, 2015). In the later development of the electronics, the load on the regulator is estimated at around 150 mA at 5 VDC. According to the efficiency curves for the regulator (Figure 48), this results in an efficiency of 80-95% (the curves are for min and max input voltage). This is in comparison to a linear regulator operating as a voltage converter, where the efficiency is directly related to the ratio of output voltage over input voltage (Zhang, 2013). In the case of our 12 VDC input and 5 VDC output, this yields an efficiency of 41.7%, explaining why so much heat was being generated, and clearly identifying the switch mode regulator as the better of the two in this regard.

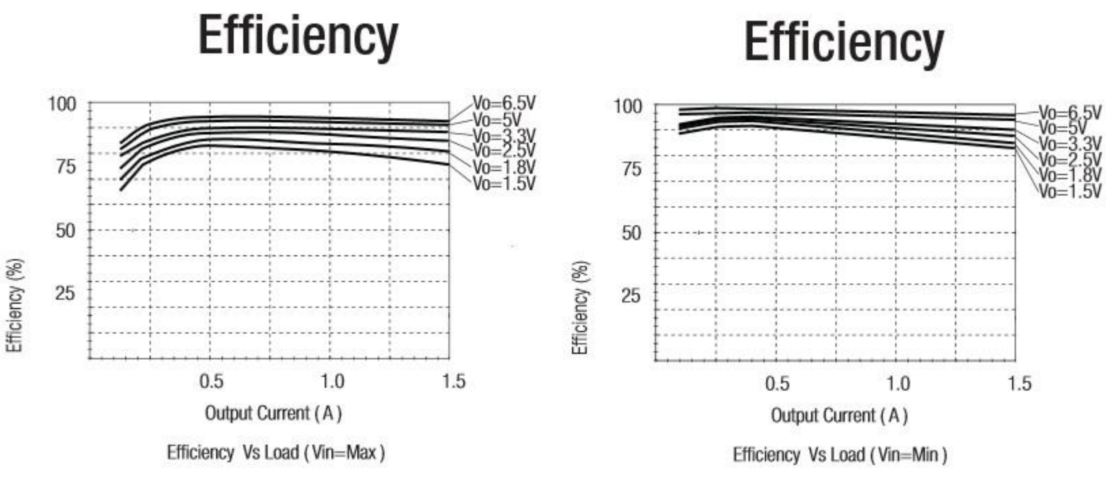

Figure 48: Switch mode Economole power supply efficieny curves, showing maximum input votlage (left) and minimum input voltage (right) (Recom Power, 2015)

The operation of the switch mode voltage regulator with the breadboarded system was verified. In comparison with the linear regulator, at one point in the design, less than half of the measured current was drawn, at 360 mA and 160 mA respectively. No detectable heat was generated, to the touch, compared to the linear regulator which could not be touched after less than one second of running.

4.2.5.2 Analogue filtering

The signal from the LVDT BICM is 0 to -15 VDC, representing 0 to 10 mm displacement from the sensor. Although the cable from the LVDT to the BICM and the BICM output connecting cable are screened, interference is possible from any high frequency sources entering the system or on leaving the system. This may be due to nearby welding during shutdowns, or from radio waves, or from mains power. To cut out any sources of noise including and above minimum mains power frequency of 40 Hz, a low pass filter was required on the BICM output. Furthermore, the Analogue to Digital Converter (ADC) for the completed circuit would require a signal in the 0 to 5 VDC range. Therefore inverting and re-ranging the signal was also necessary. A robust solution for adjusting gain, filtering, and inverting an analogue signal is the *active low-pass filter*. This is the alternative to a *passive low-pass filter*. The physical difference between the two is that the passive filter is made from only discrete components, while the active filter is made from discrete components and an operational amplifier. While a passive low-pass filter would be capable of filtering the signal, and even very coarsely adjusting gain, active filters circumvent the associated draw backs of desired signal attenuation, and change in filter characteristics upon connection to a load (Measurement Computing, n.d.). Furthermore, no signal inversion would be possible with the passive filter. The layout of an active low-pass filter, and attenuation characteristics, are shown below (Figure 49).

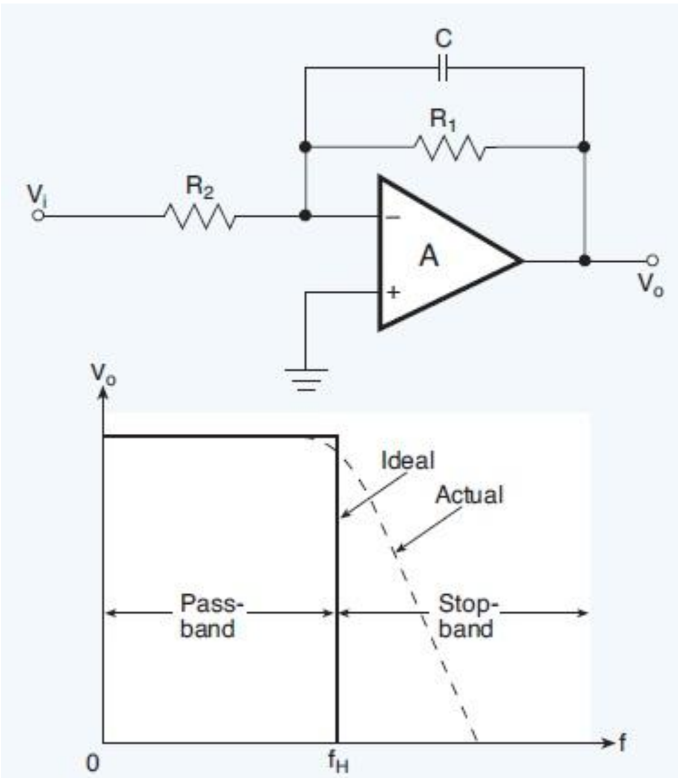

Figure 49: Active low-pass filter lay out and characteristics (Measurement Computing, n.d.)

Two equations need to be taken into account when deciding on the discrete components to be included in the filter: the low-pass filter equation and the gain equation. The equation for a low-pass filter designed using the above configuration is shown in Equation 4, below, rearranged from the formula for the reactance in Ohms of an AC circuit (Giancoli, 2009). F_{cut} is the frequency above which the signal is attenuated (filtered).

$$F_{cut} = \frac{1}{2\pi R_1 C}$$

(4)

The equation for gain using an inverting amplification in shown configuration is as follows, in Equation 5 (Measurement Computing, n.d).

$$Gain = -\frac{R_1}{R_2}$$

(5)

Knowing the cut-off frequency target of 40 kHz, re-arranging Equation 5 for the product of the discrete component values provides an idea on the order of magnitude that will be required for these components. This is shown in Equation 6, below.

$$F_{cut} = \frac{1}{2\pi R_1 C}$$

$$CR_1 = \frac{1}{2\pi F_{cut}}$$

$$= 3.98 * 10^{-3}$$

(6)

The above result means that if components of the same order of magnitude were used, they would have to be *milliohm* resistors and *millifarad* capacitors. Typical, compact, and readily accessible values of resistors range from ohms to *megaohms*, and for capacitors from *nanofarads* to *microfarads*. Higher values capacitors are the primary culprit for taking up space in the circuit. By shifting the capacitor value down six orders of magnitude to nanofarads (nF), and the resistor up by six to *kiloohms* (kΩ), the necessary product can be achieved. A 15 nF capacitor was available in the lab being worked in. Using the derived product from Equation 6 above, yields a value of 265.3 kΩ. Observing Equation 4, the cut-off frequency is inversely proportionate to the value of R_1. Lifting the value to 330 kΩ results in a cut-off frequency of 32 Hz.

The value of the other half the circuit, the gain component, was then calculated, using Equation 5. Re-ranging the signal from a maximum of -15 VDC to 5VDC required a negative gain of one third. A 1 MΩ, or one *megaohm,* resistor yields a gain of -0.33.

During breadboard testing of the prototype, significant noise, of 200 mV peak-to-peak at 400 kHz, was observed on the output of the op-amp. This was first identified during power supply testing, as explained in section 4.2.5.1, 'Power supply'. This noise was not present on the signal output from the BICMs. Upon investigation it was found only at the outputs of the active filter. Investigation was required into the op-amps *supply voltage rejection ratio,* or SVR (Carter (n.d). This is figure for describing the ability of the op-amp to attenuate any noise from the power supply that might otherwise be added to the output signal – it would ideally be infinite. The typical value provided in the data sheet for the op-amp is an SVR for supply noise over output noise of 86 dB (Texas Instruments Incorporated, 2014), though in reality, this would change according to noise frequency (Carter, n.d.). Carter (n.d) specifically mentions that attenuation of the switching noise of switch mode regulators like the one used here is almost non-existent with the SVR of an op-amp; specifically between 50 and 500 kHz, and the regulator here is switching at 400 kHz. It became clear that some form of passive filtering on the power supply to the op-amp would be required. The circuit for a passive low-pass filter is shown in Figure 50, below.

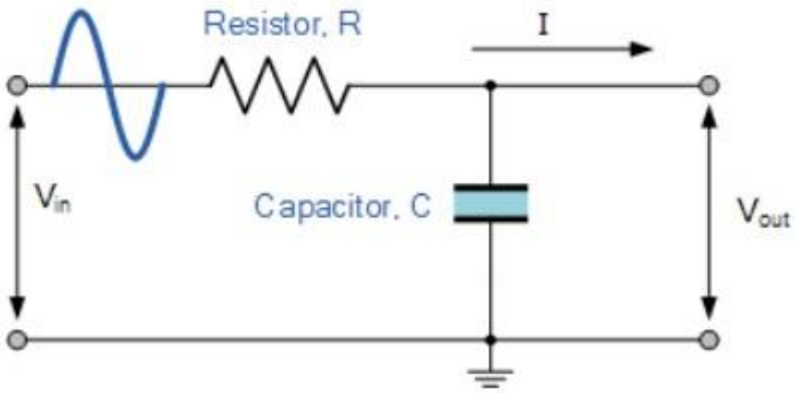

Figure 50: Low-pass filter layout (REF)

The above circuit differs from an active low-pass filter, in that there is a voltage loss across resistor *R.* This loss is proportionate to the current through the resistor and the resistance itself. The Texas Instruments TL084C op amp used is a four amplifier package, requiring a typical supply of 1.4 mA per amplifier (Texas Instruments Incorporated, 2014). Initially, all four amplifiers available were used: one active low-pass filter per LVDT, and one buffer or voltage follower per LVDT. No benefit was observed in using the voltage follower amplifiers, and they are not of much use when connected to a high impedance input as these were, so only two amplifiers were used. The gain of the signal at one third of 15 VDC, meant that only ±5 Volts was required of the ±15 VDC op-amp power supply, and 10 VDC was available to drop across the filter resistor. Ohms Law was required in calculating the resistor value, as shown below Equation 7, taken from Giancoli (2009).

$$V = IR \tag{7}$$

The above equation is rearranged to determine R, below (Equation 8), taking a nominal worst case current draw of 10 mA.

$$\begin{aligned} R &= \frac{V}{I} \\ &= \frac{10}{0.01} \\ &= 1\ k\Omega \end{aligned} \tag{8}$$

This resistor value results in a drop of 1.4 VDC under typical operating conditions (1.4 mA). Rearranging the low pass filter formula (Equation 4), to determine the capacitance is shown below (Equation 9). However, in this case, there is only one resistor. The cut-off frequency is set at 40 Hz.

$$\begin{aligned} C &= \frac{1}{2\pi F_{cut} R} \\ &= \frac{1}{2\pi * 40 * 1000} \\ &= 3.98\ uF \end{aligned} \tag{9}$$

Moving the capacitor value up to an available value of 4.7 uF yields a satisfactory cut-off frequency of 33.9 Hz. The filter was set up and tested. One resistor was placed in line with each of the op-amps two power rails, as close as possible to the op-amp, and one capacitor between each rail and ground, again as close as possible. This resulted in a of 50 mV peak-to-peak, at 50 Hz. This noise is assumed to be caused by mains interference with the probe leads to the oscilloscope.

4.2.5.3 Microcontroller and serial communication

The hardware decided on for the Minimole was the Teensy 2.0 USB Development Board. This was selected due to accessibility, flexibility, and familiarity, and ease of programming. The program to be carried out on board the Minimole would not be too complex, not involving any image processing, or processing of particularly large amounts of data. The board is available on mail order for less than 20 USD (PJRC, n.d.). It can be programmed in *C*, a common programming language, or using the Arduino language, making it useable for anyone who has done any programming, microcontroller or otherwise. Tasks required from the microcontroller will be to convert the filtered analogue signal to digital, do some averaging and processing, and transmit the resulting data out over serial. The Teensy 2.0 uses an ATMEGA32U4 8 bit AVR processor, capable of operating at 16 MHz, and with the board having 25 I/O, including 12 analogue inputs, and is more than capable of handling those tasks. A picture of the Teensy 2.0 is shown in actual size is shown below (Figure 51). It is approximately 18 x 31 mm.

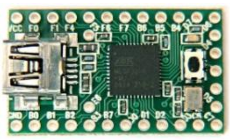

Figure 51: Teensy 2.0, actual size (PJRC, n.d.)

The Teensy 2.0 *UART* pins produce and receive 0 VDC low and 5 VDC high signals. UART stands for ‘universal asynchronous receiver/transmitter, and is a hardware device that translates data between parallel and serial, i.e. from within a computer to over a communication line (Instrument Data Communications Pty Ltd, n.d.). The Economole camera, which the signals have to interface with, uses RS-232 protocol for its’ serial communication. Figure 52 depicts this protocol, showing the difference between transmitting the ASCII character ‘J’ with a UART and with RS-232. ASCII (American Standard Code for Information Interchange) is the most common format for test files in the world, using 7 bit binary to represent 128 different characters (Rouse, 2005).

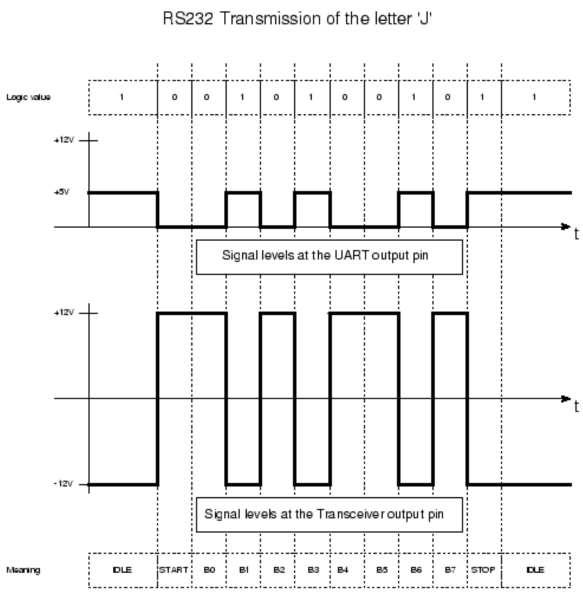

Figure 52: Transmission of ASCII character 'J' with UART and RS-232 (Best-Microcontroller-Projects, 2016)

A test was carried out to confirm that the camera serial pins functioned as expected. This exercise is depicted in the screen capture in Figure 53, below. The pins were wired from the camera directly to the serial port of a PC. The proprietary camera programme *SampleViewer* can be used to check image histograms, stream images, and transmit and receive information to and from the cameras RS-232 pins. This program was used, along with a standard windows communication terminal, to verify that the serial communication was functioning while streaming an image from the camera, thereby confirming no interference with the image capture required for Economole operation, while serial communication was being used.

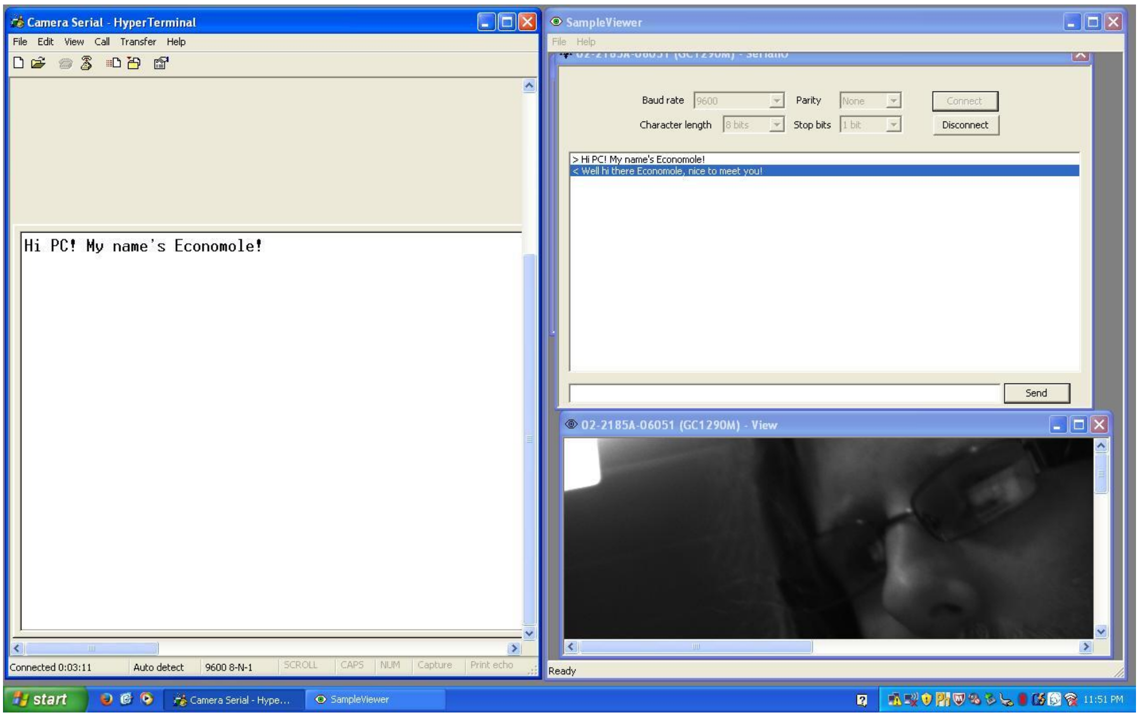

Figure 53: Economole camera serial function test

A Texas Instruments MAX202 Integrated Circuit was selected for the job of taking the UART signal and converting it to RS-232, and taking the other way around, acting as the interface between the microcontroller and the camera. The MAX202 was set up in the breadboard with the recommended decoupling and charge up capacitors (Texas Instruments Inc, 2007). As communication, firmware, and software were being developed, it was possible to test the signals between the camera and the microcontroller. After some difficulties sending and receiving transmissions, an oscilloscope was used to determine what was actually being sent. It was discovered that, taking into account the inversion, the decimal value for character return, 13, was sent after each transmission from the camera. Once a carriage return was worked into the transmissions from the microcontroller, the electronics were confirmed to be functioning correctly.

4.2.5.4 Circuit board fabrication

Once component selection, configuration, and testing was complete, circuit board design could start. Two PCB's would be required: one for the new Economole 5 VDC switch mode regulator, replacing the old loose hanging, inefficient linear regulator; the other for the Minimole electronics detailed throughout this section. The two needed two be separate, in order to provide modularity and ensure that the Economole could function as it was, including the improvements.

Schematics were drawn up in Altium Designer, which would subsequently be used in the same program for PCB design. Templates for the components were generally available, and if not, a similar footprint and pin layout could be found, or at least a header with the same pin spacings.

The schematic for the Economole regulator, to be known as the Mole Distribution Board, is relatively small, so is shown below, in Figure 54. Added into the schematic are the headers for the necessary connections, clockwise from bottom left: 12 VDC from the PoE splitter; 5 VDC out to the laser; 5 VDC to the Minimole electronics and the RS-232 connection; and 12 VDC to the camera and the RS-232 connection.

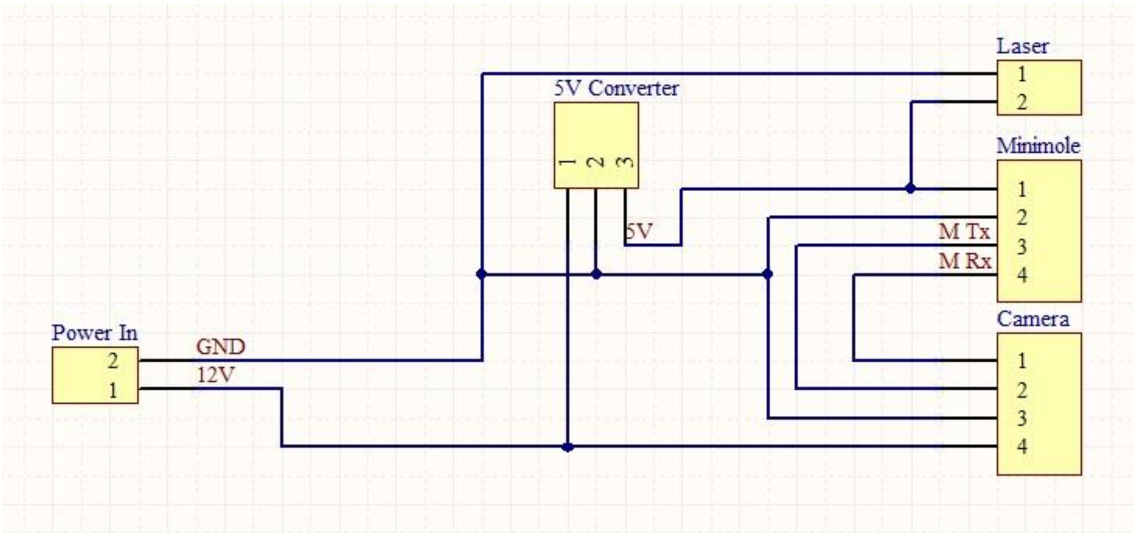

Figure 54: Altium schematic of Mole Distribution Board

The goal for the Mole Distribution Board was to be able to fit into the same general area as the existing Economole electronics sledge. Figure 55 shows the completed PCB. It was designed to be as small as possible, while using the maximum height of the existing electronics sledge.

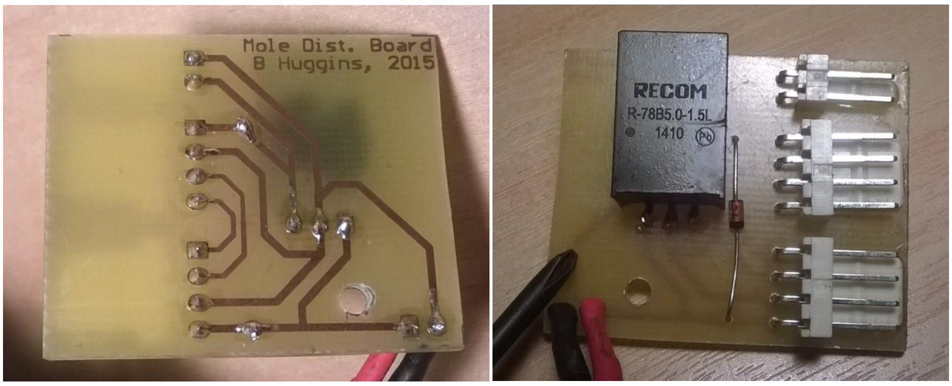

Figure 55: Mole Distribution Board PCB

The schematic for the Minimole electronics is shown in Appendix 2. This schematic breaks out the design into five sections, for ease of interpretation:

1. Plug headers, where the four wire plug for power supply and data transmission from the Mole Distribution Board connects, as described above, and the two five pin LVDT BICM headers connect;
2. Power supply, showing the BICM and op-amp voltage regulator, and associated filtering;
3. Signal filtering, showing the active low pass filters used in LVDT BICM output signal conditioning;
4. Processing, where there are two long headers representing the microcontroller. This is connected to power, to the filtered LVDT signal, and to the MAX202 interfacing device;
5. Transmission, showing the MAX202 used in UART to RS-232 interfacing. It is shown connecting to the microcontroller, the 5 VDC power supply, and to the transmission lines on the plug header.

The PCB was designed in conjunction with initial Minimole electronics sledge design. This resulted in a profile of certain dimensions, in the shape of a ‘T’. The electronics were made to fit this profile and size. Figure 56 below, shows the PCB design alongside the fabricated piece. The finished PCB measures 45 x 75 mm on the external dimensions. The microcontroller programming port can be seen on the bottom right of the fabricated PCB. This was placed in this particular orientation, in conjunction with electronic sledge design, to provide ease of programming and updating microcontroller code during testing and development.

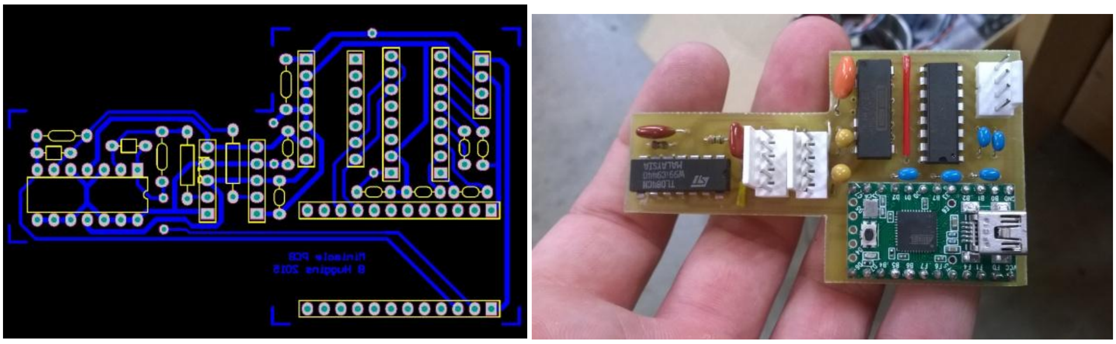

Figure 56: Minimole PCB, Altium design (left), finished fabrication (right)

4.2.5.5 Sledge design and fabrication

Sledge design was split into two main tasks: redesign of the Economole Electronics Sledge to incorporate the new distribution board, and creating a sledge to hold the additional Minimole electronics.

To redesign the Economole sledge, the existing design was modelled in SolidWorks. Measurements were made of the constraints inside the Economole electronics cavity associated with plugs in the top of the camera. As the dimensions and fit of the Mole Distribution Board were developed, the new Economole Electronics Sledge could be developed. The old and new sledges are shown below in Figure 57. The modifications made in the new sledge are the extension around to incorporate the distribution board, and the two cut outs from the top surface. The cut outs are in line with the Minimole LVDT cable entry point through the Economole Chassis.

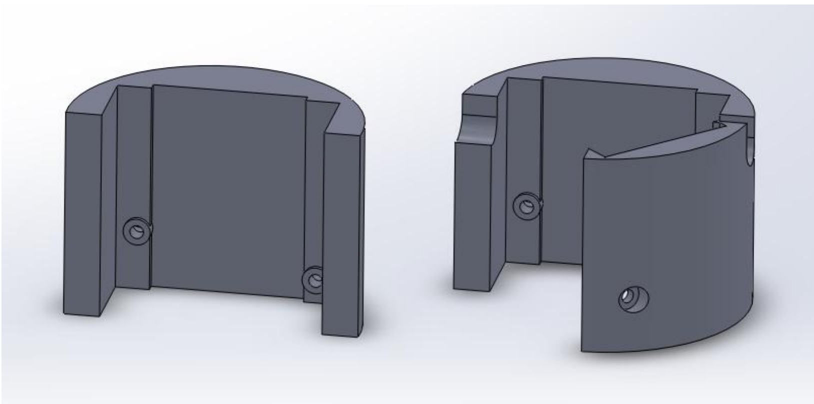

Figure 57: 3D modelled Economole Electronics Sledges, old (left), and new (right)

The new sledge was 3D printed a number of times, then tweaked to ensure a good fit in the chassis, atop the camera. The final version is shown with the PoE and distribution boards fitted in Figure 58, alongside the original sledge. All connections in the new sledge are plugged in, whereas the camera power was permanently attached in the old version, and also seen is the loose hanging regulator. The new sledge is able to be used in the existing or updated Economole design, with the simple addition of some plug ends to the camera and laser cables.

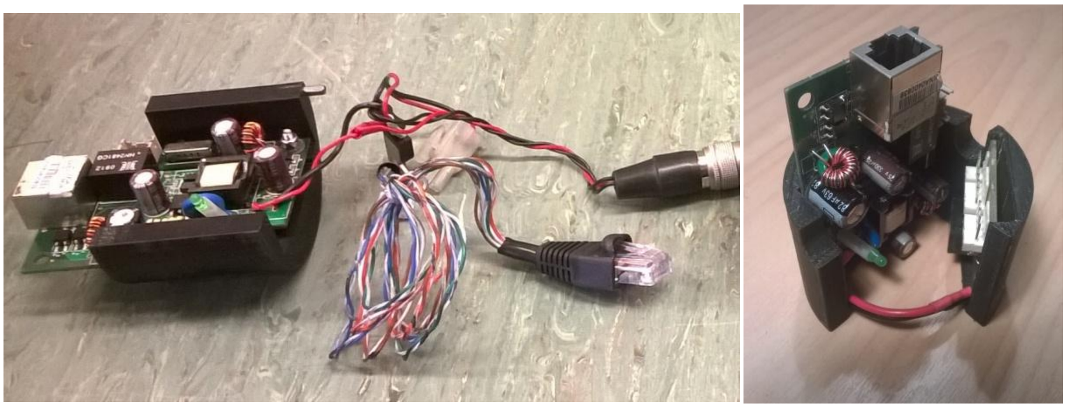

Figure 58: Original Economole Electronics Sledge (left), next to new version (right)

Initial development of the Minimole Electronics Sledge was focused on capping off the Economole cables, and slotting the LVDT BICMs as far as down the chassis on top of this as possible, before finishing with the Minimole PCB on top. A hole would be provided straight through the assembly to allow the Ethernet connection to be made at the Economole Electronics Sledge.

Measurements were taken of the BICMs, and of how far they could protrude into the depth below the top of the PoE splitter. 3D models were made with sketches detailing all of the necessary constraints. The parts shown in Figure 59 below were the result, and are shown in the sequence of being assembled over the Economole sledge.

Figure 59: Initial Minimole Electronics Sledge assembly sequence, from left to right

The total length came out at 40 mm over the intended 100 mm electronics extension for the Economole Chassis. The goal was to find a way to reduce this length, after function of the system was confirmed as a whole. Unfortunately, significant difficulty was experienced in attempting to make the Ethernet connection by feeding the cable down through the hole in the new sledge. A rethink on the design of the Minimole sledge was required.

A key aspect in going forward with a new design was contacting the LVDT manufacturer to determine whether the large casing of the BICM PCB could be removed. This was confirmed, allowing the design parameters to be finalised, with the much lower profile BICM PCB. The main considerations in developing the final Minimole electronics assembly were as follows:

- Must fit the Minimole Electronics PCB and un-enclosed LVDT BICM PCBs;
- Must fit inside the 100 mm electronics housing extension;
- Must provide ease of Ethernet cable attachment, once assembled and in the field.

It should be noted that a smaller more compact Minimole PCB design was in progress, making use of smaller, surface mount components to mirror the proven prototype. With the space saving made through removing the BICM cases, this was no longer necessary. The completion of the smaller PCB was subsequently able to be abandoned, which was part of the reason for taking on the new MXmole build, detailed in section 4.5, 'New Economole Build'.

One limiting factor in the design of the final sledge was the height of reliable 3D printing, at 100 mm. Although this is the length of the extension, a greater length was necessary in order to extend down into the rest of the Economole Chassis. A total height of 145 mm would be required, made up of four separate parts. The parts, as printed, are shown in Figure 60, below.

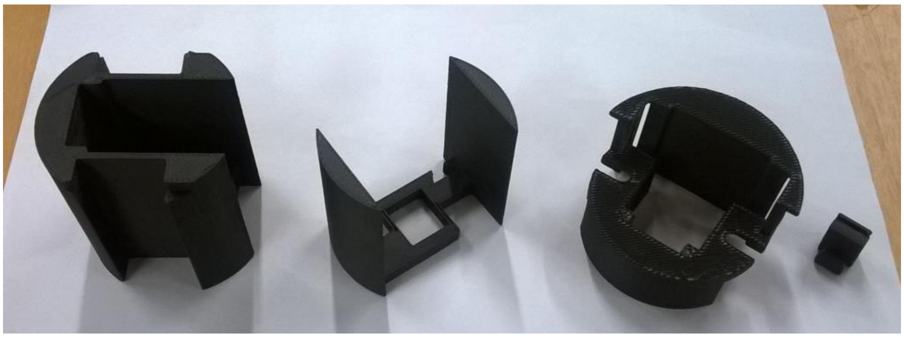

Figure 60: 3D printed final Minimole Electronics Sledge parts

The three parts on the left of the above figure were glued together to make the sledge, while the part on the far right is removable and used to secure the Minimole PCB. The constituent parts of the Minimole Electronics Module, as it is known in its assembled state, are shown in Figure 61. Note that the figure shows an encased BICM on the far right, and a BICM PCB with shortened cable just left of that. Two of the latter are required for assembly. Also seen is the interconnecting Ethernet cable, which is attached at the bottom to a fixed male Ethernet plug which connects with the Economole Ethernet jack on module fitment. The loose end of the

Ethernet cable is plugged into the female-female Ethernet jack at the top, once the three PCBs are secure and plugged in. The female-female Ethernet jack at the top subsequently provides a connection as simple as the original Economole to make. The loose blue cable in the middle is the only manual connection required during fitment. This is plugged into the Economole Power Distribution board, and fed up the Minimole module to be plugged into the Minimole PCB.

Figure 61: Minimole Electronics Module pre-assembly

The resulting Minimole Electronics Module is shown fully assembled, and during testing, in Figure 62. Here, it is seen atop the Economole Electronics Sledge, which is atop the camera and related spacers. It fully meets the relevant requirements set out in section 4.2.3, 'Electronic requirements', and in this section. The design is modular, and can be added or removed from the Economole system without issue, electronically requiring only the installation of the sensors and the connection of one four pin plug. It houses the required components, fits inside the 100 mm extension, and provides ease of Ethernet connection once assembled.

Figure 62: Assembled Minimole Electronics Module (left and centre), and module in testing (right)

4.3 Communication and Control System Development

The final version of the communication and control system was arrived at after significant time and resource constraints were experienced due to the manufacture of a whole new Economole system. The original investigation and planning is covered henceforth, before coming to the final concept used. Development and testing of the final design is then discussed.

4.3.1 Existing Economole software

The Economole software is written in C++. It presents a basic user interface, which seems fit for purpose. A third party hardware driver used to receive encoder information from the winch, through the laptop USB. This is used to trigger measurement events. Every 25 mm down the tube, a picture is taken, and measurement derived from the amount of reflected laser light captured in the image, ultimately providing a diameter at a distance down the tube. This data is then saved to an Excel spreadsheet.

Upon reviewing the code, it was found to be relatively hard to interpret in terms of author, date, and function of the various C++ header fields that make up the software.

As the basic function was known, and at that stage it is not intended to modify the existing interface and function of the Economole code, no further research into the existing code was required.

4.3.2 Existing Minimole software

The majority of the Minimole code exists in the on-board microcontroller’s firmware. This code has been written in Java using the Arduino IDE. This code is set up to use serial inputs for commands, and to transmit measurement data out in RS-232 format.

Currently there is no Human Machine Interface (HMI) proper. There is a piece of software written in MATLAB, which was used for proving the serial communication concept, and gaining actual measurement data from the Minimole.

4.3.3 Software requirements

At the beginning or the project, software requirements were broad and general. This was due to many particular software requirements being dictated by the success of the electronic concept, and the results of its further development and testing.

A brief list of requirements was broken down as follows:

- The Minimole should perform a “handshake” with the laptop to initiate activity, and allow automation of the additional HMI interface activation;

- The Minimole firmware should provide measurements when required;
- The processing and HMI software must work with the current Economole software;
- The HMI should appear seamless;
- Data should be stored following the current Economole practice.

4.3.4 Concepts

At the first stages of the project, the software and firmware requirements were essentially dictated by the mechanical and electronics systems. Later in the project, the detailed development of functionality and the HMI would be a more tangible task. For this reason, there was one overbearing concept each for software and firmware.

4.3.4.1 Software concept

The software was to be written in C++. A new header file would be written containing the main code for incorporating the Minimole into the Economole software. Minor modifications would be required to the existing Economole code to include this header and its outputs. The new header file would initiate a handshake with the Minimole microcontroller, by way of serial communication. If there was a Minimole present, the handshake would initiate the code.

The Minimole code would take in winch encoder data in the same manner currently used for image capture, and serial data from the minimole. It would output pigtail measurement data to be saved alongside the Economole data in an Excel spreadsheet. It would also provide high level feedback via the HMI. The flowchart in Figure 63 shows the basic function.

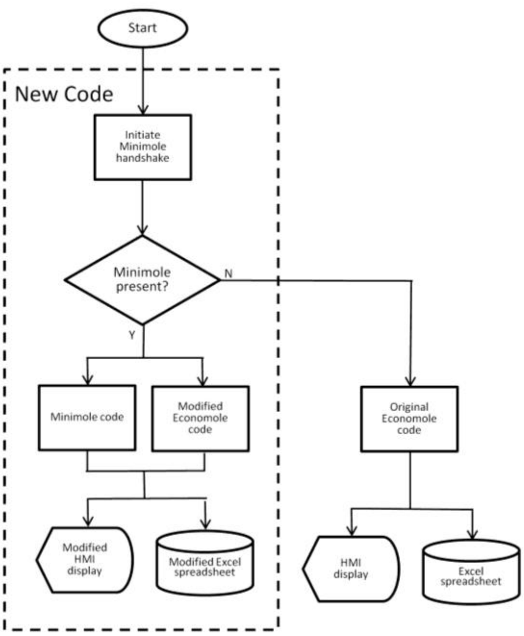

Figure 63: Software concept flow chart

As seen in the above flowchart, if there is no Minimole confirmed to be present, the Economole code will run as it does presently. The HMI will have no change, and the spreadsheet will remain un-modified in terms of additional Minimole data.

4.3.4.2 Firmware concept

The firmware would be written in Java using the Arduino IDE. The existing firmware code is compact. It would essentially be re-written to delete the use of the stepper motor, and all associated connections. RS-232 communication configuration would be set up to suit the requirements of the microcontroller, Economole camera, and laptop, with due consideration for the accuracy of data being captured and Minimole descent/ascent speed.

When a handshake request is received, the firmware would send a response. Data would be sent upon receiving a request from the host PC. The analogue 0 – 5 VDC (attenuated) LVDT signal would be taken in on the microcontroller analogue input, and converted to serial for communication to the host PC via the Economole camera.

An overview of the firmware function flow is shown in Figure 64. The firmware code would start operating as soon as the device is powered up. The Minimole microcontroller would simply wait for a handshake, and then send data each time a measurement request is received.

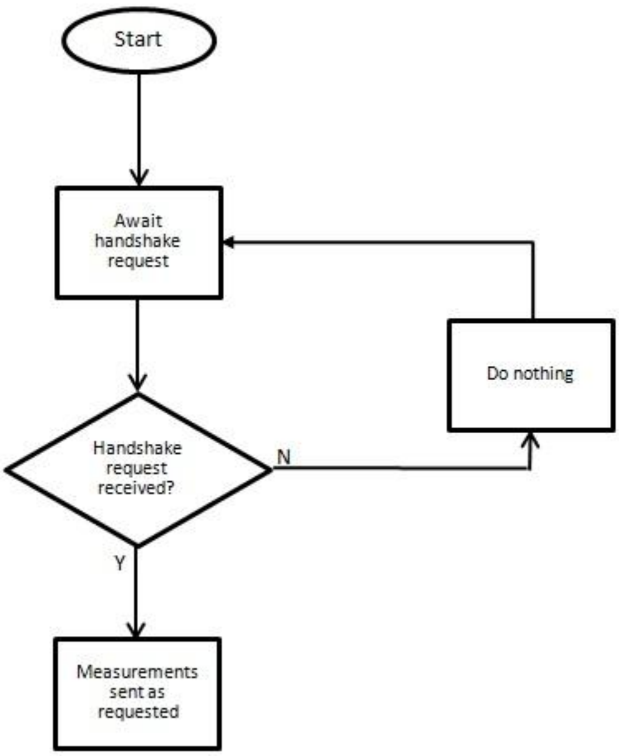

Figure 64: Firmware concept flow chart

4.3.4.3 Final concept

The Economole code was written based on camera manufacturer libraries and examples. It was found that since the code had been written, the manufacturer had released libraries and example code for many more coding languages in common usage in 2015. It was decided to attempt to write the code again in a newer, more familiar language. However, upon writing and debugging preliminary code segments, multiple bugs and issues were found with the newly released libraries. Through direct communication with manufacturer support staff, it was decided to cease efforts into this.

The build of a new Economole for an imminent plant shutdown at an overseas facility, together with the time wasted in attempting to change the Economole language, meant that a new strategy had to be developed quickly. During electronics testing, the cameras proprietary interface program, SampleViewer, was used to test serial communications. This included testing to ensure the image stream, and therefore Economole program, would not be affected. It was decided that this would be used as a means of sending commands to the Minimole and receiving data back, thereby acting as the HMI. This concept is laid out in Figure 65.

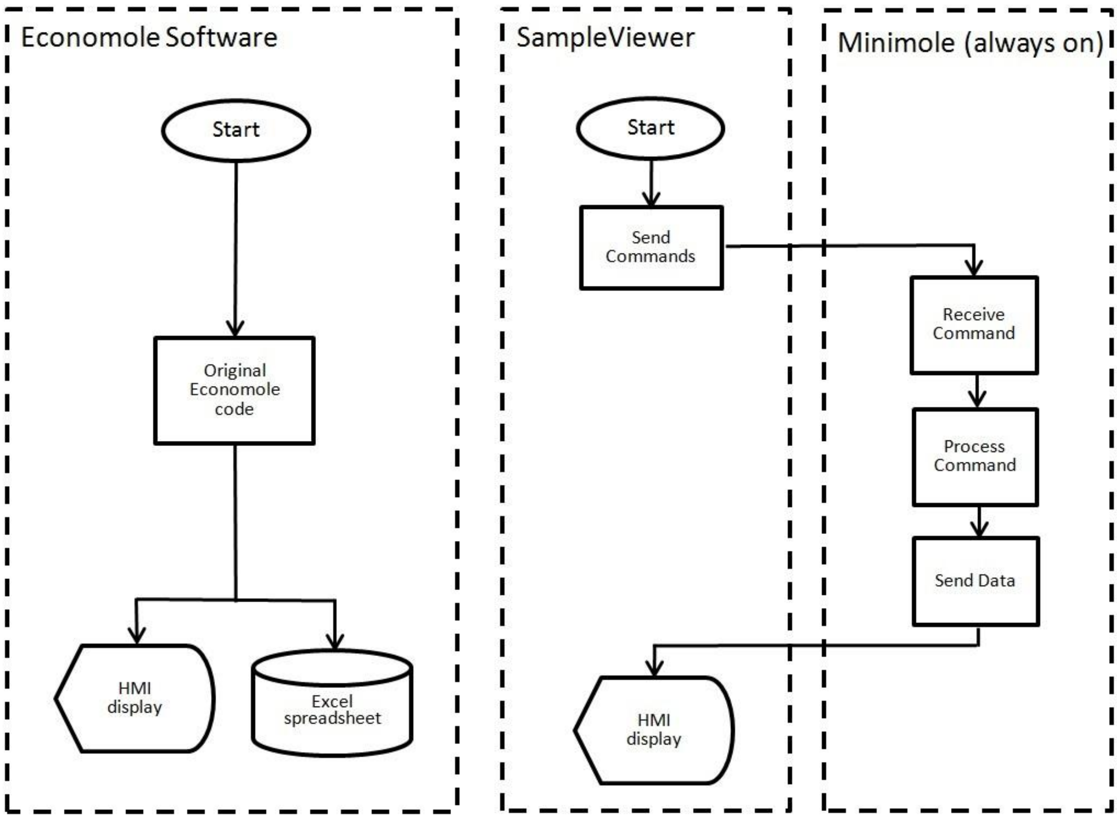

Figure 65: Final software and firmware concept flow chart

The code would be written using, *Teensyduino* which is an add-on for Teensy add in the Arduino IDE (integrated development environment).

4.3.4.4 Concept development and implementation

An overview of how the physical LVDT measurement becomes a useable piece of data in the microcontroller is shown in Figure 66. In order to derive a measurement from the 0 – 5 VDC filtered LVDT signal, and use serial communication, the microcontroller had to first be configured to suit. The serial connection was done in the start-up sequence of the code. In the Arduino IDE, using the method “analogRead(x)” returns a 10 bit number representing the analogue signal on pin ‘x’, via an Analogue to Digital Converter (ADC) so no set up was required for this. In the case of the Teensy, the 10 bit number is by default represented in reference to the 5 VDC power supply, ie 0 is 0 VDC and 1023 is 5 VDC.

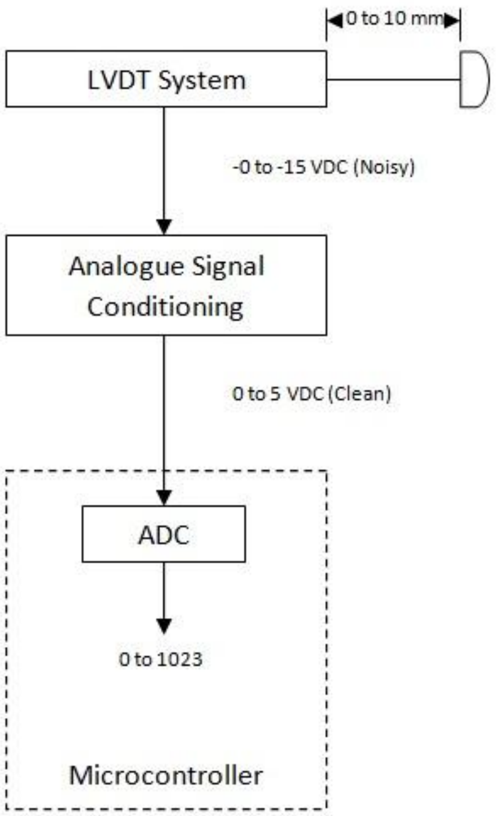

Figure 66: Flow chart showing the conversion of physical displacement to the digital signal used in the microcontroller

To test correct functionality of the ADC and serial, the code was developed to stream the raw analogue data as soon as connection was established using SampleViewer. Serial parameters were 8 bit data, at 9600 bits/second (*baud rate)*, with 1 stop bit (unchanged throughout). If using four characters per LVDT, sending both continuously, not including processing time or line limitations, this provides for a theoretical data transfer rate of around 120 measurements per second. Therefore, this baud rate was considered more than adequate. Data was successfully streamed.

A slight fluctuation in the ADC value being streamed was immediately noticed. The data was changing by up to ten points when the LVDT sensors were perfectly stationary. This would effectively be interpreted as a change in analogue signal. The calculated effect of ADC signal change in perceived LVDT measurement is shown below in Equation 10.

$$Effect\ \left[\frac{mm}{point}\right] = \frac{Analogue\ Span\ [V]}{ADC\ Points} * \frac{LVDT\ Span\ [mm]}{Analogue\ Span\ [V]}$$
$$= \frac{LVDT\ Span\ [mm]}{ADC\ Points}$$
$$= \frac{10}{1024}$$
$$= 0.001\ \frac{mm}{point}$$

(10)

Multiplying by the maximum observed ADC swing of 10 points, yields a perceived measurement change of 0.01 mm when the LVDTs are stationary. Although not effecting the required accuracy of ±0.2 mm (section 3.2.1, ‘Measurement technology’) there was a desire to display readings in mm to two decimal places, as usually seen on digital measurement devices, and last digit moving around would portray a poor quality device. The ADC was averaged in varying iterations before arriving at a figure of twenty, providing stable readouts of the raw data.

The next step was to check receipt of commands. The characters ‘1’ and ‘2’ were used to initiate transmission one time raw ADC data and streaming raw ADC data, respectively. More numbers were added to the command list to test different methods of feedback, including stored sentences. Once this functionality was achieved, the conversion of the raw data into a millimetre value was begun. This is covered in detail in the next section, ‘Minimole calibration’.

With communication code established and tested, and measurements being produced from the Minimole, the interface part of the code could be developed. Rather than using numbers as commands, a series or words relating to specific functions were developed. Functions were added iteratively leading to the final version of the programme. The following paragraphs discuss the use of the available commands.

The command *’start’* begins the main Minimole sequence. The Minimole sequence was developed to provide useful feedback only when required. This sequence is shown in Figure 67. This was based on the programme knowing the resting measurement of the Minimole, before entry into a pipe. Once the measurement dropped below the standing measurement, plus a threshold, pipe entry was assumed and data streamed. If the measurement was less than the threshold and above a given pipe growth tolerance, the text “ALERT” preceded the displayed measurement.

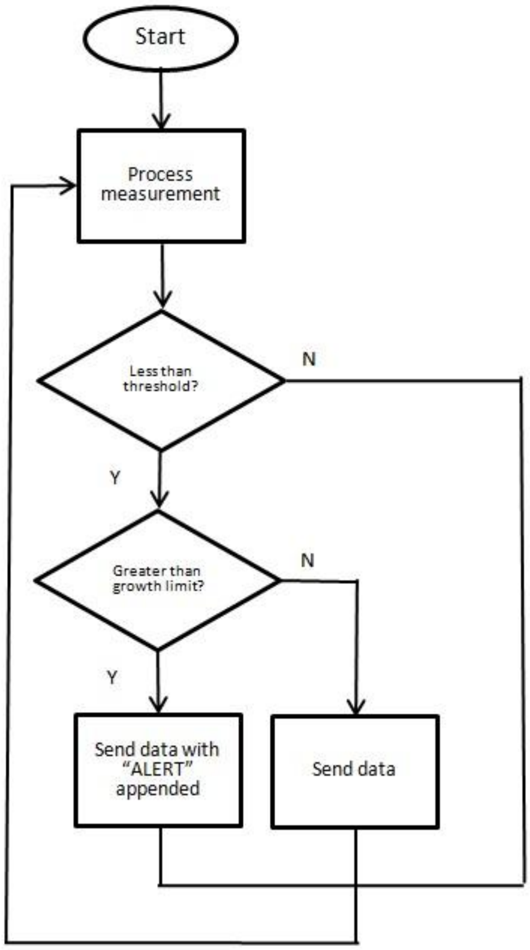

Figure 67: Main Minimole sequence flow chart

The *‘stop’* command ceases the main Minimole sequence from running. It also ceases any raw or measurement stream. In the code, the sending of data over serial is carried out with a switch, depending on the mode that the Minimole is currently in. When ‘stop’ is used, the print mode is set to ‘9’, for which there is no code to execute.

The *‘stream’* command begins a continuous stream of measurements, where as *‘diag’* provides a continuous stream of raw ADC data which is subsequently used for calibration. The command *‘once’* provides a one off measurement.

The commands *‘pipe’* and *‘growth’* allow the user to input what size of pipe is being measured, in millimetres, and the growth tolerance for this pipe, in percentage. These inputs are not required, with defaults in the code of 28 mm pipe size and 6% growth.

Lastly, the *'help'* command provides a command listing, with details about the function and use of each command. Figure 68 shows the help text in the HMI, before the 'diag' command is used to stream raw data.

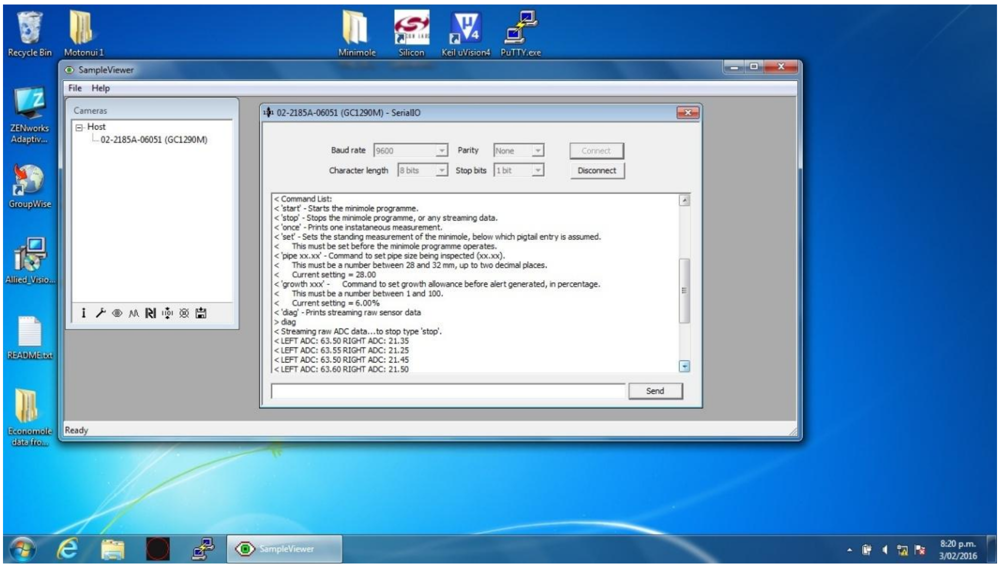

Figure 68: Screen shot of SampleViewer running as the Minimole HMI

4.3.4.5 Calibration

The Minimole measurement arms pivot about a point, with the contact surface (bearing) at one end of the arm, and the LVDT shaft at the other. This is shown in Figure 69, below. One might assume a simple lever relationship based on the dimensions of the measurement arm would be sufficient for calculating lateral extension of the arm. However, on closer inspection, one can see that the lever dimensions are not constant. The LVDT shaft end slides on the surface of the arm.

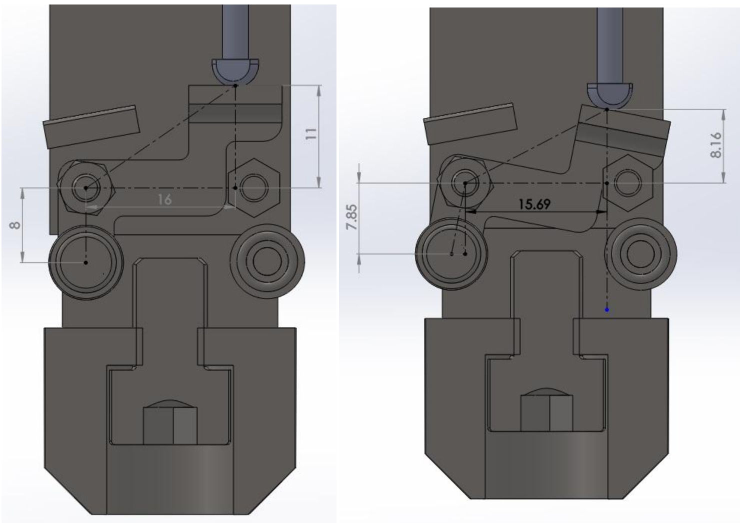

Figure 69: Section view of Minimole measurement arms showing measurement dimensions with arm in (left, and arm out (right)

A number of iterations of calibration formulae were produced, in an effort to solve the problem. Test results from the last iteration were not promising, with an error in excess of 2 mm in the middle of the range. A new strategy was required.

It was decided that the raw ADC data would be recorded at nine data points, taken and known measurements from 26 to 34 mm in 1 mm steps, in order to graph the results and fit an appropriate curve. The equation for the curve could then be loaded into the Minimole firmware. Hand held vernier callipers were used to squeeze the measurement arms together, while streaming raw ADC data from each arm. Initial test results for this were promising, with anecdotal errors in the area of 0.1 mm. This was achieved using a third order polynomial, which appeared to best fit the data.

The above method was not a soundly repeatable procedure for calibration, due to the reliance on hand held measurements. A more robust solution was required, leading to the design and manufacture of the Minimole Calibration Block. The finished block is shown in Figure 70 below, above a calibration in progress with the Minimole. The block is designed to hold the Minimole while it is moved down nine different measurements, from 26 to 34 mm. It has been precision machined out of a block of stainless steel. Due consideration was given to the machining process and thermal distortions when selecting overall size of the block.

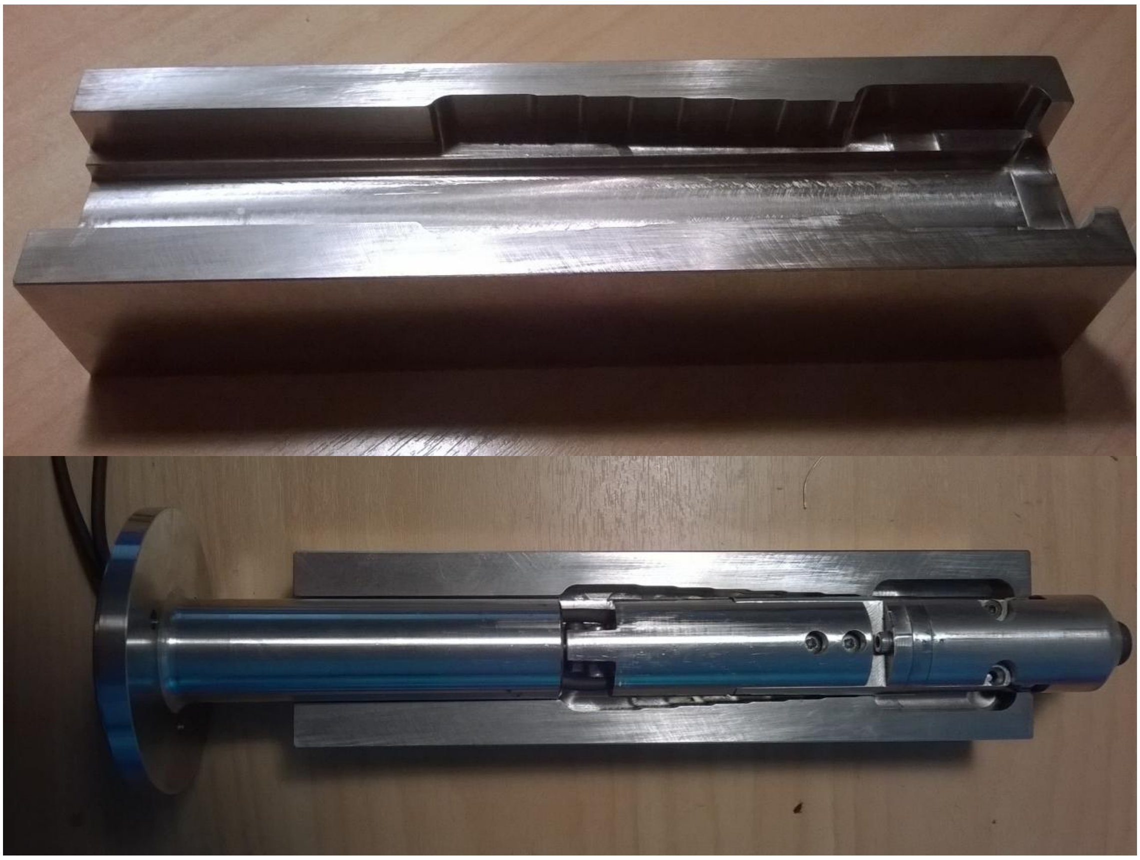

Figure 70: Minimole Calibration Block as manufactured (top), and in use (bottom)

The curves derived for each sensor and their contribution to the overall diameter are shown in Appendix 3, along with the data set used. To assess the ability of the curve to fit the data set, the R^2 value was used. In a 3rd order polynomial best fit curve, R^2 is the known as the "coefficient of multiple determination" (Devore & Farnum, 2005). It is a statistical measurement used to evaluate the fit of a line to a set of data points, as a percentage (Devore & Farnum, 2005). At greater than 99% on each the left and right curves, the polynomial is considered strong.

The calibration of the Minimole, using widths with parallel sides, did not account for the unmeasured part due to the chord of the flat measurement surfaces against the round pigtail pipe. Referring to Figure 71, a relationship was drawn between the known parameters of the system, where:

- r = actual pigtail radius;
- c = chord due to bearing surface (3 mm);
- h = unmeasured portion of the radius;
- r – h = known measurement (from calibrated Minimole sensor signal).

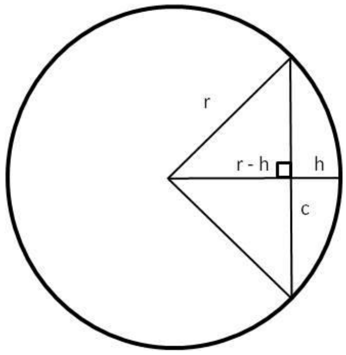

Figure 71: Representation of unmeasured part of pigtail due to chord caused by bearing surface

Pythagoras' theorem states the square of the hypotenuse of a right angled triangle is equal to the sum of squares of the other two sides (Burton, 1991). In the above instance, this would be represented as:

$$r^2 = (r-h)^2 + (\frac{c}{2})^2 \tag{11}$$

Therefore, the total radius is:

$$r = \sqrt{(r-h)^2 + \left(\frac{c}{2}\right)^2} = \sqrt{(known\ measurment)^2 + 1.5^2} \tag{12}$$

4.4 System Integration and Testing

The individual integration of the mechanical, electronic, and software systems, has been discussed in the previous sections. The completion of the constituent parts allowed for the integration and testing of one complete system.

4.4.1 Workshop testing

Prior to field trials, it was considered prudent to construct a workshop test rig, simulating field conditions. The aim of this was to address any revealed failures or bugs in the system, in the safety of the workshop, thereby facilitating rapid resolution of any issues, and mitigating finance and time loss due to mobilising for the use of a faulty system in the field.

The concept for the test rig was to use real sections of disused reformer tubes, reduced in length from 15 m to something more manageable, while having the top flange and the pigtail section attached. This would then be held in a stand keeping the test piece stable, while the Economole winch was bolted to the top. The integrated MXmole device would then be lowered in and out of the tube, testing pigtail entry of the Minimole, and correct functionality of the Economole and Minimole systems.

Sketches for the test pieces were drawn up, showing the top of a reformer tube cut at around 1500 mm from the top flange, and joined to a 300 mm length of the bottom of the tube, including a small piece of pigtal. The drawings were handed to the Methanex mechanical workshop supervisor, so that he could resource the work appropriately. Two test pieces were made. One is shown below (Figure 72) lying on sand bags on the workshop floor.

Figure 72: Test piece of reduced length reformer tube

The stand to hold the test pieces was designed as a 3D model in SolidWorks, from which drawings were produced. The work was given to a contractor normally completing similar welding and cutting work for Methanex. The received stand is shown on the left in Figure 73. The workshop gantry crane was used to lift the test piece into the stand, where it was fed down the vertical pipe, before the top flange rests on the top of the stand pipe, allowing the piece to hang.

Figure 73: Workshop test rig (left); full workshop test set up (right)

The right hand photo in the figure above shows the full test set up. This included: strapping the test rig to the steel table adjacent, to stop unwanted movement, particularly in the case of an earthquake; a platform ladder for accessing the top of the test piece; and the full Economole kit including winch, *VSD enclosure*, and laptop. The VSD (variable speed drive) enclosure is used to distribute power to the winch motor, laptop charger, and PoE injector, as well as house the winch encoder signal processor.

It should be noted that in order to carry out the workshop testing described in this section, a Job Hazard Analysis (JHA) was required. JHAs are used to minimise, contain, or eliminate hazards with the potential to cause harm to people, assets, of the environment. These may be a brief assessment, recorded in a register, or a detailed document. For this work, a Methanex JHA template document was used. The first step in completing the JHA was to assess the likelihood of a hazard causing harm to people, assets, or the environment, and what the consequences of that hazard could be. To quantify this assessment, a Risk Assessment Matrix was used, similar to that shown in Figure 74, taken from the Australia New Zealand standard for Risk Management , AS/NZS 4360:2004. There were no risks assessed as high enough to put a stop to the work, and measures such as personal protective wear, and safe work practices were used to mitigate any hazards present. Each time any person was working at the site of testing, a review of the JHA was completed, and the person signed on to the document, acknowledging having read and understood the hazards.

		Consequences				
		Insignificant	Minor	Moderate	Major	Catastrophic
		1	2	3	4	5
Health and Safety Values		A near miss, First Aid Injury (FAI) or one or more Medical Treatment Injuries (MTI)	One or more Lost Time Injuries (LTI)	One or more significant Lost Time Injuries (LTI)	One or more fatalities	Significant number of fatalities
Environmental Values		No impact	No or low impact	Medium impact Release within facility boundary	Medium impact outside the facility boundary	Major impact event
Financial Loss Exposures		Loss below $5,000	Loss $5,000 to $50,000	Loss from $50,000 to $1,000,000	Loss from $1,000,000 to $10,000,000	Loss of above $10,000,000
Likelihood	**A** Possibility of repeated events, (1 x 10^{1} per year)	Significant Risk	Significant Risk	High Risk	High Risk	High Risk
	B Possibility of isolated incidents, (1 x 10^{2} per year)	Moderate Risk	Significant Risk	Significant Risk	High Risk	High Risk
	C Possibility of occurring sometimes, (1 x 10^{3} per year)	Low Risk	Moderate Risk	Significant Risk	High Risk	High Risk
	D Not likely to occur, (1 x 10^{4} per year)	Low Risk	Low Risk	Moderate Risk	Significant Risk	High Risk
	E Rare occurrence, (1 x 10^{5} per year)	Low Risk	Low Risk	Moderate Risk	Significant Risk	Significant Risk

Figure 74: Risk assessment matrix (AS/NZS 4360:2004)

The combined probe, now known as the MXmole, was attached to the Kevlar sheathed Ethernet cable, used for fixing and for power and communications. The plug made an easy contact, and the cable was secured with the cable clamp. The MXmole was lifted to the top of the test rig, and lowered into the test tube. Normal Economole function was checked first, and returned normal results, functioning correctly. The sample viewer program was then started, and a raw data stream initiated with the Minimole. This was confirmed to have no interference with the operation of the Economole.

Pigtail entry was checked next, while the MXmole being lowered to the bottom of the test piece. A change in the raw ADC stream was immediately noticed, confirming entry. However, on retraction, the Minimole probe became jammed in the pigtail. The top, non-measuring part of the Minimole arms had spread and anchored the probe. This lead to the Minimole arm modifications as detailed previously, in section 4.1.3.3 ‘Minimole modifications’.

4.4.2 Field testing

A number of opportunities arose for field testing in a reformer during plant shutdowns. Prior to the day of a test, a meeting would be held with all parties that would be present in the reformer on the day or their supervisor, to discuss logistics and any potential hazards or issues. The person in charge of each job to be carried out in the reformer, was responsible for completing a JHA for that particular work. Each morning before a field test, a ‘toolbox’ meeting was held, where all people that would be present at the top of the reformer would review the jobs to be carried out and review the JHA. After this, sealed masks, hard hats, steel capped boots, safety glasses, overalls, and gloves were donned, and the 20 m high reformer staircase ascended. The equipment would be waiting at the top of the reformer, having been lifted by crane the day before. The tests were often completed alongside sampling of the reformer catalyst, where the catalyst is sucked out of the reformer tube to be taken away for testing. This opens up the inside out the tube for inspection.

This Economole was first field tested after the electronics modifications had been completed. The Economole was used with the new electronics, but without anything from the Minimole. The reformer inspection was carried out without issue.

The next test was carried out after pigtail entry was resolved. Figure 75, shows this test in progress. The electronics are not in their final state of assembly, so electrical tape has been used to secure loose wires. At this stage, the final program for the Minimole had not been developed, most importantly the calibration method, meaning that measurement results would carry a given error.

Figure 75: First integrated field test of Economole and Minimole

Four tubes were inspected in the first integrated test. In order to facilitate inspection, two were emptied of the large, blocky, catalyst to around 5 m down the tube, and two were completely emptied. The pigtail was therefore only available for inspection on the latter two. The Economole worked flawlessly on all four tubes. Table 3, below, shows the results of the Minimole tests. The last column in the table represents the measurements corrected for a calculated error curve post field test. Two passes were made at each pigtail. The first entry was attempted without use of the Minimole span adjustment bolt, resulting in limited pigtail entry. Maximum span was adjusted using the bolt, resulting in an immediate improvement in entry. With a design size of 28 mm, the corrected below measurements are within the expected range, and indicated no immediate end of life danger (6% added to 28 mm results in end of life indication at 29.68 mm).

Table 3: Initial Minimole field test results, including corrected measurements

Tube	**Pigtail Entry**	**Measurement Read (mm)**	**Modified Measurement (mm)**
Mot 2, 3d10, 1st Run	Limited	30.33	28.06
Mot 2, 3d10, 2nd Run	Good	30.35	28.07
Mot 2, 7d6, 1st Run	Good	30.91	28.63
Mot 2, 7d6, 2nd Run	Good	30.96	28.69

4.5 New MXmole Build

After the main design and prototyping of mechanical and electronics systems was completed, an opportunity arose to build a new MXmole, for use at the Atlas methanol plant in Trinidad. Careful consideration was given by the Methanex and Massey University supervisors, finally deciding that the additional work would benefit all parties. This additional work, however, came at a cost to the development of the HMI. This is explained in more detail in Section 4.3, 'Communication and Control System Development'.

It should be noted that this build was for the reformer tube part of the MXmole only. The pigtails in the Atlas plant were mounted perpendicular to the reformer tube, making vertical pigtail entry with the Minimole probe impossible. However, when the reformer tubes are replaced, it will be with a vertical pigtail arrangement. Therefore, the modifications made in this project to the original design, will permit the modular Minimole probe to be attached when required.

4.5.1 Cost estimate and planning

Unlike with the rest of the project, which effectively had no significant budgetary constraints, the confirmation of the build for Trinidad was dependant on the predicted cost, and timeframe in which it could be completed.

Shipping by the end of mid-January 2016 was required, in order to be available for a planned shutdown in February, when the reformer would be available for inspection. The total cost was estimated at 24,168.04 NZD. This cost took into account savings due to the use of spares in stock for the New Zealand unit. Total cost was 41,718.04 NZD when including spares replacement. All prices were taken from historical build data, of current advertised prices where available. The total cost and a confirmation that the build would be ready mid-January were submitted in October 2015. The proposal was subsequently accepted by the manager's at Atlas, at well under the third party inspection cost for Atlas of around 100,000 NZD (Peter Tait, personal communication, October 5, 2015).

4.5.2 Purchasing

Multiple vendors were contacted in parallel to achieve the best price and delivery times available, with the latter being the main objective. Late delivery could mean that the MXmole was not available for use in time for the shutdown. In some cases, plans were put in place to borrow parts from the New Zealand Economole, in case arts did not arrive in time.

Each delivery of parts was checked carefully on receipt.

4.5.3 Manufacturing

Manufacturing of engineered parts was achieved by engaging up to three contractors at once. Each contractor required drawings and a clear description, often provided in person, of the work to be carried out. Emphasis was again placed on the importance of timely delivery. At one point a contractor who had originally accepted the work, stated that it was no longer feasible within the given time frame, and so the work had to be quickly transferred to another.

The same processes decided on earlier in this chapter were used on the parts for this build. Lessons from the earlier manufacture were incorporated, particularly around communication through clearing up drawing layout and stating required accuracy.

4.5.4 Assembly and testing

The parts were assembled according to the design. During assembly, the opportunity was taken to chronicle the process with photos, mostly of the parts before and after a particular assembly. These were incorporated into a operation and maintenance manual for the MXmole. An example is shown in Figure 76.

Figure 76: MXmole top wheel-set before and after assembly

The MXmole was assembled, function tested, and calibrated in a tube the approximate diameter of those at Atlas.

4.5.5 Shipping

The parts were packed into cases for shipping. These cases were heavy-duty, water-proof, and with padding included. The padding was to be cut away to match the form of the packaged parts. Figure 77 shows the MXmole probe, winch drum, cabling, and a spares box, packed up with the case lid open.

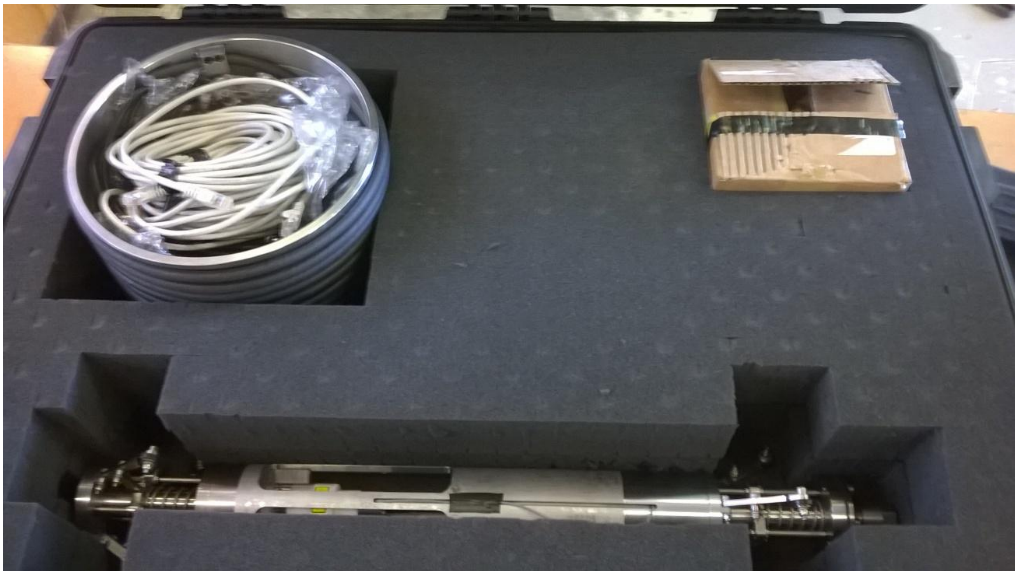

Figure 77: MXmole packed into shipping case

Three cases were required in total. One was used for the VSD enclosure, the other for the winch motor and control cabling and pendant.

4.5.6 Reception and final budget

The MXmole was received at Atlas without any apparent damage. It was set up during shut down, was used in the inspection of two tubes without incident.

On the third tube, “feedback data became inconsistent”. In order to investigate the issue, the top wheel-set was removed, providing access to the camera and electronics. In doing so, the Ethernet cable became twisted, and the end snapped off. Although the staff in attendance had experience with the inspection device, they “forgot about the need to unplug the cable before taking the cap off”. The MXmole was subsequently taken to a workshop, for cable repair and further investigation, leading to cabling repairs, “without proper tools available”. Ultimately, the lens used from the New Zealand spares was found to be severely damaged. It had come apart into two pieces, and was unusable. (Sam Tait, personal communication, March 17, 2016).

The inability to use to the MXmole past two tubes due to one failed off the shelf part, outlined the need for a complement of essential spares. Plans were subsequently made to order spare off the shelf parts for New Zealand and Trinidad. The MXmole was to be shipped back to New Zealand for repairs and testing,

The final cost of the build was 47,602.06 NZD. This was 5,884.02 NZD more than quoted, largely due to higher than expected machining costs.

Chapter 5. Results and Discussion

5.1 Integration

The definition of "integration" is the action of combining two things together to make a whole (Oxford University Press, 2016). In the context of this project, it was the action of combining the Economole with the Minimole to make one system called the MXmole.

To modify any existing Economole so that it can accept the Minimole requires a minimum of work. Two slots must be milled in the sides of the Economole Chassis, with holed ends. A hole must be drilled through the Lower Mount and Bottom Cap, and finally the Bottom cap must have three holes drilled and tapped. The ends of the camera and laser cables must be replaced with appropriate headers, and the updated Economole Electronics Sledge fitted, along with the revised Laser Holder. Once modified, the Economole will be able to work as normal, and also accept the Minimole, just as with new builds of the Economole only.

To attach a Minimole first requires the removal of the top and bottom Economole wheel-sets, and the laser assembly. The LVDT sensors are then fed from the top through the holes and grooves in the Economole chassis, before fitting the Minimole Electronics Module to the top of the Economole Electronics Sledge, connecting the one Minimole cable, screwing down the Electronics Housing Extension, and finally fitting the top wheel-set again. The laser assembly and lower wheel-set are then fixed back in place, before the Minimole Coupling, with sensors fed through, is bolted to the Economole Bottom Cap. The LVDT's are then fitted to the Minimole and the Minimole bolted to the coupling.

Once the Minimole is attached, the two devices form the fully integrated MXmole. Neither system interferes with the other, yet both achieve their purpose concurrently. The same field proven cabling and other apparatus such as the winch and laptop are used from the Economole, with no additional power or communications cabling or hardware required. The HMIs, although separate, function perfectly in parallel. Not only has the system been integrated, but it has been combined in the most practical and efficient way possible.

In order to achieve further integration, that HMI of the Economole could be focused on and updated. This could be completed as detailed in the software concept, in section 4.3 'Communication and Control System Development'.

5.2 Usability

Use of the Economole, whether an updated existing build, a new version build, or part of an integrated build with the Minimole, has not changed. Therefore, it is as useable as it was before the developments made for integration. The system is placed over a reformer tube, lowered by winch to the bottom, and then raised back up, before moving to the next tube. Important data is gathered in quick succession, with a minimum of time and effort.

Use of the Minimole HMI is straight forward. It can be run at any time in parallel with the Economole HMI. Intuitive commands are typed into the HMI, which subsequently provides feedback based on the requested function. When running the main sequence, feedback is only received on confirmed pigtail entry, with a clear alert for any pigtails that exceed the set growth tolerance. Real time decisions can be made as the system moves from tube to tube, allowing necessary actions to be taken such as blocking off at risk tubes or executing pigtail change out.

The physical measurement spread of the Minimole can be adjusted for optimum pigtail entry, while ensuring adequate range is maintained to detect any end of life pigtail measurements. The pipe size being measured can be changed in the HMI during use, ensuring the main sequence runs as expected and returns useable results. The growth tolerance can also be set through the HMI, to suit any given growth tolerance assessments.

The Minimole probe was tested in a piece of pipe with a bulge beyond the 6% growth tolerance. The HMI gave feedback of streamed measurements up to, through, and after the bulge, with the "ALERT" text clearly preceding the measurements in the middle of the bulge. This is a positive result, showing that an end of life pigtail is easily detected and clearly portrayed, making the device extremely useable and useful for its intended purpose.

A brief training session was held with Sam Tait, reliability engineer at Methanex. Sam understood the use of the device, and was happy with the modular assembly, and in particular the way the results were clearly displayed during the Minimole sequence (Sam Tait, personal communication, March 17, 2016).

Although the device has been specifically developed for Methanex reformers, the same approach may be taken with other reformers and equipment undergoing creep strain. Inspections of pigtails are explained in the literature review as completely necessary to mitigate the risk of failure, which could lead to a disaster. The approach taken here is cost effective when compared with other services on the market, at less than half of the cost of a once off inspection of one reformer; estimated cost of a one-off integrated build is less than 50,000 NZD.

5.3 Accuracy

To determine the accuracy and repeatability of the Minimole as part of the integrated system, an experiment was carried out using three different sections of de-commissioned pigtail pipe. The recorded data for this is shown in the tables in Appendix 4. Four runs of six measurements were made through a set, uniform diameter part of each pipe, and the measurements recorded.

Overall accuracy ranged from -0.01 to -0.30 mm. Overall precision ranged from 0.01 to 0.04 mm. Repeatability was finalised at ±0.12 mm, with a probability of 99.7% of repeated measurements failing within this range. This was calculated as three times the greatest standard deviation from the three pipe sizes tested, according to normal statistical practice (Devore & Farnum, 2005). The worst case repeatability occurred with a pipe measuring 29.53 mm, which also had the worst precision, and the worst accuracy occurred with a 30.14 mm pipe. The best results were all gained with a 29.22 mm pipe (repeatability ±0.02 mm), which appears to indicate a trend towards the 28 mm pigtail, common place in the reformers. The accuracy towards smaller diameters may be expected with the mechanical layout of the measurement arms and sensors providing greater resolution when the arms are closer in i.e. making a smaller measurement. Greater diameters being measured during bench tests will also be more vulnerable to human error, in aligning the sample with the probe.

A repeatability test was also carried out using the workshop test rig. The MXmole was sent to the bottom the rig ten times, with measurements taken on entry and at the lowest measurable point. This resulted in a worst case repeatability of ±0.072 mm, which occurred at the lowest point measured.

Although the first part of the pigtail is measured, as agreed with key stakeholders during concept development, this may not provide an accurate representation of the overall pigtail condition. A number of de-commissioned pigtails observed at site had significant bulges present beyond the current coverage area. Further miniaturisation of the Minimole, together with an appropriate coupling mechanism, would permit inspection of the full pigtail length.

Full testing of the system in a manner which better eliminates any human errors would provide more accurate test data, and is expected to result in more desirable figures for accuracy and repeatability.

5.4 Execution

The Project Execution Plan (Appendix 1) defined the scope and formed the structure with which this project was carried out. With this document finalised, the project was able to be kicked off in confidence, with clear tasks and timings outlaid. Mitigations were put in place to ensure key stakeholders' objectives would be addressed in the best way possible, whatever unforeseen developments might take place.

Supervisors were kept updated with regular contact and monthly reports. This helped with tracking project developments in a chronological order. Issues and opportunities that arose, changing detailed project scope or adding to the project, were clearly documented and recorded in these and in meeting minutes. Both the Massey University and Methanex supervisors were informed of, and in unanimous agreement with, project changes that resulted in a shift in milestone date or the specific objectives to be completed by that milestone.

The Gantt chart prepared for the Project Execution Plan was particularly useful in the early stages of the project, where many activities were concurrent or dependant. Rapid progress was required at this stage, in order to place an emphasis on the front end of the project and help to cement the foundation for a successful outcome.

The setting out and defining of specific project phases played a key part in the week to week planning of the work, and in communicating exactly what could be expected at the end of each set of activities. The monthly updates contained an update on when a phase was forecast for completion and whether or not this was on target and why. The end of a phase coincided with a milestone, resulting on motivation being kept high throughout the project, fuelled by the sense of that achievement.

The project would not have been able to reach its final state without the use of this execution strategy. The detail and structure it placed around the project was essential for the success of the project within the given time frame of one year.

Chapter 6. Conclusions

6.1 Meeting the Objective

The objectives of investigation and design were met in full for the project. The power and communication system of the Economole and Minimole has been completely integrated, retaining the use of the field PoE system. Mechanical modifications have been kept to a minimum, ensuring that any existing Economole can be easily modified to accept the Minimole, and that any new Economole build has minimum additional requirements. The HMI, while not being completely integrated, provides high level feedback for instant decision making during inspection. This meets the key objective of the device.

Overall, the completion objective as stated in the Project Execution Plan has been met, with an all-in-one system that can readily be manufactured for deployment globally. It provides low-cost, low-impact maintenance inspection of reformer tube equipment, including the upper section of the pigtail.

6.2 Research Implications

With a new method of gathering data from the top of the pigtail, in a low-impact and cost effective way, data can now be gathered and used more easily, on the whole, than ever before. While some other means of gathering data from in situ pigtails with an electronic device have been developed, manual measurements appear to be the norm, and all involve the removal of insulation lagging.

The adaption of this method, using the integrated solution developed here or in other forms, will help to ensure companies uptake the necessary assurance tasks at a minimum cost and effort. The result will be a more robust industry, with companies taking steps to protect their assets, people, and environments.

6.3 Execution Strategy

The execution strategy was essential in the successful outcome of the research and development undertaken in this project. The definition of scope, clarity of objectives, and agreement of change procedures allowed a smooth and consistent flow of work, in spite of unexpected changes.

6.4 Future Development

Although the aim of integratinf the two separate systems and commercialising the product has been met, resulting in a fully functional field ready device, there is scope for further development.

The original Economole HMI should be updated and modernised. The communication facilities provided for the Minimole, now proven in operation with the Economole system, should be incorporated into the Economole HMI. This should include a means of storing the data.

It is recommended that full pigtail inspection is pursued as a next step. The Minimole probe should undergo miniaturisation to permit passage through the bends in the pigtail. A powered coupling could provide a flexible means of driving the probe through the entire pigtail length.

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Appendices

Appendix 1: Project Execution Plan

MASSEY UNIVERSITY
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methanex
the power of agility

Project Execution Plan: Methanex Minimole/Economole Integration

Approval:	Massey University Supervisor:	Methanex Supervisor:
Name:	Liqiong Tang	Peter Tait
Signature:		
Date:	8/07/2015	18/6/15

1. Overview

This document details the project execution plan for the Masters work to be undertaken for the integration of the "Minimole" with the successful "Economole" reformer tube inspection system. It contains information specific to schedule milestones, objectives, and deliverables that are agreed upon by principal stake holders. This is necessary for progress and performance monitoring, and ultimately for the successful completion of the project to all stakeholders' satisfaction.

2. Objectives

Assess and design methods of power and data communication to/from the Minimole probe which are compatible with the existing Economole system:

- Investigate viable power delivery to Minimole probe electronic systems;
- Investigate current Economole data transmission method, and others;
- Investigate viable LVDT compatible with Economole;
- Design sub systems around most viable options.

Integrate HMI Software:

- Evaluate current software;
- Modify to incorporate Minimole;
- Provide high level pass/fail feedback alongside real time Economole measurements.

Design probe control and output evaluation software:

- Integrate with Economole position monitoring, to allow Minimole to measure the correct section of pipe (the pigtail);
- Store minimole data, following Methanex protocol.

Physical Integration:

- Mechanically integrate Minimole with Economole, to provide correct functionality as one unit;
- Test system in lab and in field service to verify correct functionality

Completion:

Full mechanical, electronic, and software integration of Minimole probe with Economole system, resulting in an all in one system that is readily manufacturable for deployment globally. The system will provide low-cost, low-impact maintenance inspection of reformer tube equipment, including the upper section of the pig tail.

Prepared By Ben Huggins, 9 April 2015

3. Schedule & Deliverables

The following schedule is arranged to provide a focus on research, front end design, conceptual development, and testing. It pushes the practical completion of the project forward, and thesis writing towards the end of the year-long schedule. This also allows further refining and improvement of the developed solution in the second half of the project year.

Deliverables are listed under each phase. Written deliverables are to be signed off approved by the project supervisors. These deliverables are the minimum. Additional literature, for example brief project updates and reports for information, may be produced as appropriate, and do not necessarily require approval.

Phase 1: Preliminary Works, 16 March 2015 – 8 May 2015

- Plan Project;
- Research Minimole Systems;
- Research Economole System.

Deliverables:

- Project Execution Plan;

Phase 2: Concept Development, 11 May 2015 – 12 June 2015

- Electrical Interface design;
- Mechanical Interface design;
- Software Interface design;
- Procurement of long lead items.

Deliverables:

- Concept Selection Report;
- Brief Presentation to Stakeholders;
- Quarterly Project Update (for Callaghan Innovation).

Phase 3: Fabricate/Test/Develop, 1 June 2015 – 10 July 2015

- Fabricate Elec/Mech/Soft systems;
- Test individual systems;
- Assemble and Test;
- De-bug.

Deliverables:

- Technical Drawings;
- Initial Test Report.

Phase 4: Refine and Improve, 6 July 2015 – 16 October 2015

- Improve design where possible;
- Refine HMI.

Deliverables:

- Design Improvement Report;
- Quarterly Project Update (for Callaghan Innovation).

Phase 5: Completion and Handover, 7 December 2015 – 18 December 2015

- Design drawings and instructions completed;
- Training Material provided.

Deliverables:

- Formal Training Session with Stakeholders;
- User Manual;
- As Built Drawings;
- Functioning Economole/Minimole Assembly;
- Quarterly Project Update (for Callaghan Innovation).

Milestones:

1. Initial Research Completed, 8 May 2015
2. Concept Development Completed, 12 June 2015
3. Testing of Prototype Assembly Completed, 10 July 2015
4. Design refined and Hand Over, 18 December 2015
5. Thesis Complete, 22 February 2016
6. Punchlist Items Complete, 11 March 2016

4. Stakeholders

Key Project Stakeholders:

- Peter Tait, Global Static Equipment Expert, Methanex – *Supervisor*
- Sam Tait, Reliability Engineer, Methanex Maintenance Team – *Economole Developer*
- Craig Darling, Inspection Engineer, Methanex Maintenance Team – *Economole Developer*
- Dr Liqiong Tang, Senior Lecturer, Massey University – *University Supervisor*
- Ben Huggins, Masters Student, Massey University – *Student*

Other Stakeholders:

- Malcolm Kelsen, Asset Integrity Supervisor, Methanex
- Scott , Inspector, Methanex
- Paul, Inspector, Methanex

Other Important People:

- Jeff Lowe, Technical I&E Lead, Methanex – *Professional Mentor*
- Steve McCombe, I&E Engineer, Methanex I&E Team – *Economole Software Developer*
- Leif Warren, I&E Workshop Supervisor, Methanex Maintenance Team
- Mike Armfield, Mechanical Workshop Supervisor, Methanex Maintenance Team
- Kelly Gates, Administrator, Methanex Maintenance Team

5. Assurance

A running Gantt chart will be kept to track progress on individual tasks. Progress will be communicated informally weekly to Peter Tait and Dr Liqiong Tang, and formally in a brief monthly report. Monthly meetings will be held with the professional mentor to ensure that the project is progressing in a manner befitting the attributes of a professional project undertaking.

6. Change Management

Milestones will be achieved on time unless otherwise agreed that for sufficient reason, such as further attainable development opportunities that would be advantageous to the project and its principal stakeholders, the target dates can be moved. This will require unanimous agreement between the student, Peter Tait and Dr Liqiong Tang.

The broad scope of the project is provided above in the Objectives section. The project will only go beyond these bounds with agreement between the student, Peter Tait and Dr Liqiong Tang.

7. Attachments

1. Project Gantt Chart
2. Original Masters Work Plan
3. Original Professional Development Plan

Prepared By Ben Huggins, 9 April 2015

Attachment 1

Minimole+Economole Integration Project Schedule

Gantt Chart Template © 2015 by Vertex42.com.

Massey University

Project Lead: Ben Huggins
Project Start Date: 16/03/2015
Display Week: 1

WBS	Task	Start	End	Cal. Days	% Done	Work Days
1	**Effort Blocks**					
1.1	Start Up	Mon 16/03/15	Sun 3/05/15	49	N/A	35
1.2	Block One	Mon 4/05/15	Sun 12/07/15	70	N/A	50
1.3	Block Two	Mon 28/09/15	Sun 18/10/15	21	N/A	15
1.4	Block Three	Mon 7/12/15	Sun 20/12/15	14	N/A	10
1.5	Block Four	Mon 29/02/16	Sun 20/03/16	21	N/A	15
2	**Prelim. Work**					
2.1	Research Minimole	Mon 16/03/15	Fri 8/05/15	54	40%	40
2.2	Plan Execution	Mon 30/03/15	Fri 10/04/15	12	90%	10
2.3	Research Economole	Tue 7/04/15	Fri 8/05/15	32	10%	24
3	**Concept Development**					
3.1	Electrical Interface	Mon 11/05/15	Fri 29/05/15	19	0%	15
3.2	Software Interface	Mon 25/05/15	Fri 12/06/15	19	0%	15
3.3	Mechanical Interface	Mon 18/05/15	Fri 5/06/15	19	0%	15
3.4	Procurement	Mon 18/05/15	Fri 12/06/15	26	0%	20
4	**Fabricate/Develop/Test**					
4.1	Electrical	Mon 1/06/15	Fri 12/06/15	12	0%	10
4.2	Mechanical	Mon 8/06/15	Fri 19/06/15	12	0%	10
4.3	Software	Mon 15/06/15	Fri 26/06/15	12	0%	10
4.4	Full Assembly	Mon 29/06/15	Fri 10/07/15	12	0%	10
5	**Refine & Improve**					
5.1	Improve Assembly	Mon 6/07/15	Fri 16/10/15	103	0%	75
5.2	Final Commissioning	Mon 7/12/15	Fri 18/12/15	12	0%	10
5.3	Punchlist Items	Mon 29/02/16	Fri 11/03/16	12	0%	10
6	**Thesis**					
6.1	History of Methanex	Mon 13/04/15	Fri 15/05/15	33	0%	25
6.2	Project Background	Mon 20/04/15	Fri 15/05/15	26	0%	20
6.3	Conceptualisation	Mon 11/05/15	Fri 19/06/15	40	0%	30
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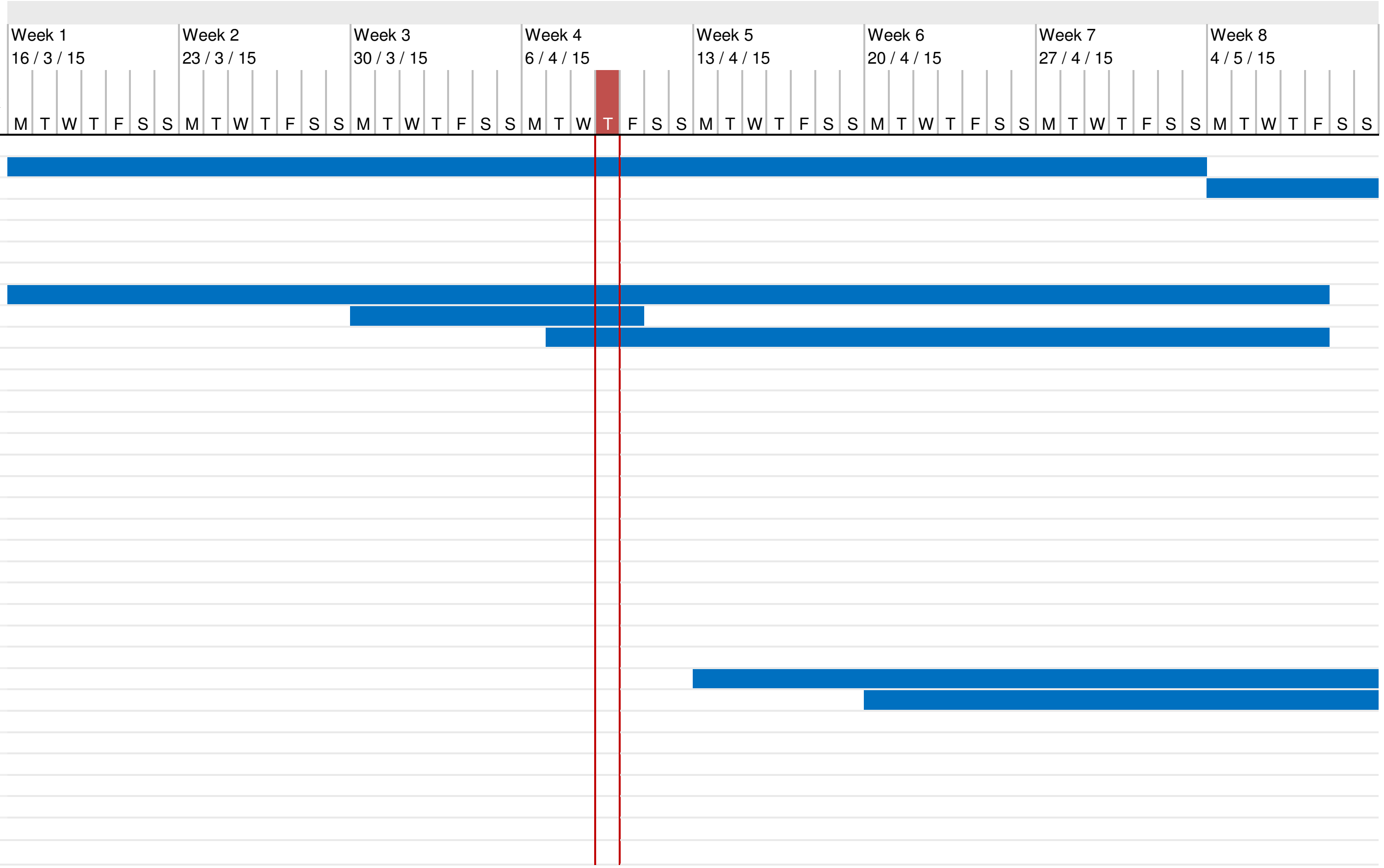
6.5	Development	Thu 18/06/15	Fri 23/10/15	128	0%	92
6.6	Testing	Thu 18/06/15	Fri 18/12/15	184	0%	132
6.7	Finalising	Mon 7/12/15	Mon 22/02/16	78	0%	56



Minimole+Economole Integration Project Schedule

Gantt Chart Template © 2015 by Vertex42.com.

Massey University

Project Lead: Ben Huggins
Project Start Date: 16/03/2015
Display Week: 9

WBS	Task	Start	End	Cal. Days	% Done	Work Days
1	**Effort Blocks**					
1.1	Start Up	Mon 16/03/15	Sun 3/05/15	49	N/A	35
1.2	Block One	Mon 4/05/15	Sun 12/07/15	70	N/A	50
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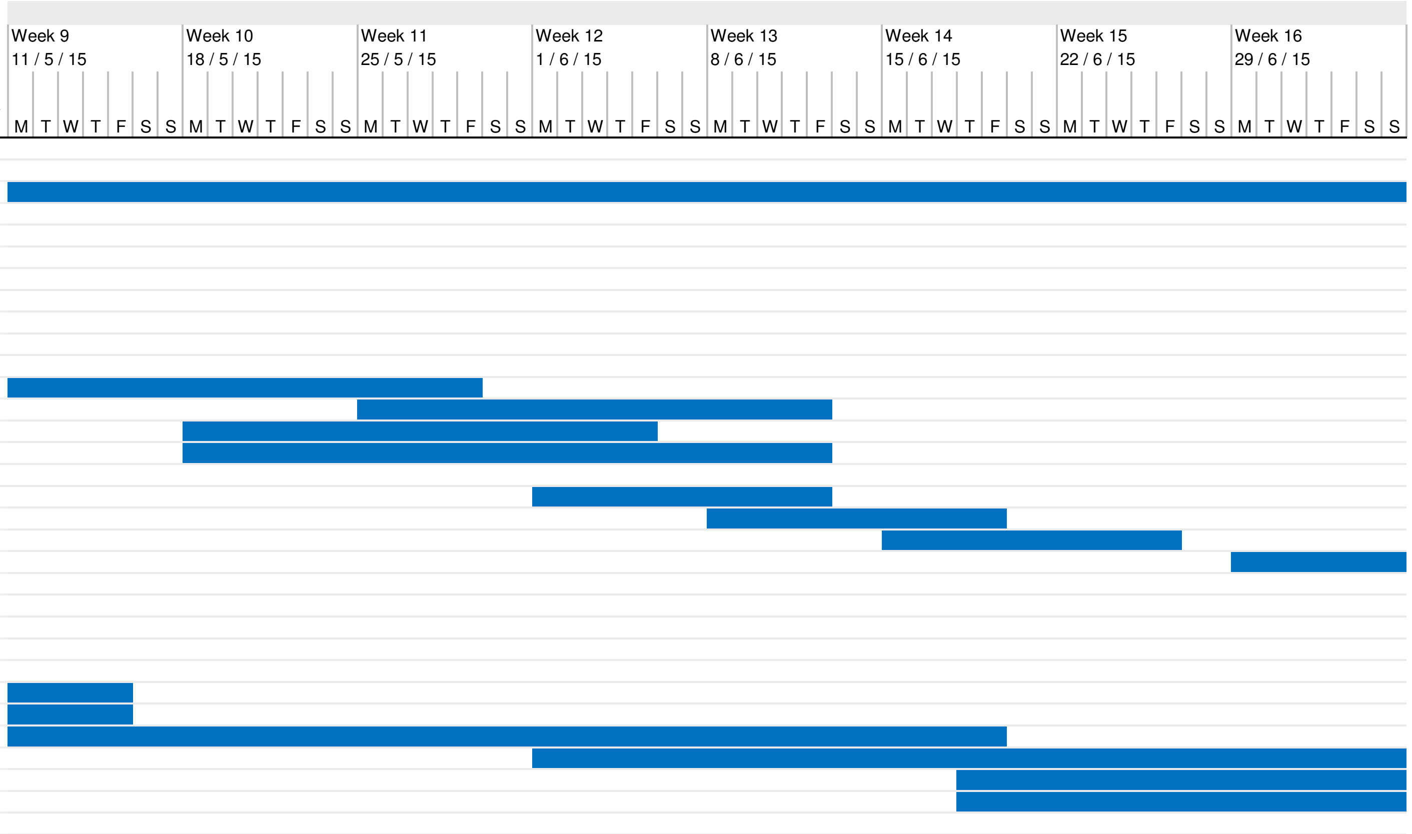

Minimole+Economole Integration Project Schedule

Massey University

Project Lead: Ben Huggins

Project Start Date: 16/03/2015

Display Week: 17

Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24
6 / 7 / 15	13 / 7 / 15	20 / 7 / 15	27 / 7 / 15	3 / 8 / 15	10 / 8 / 15	17 / 8 / 15	24 / 8 / 15
M T W T F S S	M T W T F S S	M T W T F S S	M T W T F S S	M T W T F S S	M T W T F S S	M T W T F S S	M T W T F S S

WBS	Task	Start	End	Cal. Days	% Done	Work Days
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6.7	Finalising	Mon 7/12/15	Mon 22/02/16	78	0%	56

Minimole+Economole Integration Project Schedule

Massey University

Project Lead: Ben Huggins
Project Start Date: 16/03/2015
Display Week: 25

Week 25 (31 / 8 / 15) | Week 26 (7 / 9 / 15) | Week 27 (14 / 9 / 15) | Week 28 (21 / 9 / 15) | Week 29 (28 / 9 / 15) | Week 30 (5 / 10 / 15) | Week 31 (12 / 10 / 15) | Week 32 (19 / 10 / 15)

WBS	Task	Start	End	Cal. Days	% Done	Work Days
1	**Effort Blocks**					
1.1	Start Up	Mon 16/03/15	Sun 3/05/15	49	N/A	35
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Minimole+Economole Integration Project Schedule

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Massey University

Project Lead: Ben Huggins
Project Start Date: 16/03/2015
Display Week: 33

Week 33 26 / 10 / 15 | Week 34 2 / 11 / 15 | Week 35 9 / 11 / 15 | Week 36 16 / 11 / 15 | Week 37 23 / 11 / 15 | Week 38 30 / 11 / 15 | Week 39 7 / 12 / 15 | Week 40 14 / 12 / 15

WBS	Task	Start	End	Cal. Days	% Done	Work Days
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Minimole+Economole Integration Project Schedule

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Massey University

Project Lead: Ben Huggins

Project Start Date: 16/03/2015

Display Week: 41

Week 41 21 / 12 / 15 | Week 42 28 / 12 / 15 | Week 43 4 / 1 / 16 | Week 44 11 / 1 / 16 | Week 45 18 / 1 / 16 | Week 46 25 / 1 / 16 | Week 47 1 / 2 / 16 | Week 48 8 / 2 / 16

WBS	Task	Start	End	Cal. Days	% Done	Work Days
1	**Effort Blocks**					
1.1	Start Up	Mon 16/03/15	Sun 3/05/15	49	N/A	35
1.2	Block One	Mon 4/05/15	Sun 12/07/15	70	N/A	50
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Minimole+Economole Integration Project Schedule

Massey University

Project Lead: Ben Huggins
Project Start Date: 16/03/2015
Display Week: 49

Week 49 15 / 2 / 16 | Week 50 22 / 2 / 16 | Week 51 29 / 2 / 16 | Week 52 7 / 3 / 16 | Week 53 14 / 3 / 16 | Week 54 21 / 3 / 16 | Week 55 28 / 3 / 16 | Week 56 4 / 4 / 16

M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S

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Attachment 2

Masters Work Plan: Methanex Minimole/Economole Integration

Objectives

Assess and design methods of power and data communication to/from the "Minimole" probe which are compatible with existing "Economole" system

- Investigate viable power delivery to Minimole probe electronic systems.
- Investigate current Economole data transmission method, as well as other methods of transmitting data, and decide on best suited/most compatible method for transmitting Minimole probe data.
- Investigate viable Minimole LVDT sensor variations that will be electronically and mechanically compatible with Economole system.
- Design sub-systems around the most viable investigated options.

Integrate probe software into existing software

- Evaluate current Economole software.
- Modify for correct function of Minimole system
- Provide high-level go/no-go indications about the tube being currently measured by the Minimole, alongside real-time displayed Economole results.

Design appropriate probe control and output evaluation software

- Integrate Minimole probe position monitoring with Economole position monitoring.
- Minimole sensor output monitoring for acquiring data on necessary sections of tube.
- Create a method of Minimole data storage that follows existing Methanex protocols.

Physically integrate Minimole probe systems with existing Economole systems

- Mechanical design for attaching Minimole probe to Economole system, while still allowing full correct function of both systems.
- Test both systems in a lab environment and in-situ to verify correct functionality and satisfactory measurement results.

Start date: 1/3/2015

End Date: ???

Completion Milestone

The project will result in full mechanical, electronic and software integrated Minimole probe with the existing main Economole reformer tube system. Methanex will have an all-in-one system which can be re-manufactured and deployed globally in order to perform low-cost, low-impact maintenance inspection of their reformer tube equipment.

Venture TARANAKI Te Puna Umanga

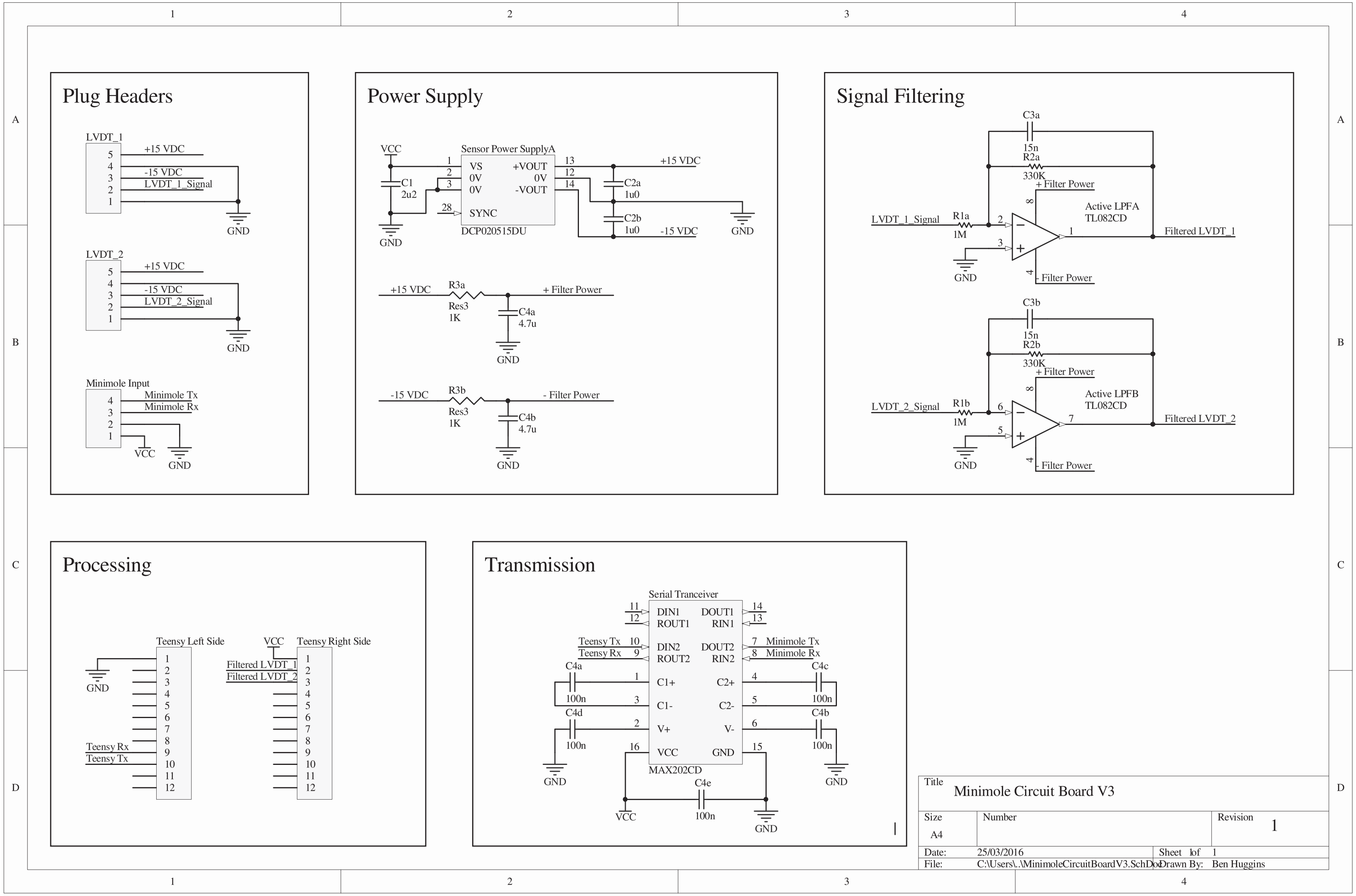
Callaghan Innovation

Professional Development Plan – Leo Allom 2015

Area of development	Learnings	How the learning will occur	Who will be involved	Achievement indicator
Health and Safety Skills	*Leo will undertake the full Safety Induction required to work on site and will have to work with the Company Health and Safety Experts when designing and performing the proof test.*	*Attend a Methanex Induction Workshop to our company health and safety systems and processes*	*Run by the Health and Safety Training Manager*	*-To be completed before the project can start* *- Required training completed and safety processes adhered to*
Technical Skills	*The Minimole project will introduce Leo to the rigour of producing a device ready for immediate field use. This is a step up from a device made and tested in a laboratory as it must be demonstrated to perform under the real life conditions of* - *Rough physical handling* - *Abrasive dust environment* - *Fluctuating power supply, voltage and sudden disconnects* - *Sustained use without repair or adjustment* *The extensive experience of Methanex staff in bringing R&D projects up to industrial standard is unlikely to be replicated in a purely academic setting. Leo will be required to effectively act as a supplier to the Technical experts and will be expected to support and defend his design and decisions.*	*Leo will come to site to make a presentation of his proposed design to describe how he will meet the project requirements.* *Leo will then take the comments back to the Massey supervisor and work through them to achieve a satisfactory design. This will be built as a prototype.*	*The Asset Integrity Engineers that are the ultimate customers will attend and critique the proposed design.* *Massey academic staff.* *Massey technical staff.*	*- Leo is confident in developing solutions for real life testing conditions* *-Leo is confident in defending his theories and decisons* *- Good progress on meeting the technical project objectives*

Commercial Skills	*The Minimole project will transition Leo from the regulated academic environment to a professional one by instigating standard project protocols* - *Formal regular reporting of progress* - *Budget control* - *Project planning and task scheduling* - *Purchasing specifications, sourcing and expediting*	*Leo will be expected to produce the project documentation for review prior to commencement.* *Regular formal reporting is required.*	*Methanex Technical Department Project Engineers* *Methanex project supervisor*	*-Leo will be able to move seamlessly into a commercial R&D or Project role upon completion of this project*
Project execution	*The proof test of the project will be the successful field testing of the device in the plant. Leo will be the project leader for this and will have to liaise with the Operations and Maintenance Departments to set up and run the tests.*	*The prototype will be trialled on site down an actual tube/pigtail setup. It will be run numerous times to test the robustness of the design. Leo will establish the test regime and results analysis.*	*Methanex Maintenance technicians and engineers.* *Operations department staff to obtain the necessary permits.*	*- Project is finished on time and on budget* *- Leo is able to multi-task and meet project deadlines*
Leadership	*Leo will be expected to create and present a training package for the device. The presentations will be across all levels of the organisation.*	*The creation of a professional quality training package.*	*Methanex senior staff, engineers and technicians.*	*-Training package completed and presented* *- New device understood clearly by all staff*

Appendix 2: Minimole Electronics Schematic


Plug Headers
LVDT_1
+15 VDC
-15 VDC
LVDT_1_Signal
GND
LVDT_2
+15 VDC
-15 VDC
LVDT_2_Signal
GND
Minimole Input
Minimole Tx
Minimole Rx
VCC
GND
Power Supply
VCC
Sensor Power SupplyA
VS
0V
0V
SYNC
+VOUT
0V
-VOUT
DCP020515DU
C1
2u2
C2a
1u0
C2b
1u0
+15 VDC
-15 VDC
GND
+15 VDC
R3a
Res3
1K
+ Filter Power
C4a
4.7u
GND
-15 VDC
R3b
Res3
1K
- Filter Power
C4b
4.7u
GND
Signal Filtering
C3a
15n
R2a
330K
+ Filter Power
LVDT_1_Signal
R1a
1M
Active LPFA
TL082CD
Filtered LVDT_1
- Filter Power
GND
C3b
15n
R2b
330K
+ Filter Power
LVDT_2_Signal
R1b
1M
Active LPFB
TL082CD
Filtered LVDT_2
- Filter Power
GND
Processing
Teensy Left Side
GND
Teensy Rx
Teensy Tx
VCC
Teensy Right Side
Filtered LVDT_1
Filtered LVDT_2
Transmission
Serial Tranceiver
DIN1
ROUT1
DIN2
ROUT2
C1+
C1-
V+
VCC
DOUT1
RIN1
DOUT2
RIN2
C2+
C2-
V-
GND
MAX202CD
Teensy Tx
Teensy Rx
Minimole Tx
Minimole Rx
C4a
100n
C4d
100n
C4c
100n
C4b
100n
C4e
100n
VCC
GND
Title
Minimole Circuit Board V3
Size
A4
Number
Revision
1
Date:
25/03/2016
Sheet 1of 1
File:
C:\Users\..\MinimoleCircuitBoardV3.SchDoc
Drawn By:
Ben Huggins

Appendix 3: Minimole Calibration Data

This appendix details information about the Minimole calibration methodology.

Table 1 shows the raw digitised sensor output of the left and right measurement arms, at nine intervals. Linear sensor displacement is shown in the table for each arm in millimetres, derived from the system parameters as follows:

$$
\begin{aligned}
&total\ linear\ displacement\ available = 10\ mm,\\
&resolution\ of\ digitiser = 1024,\\
&linear\ displacement = \frac{10\ mm}{1024\ bits} * Raw\ Signal
\end{aligned}
\tag{1}
$$

Table 1: Nine point calibration data

Real Width (mm)	Contribution of each side (mm)	Right Raw Signal	Right Linear Displacement (mm)	Left Raw Signal	Left Linear Displacement (mm)
26	0	540	5.273438	680	6.640625
27.1	0.55	444	4.335938	535	5.2246094
27.98	0.99	348	3.398438	432	4.21875
28.99	1.495	251	2.451172	334	3.2617188
29.99	1.995	176	1.71875	243	2.3730469
31	2.5	115	1.123047	167	1.6308594
31.98	2.99	69	0.673828	111	1.0839844
32.98	3.49	33	0.322266	70	0.6835938
34	4	20	0.195313	39	0.3808594

Once the data is gathered, a scatter plot is created with the calculated linear measurement of each sensor versus the contribution to the known measured width, or diameter, at that point. This is shown in Figures 1 and 2. A third order polynomial curve is fitted to the data set, which can be observed as a good fit both visually and in terms of the R^2 value. The values from the fitted curve equations are input directly into the Minimole microcontroller code.

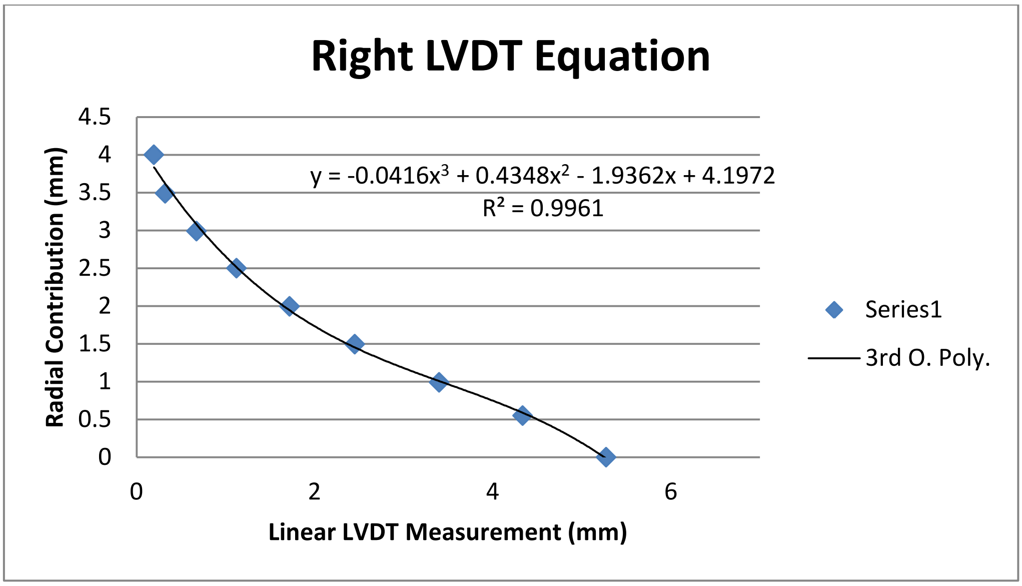


Figure 1: Scatter plot of calculated right side sensor measurement versus Minimole measurement contribution, showing fitted third order polynomial

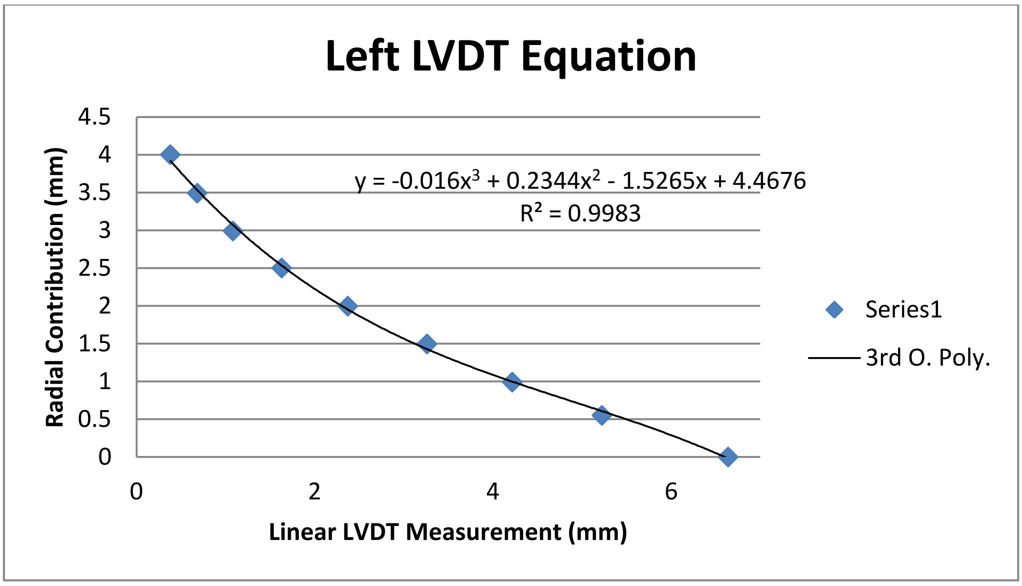


Figure 2: Scatter plot of calculated left side sensor measurement versus Minimole measurement contribution, showing fitted third order polynomial

Appendix 4: Minimole Test Data

Test data for three different pipe samples is presented in Tables 1, 2, and 3 of this appendix. The pipe samples were sections of pigtail, each around 250 mm long, that could be easily manipulated for bench top testing.

For each sample, the following steps were used:

1. The pipe diameter (*Pipe Size)* was measured for reference, with a snap gauge and electronics callipers.
2. The growth tolerance (*Growth)* was set in the Minimole HMI. Then the maximum allowable diameter output from the HMI was recorded (*Calculated max).*
3. The spread of the Minimole arms was adjusted and the 'set' command used in the HMI, and the output recorded (*Set spread).*
4. The sample pipe was run up and down the probe in a consistent manner over the same area, and the measurement output recorded for each run.

Once the data was gained, the following equations were used to calculate the results for assessment, where:

- x_{avgrun} = average measurement of a test run;
- x_{avgall} = average of all test runs for a sample;
- x_{actual} = actual measured diameter of the pipe;
- n = the number of test runs completed for a sample

$$Accuracy = x_{avgrun} - x_{actual}$$

(1)

$$Overall\ Accuracy = x_{avgall} - x_{actual}$$

(2)

$$Overall\ Precision = \sqrt{\frac{1}{n-1}\sum_{1=0}^{n}(x_{avgrun(i)} - x_{avgall})^2}$$

(3)

$$Repeatability = 3 * Overall\ Precision$$

(4)

Table 1: Pipe sample one test record

Test 1				
Pipe Size (mm)	29.22			
Growth (mm)	6%			
Calculated max	30.9732			
Set spread (mm)	31.98			
Measurements (mm)				
	Run 1	Run 2	Run 3	Run 4
	29.2	29.21	29.2	29.22
	29.21	29.21	29.2	29.22
	29.21	29.21	29.23	29.21
	29.22	29.21	29.22	29.22
	29.22	29.22	29.2	29.21
	29.23	29.23	29.18	29.21
	29.24	29.24	29.19	29.21
Average (mm)	29.22	29.22	29.20	29.21
Accuracy (mm)	0.00	0.00	-0.02	-0.01
Overall Average (mm)	29.21			
Overall Accuracy (mm)	-0.01			
Overall Precision (mm)	0.007423			
Repeatability (mm) ±	0.022			

Table 2: Pipe sample two test record

Test 2				
Pipe Size (mm)	30.14			
Growth (mm)	3%			
Calculated max	31.04			
Set spread (mm)	31.35			
Measurements (mm)				
	Run 1	Run 2	Run 3	Run 4
	29.83	29.85	29.87	29.84
	29.83	29.85	29.87	29.85
	29.83	29.85	29.82	29.85
	29.83	29.85	29.85	29.85
	29.83	29.85	29.84	29.85
	29.83	29.85	29.83	29.8
	29.83	29.85	29.75	29.84
Average (mm)	29.83	29.85	29.83	29.84
Accuracy (mm)	-0.31	-0.29	-0.31	-0.30
Overall Average (mm)	29.84			
Overall Accuracy (mm)	-0.30			
Overall Precision (mm)	0.008912			
Repeatability (mm) ±	0.027			

Table 3: Pipe sample three test record

Test 3				
Pipe Size (mm)	29.53			
Growth (mm)	10%			
Calculated max	31.01			
Set spread (mm)	31.35			
Measurements (mm)				
	Run 1	Run 2	Run 3	Run 4
	29.52	29.5	29.51	29.46
	29.51	29.57	29.52	29.44
	29.51	29.55	29.55	29.48
	29.51	29.52	29.55	29.45
	29.51	29.53	29.55	29.44
	29.52	29.55	29.55	29.4
	29.53	29.53	29.53	29.49
Average (mm)	29.52	29.54	29.54	29.45
Accuracy (mm)	-0.01	0.01	0.01	-0.08
Overall Average (mm)	29.51			
Overall Accuracy (mm)	-0.02			
Overall Precision (mm)	0.040254			
Repeatability (mm) ±	0.121			

Table 4 shows data for a test on repeatability in a field like situation. This used the test rig set up for the project, allowing the integrated assembly to be lowered down a sample of reformer tube including pigtail. Measurement was recorded just after entry in two groups: the pigtail (*top*), and at the furthest possible reach of the device (*bottom*). Precision is calculated as in Equation 3 of this appendix, except with n being the number of samples for the group, $x_{avgrun(i)}$ being each individual measurement of a group, and x_{avgall} being the average of the group.

Table 4: Field simulated repeatability record

Measurements (mm)		
	Top	Bottom
	30.14	29.05
	30.14	29.08
	30.15	29.05
	30.14	29.04
	30.16	29.05
	30.15	29.06
	30.15	29.09
	30.16	29.1
	30.13	29.07
	30.14	29.11
Average (mm)	30.146	29.07
Precision (mm)	0.010	0.024
Repeatability (mm) ±	0.029	0.072