Research and development of a real-time measurement and evaluation system for SAG mill liner wear

B Weakley

orcid.org 0000-0001-7563-2094

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Supervisor: Prof JEW Holm

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Student number: 28354737

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Thesis Overview

This thesis starts off by providing an abstract of the research and development work done followed by a list of abbreviations. A summary for each chapter is provided below:

Chapter 1 (Introduction) provides and introduction to mills and mill liners to provide context for this thesis. This is important information as it will explain the motivation for the research as well as background to real-world challenges.

Chapter 2 (Design philosophy) describes Design Science Research as a methodology and research framework.

Chapter 3 (Problem analysis) is a detailed analyses of a real-world challenge concerning mill liner wear measurement and includes clear definitions of detailed functional and environmental requirements.

Chapter 4 (Literature study) describes a study of measurement principles and technology related to the research topic, ideas and related literature studied in order to derive different technology building blocks.

Chapter 5 (Synthesis and System integration) focuses on the combination of ideas and detailed design of the system. The chapter describes the system integration process followed by a description of how artefacts were integrated into a functional system.

Chapter 6 (Development testing) describes how the system was tested and evaluated during the development phase.

Chapter 7 (Validation and conclusion) concludes the design of a system for monitoring in real-time and the evaluation of SAG mill liner wear. It includes a requirements verification matrix for the system as well as a verification and validation traceability matrix for the research.

The thesis is concluded by way of a DSR validation and verification matrix providing insight into the requirements, research challenges, literature study and formulation of the solution and artefacts.

The last section provides a bibliography of resources used in this research project.

Abstract

The mining industry regularly makes use of different processes for grinding and reducing the size of the rocks to smaller particles. The smaller particles are then further processed to recover precious metals such as gold, platinum, silver, copper and other metals.

The most commonly used mill for the reduction of material is the SAG or Semi-Autogenous mill. A SAG mill is a tumbling mill with a typical aspect ratio of shell diameter to mill length. These mills use lining on the inside of the wall to provide a lift and fall action of ore, which in turn wears down the lining due to the breaking action inside the mill.

The focus of this thesis is on the development of technology to measure, in real-time, SAG mill liner wear and thickness. Current day measurement methods are slow and time consuming and require a mill to be stopped for the purpose. Loss of production cost for stopping a mill is very high, in some instances as high as $100,000 (roughly R1,200,000) per hour. Current methods and technology for liner wear measurement are thus ineffective due to excessive costs and production loss.

The need thus exists for liner wear at shorter time intervals than the current methods. Having real-time liner wear values will improve process control by adjustment of material feed, liquid content, drum speed and other parameters for optimal adjustment of SAG mill and related operations. The immediate and early detection and indication of damaged or broken liners will be of huge value in the prevention of further loss of production and worse, damage to the mill drum due to wash-through and material wear.

The artefacts developed from this research are used to measure SAG mill liners' wear in real-time. A novel technique for sensing was developed and is used to enhance the robustness of liner wear sensors using a hybrid sensor comprised of conductive loops and semiconductor diodes. Validation of system functionality was achieved by implementing a liner wear measurement system at a mine. The research challenges were successfully addressed using Design Science Research.

Keywords: SAG mil, liner wear, design science research, real-time monitoring, low-power, hybrid sensor

Uittreksel

Die mynbou industrie maak op ‘n gereelde grondslag gebruik van verskillende prosesse om rots te reduseer tot kleiner partikels deur middel van breking. Die kleiner partikels word dan verder geprosesseer om waardevolle metale soos goud, platinum, koper en ander metale te ontgin.

Die mees algemeenste is ‘n “SAG” rolmeul, of “Semi-Autogenous” rolmeul. ‘n SAG meul veroorsaak ‘n tuimel aksie met ‘n spesifieke verhouding van drom diameter tot dromlengte. Hierdie meule gebruik n voerings meganisme aan die binnewand met die doel om erts op te lig en te laat val, ‘n aksie wat verwering van die meganisme veroorsaak as gevolg van die brekingsaksie binne die meul.

Die fokus van hierdie tesis is op die ontwikkeling van tegnologie om, intyds, SAG meule se belyningsverwering en belyningswanddikte te meet. Huidige metodes is stadig en tydrowend omdat die meulaksie gestaak moet word om metings te kan neem. Die verlies aan produksie om ‘n meul te stop is baie hoog en kan tot $100,000 (ongeveer R1,200,000) per uur beloop. Huidige metodes vir verweringsmeting is dus oneffektief weens die hoë kostes en verlies aan produksie.

Die behoefte bestaan dus vir ‘n metode om verwering te meet met korter tydintervalle as die intervalle van huidige metodes. Die beskikbaarheid van intydse verweringsdata sal die prosesbeheer verbeter deurdat voer, vloeistofinhoud, en dromspoed verstel kan word vir die optimale verstelling van die SAG meul se bedryf. Onmiddellike en vroegtydige waarneming van beskadigde of gebreekte belyning sal van nut wees om verdere verliese te beperk en om beskadiging van die meul self te voorkom as gevolg van deurwas en materiaalverwering.

Die artefakte wat ontwikkel is, word gebruik om die SAG meul se belyningsverwering intyds te bepaal. ‘n Nuwe tegniek vir meting is ontwikkel om die robuustheid van belyningsverweringsensors te verhoog deur gebruik te maak van ‘n hibriede sensor bestaande uit geleidende lusse en halfgeleier diodes. Validasie van die stelsel se funksionaliteit was behaal deur ‘n meetstelsel by ‘n myn te implementeer. Die navorsingsuitdagings was suksesvol aangespreek deur gebruik te maak van “Design Science Research”, oftewel Ontwerpswetenskapnavorsing.

Sleutelwoorde: SAG of tuimel meul, belyningsverwering, intydse meting, lae stroom, hibriede sensor.

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Table 1: List of abbreviations

AG mill	Autogenous Mill
ARM	Advanced RISC Machine (RISC - reduced instruction set computing)
Batt	Battery
CI	Communications Interface
COTS	Commercial Off The Shelf
CPU	Central Processing Unit
DEM	Discrete Element Modelling
DIN	Deutsches Institut fur Normung – (DIN 2018)
DSR	Design Science Research
EEPROM	Electrically Erasable Programmable Read-Only Memory
EI	Electrical Interface
FW	Firmware
GUI	Graphic User Interface
HMI	Human-machine Interface – such as keyboard, mouse and display
HW	Hardware
ICE	In-Circuit Emulator
IDE	Integrated Development Environment
IP	Internet Protocol or Intellectual Property (depending the context)
IS	Information System
KBD	Keyboard
LAN	Local Area Network – such as Ethernet

MCDM	Multiple-Criteria Decision Making
MCU	Microcontroller Unit, a microprocessor with on-chip peripherals
MI	Mechanical Interface
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OOK	On-Off Keying – a form of ASK frequency modulation
OS	Operating System
OTG	On The Go
PSU	Power Supply Unit
RAM	Random Access Memory
RFI	Radio Frequency Interface
ROM	Read Only Memory
RSSI	Received Signal Strength Indicator
RTC(C)	Real-Time Clock (Calendar)
RX	Receive
SAG mill	Semi-Autogenous Mill
SW	Software
TBA	To Be Advised
TBC	To Be Confirmed
TBD	To Be Defined
TRX	Transmitter / Receiver
TX	Transmit
USB	Universal Serial Bus

VSI mill	Vertical Shaft Impactor mill
Wi-Fi	Wireless Fidelity - (IEEE Standard for Information technology 2012)
WLAN	Wireless Local Area Network

Chapter 1 – Introduction to mills

A mill is a machine used in mining processes to break solid materials such as rock into smaller particles by way of crushing, cutting and grinding called comminution. Modern day milling is further classified as the process of breaking down, sizing, separating and classification of aggregate material. It is known to crush rock to a uniform aggregate size for construction purposes or to crush rock for the removal of precious metals.

Many different types of mills exist for different processes and applications. This thesis focus on the AG, SAG or Ball mill types using liners as the lifting mechanism. To name a few, mills such as ball mill, rod mill, pebble mill, high pressure grinding rolls, Buhrstone mill, vertical shaft impactor mill (VSI mill), tower mill, autogenous (AG) mill and semi-autogenous (SAG) mills are often used in modern day mining (Wills 2006), (Kumar 2015).

In all mill circuits it is of paramount importance to keep mill downtime to a minimum as loss of production amounts to huge costs to the mine. Production downtime may be as much as $100,000 (roughly R1,200,000) per hour (Dandotiya, et al. 2011). It is reported by Dandotiya that the total downtime cost during measurement may be significantly reduced by using improved measurement devices and techniques.

1.1 Definition of mill types

There exits many different types of mill types and variations. This thesis focuses on the ball, autogenous and semi-autogenous mill types. These mills are described below for clarity on their operation. All photos and images courtesy of (Goebel, Liner Intelligent System test Trials at Harmony Gold Joel Mine Free State 2016).

1.1.1 Ball mill

Ball mills are smaller type mills typically used for fine grinding of material such as in the production of Portland cement. The mills are smaller in size, from laboratory size up to 28 ft (8.5 m) in diameter with an aspect ratio (diameter to length) of typically 1.5 to 2.5 and driven by electric motors of up to 22 MW (van de Vijfeijken 2010). Ball mills are usually inclined at a slight angle and filled with stone or metal balls supporting the grinding process. Ball charge is approximately 30 % of the feed volume and introduced into the mill at the feed end. During the grinding process, the material comminution is a result of friction and impact caused by the tumbling balls. The material size is reduced to such an extent that it will be released through sized grates at the discharge end of the mill.

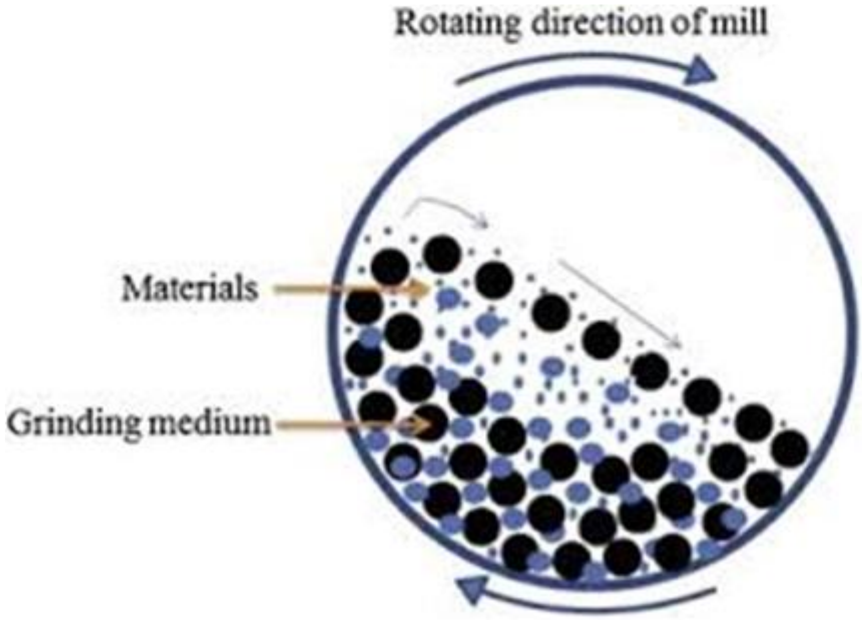


Figure 1: Operation of a ball mill

Figure 2: Photo of a ball mill (outside view)

Figure 3: Photo of a ball mill (inside view)

1.1.2 Autogenous mill

Autogenous or autogenic mills are so-called due to the self-grinding of the ore: A rotating drum throws larger rocks of ore in a cascading motion which causes impact breakage of larger rocks and compressive grinding of finer particles. It is similar in operation to a SAG mill as described below but does not use steel balls in the mill. This is also known as ROM or "run of mine" grinding.

1.1.3 Semi-autogenous (SAG) mill

SAG is an acronym for semi-autogenous grinding. SAG mills are essentially autogenous mills, but utilize grinding balls to aid in grinding like in a ball mill. A SAG mill is generally used as a primary or first stage grinding solution. SAG mills use a ball charge of 8 % to 21 %. The largest SAG mill is 44 ft (13.4 m) in diameter, powered by a 47,000 HP (35 MW) motor (van de Vijfeijken 2010). Attrition between grinding balls and ore particles causes grinding of finer particles. SAG mills are characterized by their large diameter and short length as compared to ball mills. The inside of the mill is lined with lifting plates (called “Liners”) to lift the material inside the mill, where it then falls off the plates onto the rest of the ore charge. SAG mills are primarily used at gold, copper and platinum mines with applications also in the lead, zinc, silver, alumina and nickel industries (FAB3R 2017).

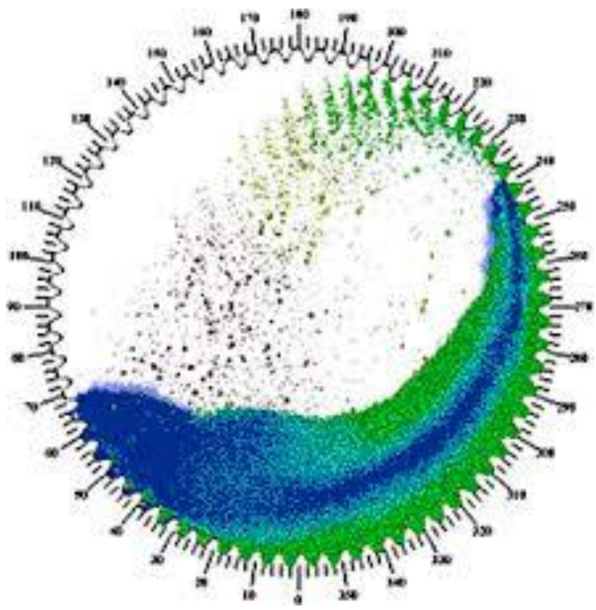


Figure 4: Principle of SAG mill operation

Figure 5: Photo of a SAG mill (inside view)

Figure 6: Photo SAG mill (left), ball mill (right)

1.2 Mill liner types

The “plates” inside the SAG mill, causing the lifting of material are called “liners”. The grinding mill liners are integral parts of a grinding mill. Generally the mill liners are treated as the protective shield for the grinding mill surfaces, but they also play a significant role in the energy transmission to the charge. In order to optimize the energy transmission and the surface protection, a liner should have a specified profile (Powell, et al. 2006).

Liners are the parts used on the inner surface of the grinding shell to provide the necessary strength and resistance to abrasive material. Lining is used on all surfaces with which pulp comes in contact in order to take the wear, and thus conserve the strength and tightness of the barrel structure (Gupta and Yan 2016).

1.2.1 Functions of mill Liners

Liners perform different functions inside a mill and are critical in the grinding process, as they provide abrasion and erosion by friction resistance to the shell surface. Liners provide the lifting action and add impact and crushing actions to solid materials. They further prevent wear and associated damage to the mill shell, heads and trunnions as well as to improve the flow ability of solids or the pulp inside the mill. Lastly, liners can be seen as the final link in the transmission of energy to the tumbling load.

1.2.2 Types of liners

Liners of different sizes and diameters are designed for various reasons. These reasons include various designs for optimal lifting capability, to reduce wear, increase grinding performance, accommodate mill design and support ease of maintenance.

Larger liners are installed using what is known as liner handling machines, which are in common use. The introduction of liner handling machines allowed the evolution of large integral liner blocks, weighing up to 1.5 ton each (Rosas and Salamanca 1996). For smaller mills the liners have to be handled and installed manually, so smaller blocks with removable lifter bars are generally favoured.

Although many liner types exist, this research only focuses on liners similar to the “solid liner” type. These include removable lifter, uni-direction profiled liners, integral wave blocks, high–low double wave ball mill liners and similar. Liners such as wedged liners and grid liners are excluded from this study (Powell, et al. 2006).

Generally liners are fastened to the mill shell using bolts and nuts. Typical bolts are shown below.

Figure 7: Photo typical SAG mill liner oval bolts

1.2.2.1 Solid liners

As shown in Figure 8 (Powell, et al. 2006), solid liners have an integral lifter. Solid liners have fewer parts and are easier to install. These liners tend to have a high scrap weight as once the lifter section is worn down the liner performance drops and necessitates replacement.

Figure 8: Solid SAG mill liner

1.2.2.2 Removable lifter

Rather than replacing the complete liner in certain designs it is possible to only replace the worn lifter (Powell, et al. 2006). This method maximises the liner life in manually relined mills. A disadvantage is that more pieces need to be installed and liners can move during relining as well as when not properly secured against the backing liner, the lifter can shift and work loose.

Figure 9: Solid SAG mill removable lifter

1.2.3 Liner materials

Many different materials are used in liner design, and material selection is a function of the application, abrasiveness of the ore, the size of the mill, corrosive environment, and size of grinding balls, mill speed and others. Liner materials chosen are typically of the following (Powell, et al. 2006):

- Austenitic manganese steel (AMS);
- Low carbon chrome moly steel (300 to 370 BHN);
- High carbon chrome moly steel (325 to 380 BHN);
- Nihard iron (550 BHN);
- High chrome irons (+600 BHM) Cr Iron;
- Chrome moly white irons (600 to 700 BHN) WI;
- Rubber liners;
- Rubber / steel composites;
- Magnetic liners.

The liner material is not of great concern for this study as the liners are all bolted down to the mill shell using liner bolts described earlier.

1.2.4 Testing and prediction of liner wear rates

Although testing of wear rates is imperative in determining the wear rate of production liners, it was found to be misleading and inaccurate for the prediction of liner performance. Test results are sometimes misleading rather than informative since a fundamental problem with prediction models is that they lack the effect of contact pressure, rates of relative movement, and abrasive material play a large role in the determination of wear rate. Poorly conceived tests can easily be inaccurate by an order of magnitude and provide misleading information. A number of test methods have been developed over the years of which the two most prominent are discussed here, namely near-field-condition testing and laboratory testing.

1.2.4.1 Near-field-condition testing

Near-field-conditional testing endeavours to reproduce the overall action and forces encountered within a mill. A test was developed (Powell and Cornelius 1992) using a 1.8m batch mill for liner profile testing as it reasonably represents the wear modes on liners of 5 m diameter. The rate of wear is then precisely monitored over a few days by measuring progressive mass loss. These tests produce a relative wear rate against a standard sample. The test has the advantages that small samples of test material are required, different materials can be tested simultaneously; it requires a simple sample geometry and requires a short test period of typically a few days. The test also provides an accurate measurement of liner wear rate.

1.2.4.2 Laboratory testing

As mentioned above, laboratory tests tend to give misleading results. Endeavours by Radziszewski (Radziszewski, Determining Impact, abrasive, and corrosive contributions to total media wear n.d.), as part of the AMIRA P9 collaborative research project (amirap9 n.d.), emphasised duplication of forces and wear modes within a production mill. With the advent of DEM techniques and their application to milling, tools are now available to mathematically derive the required forces (Mishra and Rajamani n.d.), (Cleary n.d.), (Inoue and Okaya n.d.), (Radziszewski, Modeling Comminution as a Function of Crushing, Tumbling and Grinding in a Ball Mill, MSc Thesis 1986); (Herbst and Nordell 2001) and (Zhang and Whiten n.d.).

1.2.5 Liner wear measurement

According to Powell (Powell, et al. 2006), measurement is required for optimization. Valuable information regarding wear rates of different facets of liners could allow for refinement of liner design as well as optimisation of mill speed, charge volume and other parameters which could improve production churn.

Mill liners have a typical lifespan of twelve to eighteen months and the optimisation of the liner profile for a particular mill could take a number of years. Ongoing improvement of liner measurement effort is therefore an imperative requirement to achieve success in this regard.

Current techniques for the measurement of liner profile are of simple manual and mechanical nature. Various techniques including mechanical and electronic tools exist in order to do such measurement but all require the mill to be stopped. It then usually takes a number of hours to collect data which results in downtime and loss of production.

1.2.6 Mill liner inspections

Scheduled mill liner inspections are regularly performed in order to determine liner status. Liner inspections determine signs of cracks in the castings, raceways or abnormal wear patterns, dimpled impact marks and peening of liner edges. These inspections are important since the liner status provides an indication of liner and process efficiency, protection to the mill shell and early warning on damaged liners (Royston 2007).

1.3 Conclusion

This chapter provides an overview of SAG mills and liner descriptions, liner related problems and test and evaluation methods for determining liner wear. The difficulties faced by the mining industry, as discussed above, show that automated measurement of liner wear will be advantageous to the mining community since real-time analysis of liner wear provides an indication of mill performance and efficiency.

Real-time mill liner wear rate data may be used to improve mill and liner performance over shorter periods of time, providing immediate improvement of plant production, reduction in mill downtime and ultimately increasing mill yield and productivity.

It became clear from the initial study that existing liner measurement equipment has inadequacies, such as reliability issues (due to the harsh environment), as well as adequate levels of monitoring and resolution. It can be seen from research, use cases and discussions with industry partners that a remote monitoring capability is required in order to view liner wear remotely, providing reporting and statistical capabilities.

Lastly, it was found that existing equipment should be capable of outlasting at least the lifetime of a liner without requiring being repaired or replaced, therefore a lifetime of typically twelve to eighteen months is required.

Chapter 2 – Research philosophy

This thesis follows the Design Science Research (DSR) methodology. DSR is required for the evaluation, investigation, research and design of artefacts in a context defined by a real-world problem. DSR further allows for the focus on a solution based research outcome as opposed to problem orientated research (van Aken 2004) such as is common to natural or social science research activities (which are of observational and mostly of qualitative nature).

2.1 Design Science Research

In terms of DSR, a set of analytical techniques and perspectives is used to perform research. It involves the development of one or more artefacts to be used in the evaluation of performance, or use thereof to better understand the behaviour of the research topic (Hevner, et al. 2004).

Design, in the DSR context, can be seen as a set of activities (defined in a process flow) that results in a product (artefact or meta-artefact) (Hevner, et al. 2004). It is a suitable method for the development and evaluation of the technology defined in this research. Inputs from a real-world problem (a requirement to measure liner wear in real-time) were used to stimulate design activities (synthesis and design), which were then used to develop artefacts. These artefacts were implemented in a real-world environment (a SAG mill on a mine) to measure the real-world behaviour, after which an iterative process was followed of incrementally building and evaluating artefact performance. The iterative shifting of perspective between design process and artefact development (Markus, Majchrzak and Gasser 2002) resulted in the improvement of both the quality of the design process and the end product. Figure 10 depicts a graphical view of the DSR framework (A. R. Hevner 2004) which was followed in this research.

The environment (user requirements) for a liner wear measurement system was evaluated and summarised, from which a problem statement was derived (business need). This requirement was synthesised into a design artefact (IS Research – Develop / Evaluate) by following a process of literature study (knowledge base), gathering of additional information, application of design principles, development of software models, and use of hardware technology and methods as part of the design and evaluation (Information Systems (IS) research).

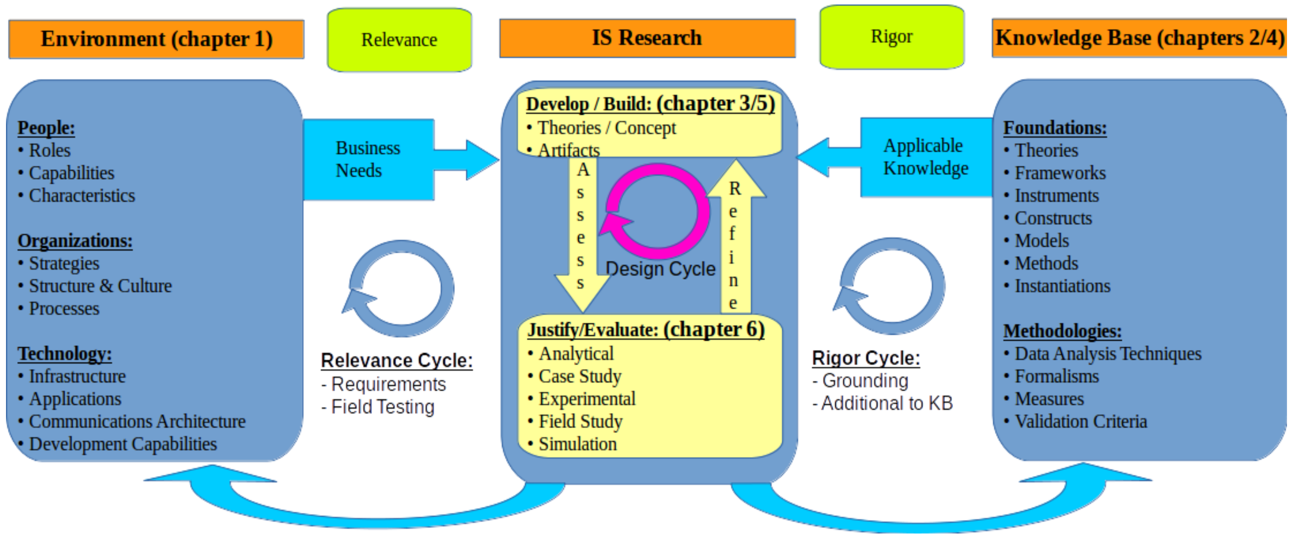


Figure 10: Information systems research framework

The IS research process provided enhanced knowledge of innovative measurement and low power monitoring techniques as well as transfer of real-time data. These principles allow potential technology development for related solutions for monitoring real-time data in mining industries.

The three cycles of DSR, namely the (i) relevance, (ii) design and (iii) rigor cycles and their relevance to this research and development project are described below.

2.1.1 Relevance cycle

"The objective of design-science research is to develop technology-based solutions to important and relevant business problems" (A. R. Hevner 2004). In the case of this project, the objective is the design of a system to monitor liner wear and associated wear rate. In this cycle, a need analysis provided system requirements as well as criteria whereby each requirement was to be accepted. A scoring model was developed and used in the evaluation of appropriate technology for defined building blocks of the system.

The purpose of the IS research cycle (requirements definition and artefact evaluation) was thus to ensure the developed artefact was tested against valid requirements where an iterative process was followed until all requirements had been met.

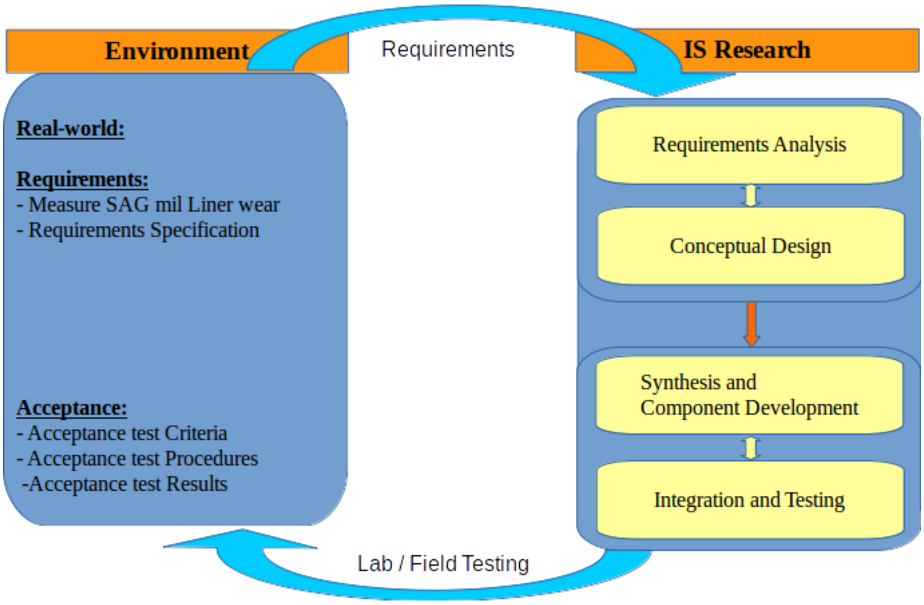


Figure 11: Relevance and design cycles

2.1.2 Design cycle

The design cycle as defined by DSR focuses on the development of theories and artefacts from conceptual to final articles. The concept of systems engineering (SE) is inherently embedded in the DSR framework. During the design cycle, an iterative SE process is followed from concept to artefact and back. This iterative process is done cognitive of the inputs from both relevance and rigor domains so as not to lose focus of the baseline.

The design cycle in this case is reduced to activities such as concept design, synthesis (artefact development) and integration (test and evaluation). The further intent of this process is to confirm the evaluation and design of alternative concepts and solutions until a satisfactory real-world problem can be solved (A. R. Hevner 2004).

Artefacts were rigorously tested against the relevant requirements before introduction to field testing. This was an important aspect of the development as field testing of artefacts are expensive and costly due to the nature of product development, evaluation time, as well as the availability of a mill and mine personnel for testing.

2.1.3 Rigor cycle

The rigor cycle is defined as the appropriate application of existing foundations and methodologies (A. R. Hevner 2004). In addition, rigor is achieved by experience and knowledge from existing artefacts in the area of interest. An important issue to be addressed by DSR is the importance to solve unsolved problems in unique or innovative ways, or in more effective or efficient ways. As opposed to routine design, DSR therefore provides a clear identification of a contribution to the archival knowledge base of foundations and methodologies. During the rigor cycle, unique principles of measurement are developed and publicised. This will add to a knowledge base for future development of similar projects.

2.2 The role of specification standards in research

Seen from the DSR life cycle process, the role of specifications is to establish a bridge between research and development. Specifications in terms of the DSR process provide the baseline requirements for which a product (artefact) procedure, processes or technology is to be developed.

A systems engineering approach was used during the entire project life cycle to define the system requirements, design and development, testing and feedback (iteration) to system requirements and definition. The requirements definition approach is based on the framework defined by MIL-STD-490A (specification practices) (US Department of Defence 1985), a document standard defining the structure, headings and layout of System documents and specifications. This paragraph is based on the definition of a Type B1 – Prime Item Development Specification as defined by MIL-STD-490A. The development falls within the scope of a type B1 since a type B1 states the technical requirements for a system as one entity as well as to allocate functional areas and to specify design constraints. It furthermore defines interfaces between functional areas and sub-systems. This approach was chosen since it correlates well with the DSR principles and the author’s familiarity with MIL-STD and Systems Engineering principles.

2.3 Conclusion

Based on the life cycle phases of the DSR process, it is a well suited methodology for the research and developmental nature of this project. The DSR process suggests a requirements definition phase that summarises and organises real-world requirements and leads the designer through technology research and literature study, which in turn leads to an iterative process for design and verification. The use of specifications during the research phase results in the alignment between research and development.

Chapter 3 - Problem analysis

The purpose of this research is to develop a system that can be used to solve difficulties with liner measurement to allow for optimal adjustment of SAG mill operations. The research therefore focused on the development of a system that could be easily installed onto existing equipment with minimum or no change required to the SAG mill components and parts. The requirement translated into that of a system for monitoring, in real-time, the liner wear as a function of time and to make the data visible to mining operations. It was foreseen that the development of this technology would be of value to the mining community and other users of SAG mills.

This system is further referred to as the “prime item“ to align it with the terminology as defined by MIL-STD-490A, and the building blocks within the system are referred to as “sub-systems”. This specification practice was followed to highlight the alignment of systems engineering with DSR in the relevance cycle, and to provide the client with a set of valid requirements. Synthesis was performed by the researcher throughout and during the compilation of these requirement specifications and was done to place the requirements and possible solutions in context. An iterative approach was taken whereby requirements were documented in such a way as to provide potential solutions to the problem while consulting with the client at operational level. Since the researcher needed to reflect on the actual process of research and development, it was required to include an element of synthesis in this chapter as opposed to presenting a superfluous approach which does not show how the DSR process and specification practices work in harmony.

Requirements elicitation was performed by the researcher and documented in this chapter. The specifications that were documented were then discussed and re-evaluated in conjunction with the client in order to establish validated objectives and plausible potential solutions to the research and development challenge. In other words, the researcher also performed a literature study on different candidate solutions while drafting the specifications. This was done in order to discuss various options with the client and to make the specification and requirements definition as accurate as possible at the onset of the project. Therefore, synthesis was performed on operational elements of the system during the drafting of requirements.

In the sections that follow, MIL-STD-490A documentation standards will be evident, as discussed above, with minor adjustments to allow for readability.

3.1 Scope

A system is required to monitor in real-time the thickness of SAG mill liners and to make the data available to mining operations. The challenges to overcome are:

- Reduce production downtime due to manual liner measurement (Rosas and Salamanca 1996);
- Prolong equipment life time (to outlast Liner lifespan) (Weakley, Requirements discussion for liner wear measurement 2015);
- Improve on the limited resolution and accuracy of existing systems (Dandotiya, et al. 2011);
- Design equipment that would survive harsh environmental conditions (Rosas and Salamanca 1996), (Weakley, Requirements discussion for liner wear measurement 2015).

These challenges were the focus points around which the requirements for the target system were defined. Paragraph 3.3 (Prime Item definition) defines the requirements for each sub-system in the prime item. It is followed by paragraph 3.8 (System and sub-system characteristics) which describes specific characteristics for each sub-system such as physical characteristics (weight, dimensions etc.), and environmental conditions. It is followed by paragraph 3.8.4 (Design and construction), which specifies in detail crucial elements that were considered during the design and construction of the sub-systems, such as parts and materials, electromagnetic consideration and safety elements. Paragraph 3.9 defines Quality assurance provisions and paragraph 3.10 describes the procedures for Preparation for delivery.

3.2 Prime Item requirements

The high-level functional requirements for a liner measurement system were extrapolated from the problem statement. These requirements were discussed in detail with the client and are defined as the following:

- The capability to measure the thickness of SAG mill liners in real-time (Royston 2007);
- The capability to measure the wear rate of liners (change in level over time) (Dandotiya, et al. 2011);
- The measurement device must be mounted onto existing mill structures without modification to the mill (Weakley, Requirements discussion for liner wear measurement 2015);
- To determine the remaining duration of a liner's ability to grind material;
- Liner data to be transmitted wirelessly to a central host system where the information from a number of liners will be analysed (Dandotiya, et al. 2011).

3.3 Prime Item definition

The building blocks identified to perform the objectives are defined in the paragraphs to follow. The defined building blocks (or sub-systems) are the:

- Liner sensor sub-system;
- Transponder sub-system;
- Host controller sub-system.

The prime item, or system of interest, is therefore the integration of all the sub-systems into an operational system with the intent of measuring at the one end, liner wear, and passing the information to the other end, a user Interface for monitoring the status of such liner wear. The liner sensor and transponder are treated as separate entities although they may be integrated into a single artefact. It is so synthesised in order to research, evaluate and design for the specific requirements of each item, as well as the fact that the sensor and transponder may under certain circumstances be assembled in separate enclosures, dependent on the specific implementation.

3.4 Prime Item diagrams

The prime item elements are defined at functional level. These elements are defined here to specify adequate requirements without dictating a specific design. These high level functional definitions were then further evaluated and developed after completion of the literature study. The design was performed during synthesis, and the researched technology was used as input to the design.

Figure 12 shows all the elements of the liner sensor system as well as the communication flow between the transponders and host components. Each element is described in more detail in the sections that follow.

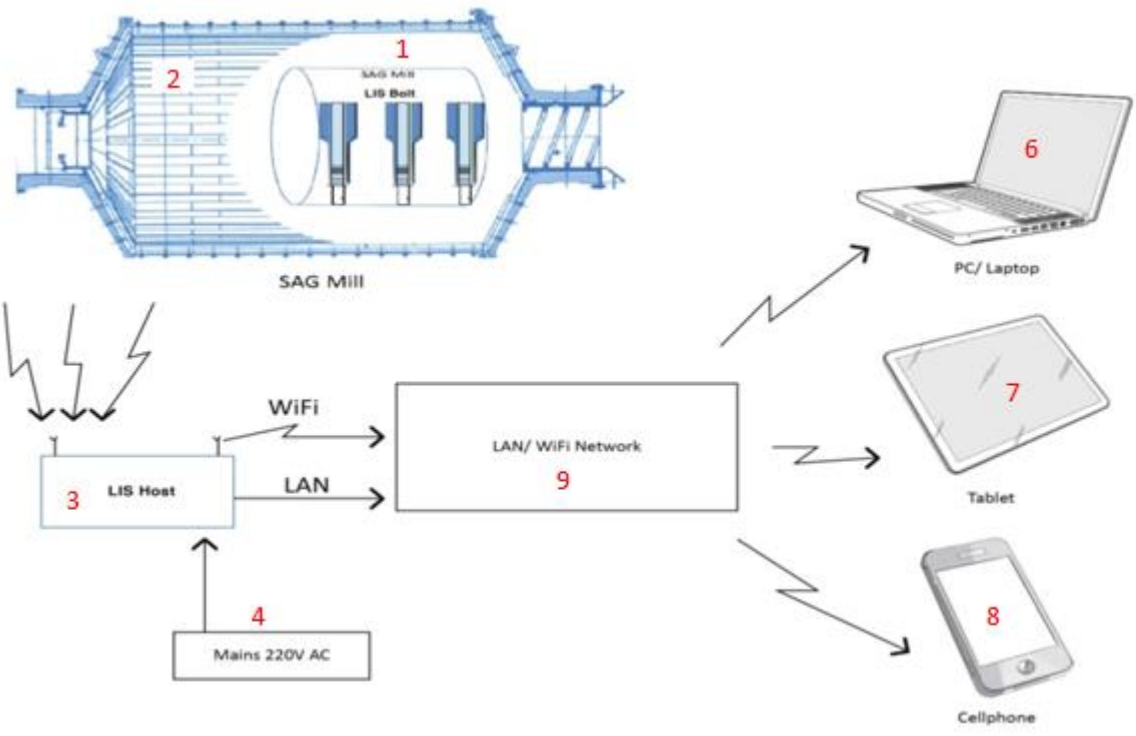


Figure 12: Prime Item concept diagram

The building blocks (sub-systems) are:

- Liner sensors and transponders (1);
- SAG mill (2);
- Host controller (3);
- Mains 230V AC to provide power to the host (4);
- Wi-Fi (mobile Interface) or LAN (hard-wired) TCP/IP network (5);

- Desktop computer (6), laptop or tablet (7) or cellular phone (8) connected to the internet (9).

3.4.1 Liner sensor sub-system concept

The purpose and objectives of the liner sensor shall be to provide an indication of the liner thickness on a continuous basis. The wear rate (rate of change in mm per day / week / month) shall be derived from this information. It shall be required to mount the liner sensor assembly within a liner without modification to the liner. The liner sensor assembly must be able to withstand the impact of the mill content (the mill charge), including abrasive materials, grinding media (metal balls), fluids and corrosive materials while the sensing capability must not be influenced by exposure to these elements while in operation in a mill. Since the sensor is required to be mounted inside a liner during the manufacturing process, or mounted inside a liner bolt, the concept may be described as a sensor assembly with various reducing levels as shown in Figure 13 below.

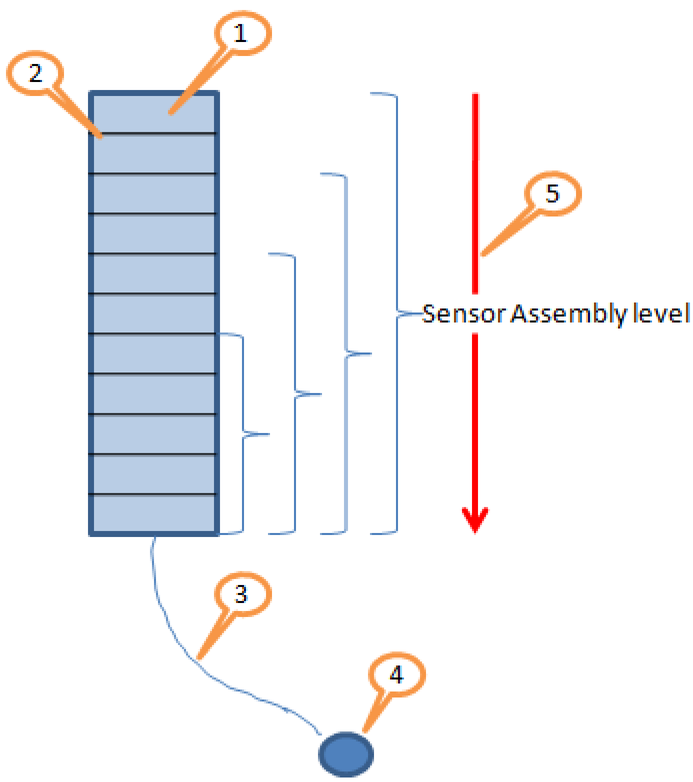


Figure 13: Sensor sub-system concept diagram

Item (1) in Figure 13 suggests a sensor mounting or structure of some sort, on which the sensor elements (2) shall be mounted. A cable (3) or wire shall be required to connect the sensor assembly to a connector (4) which shall in turn be connected to a sensing device to measure the sensor levels. Item (5) illustrates the concept of “levels” which indicate the amount of wear on a liner. The levels shall be reduced as the liner is worn down.

3.4.2 Transponder sub-system concept

The purpose and objectives of the transponder is:

- To interface to a liner sensor;
- To provide a unique identification (ID) number so it can be differentiated from others;
- To provide a function for performing periodic tasks;
- To send real-time change and event notification data to a host;
- To periodically send data to a host such as battery and sensor status;
- To periodically perform self-testing and housekeeping tasks;
- To be able to store measured data in volatile memory until it is able to download to a host. It is not a requirement to store data in non-volatile memory;
- Transmission shall be wireless (RF). No encryption shall be required;
- Receive information and provide acknowledgement thereof;
- To receive updated parameters such as time, date and update the cycle time for automated data transfer;
- To provide an independent power source, no re-charging shall be required.

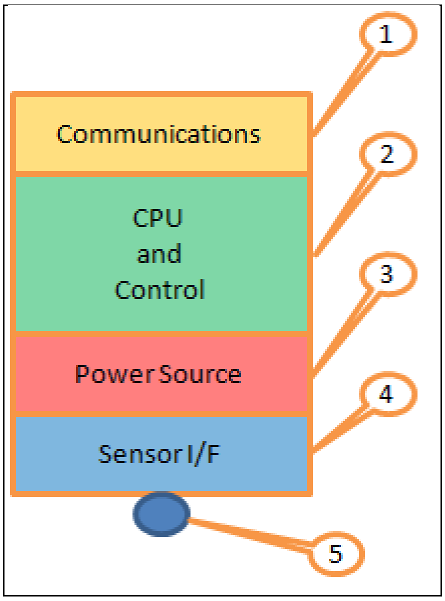


Figure 14: Transponder sub-system concept diagram

Figure 14 shows the major components of the transponder with the functional blocks defined as follows:

- Communications interface (1);
- CPU and control logic (2);
- Power source (3);
- Sensor interface (4);
- Connection to sensor assembly (5).

3.4.3 Host sub-system concept

The purpose and functional objectives of the host shall be:

- To provide a transponder compliant RF transceiver function;
- To receive and communicate information from a number of transponders;
- Transmit updated transponder parameters;
- To provide non-volatile memory for storing transponder data;
- No encryption on transmitted or received RF data shall be required;
- Provide a means to relay transponder data to an internet based client database.

The purpose and functional objectives of the host application software shall be to provide a means for a user to log in and view mill related liner data in real-time. As a minimum, the following data needs to be made available:

- Mill host ID;
- Transponder ID number;
- Transponder battery status;
- Liner thickness (level or mm);
- Liner wear rate (level or mm per unit of time);
- Date and time of measurement.

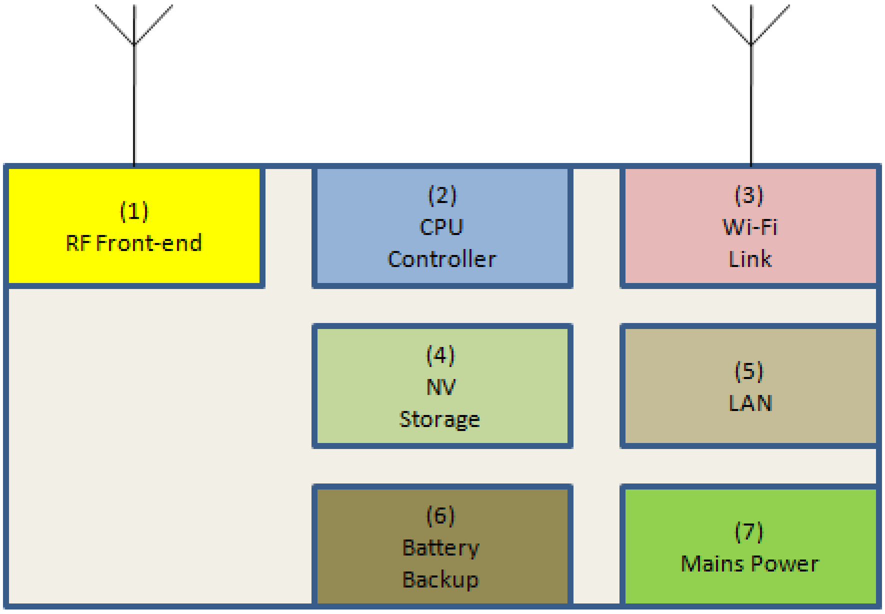


Figure 15: Host sub-system concept diagram

Figure 15 shows the major components for the host. The identified parts are as follows:

- RF front-end with antenna (1);
- CPU controller (2);
- Wi-Fi with antenna (3);
- NV storage (non-volatile memory) (4);
- LAN (5);
- Battery backup (6);
- Mains power socket (7).

3.5 Interface definition

This paragraph defines the interface definition between the sub-systems of the prime item as well as the interfaces between each sub-system and its surroundings. Interfaces are defined as a mechanical interface (MI), electrical interface (EI), communications interface (CI) or a human-machine interface (HMI) (US Department of Defence 1985).

3.5.1 Sensor interface definition

As the liner sensor does not have any requirement for communications and human-machine interfaces, this paragraph defines the interface requirements for the liner sensors' mechanical and electrical interface requirements only.

3.5.1.1 Sensor mechanical interfaces

The sensor shall be an independent item which can, as previously stated in the requirements, be mounted inside the extended head of a liner bolt or be moulded into a polyurethane (or similar compound) liner during its manufacture. The sensor should be customizable in length to accommodate various liners thicknesses. It is required to be a simple process whereby the sensor may be cut to size using simple tools such as a side cutter, knife or the like. The sensor should therefore provide a short loom and connector by which it shall connect to the transponder.

3.5.1.2 Sensor electrical interfaces

The liner sensor shall provide a suitable electrical interface to a transponder so that the liners' thickness may be measured by the transponder. Various sensor techniques were researched and evaluated during the literature study and the suitable electrical interface shall be determined during synthesis of this interface between the sensor and the transponder.

3.5.2 Transponder interface definition

This paragraph defines the interface requirements for the transponder. Interfaces are defined for mechanical, electrical, communications and human-machine interfaces.

3.5.2.1 Mechanical interfaces

It shall be possible to integrate a transponder into a liner bolt or into its own enclosure for exterior mounting to a mill. In instances where it shall be assembled into a liner bolt a potting compound shall be used to secure the transponder into the bolt.

3.5.2.2 Electrical Interfaces

The transponder shall provide a connector for an electrical interface with a single liner sensor.

3.5.2.3 Communications interfaces

The transponder shall interface to the host via an RF communications link; preferably within the (allowable ISM) frequency ranges of 433 MHz / 868 MHz / 915 MHz or 2.4 GHz. The RF transceiver frequency, protocol, bit rate and other communications parameters shall be defined during synthesis.

3.5.2.4 Human-machine Interfaces

The transponder shall provide a means for an operator to view its status. This may be by means of a low power LED or the like. The transponder shall further provide a means whereby it may be activated. It is preferred that activation be performed by way of pulling of an activation pin, the action must be non-reversible. It is further required that the transponder be activated for very short periods of time for periodic testing. This function must be available before and after the pin activation.

3.5.3 Host interface definition

This paragraph defines the Interface definition for the host in terms of its mechanical, electrical, communications and human-machine interface requirements.

3.5.3.1 Mechanical interfaces

The host shall be enclosed in an enclosure which may be mechanically fastened to a wall or structure. It shall be possible to mount the host to the structure without having to open it.

3.5.3.2 Electrical interfaces

The power requirements for the host shall be 230 VAC ± 15%, at 50 / 60 HZ ± 15% at a maximum of 2 A, nominal 500 mA. The host shall be fitted with a mains-power switch and fuse or circuit breaker.

3.5.3.3 Communications interfaces

The host will interface to the transponders using the same RF communications parameters with characteristics as used in the transponders.

The host will interface to the internet using media such as Wi-Fi, IEEE 802.11 (IEEE Standard for Information technology 2012) and 10/100Base-T Ethernet (RJ45) to connect to a TCP/IP network.

3.5.3.4 Human-machine Interfaces

User interfaces such as panel switches, power and status indicators shall be provided. As a minimum there shall be one visible indication for mains power and one separate visual indication of the hosts' status. The status indicator must provide a clear indication if the host is active or dormant.

3.6 Prime item and sub-systems interface definition

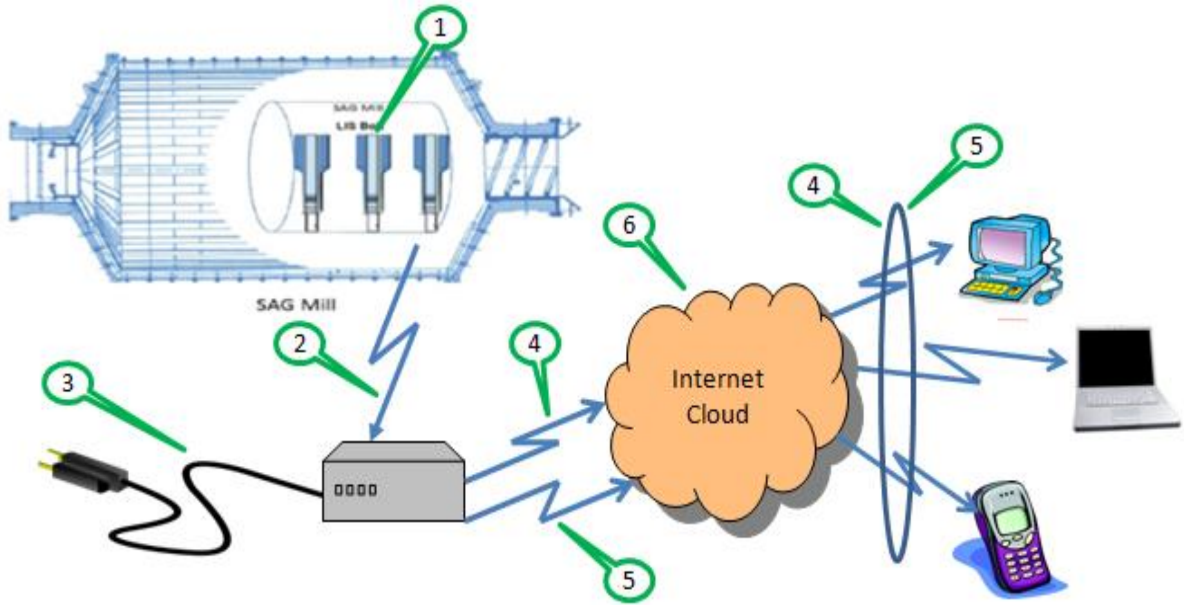


Figure 16: Prime Item and sub-systems interface diagram

Figure 16 shows a concept of the sub-systems interfaces within the prime item configuration. The liner sensors, shown as integrated into a liner bolt in the figure are mechanically mounted and Interfaced with the SAG mill (Item 1). The transponder data is sent to the host sub-system via interface (2) whereas the host sub-system is powered by an interface to mains (Item 3). The host sub-system interfaces with the internet using a Wi-Fi (4) or LAN (5) interface to the internet cloud (6). The user shall then be able to interface to the cloud via Wi-Fi (4) or LAN (5).

3.7 Sub-system functional and performance requirements

This section defines sub-system requirements in more detail. It provides a description of the functions of each sub-system as well as performance parameters as far as possible.

3.7.1 Liner sensor requirements

The sensor to be mounted into the liner is to measure the thickness of that liner in real-time. It shall be required to mount a sensor to a mill liner without modification to the liner or the mill. The liner sensor shall provide as a minimum the following functions:

- Sensor assembly with sensing elements capable of measuring liner thickness;
- The movement of particles inside the mill shall grind these sensing element(s) down and provide an indication of the thickness of the liner bolt, hence the liner thickness;
- A minimum of 42 sense levels shall be provided;

- For the first article development, the Sensor shall be 250 mm in length, with a measurement resolution of at least 2 mm;
- The sensor element shall be mounted inside the rear part of the bolt as indicated in Figure 17 below (Goebel, SAG Mil bolt structure and potential sensor position 2015).

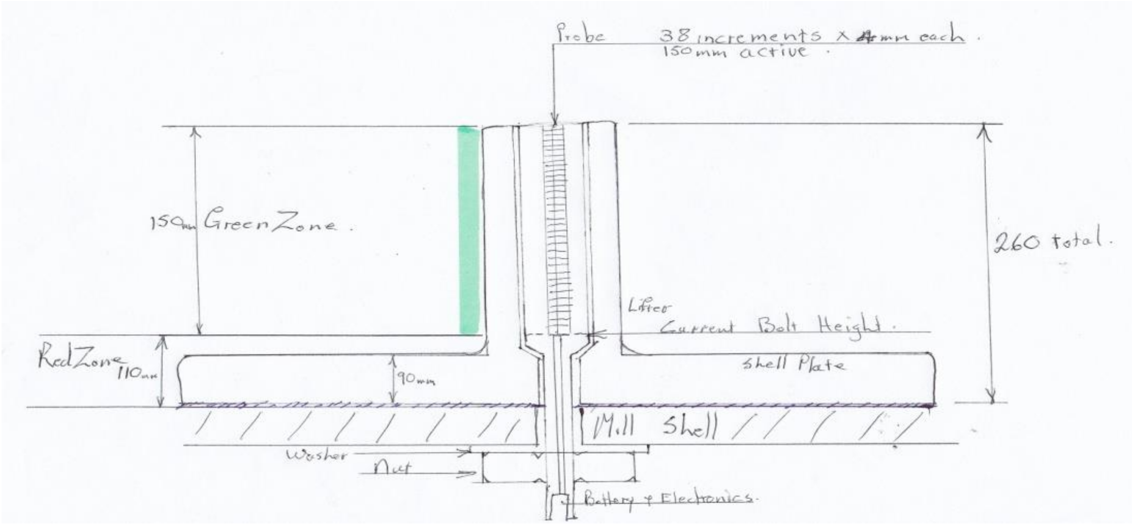


Figure 17: Sensor position in liner bolt

3.7.2 Transponder functional and performance requirements

A transponder is required to interface to the liner sensor and shall monitor any change in sensor length and transmit the information to a host system. The transponder shall be designed in such a way so that it may be mounted inside a specially designed liner bolt (with the sensor mounted into the extended bolt head) or, in the event that the sensor is manufactured within a moulded Liner, it shall be required to mount a transponder to a mill outer shell without modification to the mill. The transponder shall transmit data to the receiving station (host) using wireless technology. As a minimum requirement; the transponder shall provide the following functions:

- Provide its own power source;
- Be able to interface and measure the sensor length;
- Provide an RF communications function to communicate to a remote host;
- Perform self-tests and diagnostics functions on request;
- After activation, the transponder must be able to go to a low power state and only wake-up in the event of a change in sensor level, and periodically send its status to

a host. The periodic interval time must be configurable to a maximum of eight hours;

- The transponder data payload to the host shall include as a minimum, the liner thickness information as well as the transponder battery status;
- The transponder will only be activated once it is fitted to a liner. This shall be a non-reversible state;
- The transponder shall be enabled by pulling a pin (or the like) which shall place it in a permanently activated state;
- The transponder will then be active until the battery runs out or it is destroyed;
- Each transponder shall have a unique ID number which shall differentiate transponders from each other. The ID number may also be used as a serial number for delivery, stock keeping and traceability purposes.

3.7.2.1 Transponder states and modes

The required states and modes for both the transponder and host are explained in the paragraphs to follow. These modes and states shall be used as guideline during the design phase and could be changed as appropriate.

At power up the transponder shall enter a de-activated state. This state shall be the lowest power state of all and only allow for one of two events. The first event is when the sensing of an activation pin causes a start-up or wake-up of the transponder. The second event is a test event causing the transponder to wake-up for a test cycle.

The transponder shall have the following states:

(1) Deactivated state: During this state the transponder shall not be operational. It shall be in very low power consumption state and able to monitor for “test” conditions. After a test was activated and executed the transponder shall fall back into the de-activated state.

(2) Activated state: After activation (pulling the activation pin), the transponder shall be able to perform its allocated tasks in the modes of operation as described below. Once in this mode the transponder shall not be able to fall back into the de-activated state.

The transponder shall have the following modes of operation. These modes shall only be applicable during the transponder activated state. Activation of the transponder shall be by means of a mechanical action such as the removal of a pin or similar. It shall not be required to reverse this state back to the deactivated state. That is, once the transponder was activated it will stay in that state until the battery is depleted.

(3) Start-up mode: In this mode the transponder shall perform on-board start-up and initialisation functions. It shall transmit a start-up message to the host and receive an acknowledgement and possible configuration message from the host. The configuration message may contain information such as:

- Target ID;
- Host ID;
- Housekeeper cycle time.

(4) Sleep mode: In this mode the transponder shall remain in a low power state until a wake-up event occurs. A wake-up event may be one of the following:

- Sensor trigger;
- Housekeeper such as change in battery status, RTC time-out and others.

(5) Event mode: In this mode the transponder shall transmit an event status to the host and go back to sleep.

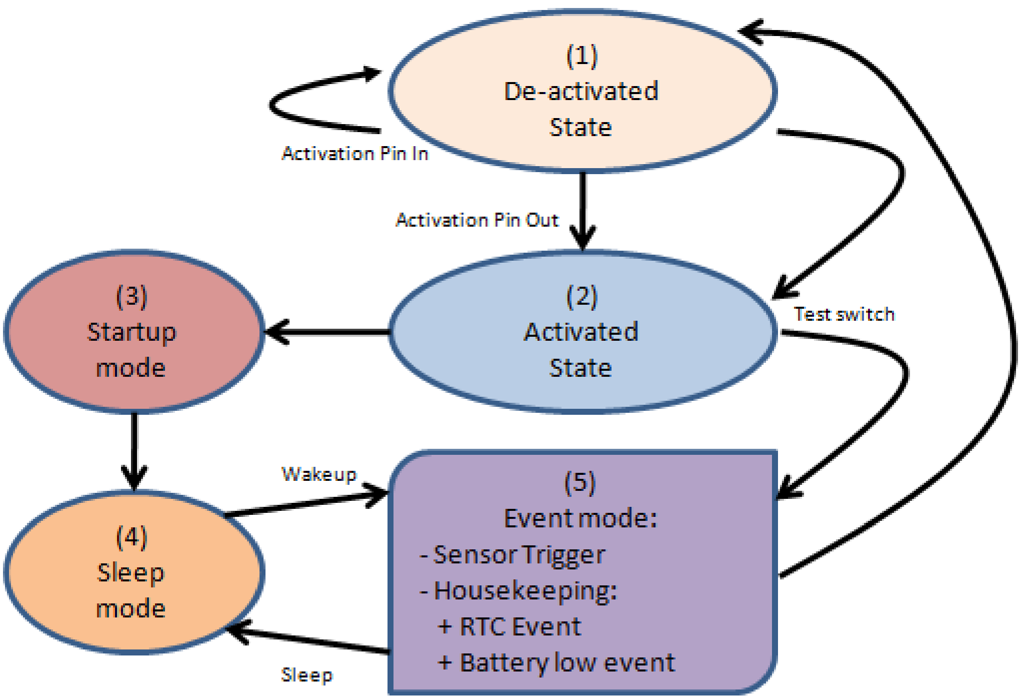


Figure 18: Transponder states and modes

The transponder may be placed in an “extended sleep or coma” by configuring the housekeeper into an extended time-out period. This shall be configurable from the host. This will prohibit a bolt from repetitive sending of data. This may be required for once the bolt is removed from a mill and placed under quarantine, such as when the last sensor element was triggered.

3.7.3 Host functional and performance requirements

The host shall provide a means to communicate to the transponders and translate and forward the information to a remote database for visual interpretation by users. It shall be required to mount a host close to a mill without modification to the mill and limited impact to the mill environment, keeping safety and mine operations into consideration.

The host shall provide a means for a user to visualise and evaluate sensor and transponder information. The user interface shall be simple to use with minimum operator training required.

A host shall provide as a minimum the functions as described in this paragraph. These functions are described on a high level and are only specified in detail where the client specified specific items or performance parameters. Further detail of the implementation is provided during the synthesis phase.

The host shall require a MCU or similar device for managing all the peripherals of the host such as LAN, Wi-Fi, RF interfaces, storage, and others. The MCU shall execute a software application to provide the required functions of the host as described in this document. It shall, amongst other tasks manage the Interface and control of the RF transceiver, communications to and from transponders and perform self-tests and diagnostics functions.

3.7.3.1 Host specific requirements

Following is a list of specific requirements which the host must provide.

3.7.3.1.1 Real-time clock calendar (RTCC)

The host shall be capable of keeping time and date as follows:

- Provide date and time in the format (yy:mm:dd) and (hh:mm:ss);
- Have a minimum of one minute resolution with one second accuracy;

- Enable the periodic sending of sensor and transponder information as configured by the user;
- Be updated and synchronised from a user interface.

3.7.3.1.2 Non-volatile storage

The host shall provide storage capacity to store records from 100 transponders on a monthly basis. This amounts to 9300 records as a minimum calculated as follows:

$$\boldsymbol{R} = \boldsymbol{t} \times \frac{\mathbf{24}}{\boldsymbol{i}} \times \mathbf{31} \quad \textbf{Equation 1}$$

Where:

- R is the number of records;
- t is the number of transponders;
- 24 is the number of hours per day;
- i is the interval period;
- and 31 is the maximum number of days per month.

Therefore, for t = 100 and i = 8, R is calculated to equal 9300 records per month. The assumption is that the host shall at least have the ability to transfer its data content to a cloud server once every month. This is a worst case scenario.

3.7.3.1.3 Wi-Fi

The host shall provide for a slave Wi-Fi connection in accordance with IEEE 802.11 (IEEE Standard for Information technology 2012). This link shall provide a user with a wireless interface to connect to the host. The Wi-Fi link shall be used to transfer data to the internet (cloud based) storage.

3.7.3.1.4 LAN

A LAN port shall be provided to connect to a 10/100 Base-T Ethernet (WG802.3 - Ethernet Working Group 2015). The connection shall be via a standard RJ45 Ethernet socket. The LAN shall be complementary to the Wi-Fi link to enable cloud storage. The Wi-Fi link shall be considered the primary link and LAN a secondary link as it is more complex to provide a LAN cable to the host controller enclosure as it would be to provide a Wi-Fi link.

3.7.3.1.5 Backup battery

A battery shall be provided to fully power the host during power failures for a period of at least 24 hours. The battery shall the charged when mains power is restored.

3.7.3.1.6 Power supply unit

An on-board power supply shall provide adequate power to all the components of the host. The power supply shall be powered from mains 230 VAC ± 15%.

3.7.3.1.7 RF transceiver

A transponder compatible RF transceiver shall be integrated with the host. This transceiver shall transmit and receive data to and from various liner transponders.

3.7.3.1.8 Enclosure

The host shall be mounted in harsh environments where sand, dust and water shall be present. The enclosure shall therefore comply with IP65 (International Electrotechnical Commission 2004) as a minimum. The rating implies that the enclosure shall be “Dust Tight” (I.e. no ingress of dust; complete protection against contact - dust tight. A vacuum must be applied. Test duration of up to eight hours based on air flow and washable by water jets - water projected by a nozzle (6.3 mm) against enclosure from any direction shall have no harmful effects).

3.7.3.1.9 HMI – display, input and output devices

The host shall not be required to provide a keyboard, mouse or a display interface. HMI functions shall be provided by means of the server-client application executed on a cloud based server and accessible from an internet capable device such as a computer station, laptop, cellular phone, tablet and the like. The intent being that no Internet application software is required to execute on the computer device other than a web- server.

3.7.3.1.10 Network server and client

An application client shall be operational on an internet server. The application client shall gather the information from various liner transponder hosts and store the information in a database. The database information shall then be made available to a web-browser application for user display and use.

3.7.3.2 Host states and modes

As depicted in Figure 19 the required host states are defined as:

(1) Power off State: During this state the host shall not be operational.

(2) Power-on reset state: After power on, the host shall be able to perform its allocated tasks in the modes of operation as described below

After power-on (and reset) the host shall be able to perform its tasks in one of the modes as define in Figure 19 on the following page.

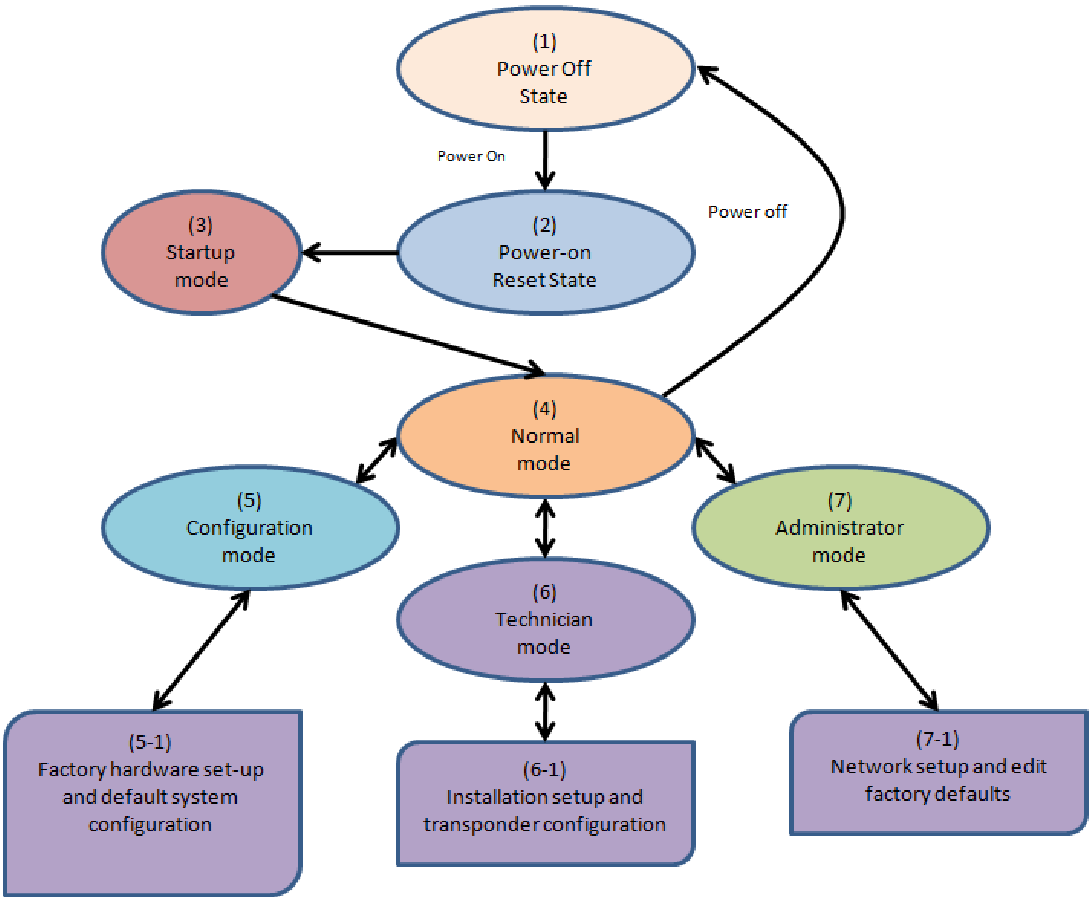


Figure 19: Host states and modes

These modes shall only be applicable during the host power on state. Power on shall be possible when the power button is in the on position with:

- Host connected to a mains power sources and/or;
- Host backup battery is sufficiently charged to power the unit.

All modes shall be password protected. Different modes may require different logins and different passwords. As an example, the administrator mode shall only be accessible for well trained staff with full control over all functions of the system, and technician mode shall be accessible to technicians with limited functions for testing purposes.

(3) Start-up mode: In this mode the host shall perform on-board start-up and initialisation functions. After system start-up, one of the following modes may be entered:

(4) Normal mode: This is the normal mode of operation where host data shall be received, logged, evaluated, and displayed. This mode shall be entered by default after start-up mode and shall remain active until the user enters a different mode.

(5) Configuration mode: This is done during factory configuration and is used for hardware set-up and default system configuration.

(6) Technician mode: This mode shall allow technicians to perform manual testing. The mode shall be used to configure transponder parameters.

(7) Administrator mode: This mode shall allow the user to set network settings and edit default factory settings.

The modes above shall allow, amongst others the following functions:

- Definition and assignment of mills, location and notes;
- The definition of transponder positions on a mill;
- Adding (removing) transponder to (from) a mill;
- Viewing of individual transponder data;
- Addition and removal of logins and assignment of passwords and user rights for viewing, changing or otherwise manipulating system parameters.

3.8 System and sub-system characteristics

3.8.1 Performance

During the deactivated state, the transponder shall not be operational and, within the environmental storage conditions specified in this document, have a shelf life of at least 24 months (2 years).During the activated state and operating conditions as specified in this document, the transponder shall be operational and have a minimum operational life of at least 12 months. The host shall have a non-operational shelf life of at least 2 years and an operation life of at least 3 years. These lifetimes shall be valid under the environmental conditions as defined in this document.

3.8.2 Physical characteristics

3.8.2.1 Weight

The mass of the transponder parts additionally added to an existing bolt shall not exceed 300g.The mass of the host shall not exceed 5 kg. This excludes the weight of cables, fasteners, and other accessories.

3.8.2.2 Dimensions

The transponder dimensions shall be such that the integrated bolt, sensing elements, electronics and battery shall fit within the current dimensions of existing liners. Current bolt dimensions are approximately: 400 mm (length) x 34 mm (diameter).The host shall have maximum dimensions of 500 mm x 500 mm x 500 mm.

3.8.2.3 Transport and Storage

Both the transponders and hosts shall be packaged appropriately to protect the electronics from damage during normal delivery, transport and storage.

3.8.2.4 Durability factors

In all stages of the design it should be considered that the equipment will be operational in a mining environment. The equipment shall therefore be designed to not only be simple and practical to install, configure and operate but also operational inside the harsh mining environment.

3.8.2.5 Health and safety criteria

Both the transponder and host equipment shall be designed to be used in a mining or factory environment (International Electrotechnical Commission 2004).

3.8.2.6 Security criteria

All functions on the system where configuration changes may be made shall be password protected. No specific requirement exists for securing of system data other than standard virus protection, firewalls and what is standard practice at a mining plant. There are no specific design requirements for security.

The scope of development excluded industrialisation and commercialisation. As a result, the requirements below are given for future industrialisation and testing. In the spirit of

DSR, the client's requirements (real-world requirements) are listed to ensure the design of a liner wear measurement system addresses, where possible and within budget, the requirements below. In agreement with the client, and as defined within scope, the requirements below are therefore not formally enforced and were not formally verified.

3.8.2.7 Reliability (Mean time between failures - MTBF)

- The MTBF of a transponder shall be at least twelve months whilst operating within the limits detailed in this specification;
- The host shall have an MTBF of at least twenty four months whilst operating within the limits detailed in this specification.

3.8.2.8 Maintainability (Mean time to repair– MTTR)

- Mean time to repair: transponder – none (throw away);
- Mean time to repair: host – none (throw away);
- Calibration requirements: transponder – none;
- Calibration requirements: host (RTC as example) once every six months or as often as required;
- The transponder shall provide a built in test capability for periodic testing.

3.8.3 Environmental conditions

These paragraphs contain the environmental conditions and requirements for compliance against which the system will be subjected. The characteristic requirements stated from paragraph 3.8.3.1 (Temperature range) to 3.8.3.14 (Fungus) are stated here for the sake of completeness and to show which standards will apply for commercial models.

3.8.3.1 Temperature range

The transponder shall withstand temperatures that vary between 0° C and +85° C. – Working environment and a storage temperature range of -10° C to +85° C (O'Connor n.d.). The host will be operated within an ambient temperature range suitable to humans. The ambient temperature range may vary between -10º C to 55º C.

3.8.3.2 Temperature shock

The transponders and hosts shall not be subjected to temperature shocks greater than 20º C per minute up or down.

3.8.3.3 Solar radiation

The transponders may be subjected to solar radiation as the mill may be situated outdoors. The host shall be mounted inside a distribution box shielding it from solar radiation.

3.8.3.4 Pressure altitude

The system shall operate within specification from sea level to two thousand metres above sea level.

3.8.3.5 Acoustic noise

The transponder shall be subjected to acoustic noise in the following spectrum of a typical SAG mill environment (Spencer, et al. 1999).

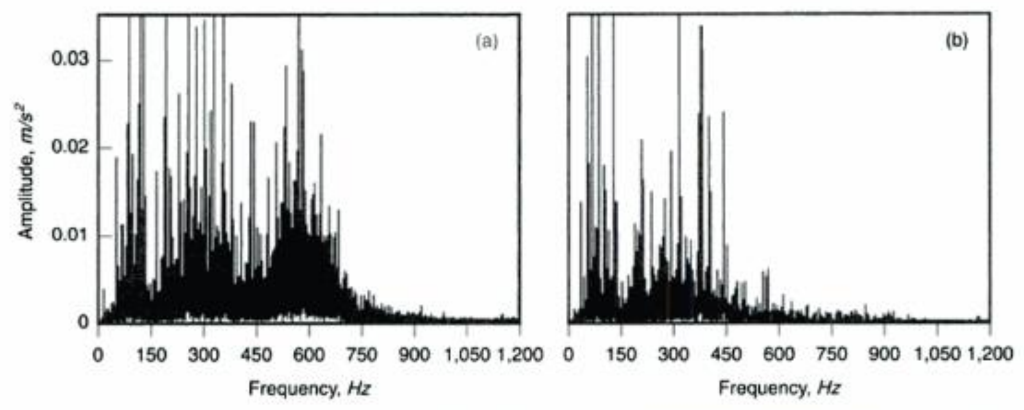
Hosts shall be subjected to the same noise levels with reduced energy of 1/d (where d is the distance in meters, away from the mill) the power emitted from the SAG mill. The host shall be mounted a minimum of five meters away from a mill, thus reducing the noise energy to 1/5th of the noise of the mill. At the point of research the researcher did not believe that there was a requirement to design for and account for acoustic noise. This specification was therefore added here as an indication of what could be expected at a mill should it during the design or testing phases become evident that acoustic noise may have an influence on the building blocks of the system.

3.8.3.6 Shock

The transponder shall be subjected to shocks in the environment as generated by a SAG mill (Kawatra 2006). Hosts shall not be subjected to shock.

3.8.3.7 Random vibration

The transponder shall be subjected to random vibration in the defined spectrum of a typical SAG mill. A typical SAG mill vibration spectrum was measured by (Kawatra 2006) and the spectrum is shown below in Figure 20.



Vibration spectra of the SAG mills: (a) new liner; (b) worn liner

Figure 20: Typical SAG Mill vibration spectrum

The host shall not be subjected to random vibration.

3.8.3.8 Acceleration

The transponder shall be subjected to the acceleration of a typical SAG mill. A typical SAG mil rotates at a maximum rate of 15 revolutions per minute (RPM) and with a diameter of maximum diameter of 42 ft (12.8 m) the expected centrifugal force is calculated to be:

$$\boldsymbol{F = m \times w^2 \times r} \qquad \textbf{Equation 2}$$

Therefore

$$\boldsymbol{F = 9.475\, N\, (kg\, mS^{-2})} \qquad \textbf{Equation 3}$$

Where:

- $m = 0.3kg$
- The angular speed of rotation $\omega = 15\, rpm$ and
- The radius $r = 12.8\, m$

The hosts shall not be subjected to acceleration.

3.8.3.9 Rain

- The transponder shall be subjected to rain and water as per IP65 standard (International Electrotechnical Commission 2004).
- Hosts shall withstand water injection as per IP 65 while fitted inside a distribution box with this rating (International Electrotechnical Commission 2004).

3.8.3.10 Fire resistance

The transponders and hosts shall not be fire resistant.

3.8.3.11 Humidity

- The transponder shall operate within specification when subjected to relative humidity of up to 100 %;
- The hosts shall operate within specification when subjected to relative humidity less than 85 %.

3.8.3.12 Salt fog

The system shall not be subjected to a salt fog environment.

3.8.3.13 Dust and sand

The system shall be subjected to sand and dust as per IP65 (International Electrotechnical Commission 2004).

3.8.3.14 Fungus

The system shall not be subjected to an environment where fungus is present.

3.8.3.15 Transportability

The system shall be transportable by land, air and sea. When transported, the system components shall be packed in bubble wrap plastic (or similar) and a carton box.

3.8.4 Design and construction

3.8.4.1 Materials, processes and parts

Standard materials, parts and processes shall be used as far as possible during the design and construction of all components of the system. No component or part within the product shall be obsolete during the design period. Components shall be selected to satisfy minimum environmental requirements as specified above.

3.8.4.2 Electromagnetic radiation

The equipment shall be designed for low levels of EMI radiation and a low sensitivity to radiated and conducted emissions. No specific testing shall be required although care should be taken during the design to adhere to national standards for radio frequency equipment as regulated by ICASA (ICASA 2005).

3.8.4.3 Nameplates and Product Markings

Each transponder shall be visibly marked with at least the following information:

- Serial number;
- Manufacture date;
- The information shall be stamped onto a flat portion on the thread end of the bolt

Hosts shall be visibly marked with a label containing at least the following information:

- Product name;
- Manufacturer name and logo;
- Connector names;
- Part number;
- Serial number;
- Supplier contact detail (i.e. website);
- LEDs to indicate on/off and status.

3.8.4.4 Workmanship

The following criteria for workmanship shall be inspected:

- Sharp edges;
- Burrs;
- Markings;
- General appearance;
- Uniformity.

The following requirements – interchangeability, safety and human engineering – were agreed upon as being within scope and had to be verified after development. This was done using interface definitions and tests.

3.8.4.5 Interchangeability

The design shall be such that all parts having the same manufacturer's part number shall be interchangeable with each other with respect to installation and performance.

Items bearing the same part number shall have the same overall dimensions, connections, installation and mounting provisions and shall comply with the performance requirements.

3.8.4.6 Safety

The equipment shall be designed so that no materials, processes or parts that might cause hazardous conditions to exist during commissioning, installation and utilisation of the system are used. Mine safety compliance shall be adhered to.

3.8.4.7 Human performance / human engineering

The system shall provide a user interface for performing configuration, operation and maintenance of the system.

3.8.5 Documentation

There is no specific requirement for the generation of documents other than listed in this thesis. Documents generated shall however be controlled in terms of general good practice configuration management in terms of issue and version control, software and hardware version control. Version control and configuration management however were not included as part of this study and the methodology is therefore excluded from this thesis.

3.8.6 Logistics

3.8.6.1 Facilities and facility equipment

A small laboratory was used which comprised of typical equipment required during electronic product development. Equipment included items such as a desktop computer, IDE tools and debuggers, oscilloscope, multimeter, soldering iron and various hand tools. All PC-boards were manufactured and assembled by local South African based PCB manufacturing facilities.

3.8.7 Personnel and training

No specific personnel or training is required since this is a development program for a Masters' thesis. Only one staff member at Southern Cross Trading Africa shall be trained on the use of the system for the purpose of evaluation and testing of the system on-site.

3.9 Quality assurance provisions

3.9.1 General

The system shall be subjected to verification in accordance with the requirements of this section to demonstrate compliance with this specification.

3.9.1.1 Responsibility for tests

The author / designer of the system were responsible for the arrangement and testing of all parts of the system. Where required, an external specialist was requested to perform tests and evaluations. Such evaluation is required at the end of the project phase where the equipment shall be tested on a live SAG mill. An independent geologist report shall be required to conclude the on-site tests.

3.9.1.2 Special tests and examinations

Verification of calibration parameters was performed using commercial off the shelf (COTS) equipment.

3.9.2 Quality conformance inspections

The following verification methods shall be used to ensure quality conformance.

3.9.2.1 Inspection

Inspection consists of a visual inspection of the item or a study of the design documentation inclusive of software code.

3.9.2.2 Analysis

Analysis consists of a theoretical analysis of a requirement or by computer simulations of the design to prove that the requirement has been met. Analysis may also be proven by similarity of design.

3.9.2.3 Demonstration

Demonstration consists of a visual demonstration of the operation of the system to verify a requirement or a basic physical measurement.

3.9.2.4 Test

Test data is reviewed where the measurement of sufficient data is possible to determine the presence of a system capability or characteristic.

3.10 Preparation for delivery

The items to be delivered (transponder and host, fittings, cables and other accessories) shall be packaged suitable for normal road delivery. There are no special requirement for delivery of the transponders or host other than already specified in this document.

The transponder shall be packed securely in boxes or containers to prevent the damage to the electronic parts during transport. The host shall be packaged in separate boxes whereas more than one transponder may be packaged in a single container. The total weight of any container shall however be limited to 10 kg. It is suggested that each part (transponder and host) be packaged using bubble wrap or similar for protection.

3.11 Conclusion

The intent of this chapter was to obtain and organise real-world requirements for a SAG mill liner wear system into a detailed specification in order to assist the client in his overall product development process. The process was also performed in line with the DSR relevance cycle where client inputs and evaluation of the environment (real-world) requirements lead to requirements analyses, the conceptual design of high level building blocks and system boundaries, and finally the definition of performance and quality parameters.

As a result, it was shown that requirements management (common to systems engineering) may be effectively used to support the DSR research process in a structured way.

The contents of this chapter were used as baseline requirements against which the final artefact (system) was developed. In all instances, specifications were discussed with the client and measured against real-world requirements, and where necessary requirements were updated in accordance with researched technologies and concepts. This is in line with the DSR concept of the rigor cycle where a knowledge base is applied to the refinement of concepts and designs as well the grounding of principles and baselines.

The chapter also includes a statement of quality assurance provisions, including quality conformance inspections that clearly state how each requirement is to be tested and how conformance to a defined requirement shall be proven (for the sake of verification and validation).

Finally, the ***research challenges*** that have been identified from the above problem analysis are as follows:

1. Reduce production downtime due to manual liner measurement;
2. Prolong the measurement equipment’s lifespan;
3. Improve on resolution of existing systems;

4. Deal with harsh environments.

The research challenges above will be addressed by means of a literature study, definition of a reliable sensing methodology, as well as design and development of a real-time liner wear measurement artefact. ***Literature research topics*** include the following:

1. Design for harsh environments;
2. Low power design;
3. Sensor solutions;
4. Microcontrollers;
5. Single board computers;
6. Remote measurement;
7. Integrated RF solutions.

Each of the above topics is researched and discussed in the following chapter.

Chapter 4 - Literature study

4.1 Background

This chapter provides research conducted on possible solutions for monitoring the thickness of a liner as described in the preceding chapters. The study was conducted to evaluate and compare different technologies for the most appropriate solution to be used in the harsh conditions as found in SAG mill mining environment.

A number of liner wear monitoring solutions currently exist, all having the same goal in mind, namely to make mill liner thickness and wear rate available to a user (Dandotiya, et al. 2011). All solutions researched have common shortcomings, including (i) not having the ability to monitor a large number of levels accurately, (ii) inconsistency in measurement, and (iii) not being available over a long period of time. Typically, none of the solutions provided more than sixty hours after first activation (Odisho and Heydweiller 2002). The system developed here overcomes these shortcomings, as well as to make data available online and in real-time. This means that an operator has the ability to monitor mill liner wear over the internet on a web browser using a PC, a laptop, cellular phone or any web browser and internet connected device.

In order to achieve these goals, the literature study focussed on the research of the project objectives namely to:

- Reduce production downtime due to manual liner measurement;
- Prolong the measurement equipment's lifespan;
- Improve on the limited resolution of existing systems;
- Operate within a very harsh mining environment.

In order to meet the listed challenges and requirements, the literature study topics to be researched were identified as:

- Design for harsh environment (harsh operational environment);
- Low power design (prolonged lifespan);
- Sensor solutions (improve on limited resolution of existing systems);
- Remote measurement techniques (reduce production downtime);
- Integrated radio solutions.

Each of the topics listed above was researched and evaluated for each building block in order to find the optimum solution for each. An in-depth literature study was performed for each building block in order to derive the best possible solution addressing the system requirements.

4.1.1 Multiple-criteria decision making model

This approach was undertaken using a Multiple-criteria decision-making (MCDM) model (Blanchard and Fabrycky 1998). A score of:

- 3 was given for a parameter which fully complies with the requirement;
- between 1 and 2 was given to a parameter that does not fully comply, but could possibly be accommodated;
- 0 is allocated to a parameter that does not comply with the requirements and cannot be accommodated;
- -1 to -3 implies a parameter is negatively influencing the decision.

The literature study bore in mind technological relevance with respect to the functional units of the system, namely:

1. **Liner bolt sensor:** Evaluation of various and potential sensor solutions adhering to the sensor requirements as stated in Chapter 3 - Problem analysis;
2. **Transponder:** The intent of the transponder is to measure bolt length using the sensor and relay the length and other information to a host system. The required functional units for the transponder are thus as follows:
    - Power supply (source) and power management;
    - Sensor interface;
    - Human-machine Interfaces (such as status LED etc.);
    - Processor with RF front-end.

    These functional units' requirements are described in more detail in the paragraphs to follow. The requirements for each functional unit and their integrated functionality are derived from the system requirements as defined in the previous paragraphs of this document.

3. **Host system:** The host shall have a transponder compatible RF interface for communications between and to the transponders. The host shall require an MCU and peripherals for communications via TCP / IP (wire and Wi-Fi as stated) and

shall be able to store data in non-volatile memory. It is therefore suggested to research and evaluate “single board computer” (SBC) technology for this functional unit.

The requirements stated above, as well as evaluation of the problem statement and subsequent requirements directed this research to literature topics for (i) the “design for harsh environments”, (ii) designing for low power consumption, including research into power sources and power management as well as principles for low power design, (iii) sensor solutions, and research of (iv) processors with integrated RF solutions, and finally (v) a literature study on single board computers. Sections 4.2 to 4.6 summarises the research effort.

4.2 Design for harsh environment

Paragraph 3.8.3 defines the requirements for the system environmental conditions requirements. The test setup, test methodology and test procedures for performing these test are based on the definitions of MIL-STD-810F (US Department of Defence 1 January 2000). These requirements were defined for the sub-system but because of budget constraints could not be tested in accordance with the standards. By means of design, the criteria for harsh environments were addressed in this research. Public papers, articles and notes were consulted in order to properly define “industry” standards and practices for the design of equipment working under harsh environmental conditions. One of these principles is Newton’s principle on mass namely:

$$\boldsymbol{F} = \boldsymbol{m} \times \boldsymbol{a} \qquad \textbf{Equation 4}$$

Where:

- F is the force as a function of its
- m is the objects mass and
- a is the objects acceleration

This states that the force exerted on a mass is proportion to its acceleration. In order therefore to reduce the external forces on an electronic component, one can either reduce its mass, or change the acceleration (a). In the liner sensor equipment case, the acceleration is a given so the only factor to reduce is the components’ mass, hence design was done as small as possible using surface mount components.

Vibration has the effect that it creates standing waves and the effect is that on the crests of the standing waves a peak in exerted force exists on a medium. These crests form in multiples of the vibrating frequency wavelength (i.e. the harmonics of these frequencies). In order to reduce the effect of standing waves, the designer should aim at reducing the size of the product to me smaller than the expected wavelengths and harmonics of vibration. Crucially in the improvement on electronic design is to be able to accurately predict the electronic components behaviour under vibration conditions (Aglietti and Schwingshackl, Analysis of Enclosures and Anti Vibration Devices for Electronic Equipment for Space Applications n.d.). In accordance with Fahlgren (Fahlgren 2013), the use of dampers for vibrations lower than 50 Hz is quite effective and at frequencies higher than 100 Hz becomes less to non-effective. As shown in Figure 20: Typical SAG Mill vibration spectrum, the vast majority of the vibration energy is from 650 Hz down. As indicated by Fahlgren, a good method for reducing vibration and shock stress on electronic components is to introduce stiffeners or a stiffening material. This may be done by the introduction of shock and vibration absorbing materials such as foams or rubber energy absorbing materials. Methods for designing for vibration and shock may be improved by way of using prediction models on electronic components and PCBs. Such prediction models are given by MILD-HDBK-217F (US Department of Defense 1995).

A study by (Aglietti and Schwingshackl, Analysis of Enclosures and Anti Vibration Devices for Electronic Equipment for Space Applications 2004) showed that the hardware failure rate distribution on military aircraft systems is 40 % due to electrical connectors, 20 % due to electronic components, 30 % to cables and harnesses and the remaining 10 % due to other factors. This implies by virtue of the numbers that, in order to reduce the failure rate that the number of cables and connectors are to be reduced in a system. In addition, the design effort and focus on electronic and other components must be increased. The study further implies that cable and wire lengths should be kept to a minimum length and properly fastened.

Designing for water resistance may be achieved by three key steps according to Weiman (Weiman 2012). These steps are based on design experience accumulated over forty years of the Bresslergroup (www.bresslergroup.com) engineers. In the article “Tips on waterproofing components in harsh environments” Weiman explains that the policy should always be to “keep it simple”. He explains that simple geometry, simple parting lines, simple interfaces and stack ups are all best practices. Simple tips for sealing are to start with circles as these shapes are the easiest to seal by using off-the-shelf O-rings and seals. He continues to suggest not to design where sealing is required between three or more parts and to implement proper gasket glands as gaskets “squirting” out of place is a common source of failure. As a last suggestion, parts are to be kept as stiff as possible so that gaskets while under compression do not disturb the gasket glands.

4.3 Low power design

This section focuses on techniques, theories and concepts underlying low power design. It also considers various power sources and, specifically, batteries required to power the transponder. The research also focused on methods to power an electronic device “on” and “off”, as a requirement for the transponder is a mechanism by which to activate the unit using positive action (pulling an activation pin, for example). Finally, low power radio frequency devices are evaluated to potentially meet the transponder and host communications requirements.

4.3.1 Power sources and power management

The transponder power supply must provide efficient power to the transponder at all times. It must further be able to provide adequate current to the transponder and sensor electronics under all conditions. As the transponder must be a self-sustaining unit, the power source requirements are as follows:

- Constant voltage, adequate current source;
- High capacity;
- Small form factor;
- Robust and fit for harsh environments;
- Long life expectancy;
- Low Internal resistance (low leakage).

External power is not an option since the transponder must be self-powered. The options therefore were limited to various types of batteries, solar powered devices and super capacitors. Solar power would not suffice as the equipment must work under all conditions during the day and night. Super capacitors do not provide adequate capacity of energy for prolonged periods of time. A combination of the two technologies may have been an option in outdoor applications, but in many instances mills are located inside an enclosed building and the option was therefore not further researched as a possibility.

The power source of interest was therefore chosen to be high-density batteries. The literature study for batteries focussed on the following types of batteries (MIT Electric Vehicle Team 2008):

- Primary cells or non-rechargeable batteries;
- Secondary cells or rechargeable batteries.

4.3.1.1 Primary cells

Primary cells are commonly known as non-rechargeable batteries. A large number of types exist, a list of a few most commonly used types is provided below:

- Alkaline battery (zinc manganese oxide, carbon);
- Lithium batteries;
- Mercury-oxide batteries;
- Silver-oxide batteries;
- Zink-carbon batteries;
- Zinc-chloride batteries.

In general, primary cells have higher energy densities than rechargeable batteries. Energy density is defined as the amount of energy stored per unit of volume. Therefore a high energy density means more energy is stored per volume (of the battery) than in a lower density battery. This is of high importance in the liner measurement system since size and weight are significant parameters to be considered during the design.

Primary batteries do not function as well under high load conditions as secondary batteries and are therefore more suitable for the liner measurement system's transponder sub-system. All batteries have what is known to be a "self-discharge" effect and rate of up to 20 % per year. This must also be taken into account when deciding on a battery for the system. Generally the self-discharge rate of primary batteries is much lower than that of secondary batteries.

4.3.1.2 Secondary cells

Secondary cells are commonly known as rechargeable batteries. A list of commonly used batteries is given below:

- NiCad batteries (Nickel–cadmium);
- Lead–acid batteries;

- NiMH batteries (Nickel–metal hydride);
- NiZn batteries (Nickel-zinc);
- Lithium ion batteries.

The energy density of secondary batteries is lower than that of primary batteries. Furthermore, the self-discharge rate of secondary batteries is in the order of 10% per month. This means that the battery source for the liner measurement transponders would have to be recharged at a regular interval should this option be chosen.

4.3.2 Low power design principles

Since the sensor and transponder circuits will be battery powered with a defined requirement for a long transponder service life, it was important to design with minimum power consumption in mind. Basic design principles for low power design may be employed in line with results from this literature research. Over the last few decades, miniaturisation of electronic components became a driving factor as a result of global warming and a global requirement to reduce power consumption as a whole. It is therefore important to consider the sources of energy consumption and to provide energy reduction techniques at all levels of design of electronic equipment (Havinga and Smit, Design techniques for low power systems 2000).

According to Havinga, many radio frequency communications protocols are basic adaptations of wired networks and do not necessarily take energy consumption in mind. A first step therefore to reduce energy consumption is to eliminate useless activity of wireless networks. An RF solution with low to zero idle time will therefore assist in lower energy consumption.

A further step in energy reduction is to reduce the amount of data to be transmitted over the RF link. It is also advised to reduce the time between switching RF power electronics on and between transmit and receive modes. It is further suggested by Havinga to implement proper error correction algorithms in order to reduce repeated retry messages of failed data as a result of transmission errors.

In the paper “Design techniques for low power systems” Havinga explains three levels where energy reduction design may be performed namely at system level, architectural level and lastly at technological level. Examples of these are such as compression methods, energy management and scheduling at system level, communication error control, parallel hardware and hierarchical memories at architecture level and clock frequency control, reducing on-chip routing and reducing voltage at technological level.

Further methods of reducing power requirements include reduction of component count, the use of integrated circuits, and hybrid solutions (chipsets with combined computing and RF functionality). It must also be noted that the reduction in number, and even disabling, of clocks and clock domains during idling and sleep modes may significantly reduce power consumption. Reduction in power may therefore be achieved by the reduction in capacitive load, supply voltage, reduction in switching frequency and reduction in circuit activity.

These principles and others described in the paper were all considered during the synthesis phases of the design. In particular attention was focussed on the following aspects of design:

- Reduced component count by way of using hybrid integrated circuits;
- Implementation of clock domains of different frequencies;
- Low power modes and disabling of circuits during idle states;
- Reduction of capacitive loads as far as possible;
- Implementation of efficient RF protocols at the hardware and at software layers;
- Power management by way of switching dormant sub-systems off, and turning them on as and when required, such as the sensing circuit electronics;
- Lowering the system supply voltage to 3 V down and designing for a supply voltage to be as low as 2 V;
- Reducing the data transfer time (increased data throughput, both on computational as well as hardware layers). This means the use of hardware error detection and error correction sub-systems.

4.4 Sensor solutions

The liner bolt sensor required has, as a minimum, the following performance parameter requirements (in no particular order):

- Low cost;
- Small footprint;
- Robust for extreme and harsh environmental conditions (refer to paragraph 3.8.3 - Environmental conditions). Specific focus was placed on shock, vibration and

temperature stability as well as the environmental susceptibility of the sensor to fluids and conductive materials;

- Low conductor count as the sensor leads need to be routed through a liner bolt in such a way as not to reduce the bolt integrity;
- High resolution of sensing capability, in the order of 2 mm increments and less;
- High number of sensing levels, up to 250 mm and more, resulting in 42 sensing levels and more;
- Accurate to each level;
- High MTBF (Mean Time Between Failures), in other words minimum failures expected.

The intent of this study is to compare a number of technologies to meet the above requirements and discuss the fundamentals and operation of the selected sensor technology. Each parameter was scored as described in section 4.1.1 (Multiple-criteria decision making model) and then compared in section 4.4.4 (Summary of sensor evaluation and selection) to have made a final decision.

During the evaluation of the system and sensor requirements, the following sensor technologies and methods for the potential measurement of liner wear were evaluated:

- Conductor or wire loops;
- Resistive sensors;
- Inductive sensors;
- Capacitive sensors;
- Semiconductor sensors.

Each sensor type is described and evaluated in accordance with the Multiple Criteria Decision Making Model (MCDM) principles during synthesis. The summary MCDM values takes into account supporting components required to make the sensor work, that is, for example the number of pull-up / pull-down resistors required. Although not necessarily mounted on the sensor itself, the effects of parameters such as “small footprint” are still a function of the devices’ MCDM scores.

4.4.1 Conductor or wire loops

A wire loop is an electrical conductor (such as a copper or similar wire conductor or PCB trace) within the sensor. In an event that the loop is broken, the current flow is interrupted through the conductor and is detected by an electronic circuit as an "open circuit". By looping the conductors at different levels, it is possible to determine the level at which the sensor is worn down to. Figure 21 (on the following page) indicates the principle:

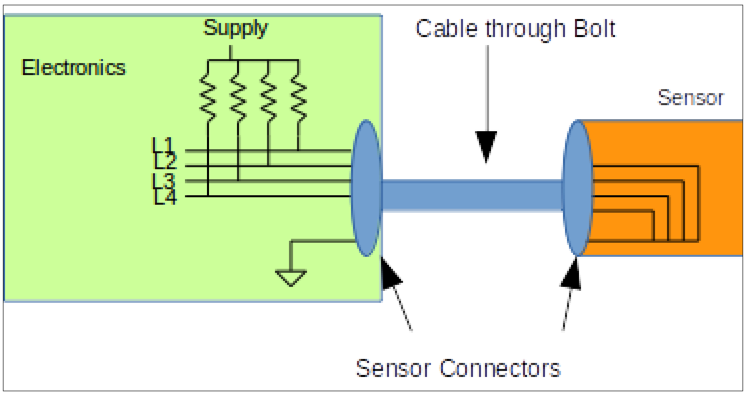


Figure 21: Sensor concept – Conductive loops

In the event that a loop is broken, the current flow in the loop is interrupted and sensed by an electronic circuit.

4.4.1.1 Advantages

The biggest advantage of such a sensor is its low cost and simplicity of implementation.

4.4.1.2 Disadvantages

The conductive loop has a major disadvantage in the number of loops that can be implemented. For each loop it means a separate conductor in the sensor to be connected to the electronic circuitry. Each of these sensor loops need to be connected via a cable (or loom) through the centre of a liner bolt. For a maximum allowable hole diameter of 6 mm the maximum number of conductors is limited to about twelve (assuming a 0.5 mm thickness wire), plus one for the common line.

4.4.1.3 Summary

A summary of the conductive loop parameters and its associated MCDM score is given below (on the following page). The conductive loop technology provides a low cost sensing element with a low number of sensing levels since the conductor count is high for a high resolution sensor.

Two examples of the use of wire loops were found and used to explain the principle. The "System for monitoring in real-time the thickness of a structure (Weakley and Holm, System for Monitoring in real-time the thickness of a structure 1993)" is a system designed to measure the thickness of a mine sill (this is the floor of a gallery or passage in a mine) (Webster 1913). A second example is a patent by (Slater and Langis 2007) for a “System for measuring wear in a grinding mill”.

Table 2: MCDM summary – conductive loop

Parameter		MCDM Score (-3 to +3)
Low cost		3
Small footprint (size)		3
Robustness	Shock resistant	2
	Vibration resistant	2
	Temperature stability	3
	Susceptibility to environment	3
Low conductor count		-3
High resolution (2mm increments)		3
High accuracy		3
High MTBF		3
MCDM Score		**22**

4.4.2 Resistive sensors

A resistive sensor relies on resistive change with varying levels as the physical resistive element is worn down. A typical resistive sensor is a network of parallel resistors where the resistors are worn down by the abrasive mechanism of the mill. A resistor network sensor concept is depicted below.

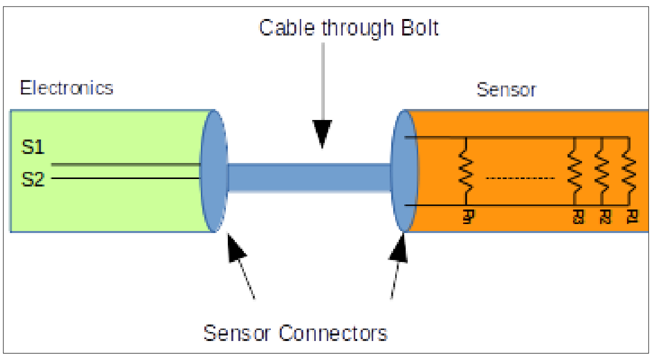


Figure 22: Sensor concept – resistive sensor implementation

The total resistance is the parallel resistance of the network:

$$\boldsymbol{R}_{\boldsymbol{p}} = \frac{\mathbf{1}}{\left(\mathbf{1}/_{\boldsymbol{R_1}} + \mathbf{1}/_{\boldsymbol{R_2}} + \cdots + \mathbf{1}/_{\boldsymbol{Rn}}\right)} \qquad \textbf{Equation 5}$$

Where:

- R_p is the Parallel equivalent resistance
- And R_1 to R_n the resistors in the circuit (*n* being the total number of resistors).

From a mathematical point of view, it can be seen that for each resistor opening (breaking due to abrasive wear) the value of R_p increases towards infinity. This means that the current flow is reduced as the sensor is worn down. This change in current may then be used to determine the sensor level. In order to achieve a good signal to noise ratio, the resistor change has to be in the order of tens of millivolts, implying a smaller network range, in turn limiting the number of levels that can be achieved.

4.4.2.1 Advantages

A resistive network only requires two conductors with a string of resistors configured in parallel. It requires low cost resistors and requires a small footprint. It allows for a very simplistic implementation.

4.4.2.2 Disadvantages

Since the resistor value increases with reduced sensor length, the sensor becomes susceptible to moisture and conductive material content in the mill (such as water, metals – copper, iron etc.). This leads to inaccurate measurements, especially when the resistor network has high impedance (lower levels become more inaccurate).

In order to get to a large number of sense levels, the network needs to have a very low to very high impedance (resistance) range, implying high current to very low current consumption from start to end. It thus results in larger current drawn when the sensor is new and reduced current as the sensor is worn down. This has a significant negative effect on battery life.

A further disadvantage in a sensor network of this kind is the complexity in measuring the resistor wear. It implies an intelligent electronic device, typically an analogue to digital converter (ADC), and a means to calculate the mathematical summation of resistor values versus voltage or current. This implies a microcontroller and ADC combination. In such a case, the ADC needs to continuously monitor the resistor voltage / current and monitor if there is a change in the resistance resulting in constant battery drain, especially when the resistance is still low. In order to reduce current consumption, the processing electronics may be deactivated and activated intermittently to measure wear. This results in a system not being “real-time” in nature. A resistive network sensor is further prone to bad connections (from sensor to electronics) since a bad connection has an impact on the resistor network value, which may lead to false readings.

4.4.2.3 Summary

The table below summarises the MCDM scores for the resistive sensor parameters.

Table 3: MCDM summary – resistive sensor

Parameter		**MCDM Score (-3 to +3)**
Low cost		2
Small footprint (size)		2
Robustness	Shock resistant	1
	Vibration resistant	1
	Temperature stability	2
	Susceptibility to environment	-2
Low conductor count		2
High resolution (2 mm increments)		1
High accuracy		1
High MTBF		2
	MCDM Score	**12**

The resistive sensor is a good sensor for use in applications where the number of levels is limited and the sensor contact to conductive material such as water and metals is limited. The MCDM score of 15 is lower than the conductive current loop element and is thus not a viable option.

Examples of resistive sensor elements include the following:

- Progressive break lining wear sensor (Odisho and Heydweiller 2002);
- Wear sensor patent by (Glowinski 2012) which is a simple resistive sensor principle used to measure the length of a sensor element.

4.4.3 Inductive and capacitive sensors

These sensors have in principle the same operational principle as a resistive sensor, with the exception that the sensing elements comprise either capacitive components or inductive components. In contrast to a resistive sensor, where a DC current is passed through the network to measure a divided voltage, an inductive or capacitive sensor needs an alternating current or current / voltage spike in order to measure its impedance.

In these sensors, the change in phase angle and amplitude thus, impedance of

$$Z = R + jX$$ **Equation 6**

is monitored to determine the change in the sensor level. This can be achieved using a simplistic oscillator circuit and electronics processing circuit to provide an estimated sensor level.

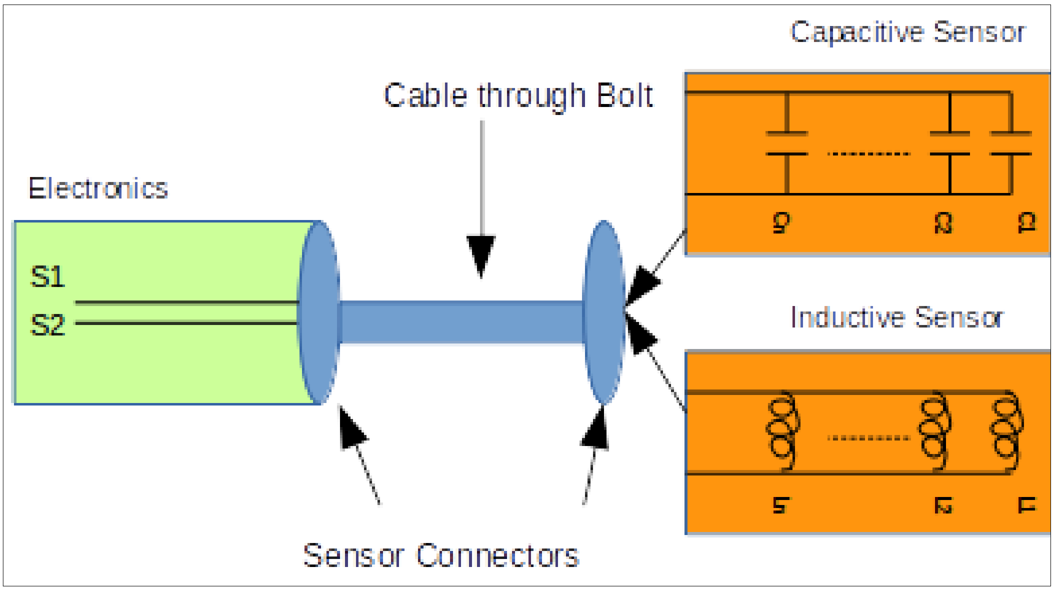


Figure 23: Sensor concept – inductive and capacitive sensor

4.4.3.1 Advantages and disadvantages

Inductive and capacitive sensors provide a low cost solution, but are not very accurate and are prone to error when in close proximity to moisture, liquid and conductive materials. It has a similar advantage as the resistive sensor in that it only requires two conductors (wires) from the sensor to the electronics circuit.

4.4.3.2 Summary

The parameter MCDM scores for inductive and capacitive sensors are summarised in the table below:

Table 4: MCDM summary – inductive and capacitive sensors

Parameter		MCDM Score (-3 to +3)
Low cost		1
Small footprint (size)		2
Robustness	Shock resistant	1
	Vibration resistant	1
	Temperature stability	2
	Susceptibility to environment	-2
Low conductor count		2
High resolution (2 mm increments)		1
High accuracy		1
High MTBF		2
MCDM Score		**11**

4.4.4 Summary of sensor evaluation and selection

Table 5 (on the following page) provides a comparison between the three sensor technologies. From the table it can be seen that the MCDM score for the conductive loops sensor type is the highest. This sensor type is however not feasible for this solution as it requires a vast number of circuits (1 for each loop plus a common) to be routed between a sensing circuit and the loops. It however further outperforms the other sensor configurations by providing the best cost-performance and outperforms all other sensors in terms of number of possible sensing levels, resolution, accuracy, temperature variation and susceptibility to the environment. Although resistive, inductive and capacitive sensors are low cost and relatively simple to manufacture they all lack accuracy due to environmental conditions such as moisture and the presence of conductive materials and are prone to damage due to the harsh environmental conditions they will be subjected to.

Table 5: Summary – sensor comparison MCDM scores

	Conductive Loops (-3 to 3)	**Resistors (-3 to 3)**	**Capacitor / Inductor (-3 to 3)**
Low cost	3	2	1
Small footprint (size)	3	2	2
Shock resistant	2	1	1
Vibration resistant	2	1	1
Temperature stability	3	2	2
Susceptibility to environment	3	-2	-2
Low Conductor count	-3	2	2
High Resolution (2mm increments)	3	1	1
High accuracy	3	1	1
High MTBF	3	2	2
MCDM Scores	**22**	**12**	**11**

None of these sensor technologies offered a final solution to the problem. From these solutions, and by using semiconductor diodes, a hybrid solution was synthesized as briefly described below. Taking into consideration that a diode has a deterministic and predictable forward voltage, a sensor may be constructed using the conductive loop principle combined with a diode so that the sensor characteristics changes as a function of its length. This concept is demonstrated with reference to Figure 24 on the following page.

At start-up, the voltage measured at Vsense will be equal to 0V (the RTN value). A break at position “loop 1” will cause current to flow from Vcc through the series combination of R and D1 (top diode). The voltage measured at Vsense will be equal to the forward voltage drop over the diode (typically 300 mV for a Schottky diode). As the remainder of the loops break, Vsense will increment in multiples of 300 mV as additional diode forward voltages are added. With all loops broken Vsense will be close to Vcc. An intelligent sensor interface circuit may then be used to measure and calculate the actual wear level by measuring voltage levels.

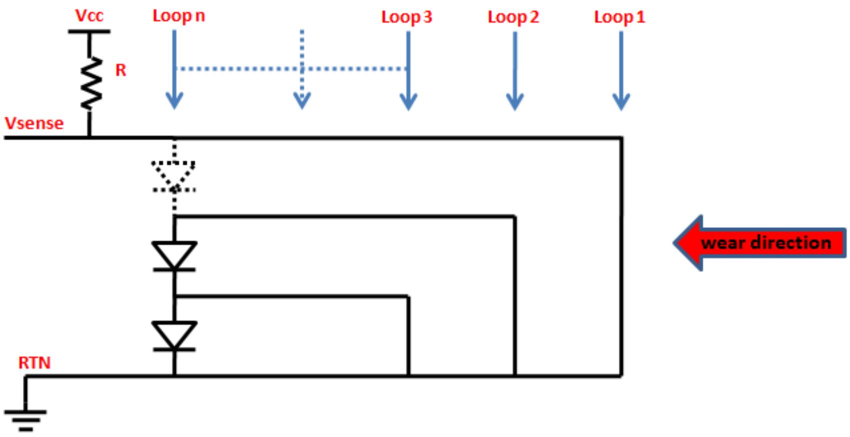


Figure 24: Hybrid diode and conductor loop sensor

More details on the implementation of this concept are provided in Chapter 5. The diodes should be placed on the innermost side of the liner bolt where it is protected from the harsh environment inside the mill and where the abrasion takes place on the liner bolt edge. The conductive loops are then the only elements exposed to abrasion. The surface area of the conductors should be kept to a minimum to reduce the effects of conductive materials inside the mill which could potentially have an influence on the measurement results.

4.5 RF communication devices

A consideration for the RF front-end is the legislation for radiating communications equipment as regulated by ICASA (ICASA 2005) in South Africa. In accordance with South African legislation, equipment radiating RF energy may only do so under strict regulations and rules. These are, amongst many others, the maximum level of RF power transmitted, its duty cycle, and its frequency of transmission. Certain “open” or unlicensed frequencies are provided by ICASA, called ISM frequencies. These frequencies are regularly used for OOK (On-Off Keying – a form of ASK frequency modulation) products and the permitted frequency range is (Apparatus exempt from radio frequency spectrum licences) defined in Annexure B of the (Radio Frequency Spectrum Regulator - ICASA 2015). According to the regulator, the maximum radiated power or field strength limits and channel spacing for the frequency band 433.04 MHz to 434.79 MHz is limited to 10 mW effective Radiated Power (ERP) (EN 300 220). The maximum allowable duty cycle must be less than 10 % (EN 301 489-1 and -3) and no channel spacing is allowed (EN 60950) for ASK, FSK, PSK, & FHSS frequency modulation. At higher frequencies of 868 MHz to 868.6 MHz a power output of 25 mW ERP is allowed at a duty cycle of less than 1 %. The frequency and bandwidth parameters are specified by (EN 300 220), (EN 301 489-1,3) and EN 60950.The choice of frequency can be made by taking into account antenna size, which should be as small as possible, as an antenna at 868MHz is significantly shorter than that at 433 MHz. The RF penetration at higher frequencies is significantly lower and more prone to obstacles than that of lower frequencies (Rysavy 2012). In the case of a mil liner telemetry system, this would not play a significant role as the transponders shall be placed in line-of-sight of the host transceiver.

The RF front-end must power down during sleep periods so that battery life can be preserved. The circuit shall therefore wake-up in a very short period of time, transmit and receive data over the RF link and power down in a short period of time. This short burst in transmission effectively also abides by the small duty cycle limitation of 1%. Frenzel (Frenzel 2010) summarises the most popular RF low power solutions available in chip or module form. These technologies significantly simplify the design of RF capability into products. These include (but are not limited to) the following standards as listed in Table 6 on the following page (Frenzel 2010).

From the table, it is clear that technologies such as NFF, passive RFID, infrared (IR) and all other short-distance communication technologies would not provide a solution to the challenge. Rather, technologies with ranges of more than 10 meter may be suitable. Thus, evaluation of the technologies shown in Table 6 directed this research to Bluetooth, proprietary ISM for factory automation, Wi-Fi and ZigBee (and related XBee and similar) technologies as these are mostly suitable for industrial monitoring and control of equipment. These technologies are further discussed in paragraphs 4.5.1 to 4.5.4

The MCDM parameters according to which the radio frequency technology and device was evaluated, includes (i) cost of the technology, (ii) the availability of the technology (in IC or modular form), the (iii) size of the device (form factor) and (iv) activity levels - in other words the level of communications activity on the frequency channel, if the channel is potentially very busy it may slow data throughput between the transponder and host, and (v) how applicable the technology is to the system in terms of its communications topology(structure) as it has to be capable of a one-to-many (1:m) (or m:m) capability and lastly (vi) how fast the device will be able to send its data to the host after a wake-up from a sleep state. Other parameters such as the communications range and data rate for all devices is well suited and therefore not required for comparison.

Table 6: Wireless technologies for short-range data transmission (Frenzel 2010)

Low-power, short-range wireless technologies for data transmission					
	Frequency	**Max range**	**Max rate**	**Modulation**	**Main application**
Bluetooth	2.4 GHz	10 m	3 Mbits/s	FHSS/GFSK	Cell headsets, audio, sensor data
IR	3.4262 GHz	<1 m	16 Mbits/s	Baseband	Short data transfer
ISM	315, 418,433MHz,902 to 928MHz, 2.4 GHz	10 km	1 to 250kb/s	OOK/ASK, FSK,DSSS w/BPSK/QPSK	Industrial monitoring and control, telemetry
M2M	Cellular bands	10 km	<300 kbits/s	GSM/EDGE, CDMA1xRTT	Remote facilities monitoring
NFC	13.56 MHz	<1 m	106 to 848kbits/s	ASK	Credit card, cell-phone transactions
Proprietary ISM	433.92MHz / 868MHz / 900 to 928MHz, 2.4 GHz	Several km	1 kbit/s to2 Mbits/s	DSSS, BPSK/QPSK	Industrial and factory automation
RFID	125 kHz, 13.56,915 MHz	<2 m	<100 kbits/s	ASK	Tracking, shipping
60GHz	60 GHz	10 m	3 Gbits/s	OFDM	Video, backhaul
UWB	3.1 to 6 GHz	10 m	480 Mbits/s	OFDM	Wireless USB, video
Wi-Fi	2.4 and 5 GHz	100 m	100+Mbits/s	DSSS/CCK, OFDM	WLAN

ZigBee	2.4 GHz	100 m	250 kbits/s	OQPSK	Monitoring and control, sensor networks

4.5.1 Bluetooth

Streaming audio, sending data or broadcasting information between devices may be done on various radio frequency devices. Bluetooth® is such a platform and defines two basic standards in doing so. There is Basic Rate/Enhanced Data Rate (BR/EDR) and Bluetooth Low Energy (BLE).A Bluetooth core system comprises, as a minimum, of a host and a primary controller and may include none or more secondary controllers (Bluetooth SIG 2016). Bluetooth wireless technology can be viewed as a low-power, short-range technology for communicating personal, handheld and portable device data. Bluetooth technology is steered by the Bluetooth SIG foundation since 1998 (Chatschik 2001). Bluetooth enables personal devices to connect wirelessly and establish bidirectional communications directly between them without the need for communications infrastructure other than the personal devices. It can be seen as a communications bubble that follows people around and empowers them to connect their personal devices with other Bluetooth enabled devices as they enter another bubble. Connectivity in this bubble can involve several devices of various computing power and may be short-lived as devices may enter and leave spontaneously without requiring a permanent connection (Chatschik 2001).

Bluetooth may be seen as the replacement of wires and cables between devices such as mobile devices and earphones, a computer and mouse, keyboard, and others. Traditional systems required cables and connectors with specific mechanical and electrical characteristics to connect, whereas Bluetooth has a flexible, universal and reconfigurable radio interface permitting several personal devices to connect. The connections may be *ad hoc*, meaning different people may connect devices in a group without having to rely on infrastructure to establish the connections.

Bluetooth was established by Ericsson, IBM, Intel, Nokia and Toshiba in 1998 by forming what is known as the Special Industry Group (or SIG) which had its focus on establishing, developing and promoting a global solution for short-range low-power wireless communications in the ISM unlicensed 2.4 GHz frequency band.

Bluetooth communications therefore take place in a networked manner in the two forms described above. These network topologies are described in paragraphs 4.5.1.1 (BR/EDR) and 4.5.1.2 (BLE) below.

4.5.1.1 Basic Rate/Enhanced Data Rate (BR/EDR)

This technology enables point-to-point (1 to 1) communications between devices and is ideally suited for applications such as audio streaming to wireless headsets, speakers and hands-free car systems.

4.5.1.2 Bluetooth Low Energy (BLE)

This technology allows for short-burst wireless connections. A variety of network topologies for different applications are provided. These are Bluetooth point-to-point (P2P), broadcast and mesh network topology.

Bluetooth LE P2P was designed for short range one-to-one (1:1) device connectivity for devices such as cellular phones, personal health monitors and wrist mounted fitness trackers.

The Bluetooth Broadcast network topology allows one-to-many (1:m) device connectivity and is therefore ideal for localised information sharing such as beacon solutions. These are also intended as short range networks.

Bluetooth Mesh topology (Mesh Working Group 2017) is ideally suited for larger networks on a many-to-many (m:m) communications principle such as in building automation and asset tracking where many devices need to securely and reliably communicate with each other. Bluetooth Mesh topology is a potential platform for connecting the liner sensor transponder to the host controller since its m:m capability makes it an ideal wireless sensor network (WSN). WSN is designed to be reliable, scalable and secure in industrial wireless sensor network solutions (IWSN) (Bluetooth SIG 2016). Although the technology is best suited for a mesh environment it is also suited for point-to-point communications. BLE defined as a power class 1 device (Bluetooth SIG 2016) has an output transmitter power of up to 20 dBm or 100 mW, suggesting a large communications range of at least a kilometre line of sight. This means that a BLE Power Class 1 device shall be capable of meeting the communications distance requirements.

It must be noted that Bluetooth Low Energy and in specific mesh model specification was only officially released by the SIG in July 13 of 2017. This technology was therefore unfortunately not available during the initial research and development of the project and will most certainly be researched as a possible future improvement of this product.

4.5.1.3 Conclusion on Bluetooth technology

Evaluation of Bluetooth confirmed that this technology is potentially well suited for the requirements of the system. The technology, especially BLE, has many advantages that would make it a perfect candidate for the solution. One of these advantages is the fact that many transponders may be able to successfully transmit their data to a host using the mesh capabilities within BLE by not necessarily transmitting directly to a host but by way of the mesh structure and message bouncing between nodes (transponders). Since the transmission time frame or window is relatively small for a transponder to communicate its message, the mesh network is well suited where transponders can be defined as “friends” and passing messages on their behalf to a host, either directly or via other “friends”.

Table 7: MCDM matrix for Bluetooth technology

Parameter		Notes	MCDM Score (-3 to +3)
Cost		Relatively affordable in IC form	2
Availability of technology		BLE was only available from 2016 after the system design was completed	-3
Form factor (size)		Small, chip sizes from 5mm x 5mm	2
Activity level		BLE allows many-to-many connections inside a bubble	2
Conformance to the system requirements	Many to one topology	1:m, 1:1 and m:1. point to-point and mesh and combinations available	3
	Reaction time after sleep	Once connected, does not have to reconnect and immediately starts to communicate after a wake-up.	3
		Total MCDM Score	**9**

The BLE technology was not fully supported during the synthesis of the liner measurement system and not readily available for implementation. However, future development may *include the use of BLE, but as a reliable and established solution was required at the time of development, an alternative had to be sourced.*

4.5.2 Proprietary RF communication devices

Many suppliers of radio Frequency devices offer devices with “Proprietary communications” capabilities. This means that the product, in some cases, includes hardware building blocks in the form of an RF front end, a modulator-demodulator (MODEM) and in some instances “packet handlers” as well as error correction and detection building blocks. These building blocks may then be used by developers to implement their own or “proprietary” protocols. This allows for flexibility in the implementation and complete control of events. This is an especially handy feature when designing for low power as the developer has complete control over how and when the RF front end, the MODEM and other building blocks are powered on and off, and how data transmission, handshaking and message retries are managed. The customised protocol has a further advantage over industry standard protocols in that the data payload may be reduced to the absolute minimum since the protocol only has to implement the products’ specific functions, and not necessarily cater for a “generic” pool of functions as required for industry defined protocols.

A proprietary protocol has a shortfall in that the developer has to define, implement and test the custom protocol, including error detection and correction, network security and so forth which are all time consuming and more costly activities than what is required for development in many cases.

Once completed, a proprietary solution is bespoke and addresses specific requirements of an application, which often allows for flexibility and reduced overheads in terms of computation, storage and communication.

4.5.2.1 Conclusion on Proprietary RF communication devices

From Table 8 below (on the following page), it is clear that a proprietary solution scores very well on most criteria, apart from the activity level criterion. However, the communication activity of a proprietary solution on a specific channel can be controlled and customised to suit the application.

Table 8: MCDM matrix for Proprietary RF communication devices

Parameter		Notes	MCDM Score (-3 to +3)
Cost		Relatively affordable in IC form	2
Availability of technology		The technology is readily available from various manufacturers.	3
Form factor (size)		Small, chip sizes from 5mm x 5mm	3
Activity level		A proprietary protocol may be developed to support a many to one system with limited channel occupation.	0
Conformance to the system requirements	Many to one topology	1:m, 1:1 and m:1. point to-point and mesh and combinations available	3
	Reaction time after sleep	Once connected, does not have to reconnect and immediately starts to communicate after a wake-up.	3
		Total MCDM Score	**14**

4.5.3 Wi-Fi

Wi-Fi or formally known as devices based on the IEEE 802.11 standards, is a set of media access control and physical layer specifications and is a trademark of the Wi-Fi Alliance (Wi-Fi Alliance 2017). These specifications define the implementation for wireless local area network (WLAN) computer communications. Wi-Fi standards are maintained by the Wi-Fi alliance (www.wi-fi.org) a world-wide network of companies striving to make Wi-Fi the most widely used and valued wireless communications technology.

Three major Wi-Fi technologies are used namely “Wi-Fi Agile Multiband” which aims at facilitating devices to better respond to changing networks, “Wi-Fi Vantage” which aims at larger and more densely populated and dynamic environments, and “Wi-Fi Home Design” which focuses on the integration of smart home products. All three Wi-Fi technologies support direct and persistent connections and provide platforms for mainly streaming of data at high bit rates. These platforms are therefore widely used for devices requiring persistent data flow such as required for video and audio communications.

Although Wi-Fi has the ability to transfer data between sensors and devices, it is probably not best suited for such applications which require bursts of data in smaller packet sizes. Once a connection to a Wi-Fi network has been lost, a reconnection process is required, resulting in non-persistent (such as low power devices which go into low power or sleep states) devices requiring more power and active time to re-establish connections before communication can take place, which in turn is a major drawback for low power systems.

Wi-Fi, although theoretically sound and practical for larger areas and high bandwidth, requires significantly more power than competing low power technologies. The protocols are also defined and the standard does not allow for significant change, hence limiting the use of Wi-Fi to telecommunications type applications as opposed to low power telemetric applications.

4.5.3.1 Conclusion on Wi-Fi devices

From Table 9 below, it is clear that Wi-Fi does not provide a viable solution to the challenge.

Table 9: MCDM matrix for Wi-Fi devices

Parameter		**Notes**	**MCDM Score (-3 to +3)**
Cost		Relatively affordable in IC form	-1
Availability of technology		Wi-Fi is available from many manufacturers and is widely used.	3
Form factor (size)		Small, chip sizes from 5mm x 5mm	1
Activity level		Allows for many users by making available a number of channels.	3
Conformance to the system requirements	Many to one topology	1:m, 1:1 and m:1. point to-point and mesh and combinations available	3
	Reaction time after sleep	Once connected, does not have to reconnect and immediately starts to communicate after a wake-up.	-3
		Total MCDM Score	**6**

4.5.4 ZigBee

ZigBee, also defined as an IEEE 802.15.4 based specification, implements communication protocols for personal area networks (PANs) using small and low power radio devices and is managed by the ZigBee Alliance (Zigbee Alliance 2002). ZigBee is used for networks such as in home automation and data collection for medical devices that do not require high data rates and is operated on a small – such as a local or personal – network scale. The specification requires line-of-sight communication between devices and its range is limited to typically between 10m to 100m. The range can however be extended in a mesh formation keeping in mind the low data rate will result in delays for messages passed over an extended network.

ZigBee utilises frequency bands at 784 MHz, 868 MHz, 915 MHz and 2.4 GHz with data rates of 20 Kb/s for sub GHz frequencies and up to 250 KB/s for the 2.4 GHz transceiver. ZigBee is well suited for sensor networks, but was designed with static networks and line-of-sight communications in mind (home and building automation, industrial control and others), and not for mobile environments.

4.5.4.1 Conclusion on ZigBee devices

Table 10 below shows that ZigBee is not well-suited to the robust environment as required in this project.

Table 10: MCDM matrix for ZigBee devices

Parameter		Notes	MCDM Score (-3 to +3)
Cost		Relatively affordable in IC form	-3
Availability of technology		The technology is only available from one manufacturer having propriety rights of the technology	3
Form factor (size)		Small, chip sizes from 5mm x 5mm	-2
Activity level		Allows for limited connections due to limited bandwidth and channels.	2
Conformance to the system	Many to one topology	1:m, 1:1 and m:1. point to-point and mesh and combinations available	3

Parameter		Notes	MCDM Score (-3 to +3)
requirements	Reaction time after sleep	Once connected, does not have to reconnect and immediately starts to communicate after a wake-up.	-1
		Total MCDM Score	**2**

4.5.5 Conclusion on RF communication devices

The RF Communication devices MCDM parameters and scores summary is shown in Table 11 below.

Table 11: Summary MCDM scores for RF technology

Technology	Notes	MCDM Score (-3 to +3)
Bluetooth	Technology not available during development	9
Proprietary RF	Custom structure makes it flexible and adaptable to the system requirements	14
Wi-Fi	Busy network, slow to connect after sleep	3
ZigBee	Bulky form factor, slow to connect after sleep	2

It is clear from the comparisons that power consumption, control over system characteristics, and cost played significant roles in decision making, resulting in Proprietary RF being the most suitable candidate.

The technology mentioned in sections 4.5.1 to 4.5.4 may be implemented as standalone devices (only radio frequency device), or integrated into a microcontroller. The above sections summarised the hardware and communications layers and did not take into consideration other requirements of the liner wear measurement system such as the requirement to interface to the sensor. In order to comply with the remainder of the functional requirements, a microcontroller shall be required. Taking into consideration the design challenges such as designing for low power, it becomes necessary to use as little as possible and more integrated circuits as best suited to minimise component count (harsh environment) as well as for low power design consideration (extended battery and operational life). It is therefore required to look at radio microcontroller solutions with built-in radio frequency devices and peripherals suited to comply with the system requirements.

4.5.6 Processors with integrated RF modules

In terms of the user requirements, the unit must have a very long mean time between failures. This implies a long battery life with associated low power consumption to meet physical / size constraints. A further deciding factor on choosing a processor is the availability of on-board resources, which implies the use of fewer components. Such a feature will not only lead to a reduction in component cost but will add value to a design that must comply with harsh environmental requirements, particularly in terms of the shock and vibration spectrum requirements.

A processor was therefore required to provide at least the following on-board resources:

- CPU core to execute the required software procedures;
- Flash to store and execute the application software;
- RAM to store and process variables required by the application software;
- Oscillator(s) for CPU and peripherals;
- Watch dog timer (WDT) to restart the CPU on code or other unforeseen errors;
- Analogue to digital converter (ADC) – measures battery voltage and sensor levels and potentially on-board temperature(not a requirement however);
- Comparator to measure a change in the sensor level;
- Power saving modes during rest states, such as a “sleep” function;
- Timers for timing of power-on/off events and others;
- Flexible IO pins capable of input / output and open drain functions;
- Proprietary RF communications interface for communication between the device and a remote host;
- Development and debug interface(s) for ease of development, programming, fault finding and debugging.

Processors from different manufacturers were researched to find a suitable candidate. An important consideration that had to be factored in, was the availability of development tools, compilers, device programmers and an integrated development environment (or IDE) providing debug and evaluation capabilities. These may be costly tools and would certainly have an impact on the cost of development. It is a prerequisite that the IDE must be C-language and object orientated as the author of the software is well familiar and experienced with the languages.

The following manufacturers were evaluated:

- Nordic semiconductors;
- Silicon laboratories (SiLabs);
- Texas instruments.

These manufacturers were selected based on the list of processor requirements given at the beginning of this section and an evaluation of available products with potential to meet the requirements of this project. The sections that follow provide a detailed discussion on each identified processor. Scoring in terms of the MCDM approach is included in order to identify an appropriate solution. In the assessment of processors for the transponder and host transceiver, MCDM scoring was done according to the following parameters:

- Available on-board processor peripherals that address functional requirements;
- Availability of development kits for the processor to speed up development time and reduce risk;
- As this development was self-funded, the availability of free or open source tools and software;
- Availability of industrial grade components for implementation of a robust solution for this harsh environment.

The selected manufacturers' processors provide a variety of functions, but the following parameters were considered essential for this system (derived from requirements):

- The processor must be able to operate in the temperature range between -10° C to +85° C and be able to work off a power supply voltage between 2 V and 3.6 V;
- Since the CPU will be working off a primary cell and the sensor supply can be no lower than 2 V, the supply may not be lower than 2 V but may be higher than 3.6 V (although not required);
- The processor shall have as a minimum the following built-in peripherals:
  - Program memory (16 Kbyte minimum), data memory (2 Kbyte minimum);
  - RF front-end (within the required frequency range and bandwidth) with built-in modem and packet handling capability for assembling, detecting, and validating (receiving) data;

- ADC, 8 bits minimum, sample rate of at least 1 Ksps;
- Timers (minimum of 2) and a watchdog timer;
- Power saving (low power or sleep) modes;

- It must be possible to develop, integrate, debug and perform on chip using an ICE or debug tools. This is a requirement in order to simplify software development and reduce development risk, effort and time.

The functions of each processor were scored and compared to other processors in order to identify the most suitable processor regarding technology and ease of development.

4.5.6.1 Nordic Semiconductors MCU

Nordic semiconductors provide a range of processors with the required peripherals on-board. Data sheets and further information on these products may be found at http://www.nordicsemi.com/ (Nordic Semiconductor 2018).

Nordic supports this processor with development tools for software development in assembler and C. More specifically, the nRF24LE1 (Nordic Semiconductor 2010) chip was evaluated since it provides features which meet with the transponder and host requirements. Product highlights and MCDM scores for the nRF24LE1 are:

Table 12: Nordic nRF24LE1MCDM matrix

On-board and other Functions	Available / specification	Notes	MCDM Score (-3 to +3)
CPU core	8bit 8051 compatible	up to 12 times faster than 8051	2
Program Flash	16Kbyte program + 1Kbyte NVRAM		3
Data RAM	1Kbyte		1
Oscillator(s)	On-chip oscillators	Various power modes	3
ADC	12 bit	16 kbps / internal reference	2
Analogue comparator	1	standby with wake-up function	3
Power savings modes	Standby / sleep	2.5μA standby mode	2

On-board and other Functions	Available / specification	Notes	MCDM Score (-3 to +3)
Timers	X 3 + RTC + WDT	Wake-up sources	3
Flexible IO pins	In / Out and Open drain	High Drive / Sink capability	3
RF front-end	2.4GHz transceiver	up to 10dBm and 1 Mbps	3
IDE, ICE and Debugger	Built-in hardware debugger	ICE and IDE available. Keil ISD51 in-system debug monitor and µVision2 debugger available at extra cost.	-3
		Total MCDM Score	**22**

Notes:

The nRF24LE1 is generally a good selection for a processor since it adheres to most of the requirements. The processor however lacks an on-board program flash and an analogue comparator. A further requirement is a development environment which is provided by Keil ISD51 in-system debug monitors as well as a Keil µVision 2 debugger (Keil C51 Development Tools 2017). This environment has to be purchased and therefore introduces a cost element to the development.

Nordic and other suppliers do provide development kits which may be used during evaluation of the processor.

4.5.6.2 Texas instruments

Data sheets and further information on these products may be found at: www.ti.com (Texas Instruments 2017). As for the remaining manufacturer devices, Texas Instruments provides a wide range of RF capable devices that could potentially meet the requirements for the liner wear sensor transponder. The author has therefore performed a pre-study on the available devices and selected the product with the highest probability of meeting the transponder requirements. The selected device is the CC1310 SimpleLink™ Sub-1 GHz ultra-low power wireless microcontroller, product highlights and MCDM scores are given in Table 13.

Table 13: Texas Instruments CC1310 MCDM matrix

On-board and other Functions	Available / specification	Notes	MCDM Score (-3 to +3)
CPU core	ARM® Cortex® -M3	CoreMark® Score 142 ULPBench™ Score 158	3
Program Flash	128Kbyte		3
Data RAM	20Kbyte		3
Oscillator(s)	On-chip oscillators	Various power modes	3
ADC	12 bit	200 kbps with internal reference	3
Analogue comparator	2	standby with wake-up function	3
Power savings modes	Standby / sleep modes	700 nA sleep mode RTC enabled	3
Timers	X 4 + RTC + WDT	Wake-up sources	3
Flexible IO pins	In / Out and Open drain	High Drive / Sink capability. constant current source	3
RF front-end	315, 433, 470, 500, 779, 868, 915, 920MHz ISM and SRD	up to 15 dBm and 50 kbps	1
IDE, ICE and debugger	Built-in hardware debugger	ICE and IDE available at no cost. XDS200 USB Debug Probe at extra cost.	1
		Total MCDM Score	**29**

Notes:

The CC1310 processor from Texas instruments is another very good processor and accordingly achieved the second highest MCDM score. Its demise is unfortunately the low data rate of 50 kbps as well as high cost for the in-circuit debugger and programmer. The development tools are free of charge and readily available for download over the internet. Texas Instruments and other suppliers further provide development kits for evaluation of their products.

4.5.6.3 Silicon Laboratories (SiLabs)

Data sheets and further information on these products may be found at: www.silabs.com (Silicon Labs 2017). Amongst other wireless products, the best fit processor for this project is the SiLabs Si106x/8x wireless MCU family (Silicon Laboratories Inc. 2013). A pre-study of these microcontrollers was performed and the best device was selected according to the highest MCDM score, as may be seen below. The successful device was the Si1060 as it provided the highest Flash memory and RAM capacity, covered the required frequency band as well as provided adequate RF power levels. Product characteristics and MCDM scores for the Si1060 are:

Table 14: SiLabs Si1060 MCDM matrix

On-board and other Functions	Available / specification	Notes	MCDM Score (-3 to +3)
CPU core	8bit 8051 compatible	25 MIPS peak throughput	3
Program Flash	64 Kbyte		3
Data RAM	4 Kbyte		3
Oscillator(s)	On-chip oscillators	Various power modes	3
ADC	10 bit	300 kbps with internal reference	3
Analogue comparator	2	standby with wake-up function	3
Power savings modes	Standby / sleep modes	600 nA sleep mode RTC enabled	3
Timers	X 3 + RTC + WDT	Wake-up sources	3
Flexible IO pins	In / Out and Open drain	High Drive / Sink capability	3
RF front-end	142 MHz to 1050 MHz transceiver	up to 20 dBm and 1 Mbps	3
IDE, ICE and debugger	Built-in hardware debugger	ICE and IDE available. µVision2 debugger available at extra cost. Keil ISD51 in-system IDE and debug monitor at no extra cost.	3
		Total MCDM score	**33**

Notes:

The SiLabs Si1060 MCU achieved the highest MCDM score. The development tools are free of charge and available for download over the internet. SiLabs offers a free Keil development IDE licence for users of their products, which makes this an attractive option for low cost research and development projects. However, a Keil µVision 2 debugger (Keil C51 Development Tools 2017) has to be purchased but fortunately is a low cost item that is readily available. SiLabs and other suppliers also provide Si1060 development kits which may be used to evaluate the device.

4.5.6.4 Conclusion on integrated RF devices

The MCDM scores for the comparison of the MCUs with Integrated RF solutions are summarised in Table 15. The SiLabs Si1060 MCU is very flexible and is supported with tools, support and design examples for development. The SiLabs solution has flexible IO and on-board peripherals available and is therefore a very good choice to be considered for this project.

Table 15: Summary – MCDM scores for transponder MCU

Manufacturer	MCDM Score (-3 to +3)
Nordic Semiconductor	22
Silicon Laboratories (SiLabs)	33
Texas Instruments	29

The SiLabs device is available in a development kit for ease of development. An RTOS51 (Real-time operating System) is available for the SiLabs MCU to be considered for software development.

4.6 Host system

Sections 4.4 and 4.5 explained and provided information on the building blocks of the liner sensor and the transponder unit. The host system is required to interface to the transponder via a similar and compatible Radio Frequency Interface (RFI) link as that of the transponder unit using the same technology for compatibility purposes.

The host system however requires additional capabilities in the management, storage, and display of transponder and liner sensor information. The research performed on the host system focused on the selection of components and building blocks to fulfil the computational, storage and web communication requirements as the RF building block and interface have been defined in the transponder technology selection above.

The host system requires a component which would easily integrate with the MCU and RFI circuits used in the RF interface. Further requirements for the host system, traceable from the user requirements, can be summarised as follows:

- CPU core capable of execution of host system software;
- Operating system capable of hosting a server and TCP stack as the host is required to provide information to an internet based client for storing and display liner data;
- TCP or network connection such as Wi-Fi or other to connect to the internet;
- Storage medium for temporary storage of liner data until it is uploaded to a web client or data base;
- Real-time clock and calendar for tagging events with time and date.

Amongst different available options, the Raspberry Pi 2 and 3, BeagleBone and Freescale IMX.6 single board computers were researched for application as host controller. Smaller computer solutions such as Microchip PIC, Arduino and the like were not evaluated due to their limitations in processing power, program and data storage size limitations.

4.6.1 Raspberry Pi 2 and Pi 3

These low cost devices were developed and are supported by the Raspberry Pi foundation of which further information may be found at www.raspberrypi.org. The Raspberry Pi 3 device is a the latest version and is based on a BCM2837 (https://www.broadcom.com/), ARMv8 Cortex A53 quad-core cluster processor from Broadcom offering a Linux based operating system called Raspbian (based on Linux Debian, optimized for the Raspberry Pi hardware).

The hardware design, operating system (OS), and peripheral drivers are open source, meaning that all the hardware designs, software code and information are made publicly available. It further means that the device is understood and simple to operate and support is available, should it be required.

There is no need for costly compilers and development tools as all that is needed to use and program the device is open source and available for download from various sources off the internet.

The device is powered by a 5 V / 2 A power supply. The Pi allows USB interfaces for a keyboard and mouse, and provides an HDMI output for digital video to a monitor.

Software is developed using C or C++ for which the on-board GNU GCC compiler may be used. Detailed information on the GNU-C compiler may be found at https://gcc.gnu.org.

The hardware supports an external connector with a serial UART interface, I2C and discrete IO. The Raspberry Pi 3 provides Bluetooth and Wi-Fi wireless communication interfaces as well as an Ethernet connection for a local or word wide web connection.

Figure 25: Raspberry Pi 3

4.6.1.1 Advantages of the Raspberry Pi 3

The following advantages are provided by the Raspberry Pi:

- Low cost, readily available;
- Simplistic to operate;
- Open source hardware and software, Linux OS;
- Simple GNU GCC C/C++ compiler;
- Small footprint, low power device;
- Provides for all hardware interfaces required to interface to a transponder interface;
- Allows for easy software integration and internet connectivity to implement a server, capable of transferring data to a web client.

4.6.1.2 Disadvantages of the Raspberry Pi 3

After analysis, the following disadvantages became evident for the Raspberry Pi:

- The device does not have a hardware real-time clock calendar, it requires a backup battery to hold clock data alive;
- An external RFI is required to communicate to the Liner sensor transponder;
- It does not have on-board flash storage and boots from a solid state disc (SD) card which could lead to inconsistent boot-up, failures, and intermittent program execution in environments where noticeable vibration (or acoustic noise) is present;
- Since the SD card contacts may be corroded by acidic or other chemical substances the housing would need to be sealed properly to reduce the risk of contamination with substances (gasses) which may be present in a mining environment.

A summary of the Raspberry Pi MCDM parameters and scores is given in Table 16 (on the following page):

Table 16: Raspberry Pi 3 MCDM matrix

Parameter	Available / Specification	Notes	MCDM Score (-3 to +3)
Cost	Affordable	Readily available	3
CPU core	Quad core ARM	1.2 GHz Broadcom 64 bit CPU 1 G RAM	3
Operating system	Raspbian	Debian-based Linux OS	3
Network connection	LAN / Wi-Fi / Bluetooth		3
Storage	SD Card	Both Operating System and Data	1
RTC	Not available	Loads from Network Time Server	-3
		Total MCDM Score	**10**

4.6.2 BeagleBone Black

Similar in functionality to the Raspberry devices, these low cost devices were developed and are supported by the BeagleBoard.org foundation. Further information may be found at www.beagleboard.org.This mini computer's hardware is based on the AM3358 ARM™ Cortex-A8 Sitara processor form Texas instruments. Information on the processor may be found at http://www.ti.com/product/am3358.The processor is equipped with a single ARM core, two additional real-time processing units, a 3D graphics engine, and additional functions such as a 24 bit LCD interface and touch screen controller. It furthermore includes an HDMI video output to a monitor, a single master USB port, and a single USB "On the Go" (OTG) port.

An advantage this device has over other single-board computers of this class is that it has adequate on-board Flash memory and RAM to host an operating system. It comes standard with a Linux based operating system configured using a board support package that makes it operational on the BeagleBone hardware. Since it is Linux™ based, software may also be written and compiled using POSIX™ based software drivers and the GNU C compiler and tool chains.

Figure 26: BeagleBone Black

4.6.2.1 Advantages of the BeagleBone Black

The following advantages are provided by the BeagleBone:

- Although a bit more expensive than the Raspberry Pi 3, it is still low cost and readily available;
- Simplistic to operate;
- Open source hardware and software, Linux OS;
- Simple GNU GCC C/C++ compiler;
- Small footprint, Low power device;
- Provides for all hardware interfaces required to interface to a transponder Interface - a host module required however with RFI;
- Allows for easy software integration and internet connectivity to implement a server, capable of transferring data to a web client;
- On-board eMMC flash for operating system;
- External SD card interface for storing data – should it be required. Data may be stored more safely on on-board eMMC flash.

4.6.2.2 Disadvantages of the BeagleBone Black

Disadvantages of the BeagleBone include the following:

- The device does not have a hardware real-time clock calendar, it requires a backup battery to hold clock data alive;

- An external RFI is required to communicate to the liner sensor transponder;

A summary of the BeagleBone Black MCDM parameters and scores are given below:

Table 17: BeagleBone Black MCDM matrix

Parameter	Available / Specification	Notes	MCDM Score (-3 to +3)
Cost	Affordable	Readily available	2
CPU core	Cortex-A8 + Dual PRU	1 GHz clock	3
Operating system	Linux based	Debian-based Linux OS	3
Network connection	LAN	Fast Ethernet (MII Based)	3
Storage	4 GB NAND Flash and 512 MB DDR3 RAM	SD Card slot available for additional storage	3
RTC	Not available	Loads from Network Time Server	-3
		Total MCDM Score	**11**

4.6.3 NXP (Freescale) IMX6

The Freescale devices were developed and are supported by NXP. More information may be found at www.nxp.com. The IMX6 series of application processors are feature and performance scalable multi-core platforms that include single-, dual- and quad-core families based on the Arm® Cortex® architecture, including Cortex-A9, combined Cortex-A9 + Cortex-M4 and Cortex-A7 based solutions.

A variation of single-board computers exist which utilize the IMX6 processor. One such board is the ConnectCore 6 system on chip (SoC) from Digi. The ConnectCore 6 is an ultra-compact and highly integrated system-on-module solution based on the NXP/Freescale i.MX6 Cortex-A9 processor family.

The Digi ConnectCore 6 may be hosted onto a single-board computer such as the Digi SBC baseboard (CC-WMX6-KIT), by Symmetry Electronics, which enables a user to create proof-of-concept designs.

This solution is significantly more expensive than the Raspberry Pi and BeagleBone solutions.

Figure 27: ConnectCore 6 IMX.6

4.6.3.1 Advantages of the ConnectCore 6

The following advantages of the ConnectCore 6 are listed:

- Real-time clock calendar, with backup battery to hold clock data alive;
- Simplistic to operate;
- Open source operating system, Linux Debian and others;
- Simple GNU GCC C/C++ compiler;
- Yocto project provides capability to add or remove lower level board drivers;
- Provides for all hardware interfaces required to interface to a transponder interface;
- Allows for easy software integration and internet connectivity to implement a server, capable of transferring data to a web client;
- On-board eMMC flash for operating system, adequate space available to store project data.

4.6.3.2 Disadvantages of the ConnectCore IMX.6

The ConnectCore 6 has the following drawbacks:

- The device has a larger footprint and is a higher power device;
- The hardware is not open source (proprietary with less support);
- It is a costly device, making it an unlikely host solution;
- Although available, the IMX.6 is relatively difficult to procure, a limited number of suppliers keep these devices in stock;
- An external RFI is required to communicate to the liner sensor transponder.

The summary of the ConnectCore 6 MCDM parameters and scores is given the Table 18 below.

Table 18: IMX.6 MCDM matrix

Parameter	**Available / Specification**	**Notes**	**MCDM Score (-3 to +3)**
Cost	High cost	Readily available	-3
CPU core	4 x Cortex-A9 multi-core	1.2 GHz clock	3
Operating system	Linux based OS	Debian-based Linux OS	3
Network connection	LAN / Wi-Fi	1 Gbit Ethernet + IEEE 1588 802.11a/b/g/n:	3
Storage	64GB EMMC Flash and 2GB DDR3 RAM	SD Card and other external Interfaces (SATA etc.) available for additional storage	3
RTC	Available + WDT	Can also load from Network Time Server	3
		Total MCDM Score	**12**

4.6.4 Conclusion on host processor selection

The MCDM scores for the potential host processors are summarised in Table 19 on the next page. Both the BeagleBone Black and Raspberry Pi 3 are good candidates for the system. The characteristic in favour of the BeagleBone Black is on-board Flash from where the operating system executes. This factor reduces the risk of a system stalling or acting in an unpredictable manner. The system will operate on a mining plant in remote distances and requires reliable operation and low maintenance.

Table 19: Summary – MCDM scores for the host processor

Manufacturer	MCDM Score (-3 to +3)
Raspberry Pi 3	10
BeagleBone Black	11
ConnectCore IMX.6	12

4.7 Conclusion

This chapter focussed on available technology to be used in solving the design challenges as outlined in Chapter 3. In particular, sensor solutions were researched including conductive loops, resistive, inductive and capacitive sensor configurations. For the sensor solution, it was concluded that the best option was a combination of conductive loops and semiconductors (or diodes). In such a manner the best of both technologies could be employed in that conductive loops are small, robust and of low cost and the diode combination provided immunity to environmental conditions and provides a stable, accurate and reliable measurement method.

Research into communications devices concluded that an MCU with an integrated RF solution will be the most practical and that a proprietary protocol will be most suited to address the requirements for low power, high speed and reliable communications under harsh conditions.

Finally, the literature study focussed on finding an adequate solution for a host MCU and in particular a small and robust platform that is easily programmable for internet connectivity. The BeagleBone Black single board computer was selected for its functional capability, low cost and ease of use. Although the BeagleBone Black does not have all the required capability, it was found to be best suited to use as a host controller.

Chapter 5 – Synthesis and system integration

This chapter focuses on the design and implementation of building blocks of the liner wear measurement system. In particular, designs of the following building blocks are described in detail:

- Liner bolt sensor;
- Transponder electronics;
- Host electronics;
- Host server and client software (web interface / browser).

5.1 Liner bolt sensor

Existing conductive loop sensors may be improved upon by using semiconductor diodes to address the shortfalls of a purely conductive loop sensor. The hybrid sensor (referred to as a "semiconductor" sensor) philosophy of operation has been introduced in the literature study, and is expanded upon in the sections that follow.

5.1.1 Hybrid semiconductor-conductor principle

As described in section 4.4.4, the hybrid semiconductor sensor is a sensor implemented by the series and parallel combinations of low voltage Schottky diodes and conductive loops. The sensor works on the principle that a Schottky diode has a predictable forward voltage under constant current and temperature conditions. When arranged in a specific configuration, diode voltages will be incrementally added when shunt circuits (or conductor loops) across specific diodes are broken due to wear. The major drawback of a conductive loop sensor is addressed by the hybrid solution in that the large number of lines to be measured is reduced, and only the forward voltage drop across a series combination of diodes is measured by a measurement circuit. Figure 28 below provides more clarity on the hybrid approach. The specific value at which the forward voltage rises every time a next level is reached is not that important, since a comparator may be used, with a similar diode and divider network to set a reference voltage on the comparator. Once a break occurs, the diode forward voltage will rise to more than half that of the reference value and cause a change in comparator output state. An ADC may further be used to measure the resultant forward voltage and then calculate the level reached as a function of forward voltage and the known characteristics of a Schottky diode. The sensor interface design is shown in Figure 31.

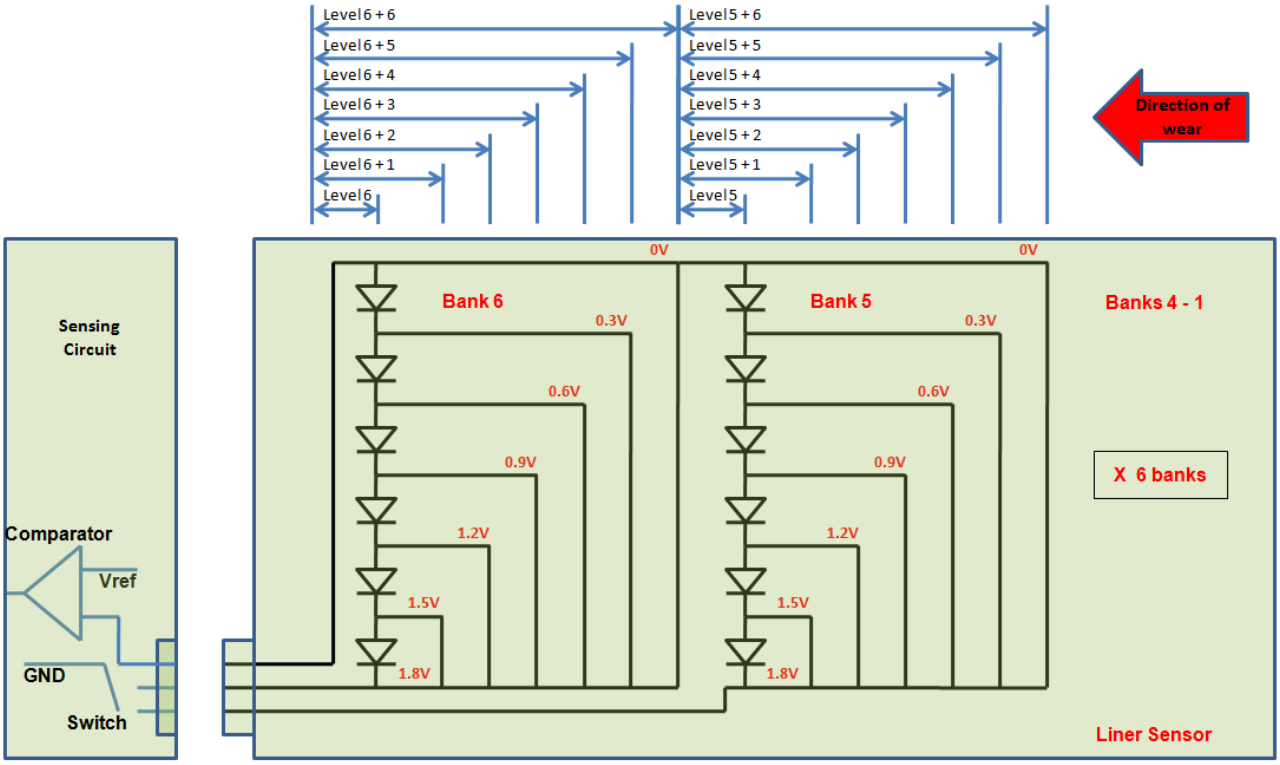


Figure 28: Sensor concept – Hybrid semiconductor sensor

In order to perform a comparison with existing sensors as discussed in the literature study (refer to Chapter 4 - Literature study), a critical evaluation of the hybrid semiconductor sensor is provided below.

The hybrid semiconductor sensor has the following advantages:

- Small footprint for easy fitting in small to very large bolts and other sensing bodies;
- High repeatability in terms of dynamic characteristics (i.e. as lines are broken over time);
- Good resolution, providing an almost continuous wear rate indication;
- Robust and not affected by moisture or conductive materials, liquids or chemicals;
- Self-calibrating, therefore providing the best possible accuracy in level sensing, over prolonged periods of use;
- High reliability due to its packaging and inherently predictable nature;
- Sensor size may be adjusted by cutting the sensor to required length. The system determines the starting length at activation;
- Stable under varying temperature conditions.

5.1.1.1 Disadvantages

The following disadvantages have been identified:

- The hybrid sensor has slightly increased cost in comparison with resistive and purely conductive loop sensors;
- The sensor employs slightly more complex electronic circuitry required to measure the sensor levels.

The disadvantages shown above are not prohibitive and were found to be acceptable by the client in light of the advantages discussed prior to this section.

5.1.1.2 Summary

The semiconductor sensor and transponder combination potentially offers the best sensor solution for this project. It is a relatively low cost solution, providing real-time and online liner wear rate and levels. Levels are reported instantly as the liner level is reduced. In order to perform a like-for-like comparison, an MCDM matrix similar to the matrices in Chapter 4 is drawn up for the semiconductor sensor in Table 20 below:

Table 20: Hybrid semiconductor compatibility matrix and MCDM score

Parameter		**MCDM Score (-3 to +3)**
Low cost		2
Small footprint (size)		3
Robustness	Shock resistant	1
	Vibration resistant	1
	Temperature stability	3
	Susceptibility to environment	3
Low conductor count		2
High resolution (2mm increments)		3
High accuracy		3
High MTBF		3
MCDM Score		**24**

Table 21: All sensors compatibility matrix and MCDM scores

	Conductive Loops (-3 to 3)	Resistors (-3 to 3)	Capacitor / Inductor (-3 to 3)	Hybrid (-3 to +3)
Low cost	3	2	1	2
Small footprint (size)	3	2	2	3
Shock resistant	2	1	1	1
Vibration resistant	2	1	1	1
Temperature stability	3	2	2	3
Susceptibility to environment	3	-2	-2	3
Low Conductor count	-3	2	2	2
High Resolution (2mm increments)	3	1	1	3
High accuracy	3	1	1	3
High MTBF	3	2	2	3
MCDM Scores	**22**	**12**	**11**	**24**

From Chapter 4 - Literature study, where research was performed on different sensor options and possibilities as summarised in the first three columns to the left in Table 21 above, it was decided to implement the hybrid semiconductor sensor in the form of series and parallel combinations of Schottky diodes. A comparison of all scores, including the last column for the hybrid semiconductor solution, is given in Table 21 for clarity.

The hybrid semiconductor sensor meets the sensor requirement in that up to 42 levels at a 2 mm spacing interval can be achieved. More levels may be implemented by adding a single common reference wire to a second sensor bank and placing the return switch lines in parallel. In such a way, many signal banks may be cascaded to produce higher resolution. This principle is discussed further in the synthesis sections below.

5.1.2 Implementation considerations

The sensor headroom voltage is defined as the voltage difference between a fully functional battery and the minimum voltage at which the sensor must still be operational. For practical reasons a CR123A / 1400 mAh Lithium (or non-rechargeable) battery was chosen as power source. These are 3 V batteries and since they are made of lithium, the terminal voltage does not drop significantly when the battery is drained. In order to ensure a safe margin, headroom of 1 V was chosen to make sure the sensor works as intended. The headroom of 1V was further chosen as 2 V is the minimum voltage at which the transponder MCU can safely operate. At 1 V adequate current may be provided to the series diodes of the sensor. At 1 V it is furthermore possible to generate a suitable reference voltage for a comparator circuit to determine any sudden change in voltage (in the event of a broken loop due to liner wear).

Based on the above facts as well as the known characteristics of the chosen diode, the BAT54 is used for implementation of the sensor circuit. For this diode to be effective and to provide a constant (and stable) forward voltage (Vf), a minimum current of approximately 300 uA was chosen. This value was chosen in accordance with the prime item specification since the sensors are to be battery operated with an operational life of twelve months. In other words battery life and hence circuit current is to be taken into account. The lowest practical current to voltage ratio on the graph was therefore used resulting in a battery of 1400 mAh capacity to last between 400 and 450 days.

Signal to noise ratio on the measurement of diode forward voltage was not factored into the calculations since the sensor is to be mounted within a metal liner and metal SAG mil, therefore no (negligible small amounts of) electromagnetic radiation (susceptibility) is expected as well as the fact that the power source is a stable DC battery inducing negligible low levels of noise. It is evident from the design that relatively large spikes of over 300 mV could have an adverse effect on the sensor making it largely immune to local environmental electromagnetic interference.

5.2 Transponder electronics

As defined by the product requirements and researched during the literature study, the required building blocks for the transponder to be designed were:

- Microcontroller;
- RF device;
- User functions such as an LED status indication, and an activation cord;
- Power supply (source) and power management;
- Sensor interface.

For the purpose of synthesis, the requirements for the transponder are broken down in smaller functional units described in the paragraphs below.

5.2.1.1 Microcontroller Unit (MCU)

The MCU shall be capable of performing the following functions:

- Measure the sensor assembly;
- Manage all the peripherals of the transponder assembly;
- Run a software application to provide the required functions of the transponder;
- Interface and control of the RF transceiver;
- Manage communications to the host receiver;
- Perform self-tests and diagnostics;
- Go to a low power state and only wake-up on the following conditions:
    - At first time power up after installation;
    - In the event that a sensor level was triggered.

At programmable RTC events, the transponder will communicate and transfer its status and sensor data to the host. The RTC will typically be configured to wake-up and transfer its status to the host once event every eight hours.

5.2.1.2 Real-time clock

The RTC will have a minimum of one minute resolution with one second accuracy. The RTC must allow for periodic transmission of transponder status to the host as configured by the host. It will be possible to update and synchronise the RTC from the host.

5.2.1.3 Battery supply

The transponder will provide its own on-board battery. The battery must be connected to the electronics during storage. The electronics will be kept in a low power consumption state. It will not be able to disconnect the battery since the electronics and battery will be enclosed in an epoxy or resin material.

5.2.1.4 RF transceiver

The RF transceiver will be provided to transmit and receive data to a host. The specific performance and protocol shall be defined during synthesis as an interface definition.

5.2.1.5 Unique ID

Every transponder will have a dedicated ID number. This ID number will differentiate transponders from each other and data logged will be logged against each ID number. This ID may also be used as a serial number for delivery, stock keeping and traceability purposes.

5.2.1.6 RAM

The controller will provide adequate RAM for housekeeping, processor functions and variables. It must not be required to provide for storing of large amounts of data in RAM other than the last event data.

5.2.1.7 ROM / FLASH

The controller will provide adequate ROM for all the software functions as set out in these requirements.

5.2.1.8 Enclosure

The transponder electronics, sensor, battery and all required parts and components will be fitted inside a specially designed and manufactured liner bolt. The parts will be fixed to the bolt using special epoxy, glue or resin to fix it permanently to the bolt. Once fitted, it will not be possible to remove the parts from the bolt. The enclosed bolt with resin will withstand the environmental conditions as stated further in the requirements. The transponder may also be fitted in a rugged enclosure to be mounted exterior to the mill. This may especially be useful on rubber liners since the sensor elements will be moulded into the rubber liner during manufacture and not form part of a bolt assembly.

5.2.2 Microcontroller selection

All of the MCUs from the various manufacturers evaluated during the literature study are generally very good and a decision was made on the device with the highest MCDM score. The scores are summarised in Table 15: Summary – MCDM scores for transponder MCU. The SiLabs MCU was chosen for its flexibility and vast number of on-board peripherals including a Proprietary RF block including a MODEM and packet handling error detection capabilities. The MCU is readily available at low cost and development tools are freely available.

5.2.3 RF front-end

The RF front-end must provide a means to communicate between the transponder and the host system. It must be able to transmit data as well as receive acknowledgements of transmitted data. The RF front-end must also provide sufficiently high levels of RF power in order to reach the host system, taking into consideration the mining, plant and environmental conditions. An Si1060 processor from Silicon Laboratories (Silicon Laboratories Inc. 2013) was chosen according to the MCDM decision matrix in Chapter 4. The microcontroller provides an RF front-end with the required capability so that interfacing can be done easily with a matching antenna interface. A suitable dipole antenna was chosen and the antenna proved to be more than adequate during communications testing.

The RF front–end includes an antenna switching circuit for switching between receiving and transmitting modes of operation. The switching is performed automatically by the on-board RF and packet handler. The RF front-end is capable of providing bi-directional radio communications between the transponder and the host system. The front-end provides adequate RF power in order to reach the host system, taking into consideration the mining, plant and environmental conditions. The typical power level required was estimated to be a minimum of 0 dBm. For a typical dipole antenna with gain of 2 dBm, receiver sensitivity of -103 dBm and transmit power of 0 dBm a line of site distance of at least 170 m may be achieved indoors, and an effective range of up to 1100 m outdoors. This is far better than what is required for the system, and since the SiLabs device is software configurable, higher transmitter power may be configured should it deemed to be necessary. The RF front-end is capable of being powered down during sleep periods so that battery power is preserved.

Figure 29 (on the following page) gives the design for the MCU and RF interface. The processor has an on-board analogue to digital converter and an on-board voltage comparator as well as a low power sleep mode for low power consumption. It further provides adequate ROM, RAM, Timers and other peripherals required to address the requirements for the transponder.

The circuit allows for an on-board C2 IDE (integrated development environment) (Silicon Laboratories Inc. 2013) to connect to the device during system development, evaluation, fault finding and programming of hardware and software.

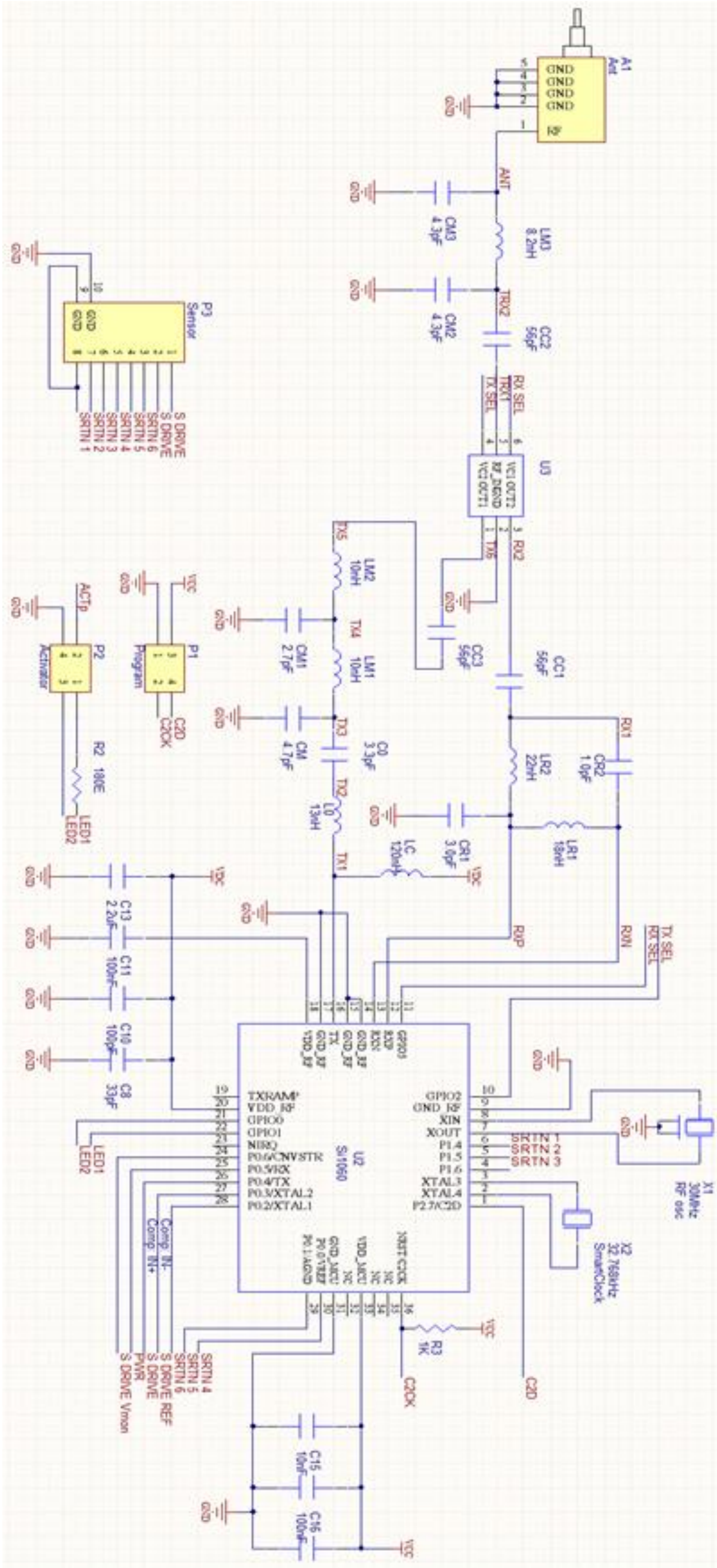


Figure 29: Transponder design – MCU and RF interface

When the transponder is placed in sleep mode, the MCU draws as little as 100 nA. This is low enough to keep power on the device during storage. It is therefore only required to enable the device when required to activate the device for operational mode. This was implemented as described in paragraph 5.2.5.2 - Power supply design below.

5.2.4 User functions

In terms of the user requirements as stated in section 3.2 (Prime Item requirements in this document), the user shall be required to view the operational status of the transponder. An easy and low power solution is to use an LED. In order to display various states of both error and normal status, it was decided to use a bi-colour LED capable of displaying both a red and a green status.

This provides the transponder with the capability to display an error status using the red LED. Different error states may be indicated by the flickering of the red LED at different intervals. As an example, two flickers of the red LED every 60 seconds may mean the battery is low.

Similarly, normal or success statuses may be indicated using the green LED. As an example the green LED may be flickered two times after a successful transmission and acknowledgement of data to the host.

In order to preserve battery power, the LEDs must be of a high brightness and low power type. LEDs are robust and sealed units and therefore ideal for this purpose.

5.2.5 Power supply (source) and power management

As can be seen from the information provided in paragraph 4.3.1.1 (Primary cells) and 4.3.1.2 (Secondary cells) a primary cell battery is a preferred source of power to the transponder. Because of availability, price and power density a Lithium-metal battery was chosen. These batteries provide up to 4.32 MJ/L of energy densities as opposed to Alkaline and Nickel metal batteries of lower than 3 MJ/L of energy density.

A battery with a capacity of 1400 Ah was chosen as it fitted the available space and power density requirements. Power requirement was calculated to last over a period of twelve months with a power-on duty cycle for a sensor with 42 levels and a maximum on-time of three transmission cycles per level (3 retries per transaction and five retry cycles every five minutes).

5.2.5.1 Power-on and enable

As defined under user requirements, the transponder is required to have a shelf life of at least two years (or more if possible). In order to reach this goal, it must be able to remove all electrical loads from the battery while the unit is not in an operational mode and only be powered up once it is ready for use.

In order to achieve this goal, it is required to add a function where power can easily be enabled when the unit is ready to be activated. Different methods were evaluated for this purpose. It must be remembered that the transponders will be used in a mining environment with operators not necessarily knowledgeable on electronic equipment and the associated fragile nature. It was therefore required that it must not be possible to power the unit off once it has been activated, otherwise units are switched on during storage with associated battery drain. The power-on feature is therefore required to be an “on” function only. It must however be possible to test the unit prior to installation. The test function must enable a user to measure the unit’s remaining battery capacity and functions, and then switch the unit off automatically after completion.

The following options for a power-on function were researched:

- On-off switch;
- Magnetic switch;
- Activation pin;
- Connection on the sensor connector.

5.2.5.1.1 On-off switch

The use of a simple mechanical on/off switch may be used to power the device on and off, however in this case a function is required to power the device on only (no off function must be possible). An electronic circuit can however be designed to only activate the circuit in the event of an “on” pushbutton event. There must however be an option to prevent accidental activation of the unit. Further concern on such a switch is the harsh environment the unit will be operated in and it must be possible to seal the switch off from water, liquids and dust.

5.2.5.1.2 Magnetic switch

A magnetic switch may be used to enable the unit using a magnet. Such a switch may be built inside and enclosed properly within the housing of the transponder sealing it off from the external environment such as liquids and dust.

5.2.5.1.3 Activation pin

The idea of an activation pin is based on the principle of a pin similarly used to activate a hand grenade. When the pin is pulled, it activates an electronic circuit which will enable the battery supply to the transponder electronics.

5.2.5.1.4 Connection on the sensor connector

A simplistic solution would be to place the battery supply or battery supply activation circuitry onto the connector pins to the liner sensor in such a way that when the sensor is connected to the transponder that it would start to operate. This function requires an additional pin on a connector.

5.2.5.2 Power supply design

The chosen power source is a Lithium battery of 1400 mAh capacity. The battery was chosen for the reasons stated in the summary of the power source literature study, and specifically for its size, capacity and low cost as well as its capability in providing adequate power to the transponder and sensor for the duration of the life expectancy of the device.

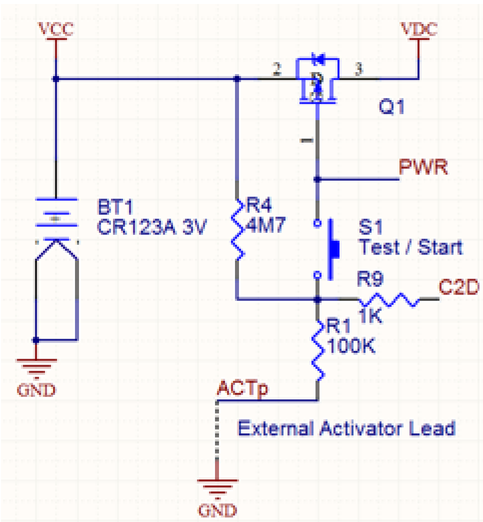


Figure 30: Transponder design – power source

The supply is enabled by way of the electronic circuit shown in Figure 30: Transponder design – power source in the following manner. With PWR normally high and then:

Pulling a ripcord (ACTp on connector P2) which, under normal conditions, short circuits ACTp to GND. When short circuited, power to the circuit is disabled through MOSFET Q1. By pulling the ripcord (breaking the circuit ACTp to GND) the MOSFET is turned on by the MCU PWR pin and current flows to the transponder circuits. The MCU then holds the PWR pin (MOSFET Gate) low, enabling power to the remaining circuits.

By using a magnet, switch S1 may be closed temporarily. The MCU will detect the change and determine that it was a switch event, perform a test and will go back to sleep again.

5.2.6 Sensor interface

The sensor interface on the transponder must be able to provide (preferably) a constant current source to the sensor circuit. It can be seen by evaluation of forward voltage vs forward current graphs from data sheets of various diode (semiconductor) suppliers that the forward voltage does not change significantly with the change in current over specific areas in forward voltage vs. current at a specified temperature. The change in forward voltage over temperature is also predictable and may be used during calculations. For this reason, the forward voltage and current were chosen to be in an area of little change in voltage as a function of current and temperature, hence low sensitivity. This simplifies the design as a simplistic resistor network and diode may be used as voltage (and current) supply.

Since the change in forward voltage vs. change in current over the semiconductor is small over certain areas on the graph, it can be seen that small changes in current (due to a non-constant current source) do not have significant effect on forward voltage. This implies that an unregulated current source is suitable for the design.

Furthermore, the sensor interface must provide a means by which the sensor forward voltage can be measured so as to calculate the number of diodes in series at any time. The number of diodes in the circuit is then directly related to the voltage level of the sensor. Since the distance between diodes is known, the sensor voltage levels translate to specific lengths of the sensor (thus, wear) in the case of SAG mil liner measurements.

The sensor current is very low and the input impedance of an ADC will have a direct influence on the measured voltage. It is therefore necessary to buffer the measured voltage with a very high impedance operational amplifier with low output resistance.

5.2.6.1 Sensor interface design

The sensor requires an electronic front-end circuit or interface able to detect a change in diode voltage levels and to measure the series forward voltage of the diodes of the sensor circuit. Power consumption of all circuits must be considered in the design of the transponder electronics. Design consideration must include the following:

- Low power consumption;
- Small size;
- Minimum component count;
- Low cost.

These parameters are in lieu of the cost, vibration and robustness requirements for the transponder, considering its expected working environment.

The above functionality may be achieved by a circuit able to detect a change in forward voltage and a second circuit able to measure the forward voltage. A circuit to monitor a "break" in the sensor may be realised by a voltage comparator circuit. Such a circuit is implemented by setting a reference voltage on one pin of the comparator and the hybrid semiconductor circuit on the other pin. Depending on the polarities used on the pins, the circuit's output will change state on a change in diode forward voltage event. This change in output may then be used to wake a secondary circuit to measure the forward voltage on the sensor. This circuit may be realised by using an analogue to digital converter (ADC).

As can be seen from Figure 31, diode D1 and resistor R5 provide current to the sensor network SDRIVE. The supply voltage was chosen to be 3 V (as a non-rechargeable primary battery is used). This means that the maximum number of series diodes are:

$$\boldsymbol{D \times 0.3\,V = 1.8\,V} \quad \textbf{Equation 7}$$

For $D = 6$, added to the 300 mV of D1, giving 2.1 V across the entire diode chain and current source. When all circuits are open (all levels depleted), the voltage reaches a maximum of 3 V (supply). In order to provide adequate current through the network within the operating window, a resistance (R5) of adequate value is chosen to provide the minimum current flow when the diode chain is at its maximum voltage (6 diodes – all levels depleted) and a small enough current at the chain's minimum value (0 diodes – no level reached yet) so that the battery will not be drained during the sensor initial state. The battery will also have adequate voltage (and subsequent current) when the diode chain is at its maximum voltage (6 diodes and open circuit).

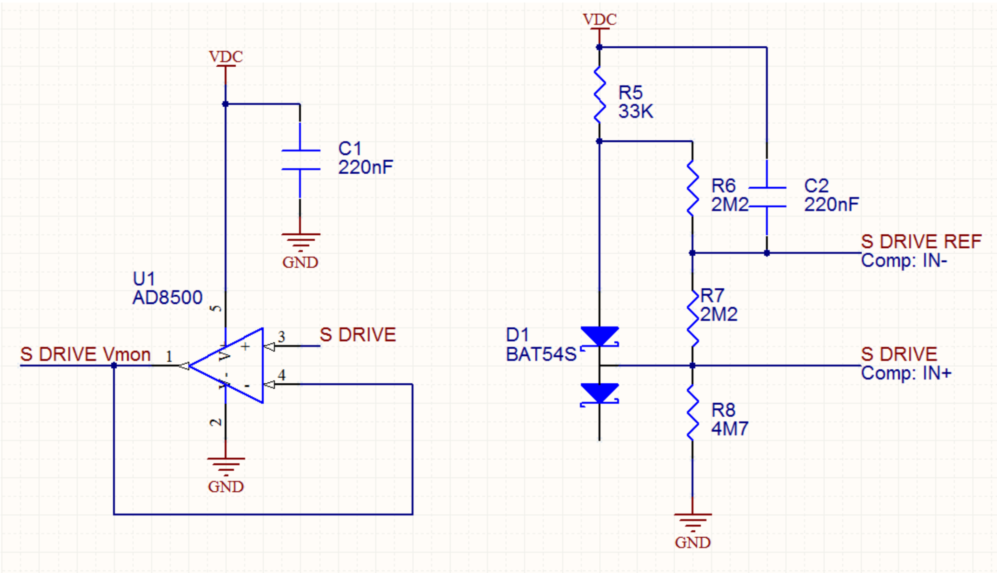


Figure 31: Transponder design – sensor interface

During the rest period (the time the MCU or intelligent electronic circuit is kept in a sleep or power low state), the circuit draws minimum current and because of the resistor divider network R6:R7 across D1, the voltage at the comparator negative input (SDRIVE REF) is higher that the voltage at the positive input (SDRIVE). The selected MCU (SiLabs Si1060) draws approximately 700 nA, which is acceptable.

This results in the comparator output to be at a logic low level. In the event that a diode chain is broken (next level of the sensor reached) the low pass filter (C2) and Resistor network cause the negative voltage input to rise at a much slower rate than the voltage at the positive input. This change in ratio negative to positive on the comparator inputs will cause the comparator output to rise to a positive level according to a time constant T as a function of (R5:R6:R7:R8 * C2). This pulse on the comparator output is of adequate width to wake-up the CPU and electronic circuits from its sleep mode.

The MCU incorporates an on-board ADC that measures the sensor voltage (via buffer U1) to determine the level at which the diode chain is. An initially estimated forward voltage is used to determine the assumed level, compensate for process variations and adjust the next trigger level accordingly. After sending the information to the remote host over an RF link, the MCU goes back to sleep and the process is repeated at the next sensor break.

For a 3 V supply, a sensor bank can typically provide seven levels of accurate measurement. For a loom of 6 mm diameter, it means at most six banks of seven levels each may be implemented resulting in a total of 42 levels. More levels may however be achieved with a larger hole diameter or using two or more batteries in series, providing a higher forward voltage and consequently the number of diodes that may be placed in series. For the suggested design, each bank can only accommodate 7 levels, so different banks are switched in as the level of wear progresses. This is done by switching in the relevant bank return by means of an open collector switch “SRTN1 – SRTN6” (O/C pins on CPU are used) as indicated in Figure 29.

A further method for improving the number of levels is to add an additional sensor module (with 42 levels) in parallel with the first, but with a separate SDRIVE signal and the return lines set in parallel with those of the first sensor module. This means the addition of one extra wire to add an additional 42 levels.

5.2.7 Electrical power budget for transponders

The power budget for the transponder was calculated for its different states to determine the battery life expectancy. The total average power consumption was determined from taking into account contributions from different components and considering the duty cycle of operation and typical use patterns of the transponders. A comparison is drawn between total average power consumption and available battery energy to show that the transponder will meet battery life requirements.

5.2.7.1 Power Budget - de-activated state

The transponder electronic circuit is divided into two sections. One section powers the Si1060 MCU and the other section powers all the surrounding electronics such as the sensor interface and LEDs. The Si1060 has also the function to enable or disable internal circuitry such as ADC, radio frequency functions and support devices such as the modem and packet handler, timers and the like.

In the de-activated state (the state the transponder is held in during storage), the only part that is powered by the battery is the MCU. At power up, the software disables all internal peripherals, the radio as well as the external circuit powering external electronics on the PCB. In this mode, the MCU is placed in a “sleep” mode and in accordance with the Si106x data sheet; the device draws 0.09 uA (90 nA – Si1060 data sheet page 44/358 table 4.2). On a battery of 1400 mAh it is calculated that the standby life will be 1775 years (1400 mAh / 90 nA) which is significantly above the battery (or any systems’) life expectancy.

5.2.7.2 Power Budget - activated state

Once the transponder has been activated by the activation cord or an external magnet (test mode), electronics external to the MCU are powered by a MOSFET switch. The MCU wakes up on detection of the pin change and starts all on-board peripherals and enters a normal mode of operation. The transponder software will detect if the pin change was due to an activation pin event or due to a test (magnet switch) event. In case of an activation pin event, the transponder will transmit its ID and status up to 3 times and then go back to a sleep mode, but in an activated state. Should there be a host in the vicinity to acknowledge the transponder ID message, the transponder MCU will immediately go back to sleep without further delay. In this state, the transponder’s external electronics (such as the sensor interface) are powered and in a ready state, but the MCU is placed back into a low power sleep state.

Table 22 Activated and sleep state

Circuit Description	**Calculated Current**	**Notes**
Antenna Switching Circuitry	Negligibly small and close to 0	Passive filter network and antenna switch in receive mode draws insignificant current.
Sensor ADC buffer amplifier (AD8500) circuit	Maximum of 1 uA in accordance with the manufacturer data sheet.	This includes input bias currents in the order of 600 pA.

Circuit Description	Calculated Current	Notes
Sensor interface circuitry	1.34 uA	Worst case calculated when all sensor levels intact (sensor is a short circuit).
MCU with SmartClock running	760 nA	Ready to wake-up on sensor trigger.
Total calculated current consumption	**3.1 uA**	Worst case scenario.

During this period, the current consumption is approximately 90 nA plus that of the internal RTC timer and the current consumption of the external circuitry. In accordance with the SiLabs Si1060 data, the current consumption of the MCU with SmartClock running is in the order of 0.76 uA (760 nA – Si1060 data sheet page 44 / 358 table 4.2). The calculated Power budget for the external circuitry is shown in Table 22 on the previous page.

Once the transponder is within an activated and sleep state, and is then woken, the MCU will enable a number of internal peripherals such as the ADC, the radio and its internal oscillators. In accordance with the manufacturer data sheet the MCU in this mode draws in the order of 170 uA/MHz and therefore at 20 MHz will draw approximately 3.4 mA. Add to this current the radio power, which draws a maximum of 10 mA (low power receive mode) and a maximum of 18 mA at 10dbm transmit power. The ADC draws an approximate 680 uA and the internal ADC reference a maximum of 200 uA. The on-board comparator requires only 400 nA. The budget is summarized in Table 23 on the following page.

Taking into consideration that the transponder is mostly in a sleep mode and only woken upon a sensor level change or RTC cycle timeout, the transponder power consumption is a function of its duty cycle. Since there are only 42 levels on the sensor, the wake-up due to sensor activity will for first be ignored as this is a very small percentage of the on-time of the transponder.

In all calculations, the approximations are used since the current consumption and duty cycle values are small in comparison with the requirement. That is, overly precise values are not necessary in calculations.

Taking the above into account and assuming the cycle timer is set to once every eight hours and the total transmission and communication time is one second (it actually is around 22 ms, as from the above power budget calculations in Table 23), the duty cycle is around 0.0035 %.

Given a battery capacity of 1.4 Ah, the total battery life cycle is calculated to be approximately:

$$\frac{1.4}{0.02228} \times \frac{1}{0.0035} = 1.8E6\ hours \quad \textbf{Equation 8}$$

This equates to approximately 75400 days which equals approximately 206 years. This is significantly longer than the battery shelf life of 10 years and much higher than the required 365 days of operation.

Table 23 Activated and operational state

Peripheral description	**Current consumption**	**Notes**
MCU	3.4 mA	Active and fetching
Radio	18 mA	Worst case in TX mode
ADC	680 uA	When enabled
ADC Reference	200 uA	Always enabled
Comparator	400 nA	Always enabled
Total calculated current consumption	**22.28 mA**	Worst case

Although these values are approximations, they correlate with measurements taken with a high precision multimeter which measured an average current consumption in the same order of magnitude of 22 mA during peak consumption and 3 uA in sleep states. A further indication of the battery life is the fact that one of the test transponders, ID number 1005 is still running more than a year after installation and its battery level was still at more than 85 % capacity at the time of documenting this thesis.

5.3 Host electronics

The MCDM scores for the three devices, as obtained from Chapter 4, are given in Table 24 (on the next page) so that the final decision for the selected device may be explained and defended.

Table 24: Host controller parameters summary and MCDM scores

Parameter	Raspberry PI 3	BeagleBone	IMX6
Cost	3	2	-3
CPU core	3	3	3
Operating system	3	3	3
Network connection	3	3	3
Storage	1	3	3
RTC	0	0	3
MCDM Score	**13**	**14**	**12**

The host receiver is a combination of a BeagleBone MCU and a dedicated host "cape". The cape is an add-on to the MCU board and plugs into the host by means of two header connectors. The cape provides an RF interface and real-time clock with battery backup. Figure 32 shows the RTC and backup battery design and the design for the cape MCU and RF interface is shown in Figure 33.

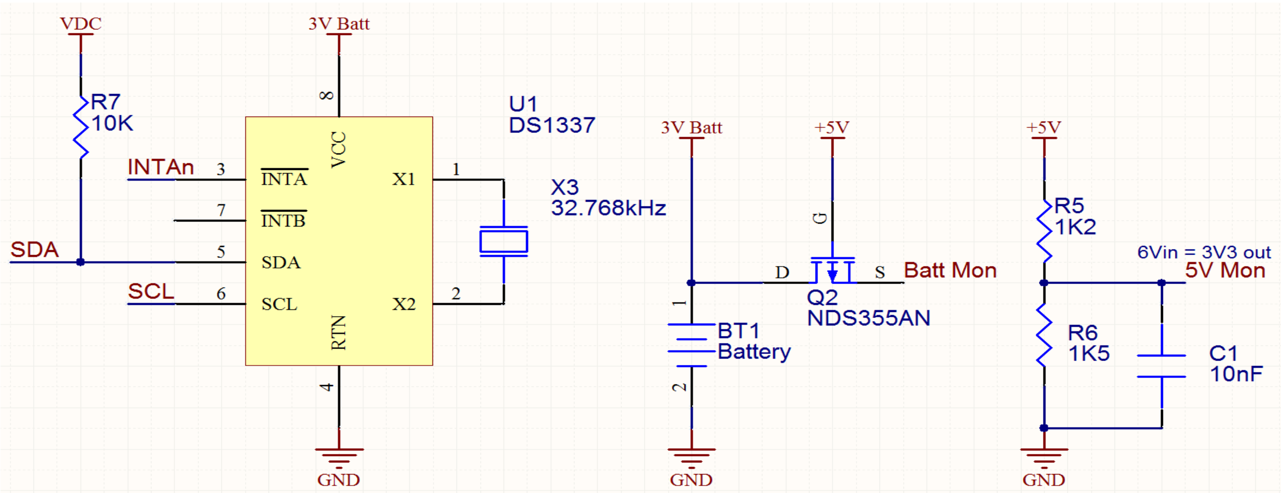


Figure 32: Host cape design – RTC interface and battery

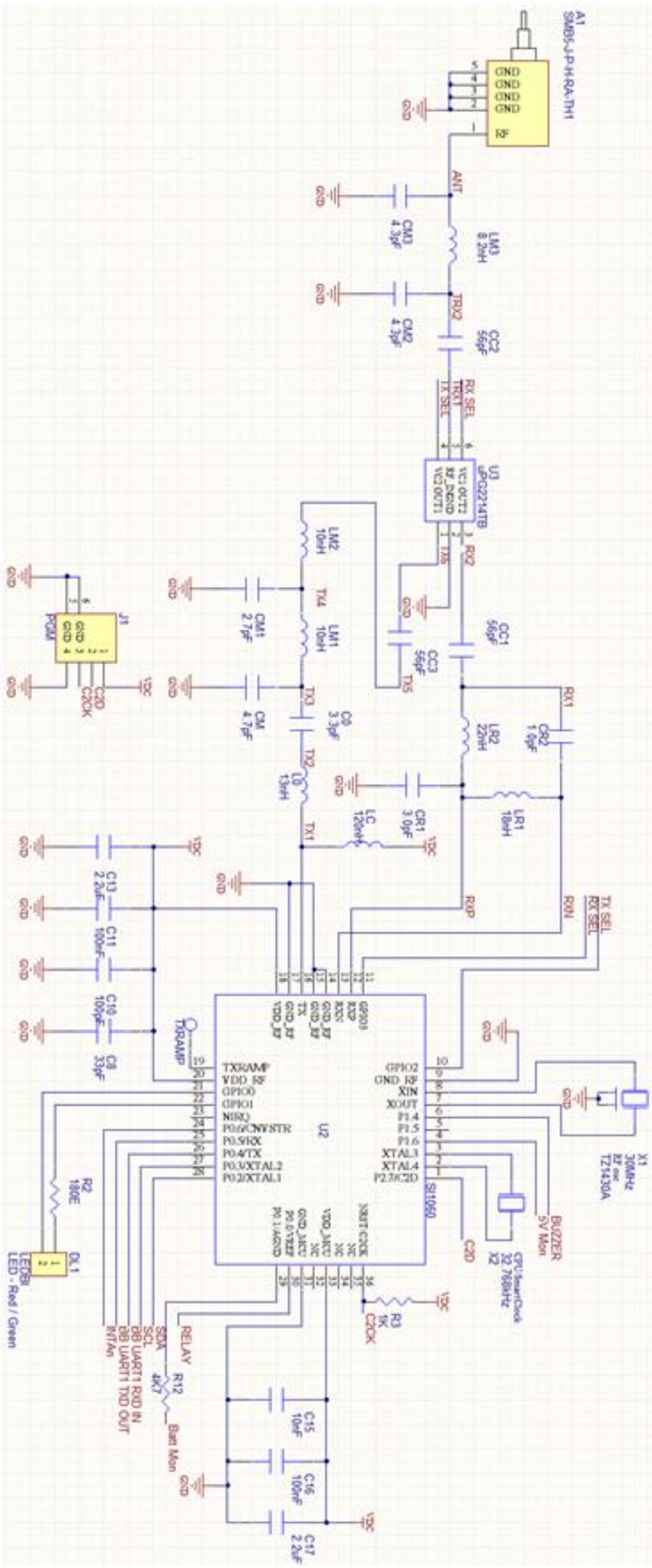


Figure 33: Host cape design – MCU and RF interface

5.4 Host server and client software

The host application is a software program executed on the BeagleBone MCU. This application implements a hardware layer (item 1) which is the protocol engine to the host cape on one end and a network interface on the other. The network implementation is a socket (item 2) which in turn connects to a TCP server (item 3). The server is responsible for posting received transponder sensor data to a client (item 4). A client is typically implemented by using a normal web browser such as Firefox™ or Chrome™.

The protocol between the host and transponder as well as the protocol between the host and server, and host server and client are described below.

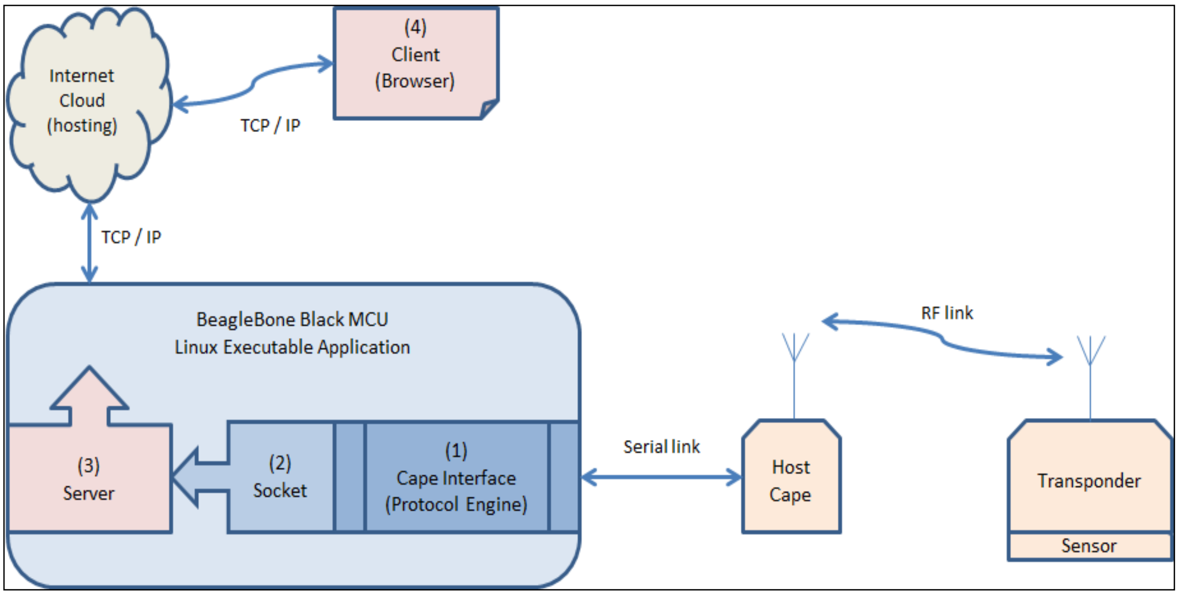


Figure 34: Host application, server and client

The executable program was written in the C programming language and implemented on a Debian based Linux operating system (The Debian project n.d.). The server is written and compiled in C using the GNU tool chain (GCC, the GNU Compiler Collection n.d.) and the TCP stack based on "Node.js" (Node.js® n.d.).

5.5 System integration

To provide a fully operational system, all components of the system were integrated to provide functionally capable resources to a real-time monitoring process for the measurement of liner wear rate. This section on integration describes the process flow and interfacing between the system's functional units.

5.5.1 System process flow

Once the sensor and transponder have been installed on the SAG mill, it will start sending system and sensor status to the host. The transponder is configured to transmit its status every few hours so that the battery and liner sensor statuses are available to an observer. The transmission duty cycle is limited in order to preserve battery life. On a break in the sensor level, the transponder will immediately send a status update to the host. The host acknowledges the message and the transponder will then go back to sleep. On receipt of the transponder message, the host application will push the transponder and sensor status message to the server, which in turn sends the message to the internet hosting server where the information is stored in a database. These statuses and messages may then be viewed by way of a web browser which retrieves the information from the database and presents it in a visual format to the end user.

The TCP / IP messaging structure is according to the (IEEE Standard for Information technology 2012), and is not discussed in detail. The protocols for the flow defined in Figure 35: Communication (message) flow, are discussed in detail further in this chapter.

In principle, there exist four message types namely:

- DC1 – Solicited messages;
- DC3 – Unsolicited messages;
- ACK – Acknowledgement messages, and;
- NAK – Not Acknowledgement messages.

The DC1 message is used to send a command from a master device to a slave device. In this case, the host cape (as interface between the host application and transponder) is defined as the master device. The transponder is defined as the slave device. DC1 messages are used during system configuration and initial setup at factory level. It is primarily used to configure each transponder with a unique ID number and other manufacturing information such as date of manufacture and modification status (if any). DC1 messages in this case are therefore not used during normal use of the system.

The DC3 or unsolicited message is used in instances where the transponder cycle timer reached a timeout and the transponder woke up to send a status message. The status message contains the transponder ID number, the battery status and also the current sensor level

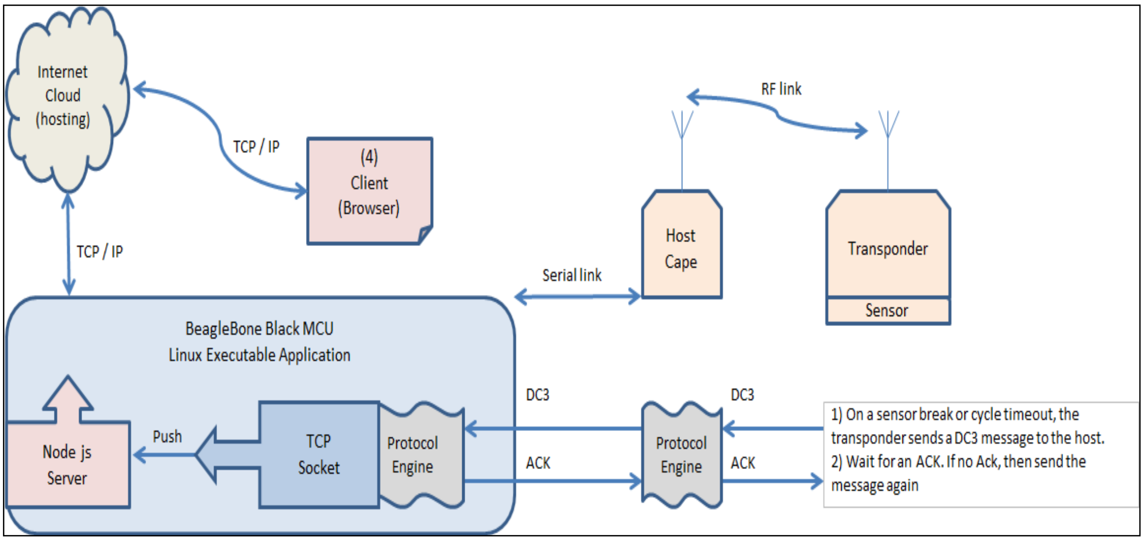


Figure 35: Communication (message) flow

All originated messages are acknowledged by an ACK or NAK. An ACK reply is sent on a successful receipt of a valid command. A NAK is replied on CRC error or incorrect parameters or parameter range provided in the transmitted message.

On successful transmission, the transponder will go back to a sleep (low power) state until the next event occurs. Since the transponder is in a sleep state, it cannot be communicated to from the host during this period. After the message had been acknowledged to the transponder, a message with the transponder battery and sensor status is pushed to the Node js server, which in turn communicates the message to the internet hosting server.

5.5.2 Transponder process description

The transponder processes are defined as the following:

- Transponder power on sequence;
- Configuration sequence;
- Test sequence;
- Activation sequence; and
- Sensor levels break sequence; and a
- Periodic cycle timeout.

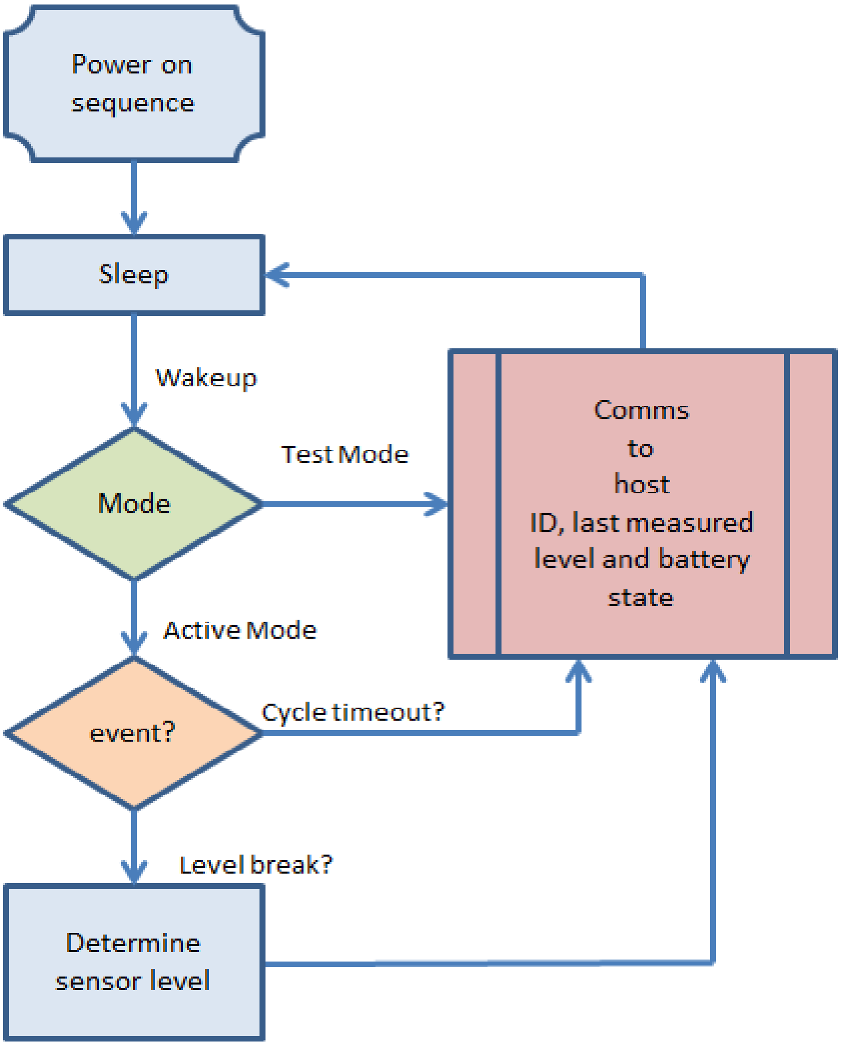


Figure 36: Transponder states

At power on, the transponder loads default values and then enters a low power sleep state. The default parameters loaded include the following:

- Transponder ID (serial number);
- Transponder wake-up cycle time (disabled at power on);
- Activation status (disabled by default);
- Sensor input is assumed zero (as if no sensor connected).

These parameters (excluding transponder ID), may be reconfigured by the host. This is done in the configuration state.

The transponder is placed in a configuration mode by activation of a magnet on the outside of the transponder enclosure. The magnet closes a magnetic switch which enables the transponder and places it in a test state. In this state, the transponder sends a test message to the host. On receipt of the ACK message, the transponder will evaluate one of the parameters in the reply message and if evaluated to a configuration message will read the configuration parameters. The configuration parameters are then programmed into the transponder device storage (flash). These newly programmed parameters then replace the default parameters loaded at power up.

The transponder enters an activation state once the ripcord has been pulled. This indicates to the transponder that the unit is now active and enables the hardware interfaces to the transponder sensor. The transponder hardware will then react to changes in sensor levels as described in this document. The transponder sends the following information to the host, transponder ID number, transponder battery status, liner thickness (level number) and battery status.

Once activation state has been entered into, it cannot be abandoned. This feature was designed so that it will not be possible to re-use a previously installed transponder with the intention to improve and guarantee the meantime between failures (MTBF) of the system.

5.5.3 Host process description

The host system states and processes are defined as follows:

- Power on sequence (rc.local);
- Keep alive process (cron);
- Configuration sequence;
- Normal execution state.

At power on, the host cape CPU will initialise its RF front end and all peripherals required to place the cape in an active state, ready to communicate to a transponder. It will also initialise the communications interface to the RTC and to the host MCU serial port.

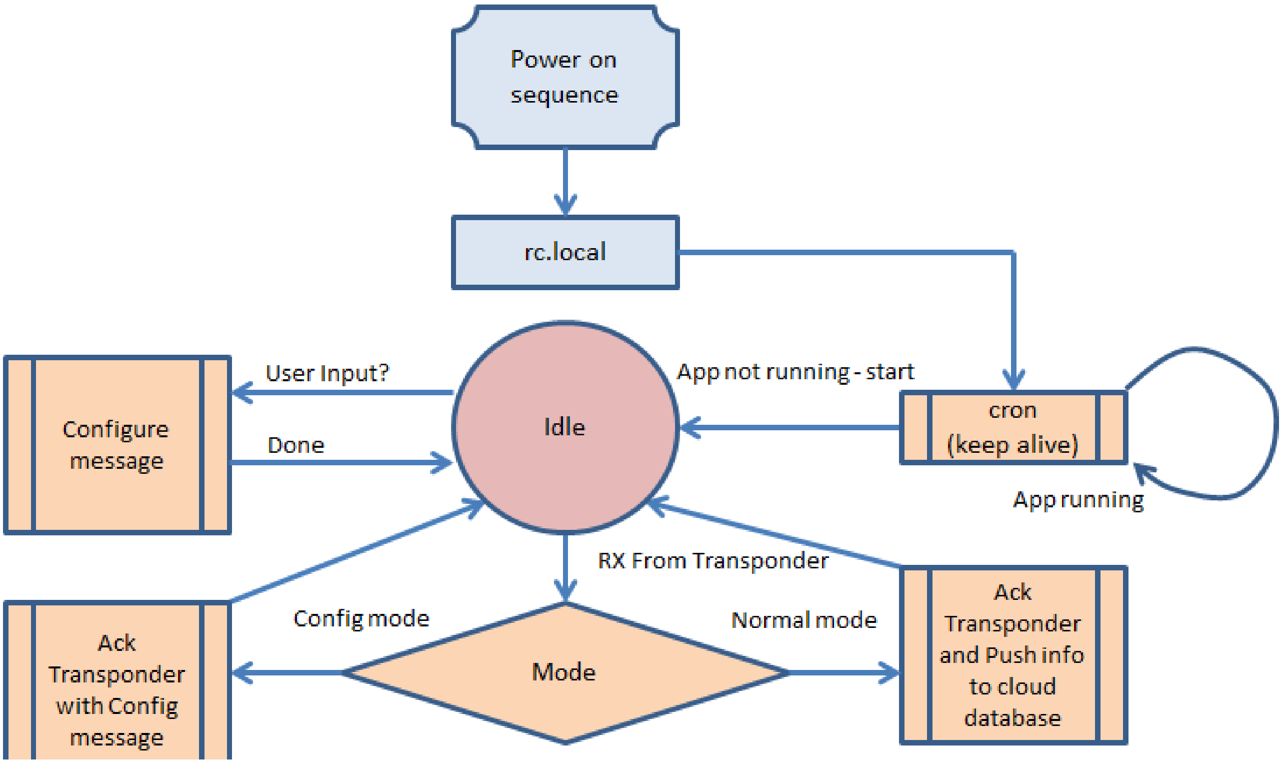


Figure 37: Host states

The host MCU (BeagleBone) Linux operating system is executed and will load the host application for which parameters were defined with rc.local (a Linux script executed at start-up). The start-up script also includes an entry into "cron" (a Linux daemon which executes scheduled tasks) which continues to monitor the host application execution. In the event that the host application fails to execute, the cron will re-start the application. This is to improve on the MTBF and reliability of the system.

The configuration sequence is entered upon user request. This is done to configure a transponder with its required parameters, such as cycle time. The configuration mode also enables a user to set the host cape RTC date and time. The date and time are used to timestamp events before they are pushed to the system cloud database.

During normal execution, messages are received from and acknowledged to the transponder. Once a message has been acknowledged by ACK, the time-stamped content is pushed via the socket to the server application. The server then in turn pushes the message onto the internet cloud based database.

5.5.4 Communications protocol - transponder and host

The communications protocol between the host cape and the transponder is defined as a command–response protocol, where data is sent from one device to the other and a handshake is expected in the form of an “ACK” or “NAK”. The protocol is “wrapped” within a packet handler data structure on hardware level. The packet handler adds fields such as preamble, synchronization word, headers, packet length, and CRC to the data payload. These additional fields support the RF modem in transmitting and receiving messages and parsing the payload without software intervention. The packet handler further adds field for data de-whitening and Manchester decoding for synchronisation and data extraction.

The RF baud rate is set at a high bit rate of 500 kbit/s so that forward transmission and reply transmission times are reduced to a minimum. The transmission time has an impact on the battery life of the transponder as well as the time window available for communication between the transponder and the host. Taking into account that a SAG mil turns at a rate of up to 14 revolutions per minute and the available time window (line of sight) between the transponder and the host is in the order of two seconds, the period is calculated to be approximately 4.3 seconds per rotation and it is assumed that the transponder will be visible (in line of sight) to the host for at least 180 ^{o} of the rotating SAG mill drum. This could be only 90^{o} in some instances, reducing the visible time to less than one second per rotation. For a chosen RF baud rate of 500 kbit/s and payload length of 64 bytes, it means that the payload (with added de-whitening, synchronisation, headers and CRC, totalling a maximum of 128 bytes) would be delivered within approximately 25 μs. This message is transmitted several times (burst transmission) in the available window to improve the “hit rate” of the host receiving the message. Only one of the transmitted messages needs to be acknowledged. If not, the transponder will retry for a number of times at random rest periods in between. This strategy proved to be successful in transmitting data between transponder and host.

Data is stored on the application MCU (BeagleBone) flash storage since the time to deliver a message to the internet cloud database is significantly longer. Once a message has been received and acknowledged by the host to the transponder, the application server will forward the data to the cloud server’s database. This process is a separate one from the host transponder communications process and is executed in parallel. This ensures that the host is always available for communications to a large number of transponders communicating their data on a regular basis to a single and central host. This strategy allows for a single host to communicate to a number of SAG mill transponders on a factory floor.

5.6 Conclusion

This chapter focussed on the synthesis and integration of prime item building blocks, namely the liner sensor, the transponder and the host sub-systems.

The liner sensor was designed using the hybrid sensor solution by the implementation of conductive loops and addition of diodes into a 250 mm sensor capable of measuring up to 42 levels successfully. It was shown how the sensor was integrated into the transponder by a sensor interface circuit and that the circuit was designed to wake-up on a change in sensor level, measure the voltage across the sensor and determine the sensor level, as well as how the sensor interface circuit would progress through the various levels of liner wear by switching up to six banks of hybrid sensing circuits in order to determine its level.

Further to the host design was the development of a transponder compliant RF interface by duplicating and adapting the transponder RF sections with added functionality into a host cape. The additional features include a real-time clock calendar and battery backup as stated by the prime item requirements.

The section on integration describes how the building blocks (sub-systems of the prime item) were integrated into a working system. It was described how each sub-system was integrated and shows the interaction between system architectural elements by means of process flows. The process flow for each sub-system was described. Communication-related risks were reduced by the introduction of a handshaking protocol with CRC generation and validation. Finally, it was shown how the change in sensor level was detected, measured and transmitted to a host and internet server.

In light of the initially defined ***research challenges***, this chapter effectively provided ***solutions*** to those challenges by means of systematic research and design from Chapters 4 and 5, respectively. The research challenges were addressed as follows:

1. Real-time measurements can be made with the proposed (designed) system using an integrated remote RF solution. This reduces production downtime;
2. Extended battery life is provided by designing for low power and using low duty cycle operation. This design thus prolongs measurement equipment’s life;

3. High resolution measurements are provided by using a robust, hybrid sensor. This effectively addresses the research challenge for high accuracy measurement;
4. A robust design is provided. This design was specifically done to ensure operation in harsh environments.

Development testing

Testing of the system elements formed a major activity during the developmental phases of the system. Testing was performed on an ongoing basis to confirm, not only functional, but also performance parameters, quality and consistency of all building blocks. Test benches and equipment were developed to simulate system inputs and to monitor system outputs. The following building blocks were tested individually and thereafter tested in system context:

- Liner sensor;
- Transponder – liner sensor interface;
- Transponder – RF interface;
- Host – Transponder RF interface;
- Host – Internet connection (Wi-Fi and Ethernet).

Test equipment was also used during the development of software to simulate inputs and to measure and visualise outputs. The equipment was used to simulate undefined conditions in order to confirm that system elements are robust and stable under all possible conditions, even undefined or unlikely conditions.

For each building block, the tests are described under the headings (i) purpose of tests, (ii) test setup, (iii) test procedures, and (iv) test results.

The purpose of testing was to confirm the requirements as stated in section 3.2 (Prime Item requirements) had been met. This includes compliance to functional as well as performance characteristics.

The test setup sections describe the test environment setup and methods for each of the building blocks. The test setup sections are followed by test procedures, which are step by step guidelines for testing each system building block.

Lastly, the test results section follows for each item, providing an indication of the parameters that were tested, and results obtained.

6.1 Liner sensor test

6.1.1 Purpose of test

For the liner sensor, it was important to confirm that the circuit will in fact perform its defined purpose as follows:

- That the voltage level across the hybrid sensor do increase as the sensor level decreases;
- That the sensor voltage is not severely influenced by environmental conditions such as liquids and materials;
- That the sensor is rugged and will endure the vibrations and conditions it will be subjected to.

A special hybrid sensor emulator was constructed for development testing, with the capability of emulating a change in level by opening of a switch placed in series with a diode and conductive loop (effectively simulating a loop break). The concept is shown in Figure 38 below.

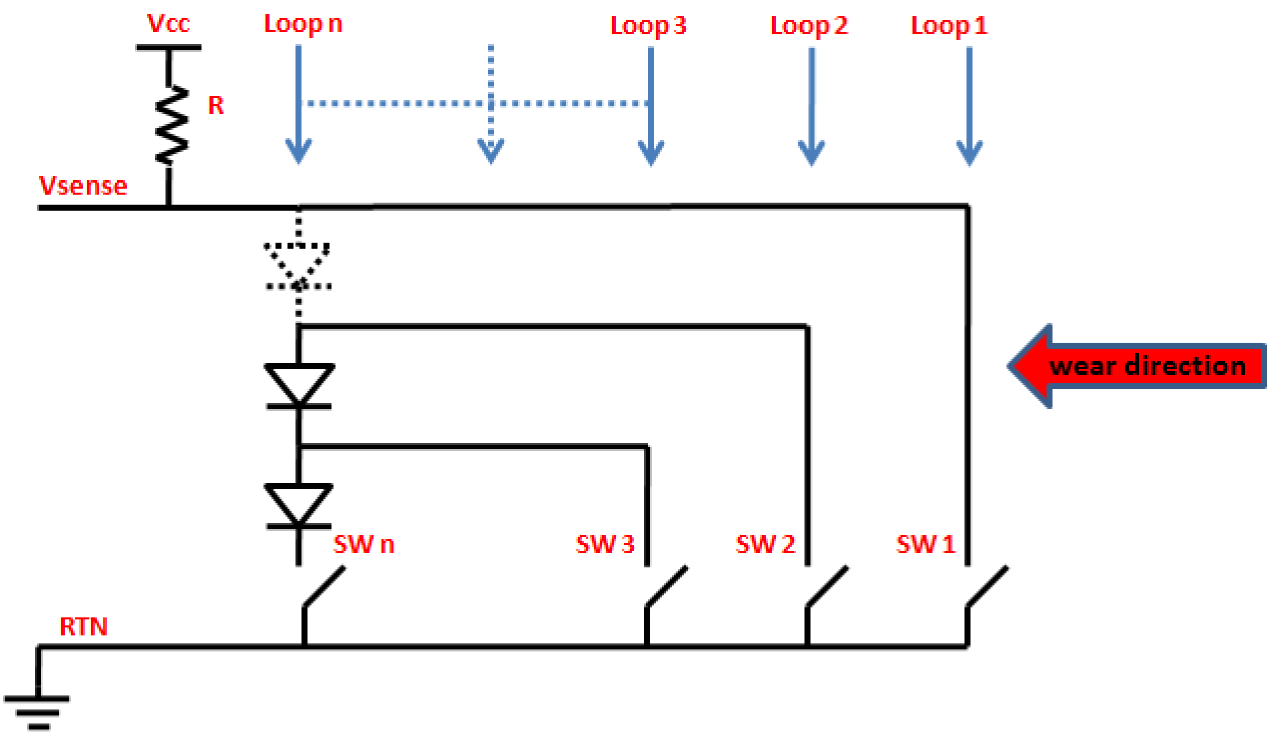


Figure 38: Hybrid sensor emulator schematic

The switches are normally in the “closed” position and opened one by one from right to left as shown in Figure 38 to emulate the change in level as the sensor (and hence the liner) wears down. The sensor emulator and sensor tester are shown in Figure 39 and Figure 40.

Figure 39: Hybrid sensor emulator

Figure 40: Hybrid Sensor tester

6.1.2 Test setup

The liner sensor design was tested using a specially manufactured loom, a bench power supply with a constant DC voltage and current, and a high resolution digital multimeter. The test setup schematic diagram is shown in Figure 41 below.

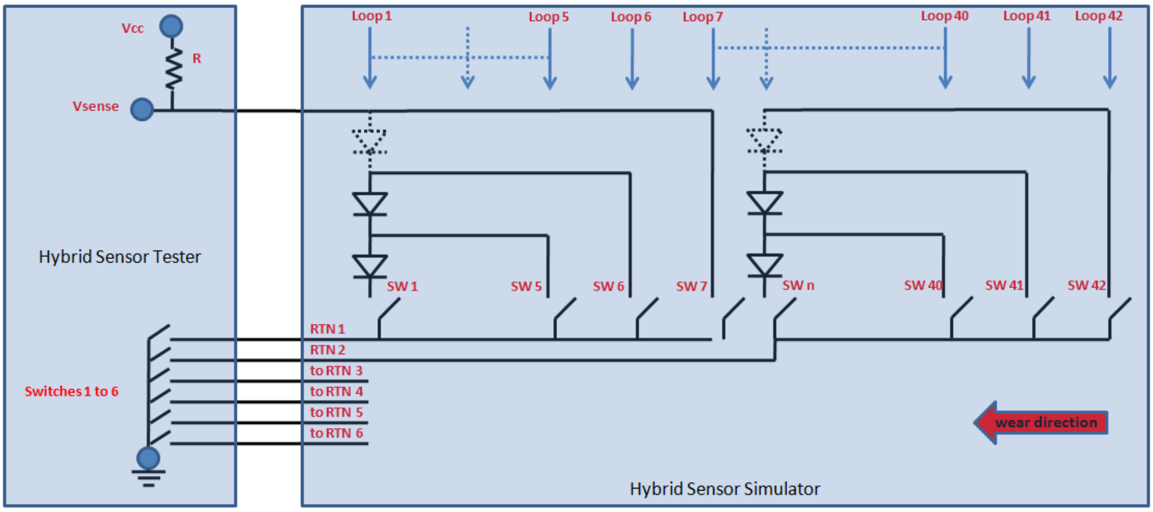


Figure 41: Liner sensor test setup schematic diagram

The power supply is set to 3 V output and current limit set to 500 mA. A series resistance of 1 KΩ is placed in series with the common supply to the sensor and the sensor returns individual switches as shown in the sensor tester schematic diagram (Figure 41).

6.1.3 Test procedures and results

These steps were taken in the verification of performance and functions. The test results provide an indication of the measured results taken.

1. Configure the PSU for 3 V and 500 mA. Switch the Power Supply off;
2. Connect the special test loom and tester to the hybrid sensor board and to the power supply;
3. Connect the multimeter to the test pin (Vsense in Figure 41);
4. Turn all switches on the Sensor Tester to the “open” position, except for switch 1 which must be in the closed position;
5. Ensure all switches on the sensor simulator are closed;
6. Switch on the power supply and measure the voltage at the Vsense pin;
7. Each time a switch on the Hybrid Sensor Simulator is opened, the value at the Vsense pin should rise with a constant value until all switches for the particular bank have been opened, where the value should then be equal to 3 V. The diode forward voltage should be between 250 mV and 350 mV.

In all instances, the software and hardware were tested to provide the functionality and performance as defined above.

6.2 Transponder sensor interface test

6.2.1 Purpose of test

For the transponder sensor interface it was important to confirm the following characteristics of the transponders’ liner sensor interface:

- That the sensor interface correctly react to a change in sensor level;
- That the interface correctly measure the sensor level and that;
- The sensor interface correctly interpret the measured sensor voltage;
- That the sensor interface is robust and not sensitive to noise and undefined sensor characteristics (such as faulty or broken diodes lower down the sensor bank).

Tests include the simulation of a damaged liner sensor. Conditions were simulated where the liner sensor elements are damaged lower down than the actual level of sensor wear. This is a possible scenario taken into consideration the harsh environment in which the sensor will operate. In such an event, the sensor interface should not respond to an incorrect (or damaged) sensor element and not measure a false level change. The sensor simulator was also used to develop and confirm that the sensor level will not "grow backwards" such as in the event that a sensor diode's functionality is intermittent due to damaged or dry connections. This could potentially mean that a sensor level is worn down, and by an intermittent component may appear to be growing back again. The sensor interface software was developed to accommodate such instances to prevent false readings.

6.2.2 Test setup

During tests, the sensor simulator is connected to the transponder using a sensor interface loom and connectors between the devices. The sensor interface is tested using the sensor simulator by switching loops out of the circuit and simulating liner wear. During these tests, the transponder is placed in an activated state using the magnetic test switch. In this state, the transponder will wake-up on a change in sensor level and report the measured level to the host via the RF link.

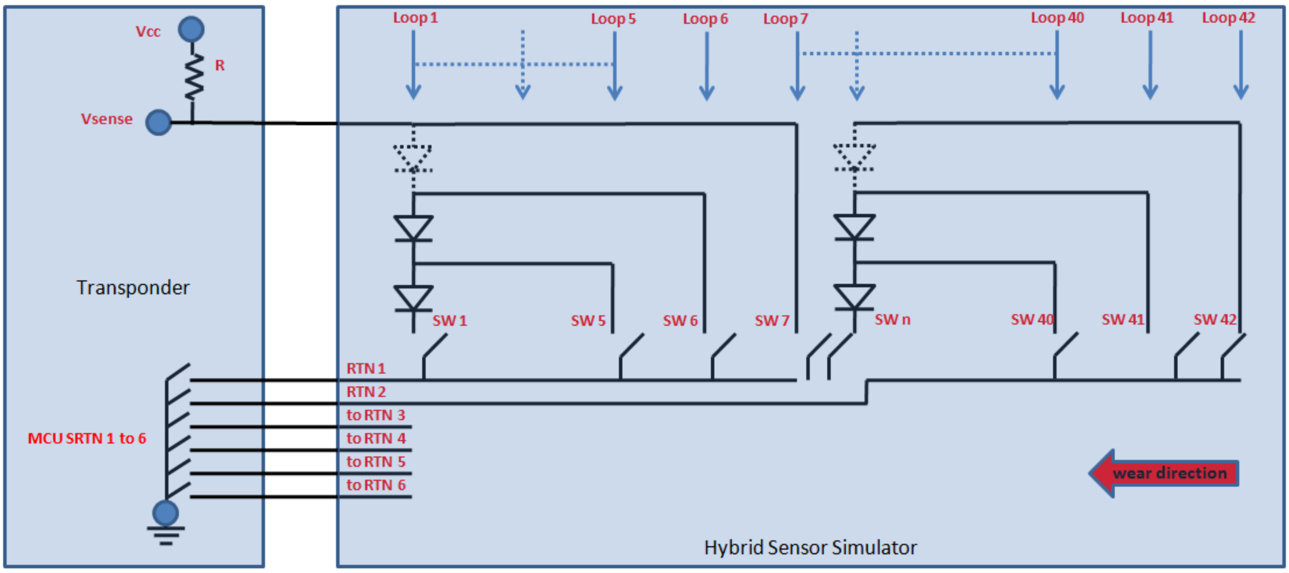


Figure 42: Transponder sensor interface test setup schematic diagram

6.2.3 Test procedures and results

The following steps were taken for verification of performance and functionality of the transponder sensor interface:

1. Connect the hybrid sensor simulator to the transponder and ensure all switches on the sensor simulator are closed:
2. Activate the transponder by holding a magnet close to the transponder body, this will place the transponder in a test mode, the LED indicator will flash green;
3. Each time a switch on the Hybrid Sensor Simulator is opened, the transponder will transmit the new measured level to the host. Confirm the level on the host;
4. During testing, generate a false level by opening a switch lower down the sensor chain than the actual simulated level and verify that the transponder does not react to the change;
5. Verify that once a level has been reached, the transponder will not react to the closing of a switch (level growing back) as this would indicate a liner thickness increase instead of liner wear.

In all cases, software and hardware were tested and performed successfully to meet the above test requirements.

6.3 Transponder and Host RF interface test

6.3.1 Purpose of test

For the transponder and the host's RF interfaces it was important to test and measure the radio devices' ability to send and receive data in short bursts and successfully deliver the transponder status to the host. This was done by confirming the following characteristics:

- That the transponder can successfully communicate to a host, with limited to no data errors;
- That the transponder can successfully receive acknowledgement data from a host;
- That the transponder and host can successfully communicate over a variety of distances and orientations.

These tests should rather be performed before testing the transponder sensor interface tests since those tests require an RF interface and communications to a host to be present.

6.3.2 Test setup

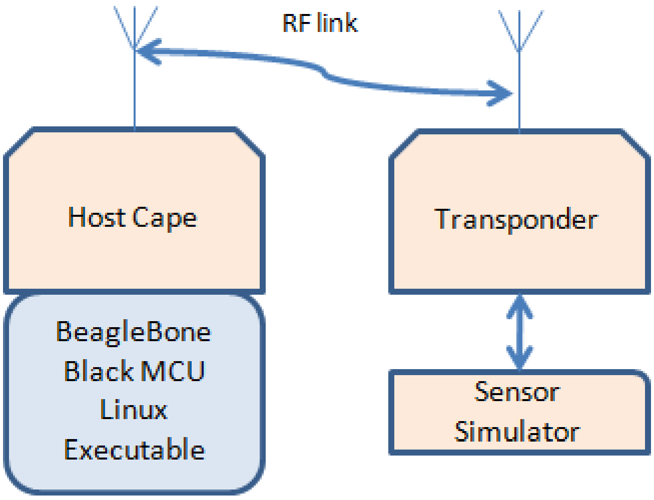


Figure 43: Transponder and Host RF interface test setup

Testing of the RF communications link was done using a host cape connected to a host BeagleBone Black MCU and a transponder connected to the hybrid sensor simulator. The host was placed in “Technician mode” which has the capability to display transponder and sensor levels as and when changes occur. During initial development testing, the RF output and RSSI (Received Signal Strength Indicator) levels of the receiver were measured and components optimised to reach an optimal RSSI value on the receiver path and optimal power output of approximately 10 dBm on the transmitter path.

6.3.3 Test procedures and results

The transponder and host RF communications were tested using the following procedures:

1. Place the host application in the “technician mode” to view the monitor for communications activity;
2. Place a transponder 10 m away from the host in a line of sight position, in no specific orientation;
3. Activate a transponder by placing it into test mode using a magnet in close proximity;
4. Note the communications on the host monitor, specifically the RSSI indicators. These are displayed for both the transponder and host. The transmitted power may be measured using specialist equipment such as a spectrum analyser. Specialised RF test equipment is very expensive and was available during the development of

this project. The RSSI levels of different transponders were compared to determine transmitter and receiver efficiency – the RSSI levels should differ less than 10 %;

5. Adjust the orientation of the transponder and observe the measured RSSI for different orientations, the deviation should not exceed 20 %.

6.4 Host internet connection tests

6.4.1 Purpose of tests

These tests were conducted to confirm that the host will successfully transfer data received from transponders to the internet. The tests included the following:

- To confirm that the host will connect and transfer data to the internet via its Wi-Fi connection;
- The host will successfully connect and transfer its data to the internet via its LAN (Ethernet) connection;
- To confirm that the above will be the case during power down conditions, given that an internet connection is available;
- To confirm that, should an internet connection not be available that the host would store such information and upload to the internet once a connection was re-established.

6.4.2 Test setup, procedures and results

The test setup for internet connectivity is shown in Figure 44. It is not required to test the connectivity with a transponder, but the complete communications path may be confirmed in doing so, that is, from transponder to host to the internet.

- Connect the host to the internet using its Wi-Fi WLAN link and confirm connectivity by performing a ping test to a target server, i.e. ping a known web site or server;
- Then connect the host to the Internet using its RJ45 Ethernet LAN connection and perform the same ping test and confirm that a connection is made;
- For both tests above, confirm that a transponder uploads its content to the system web browser. The web browser includes an activity list with an indication of each device's ID, date and time of last connection and sensor level.

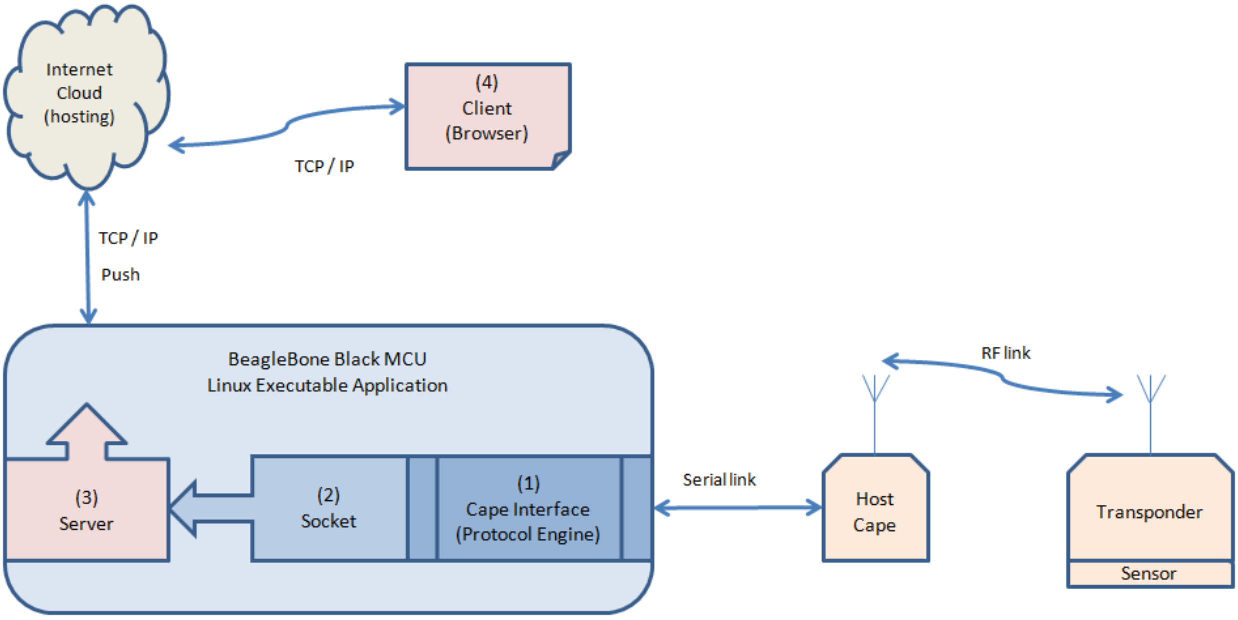


Figure 44: Host Internet connection test setup

6.5 Conclusion

This section focussed on the testing of sub-systems of the liner wear monitoring system by defining step-by-step procedures and documenting expected test results for each item. Once these test procedures have been followed for a device, it was deemed functionally capable for assembly onto a mill. These test procedures were also used in the design of the system to test consistency and interchangeability of items.

Table 25 to Table 27 provide a summary of functional capability tests.

Table 25: Liner sensor test summary

Test description	Result
Test that the voltage level across the hybrid sensor do increase as the sensor level decreases	The sensor performed successfully using the hybrid sensor tester
Confirm that the sensor voltage is not severely influenced by environmental conditions such as liquids and materials	Tests were performed as indicated and the sensor did not show signs of environmental contamination or false indication of levels

Table 26: Transponder sensor interface test

Test description	Result
Tests were performed to confirm that the sensor interface correctly reacts to a change in sensor level	The tests demonstrated that the transponder will wake-up on a change in sensor level
Test that the interface correctly measured the sensor level	Testing provided evidence that the sensor interface correctly measures the sensor level
The sensor interface correctly interpret the measured sensor voltage	The sensor interface correctly calculates and translates the sensor value to the correct sensor level
That the sensor interface is robust and not sensitive to noise and undefined sensor characteristics (such as faulty or broken diodes lower down the sensor bank)	The test procedures confirmed that an incorrect or faulty sensor will not result in an incorrect sensor level indication
Tests include the simulation of a damaged liner sensor and that a sensor level will not “grow backwards”	Testing by random switching of level and “growing” the sensor level have no effect on the level indication, the levels are always reported correctly

The above tests show that the transponder will, in a robust manner, measure and translate sensor levels to correct digital values, while not being affected by exceptions such as sensor “growth”.

Table 27 provides a summary of tests performed to ensure functionality of the transponder and host RF interfaces. These tests were done to ensure communication between an RF transponder to its host.

Table 27: Transponder and Host RF interface tests

Test description	Result
Testing was performed to confirm that the transponder can successfully communicate to a host, with limited to no data errors	The test procedures confirmed that data is successfully transmitted and received by both the transponder and host and that the error detection and correction algorithms performed well.
That the transponder and host can successfully communicate over a variety of distances and orientations	An Increase or decrease in the distance between the host and transponders did not affect data communication success. Tests were performed for up to 100 m apart without any data errors reported. Changing the transponder orientation did also not have an influence on the successful delivery of transponder data.

In summary, all tests above were done to ensure a functionally capable transponder for fitment onto a SAG mill. Final verification and validation of the concept demonstrator was done as reported in the following chapter.

Verification, validation and conclusion

Section 3.9.2 (Quality conformance inspections) defines verification methods used to ensure quality conformance. These methods are (i) inspection, (ii) analysis, (iii) demonstration and (iv) formal test. During the validation and verification phases, the designed and developed artefacts were tested against the defined requirements as defined in Chapter 3. This is in line with the DSR process and specifically as described by the Relevance cycle (paragraph 2.1.1) and the Design cycle (paragraph 2.1.2). Figure 45 is repeated below for clarity and indicates the process.

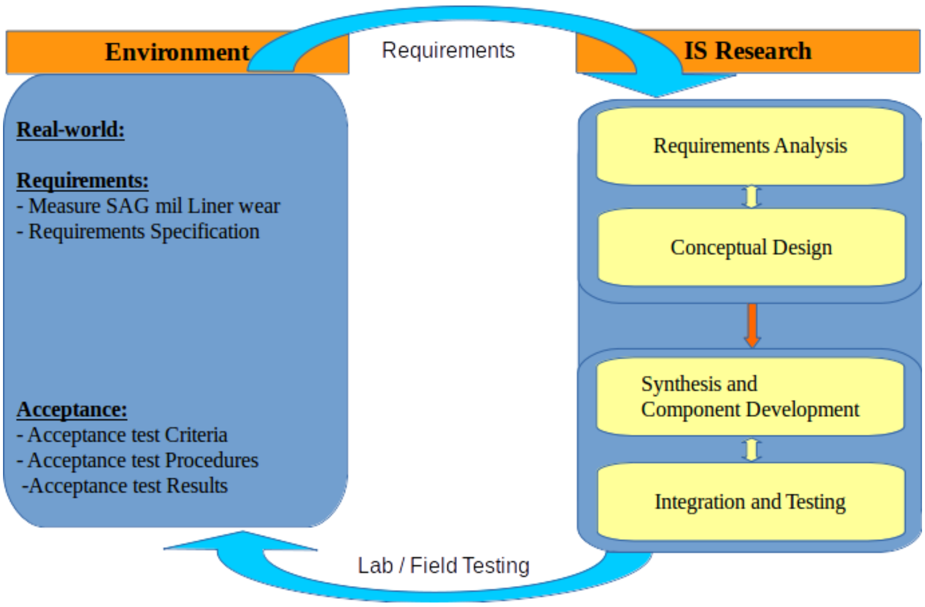


Figure 45: Relevance and design cycles

In order to test the artefacts and the system against defined requirements, the development phase included the design and construction of test equipment for each of the system's building blocks. This was required to facilitate the integration and testing of sub-systems and to simulate interfaces which were not clearly defined or completed. A device was manufactured for the simulation of a hybrid sensor (sensor simulator) which was used to test and evaluate the sensor interface circuit on the transponder sub-system. The sensor simulator was a true sensor board modified with switches, where each switch represents a loop that, when opened, simulated the breaking of a loop. This sensor simulator also assisted in software development of the transponder and finally the integration and testing of all parts of the complete system. The sensor simulator and a transponder were also used to demonstrate the operation of the system to the client and other users.

The transponders were tested on the one end by using the hybrid sensor simulator (Figure 49). The transponder user functions, such as the magnetic switch and activation pin, were tested manually and the LED functions were visually inspected for conformance. In order to test the transponder's affinity to environmental conditions, the unit was simply placed inside a domestic dishwasher and into a domestic tumble drier. It was also subjected to hours of repeated washing cycles. The transponder was activated and configured for a fast cycle time of 10 minutes whereby the transponder's status was transmitted repeatedly to a host station during this time.

As a final test, the complete system was tested at Joel mine in South Africa and test results were compiled by a geologist (da Silva 2017).

Apart from the physical tests, visual and inspection testing were performed on specific parts of the design, manufacturing and completed artefacts. This was done in lieu of the fact that the researcher developed the system at a very low budget and was not able to use formal facilities for environmental stress screening or enhanced and accelerated testing.

Table 28 (on the next page) provides a cross reference of requirements and required test and evaluation methods. The intent is to indicate, for each specified parameter of the system, how that parameter was tested for conformance. The test methods Inspection (I), Analysis (A), Demonstration (D) and Test (T) are as defined in paragraph 3.9.2 (Quality conformance inspections).

7.1 Requirements cross reference matrix

Table 28 indicates, for each requirement, what the desired conformance test method was. For example, the liner sensors compliance with the requirement must be proved by way of demonstration, and so on.

Table 28: Requirements (specification) cross-reference matrix

Requirement Reference	Test Method			
	I	A	D	T
Liner (section 3.7.1)	X		X	X
Transponder functional and performance requirements (section 3.7.2)	X	X	X	X
Host functional and performance requirements (section 3.7.3)	X	X	X	
Host specific requirements(section 3.7.3.1)	X	X	X	
Weight (section 3.8.2.1)			X	X
Dimensions (section 3.8.2.2)			X	X
Nameplates and Product Markings (section 3.8.4.3)	X			X
Workmanship (section 3.8.4.4)	X			X
Interchangeability (section 3.8.4.5)			X	

Environmental and industrialisation requirements were not within the scope and were not formally evaluated or tested. The requirements below all fell within scope, with the relevant test method / process indicated and summarized.

Section 7.2 below describes how each of the test requirements stated in Table 28 was confirmed.

7.2 Requirements validation summary

Section 7.1 provided an indication of the validation method to be used to confirm compliance. This section provides a factual description of how each of the requirements was tested and the procedures that were followed (where applicable) to confirm that the requirements were indeed met. In the tables below, the verification method for each requirement is briefly discussed and an indication to the method(s) used provided in brackets (I, A, D, T) – Inspection, Analysis, Demonstration or Test.

7.2.1 Liner sensor requirements validation

The Liner (paragraph 3.7.1) was addressed in paragraph 5.1 (Liner bolt sensor) as follows:

Table 29: Validation matrix - Liner sensor requirements

Requirement	Validation procedure / process (I, D, T)
A sensor assembly with sensing elements capable of measuring liner thickness;	A hybrid sensor was synthesised into a working module. (D)
The movement of particles inside the mill shall grind these sensing element(s) down and provide an indication of the thickness of the liner bolt, hence the liner thickness	The concept was tested in the laboratory by gradually cutting the sensor shorter and viewing that the transponder sensed the correct length. (D, T)
A minimum of 42 sense levels shall be provided	This was confirmed by inspection. (I)
For the first article development, the sensor shall be 250 mm in length, with a measurement resolution of at least 2 mm	This was confirmed by inspection. (I)

Requirement	Validation procedure / process (I, D, T)
The sensor element shall be mounted inside the rear part of the bolt	A special liner bolt was manufactured and the sensor mounted inside the extended bolt head. The sensor hole was then filled with potting epoxy (D, I).

7.2.2 Transponder functional and performance requirements validation

The Transponder functional and performance requirements (paragraph 3.7.2) were addressed in paragraph 5.2 (Transponder electronics) by the following procedures:

Table 30: Validation matrix – Transponder requirements

Requirement	Validation procedure / process (I, A, D, T)
Provide its own power source	This was implemented by way of a “primary cell” of 1400 mAh capable to deliver power for over 24 months. Refer to paragraph 5.2.5 (Power supply (source) and power management). Since the power consumption of the transponder during sleep mode is in the order of 100 nA, the power budget calculation was done by analysis and the sum of the current consumption of the various individual electronic circuits. (A)

Requirement	Validation procedure / process (I, A, D, T)
Be able to interface and measure the sensor length	The transponder is equipped with a sensor interface as defined in paragraph 5.2.6.1 (Sensor interface design). The sensor interface was tested using a dedicated “sensor simulator” of which a photo is provided in Figure 39. (D, T)
Provide an RF communications function to communicate to a remote host	The transponder was realised with an MCU form SiLabs (Si1060) with an integrated RF front-end providing an RF communications link to a host, refer to paragraph 5.2 (Transponder electronics). (I, D)
Perform self-tests and diagnostics functions on request	As stated in paragraph 5.5.2 the transponder is placed in a self-test mode by means of a magnet held external to the device. On activation the transponder sends its data to the host. (D)

Requirement	**Validation procedure / process (I, A, D, T)**
After activation, the transponder must be able to go to a low power state and only wake-up in the event of a change in sensor level, and periodically send its status to a host. The periodic interval time must be configurable with intervals of at least 8 hours or less	The transponder is placed in a low power state and wakes up on the sensor level change as described in paragraph 5.2.6.1 (Sensor interface design). This function was verified by demonstration. (D) A configurable cycle timeout (paragraph 5.5.2) allows the periodic transmission of transponder status to the host. This function was verified by demonstration. (D)
The transponder data payload to the host shall include as a minimum, the liner thickness information as well as the transponder battery status	As described in paragraph 5.5.2 the payload includes the device ID, sensor level and battery status. (D)
The transponder will only be activated once it is fitted to a liner. This shall be a non-reversible state	An activation state is entered upon pulling the ripcord – refer to paragraph 5.2.6 (Sensor interface), Verified by Analysis of the design and demonstration. (A, D)
The transponder shall be enabled by pulling a pin (or the like) which shall place it in a permanently activated state	As described in paragraph 5.2.6 this is a hardware function – see Figure 30: Transponder design – power source. (A, D)

Requirement		Validation procedure / process (I, A, D, T)
The transponder will then be active until the battery runs out or it is destroyed		Described by Figure 30: Transponder design – power source. (A)
Each transponder shall have a unique ID number.		As defined by paragraph 5.5.2 this function was demonstrated by observing a number of different transponder ID numbers.(D)
Transponder states and modes	Deactivated state	The power consumption was estimated to be approximately 90 nA. After activation with a magnet, the device enters a test mode (draws approximately 18 mA during transmission) and when executed falls back into the de-activated state. (A, D)
	Activated state	After pulling the activation pin the transponder stays active until the battery is depleted. (A, D)
	Start-up mode	At start-up the transponder transmits a start-up message to the host (D).
	Sleep mode	The transponder remains in a low power state. (A, D)

Requirement		Validation procedure / process (I, A, D, T)
	Event mode	When a level trigger, cycle timeout or battery low occurs a message is sent to the host and the transponder goes back to sleep. (D)

7.2.3 Host functional and performance requirements validation

The Host functional and performance requirements (paragraph 3.7.3) are adressed in paragraph 5.3.

Table 31: Validation matrix – Host requirements

Requirement	Validation procedure / process (I, A, D)
Real-time clock calendar (RTCC) with:	An RTC was synthesised from a DS1337 Integrated Circuit – refer to Figure 32: Host cape design – RTC interface and battery. (A, D)
Provide date and time in the format (yy:mm:dd) and (hh:mm:ss)	These are implemented by the DS1337, refer to the data sheet (Maxim Integrated 2015). (A)
Have a minimum of one minute resolution with one second accuracy	These are functions of the DS1337, (Maxim Integrated 2015). (A)

Requirement	**Validation procedure / process** **(I, A, D)**
Enable the periodic transmission of sensor and transponder information as configured by the user	Wake-up from sleep by alarm, DS1337. In addition a “heartbeat” transponder was placed inside the host enclosure. This transponder was configured to transmit a signal once every minute. This was done to confirm that the communications channel between the host and the server was always active and established. (D)
Be updated and synchronised from a user interface	This function was demonstrated, how to enter a new date and time from the user interface. (D)
Non-volatile storage, 9300 records Each include: dd:mm:yy, hh:mm:ss, batt (0-100)%, ID (2 bytes), Sensor level (1 byte)	Although the payload size was calculated to be only a few bytes in size, provision was made for 128 bytes per record; that is 1.14 MByte for 9300 records. A separate drive of 2 MByte was mapped on the BeagleBone Flash. (D)
Wi-Fi	A router with Wi-Fi (IEEE 802.11) was fitted into the host enclosure. (D)
LAN	The router includes an RJ45 10/100Base-T Ethernet socket. (D)

Requirement	**Validation procedure / process (I, A, D)**
Backup battery 24 hours	A 24 Ah lead acid battery and charger was assembled into the host enclosure. (D)
Power supply unit	Mains power (230 VAC) is supplied to the host through a circuit breaker and power switch; and a power on status lamp. (D)
RF transceiver: transponder compatible RF transceiver	The host (BeagleBone Black) is fitted with the cape design as described in paragraph 5.3 and Figure 33: Host cape design – MCU and RF interface. (A, I, D)
Enclosure	The host is assembled inside a commercial off the shelf (COTS) IP65 rated enclosure. (D) It was not tested for compliance as the rating is in line with the requirements.
HMI – display, input and output devices	As the BeagleBone hosts a Debian (Linux) based operating system an SSH shell (Putty) was used to configure the device. (D)

<table>
<tr><th colspan="2">Requirement</th><th>Validation
procedure / process
(I, A, D)</th></tr>
<tr><td colspan="2">Network server and client</td><td>The application and database was installed and executed on the BeagleBone and conformance to the requirements was demonstrated. (D)
The integration of all devices was demonstrated by activating a transponder, triggering a sensor level and confirming that the event was logged on the internet server with the correct transponder ID, battery status and sensor level, with the correct date and time of the event. (D)</td></tr>
<tr><td rowspan="3">Host states and modes</td><td>Power off State</td><td>During this state the host is non-operational. (D)</td></tr>
<tr><td>Power-on reset state</td><td>After power on and initialisation, the host application is started by a cron. (D)</td></tr>
<tr><td>Start-up mode</td><td>After application initialisation, the application goes into the Normal mode of operation. (D)</td></tr>
</table>

Requirement		Validation procedure / process (I, A, D)
	Normal mode	This mode is entered by default after start-up. The system remains in this mode until the user enters a different mode. (D) Once in this mode, any of the desired states namely Configuration mode, Technician mode and Administrator mode may be entered. (D) All modes are password protected. (D) In the normal mode of operation the host receives and logs transponder data. (D)
	Configuration mode	This mode is used for factory configuration and is used for hardware set-up and default system configuration. It is not available to the end user. (D)
	Technician mode	This mode is used to configure transponder cycle timeout parameters. (D)
	Administrator mode	This mode allows a user to set network settings and edit default factory settings. It is not available to the end user. (D)

The physical characteristics of the equipment under development was addressed and confirmed as follows:

Table 32: Validation matrix - Physical characteristic

Physical characteristics	Validation procedure / process (I, A, D, T)
Weight (paragraph 3.8.2.1)	These characteristics were all confirmed by way of demonstration to the client. Sizes were taken and the weight of items was measured. (D, T)
Dimensions (paragraph 3.8.2.2)	
Transport and Storage (paragraph 3.8.2.3)	

7.2.4 Environmental conditions requirements validation

The environmental capabilities of the transponder and host were confirmed to be compliant as indicated in Table 33:

Table 33: Validation matrix - Environmental conditions

Environmental conditions	Validation procedure / process (I, D, T)
Nameplates and Product Markings (paragraph 3.8.4.3)	These characteristics were validated by way of inspection and confirming that it conforms to paragraph 3.8. (I)
Workmanship (paragraph 3.8.4.4)	
Interchangeability (paragraph 3.8.4.5)	Confirmed by the addition, removal and replacement of transponders to the system and verified that the system accommodated the changes. (D)

Table 29 to Table 33 above show how each relevant requirement was verified. A cross reference is provided for each requirement to show that the initially defined requirements had been met by means of design.

In this research, the DSR process was aligned with a development project to show that the systems engineering process aligns with DSR to produce a functional prototype in the engineering sense, and thus an artefact in the DSR sense. The value of using formal requirements is evident in that verification can be achieved in a systematic way, thus adding value to the DSR methodology.

In order to show that the DSR method produced valid results, a DSR validation and verification matrix will be used. This is different from development verification and validation as the focus is on the research process itself as opposed to the developed artefact.

7.3 DSR validation and verification matrix

Table 34: DSR validation and verification matrix

Chapters	Item					Validation
Chapters 1 and 3	**Source 1 – Cases**					Problem validation
	Availability Improvements in SAG Milling at Chuquicamata	X			X	
	Evaluation of Abrasive Wear Measurement Devices of Mill Liners	X		X		
	Source 2 – Observations					
	1) On-site observations 2) Discussions with client	X	X	X	X	
	Source 3 – Publications					
	The eyes have it: Improving Mill Availability through Visual Technology		X			
	Information Sources → **Research Challenges**	**Reduce production downtime due to manual liner measurement**	**Prolong the measurement equipment's lifespan**	**Improve on the limited resolution of existing systems**	**Harsh Operational Environment**	Problem and solution verification and validation
Chapter 4	**Literature focus areas**					
	Literature topics: Design for Harsh Environment		X		X	
	(Low) Power Design		X			
	Sensor Solutions			X	X	
	Micro Controllers	X		X	X	
	Single Board Computers	X				
	Remote Measurement	X				
	Integrated RF Solutions				X	
	Literature focus → **Research Solutions**	**Real-time measurement and reporting of liner thickness**	**Extend battery life**	**High resolution and high accuracy sensor**	**Robust design**	
Chapters 5 and 6	**Detailed Solution**					
	Processes / Procedures					Solution validation
	Real time Sensing	X				
	Remote monitoring	X				
	Low Power Design		X			
	Design for harsh environment				X	
	Artefacts and Theories					
	Sensor, Transponder and host	X	X	X	X	
	Methods and Techniques					
	Semiconductor Sensor			X		
	High speed RF link	X				
	Reports					
	Liner Intelligent System (LIS) for Measurement of Abrasive Mill Liner Wear	X				

From the table above, it is evident that the initial problem has been validated in the form of a clear definition of the problem as presented in the background (Chapter 1) and formal problem definition in Chapter 3. That is, a valid problem had been solved.

The literature study in Chapter 4 added valuable information and guidance for the design process. In this chapter, the selection of appropriate methods (the liner sense method) and technology was validated by means of multiple-criteria decision making.

Finally, the design, integration and testing of artefacts verified the design process and validated the research process in that all initial requirements have been met by means of design. Chapters 5 and 6 provide evidence to this effect and the design patent of the liner wear sensor provides final verification of the unique contribution of this study.

The final validation of the product, and the research, lies in field testing. The following section provides evidence to this effect.

7.4 On-site testing and test results

As a final test and validation, the system components were manufactured and tested at Harmony Gold mine (Joel plant) near Welkom, a small town situated in the Orange Free State, South Africa. The tests were performed during July of 2016 and sensors installed on liner rings 2 and 3 of a SAG mill, these rings are considered to be the high wear zone of the mill shell. A number of pictures of the manufactured artefacts and installations are shown in paragraph 7.5 (System Artefacts). A performance report was compiled by a geologist (da Silva 2017) to confirm satisfactory system operation.

da Silva stated that the overall trial at Joel mine was a success with the transponders and sensors being able to display actual liner wear profiles without having to incur production losses due to unnecessary mill inspection downtime (da Silva 2017). In his report he provided a daily information chart as shown in Table 35. This chart is an indication of the transponder (or bolt) ID, its wear length, the battery status and date and time of event report. Transponder 911 was defined as the designated “heartbeat” used to test the system’s up time.

Table 35: Daily information chart

Bolt ID	Length	Battery	Host Last Update
911	0	100%	27 October 2016 17:37:27
1001	0	100%	27 October 2016 09:48:26
1002	0	100%	11 October 2016 12:42:16
1004	20	100%	11 October 2016 12:47:46
1005	0	100%	27 October 2016 15:32:31
1006	70	100%	11 October 2016 09:01:29
1016	100	100%	11 October 2016 12:48:11
1018	100	100%	08 October 2016 08:27:42

In addition to the daily charts, the system provides graphs indicating per transponder, its history and current status. Typical graphs are shown in Figure 46 and Figure 46.

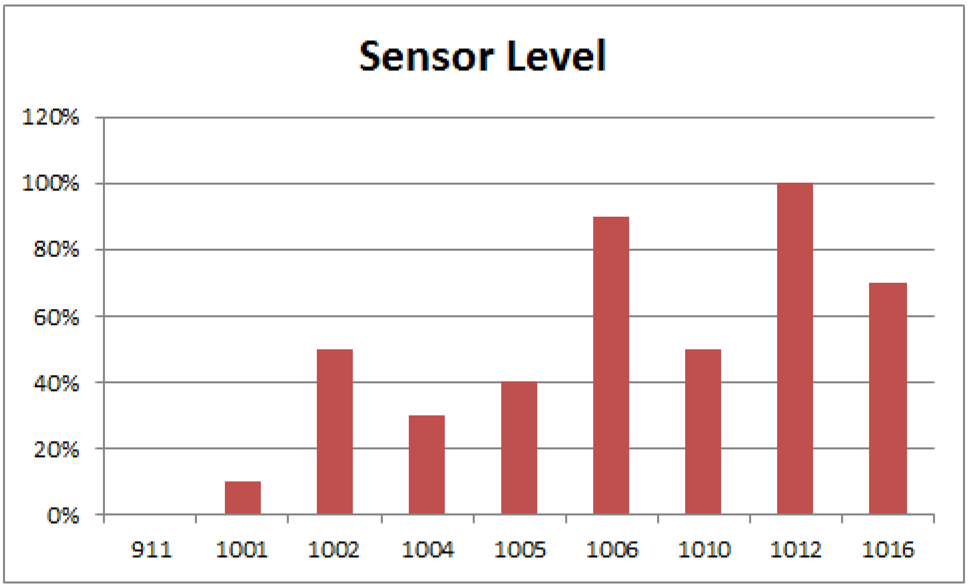


Figure 46: Liner length indication

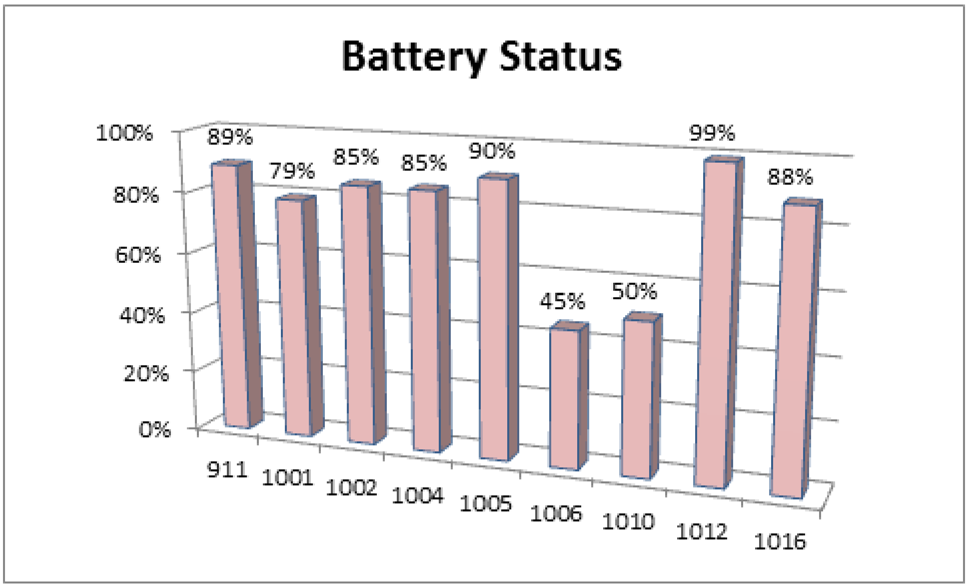


Figure 47: Transponder battery status

Future enhancements of the project will include a variation of sensors for not only monitoring liner wear rate, but other mill parameters such as “wash through”, a phenomenon where slurry washes through in and between liners, exposing the mill shell to abrasive materials that cause damage. Lastly, da Silva pointed out a typical results graph indicating the liner wear as a function of time as shown in Figure 48.

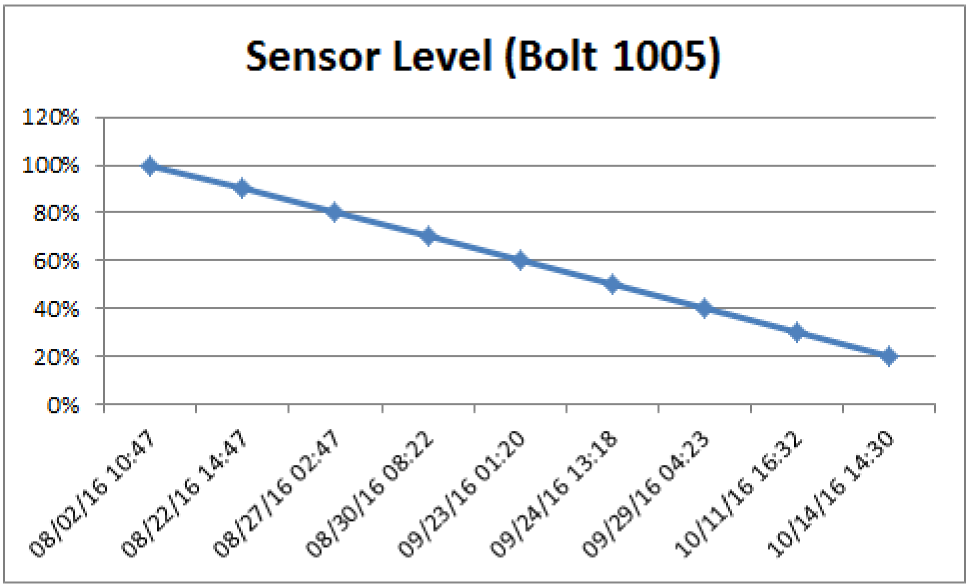


Figure 48: Bolt length graph

7.5 System Artefacts

7.5.1 Artefact: liner bolt sensor emulator

Figure 49 illustrates the liner sensor test module. When a switch is opened, the action simulates breaking of a loop and the sensor would artificially advance to the next level. This tester was used during integration of the sensor assembly and sensor interface and was used to verify functional capability of the hardware design. It was further used during software development to ensure the sensor level detection algorithm functioned. It was also used to demonstrate the decaying sensor concept to the client and to confirm that the sensor interface and software were robust against “false” levels. This was demonstrated by opening a switch further down the sensor assembly, the software was not to react on such a break as it simulated a component failure, possibly as a result of vibration. The sensor would simply continue to function until the “failed” loop was reached and the system then simply adjusted to the level accordingly and self-rectified as the next level was reached.

Figure 49: Hybrid sensor emulator

Figure 50: Hybrid Sensor tester

The sensor tester and hybrid sensor simulator were both used during laboratory acceptance testing of the system to demonstrate compliance to the system’s functional requirements.

7.5.2 Artefact: liner bolt integrated sensor and transponder

Two variations of the liner sensor and transponder configuration were designed. One configuration is where the liner sensor and transponder electronics are all built into the liner bolt and a second version where the liner sensor is built into the liner bolt extended head and the transponder housed in a separate enclosure and mounted exterior to the mill. Figure 51 is a picture of the second solution. The bolt with extended head is shown where the sensor connector protrudes from the bottom of the bolt where it is connected via a loom to the transponder. The transponder is mounted exterior to the mill on the (blue) bracket as shown in the figure. This artefact was simply manufactured on request of the client as the procedures for mounting and assembly of the equipment on the mill dictated this configuration. One of the many reasons the client argued was that the electronics inside the bolt could possibly be damaged during insertion of the bolt into the liner and through the mill shell. The bolts are usually hammered into place. As these were the first tests and proof of concept the client did not want to take any unnecessary risk in assembly, taking into consideration that the technical staff has never installed electronic devices of this nature into a mill and that the success of the system relied much on the proper installation of the first articles.

Figure 51: Bolt with sensors fitted and transponder on bracket

Figure 52 shows the same assemblies from a different perspective.

Figure 52: Bolts with sensors fitted and transponders

The sensor connectors were sealed off by using galvanising tape. This was to make sure that the connector would not turn loose and that no water or moisture would leak into them. It was taken as an extra precaution, again to reduce risk during first article testing and evaluation. The galvanising tape can be seen in Figure 53 as well as the remaining water after a thorough water jet spray test. The transponder was still functional with no reported problems.

Figure 53: Bolts with sensors and transponders fitted to a mounting bracket

Figure 54 is a picture of the transponder electronics shown without its enclosure. The antenna is shown on the left, then moving to the right can be seen an LED indicator, the transponder PCB with electronics and to the right is the loom connecting the transponder sensor interface to a liner sensor connector. The black IC in the centre of the PCB is the SiLabs Si1060 MCU, to the north can be seen the oscillators and on the far northern edge of the PCB is a magnetic reed switch for testing purposes. Two different antennae were used during testing. Figure 54 shows a dipole antenna and in Figure 55 a monopole antenna was used. Both antennae were found to be satisfactory.

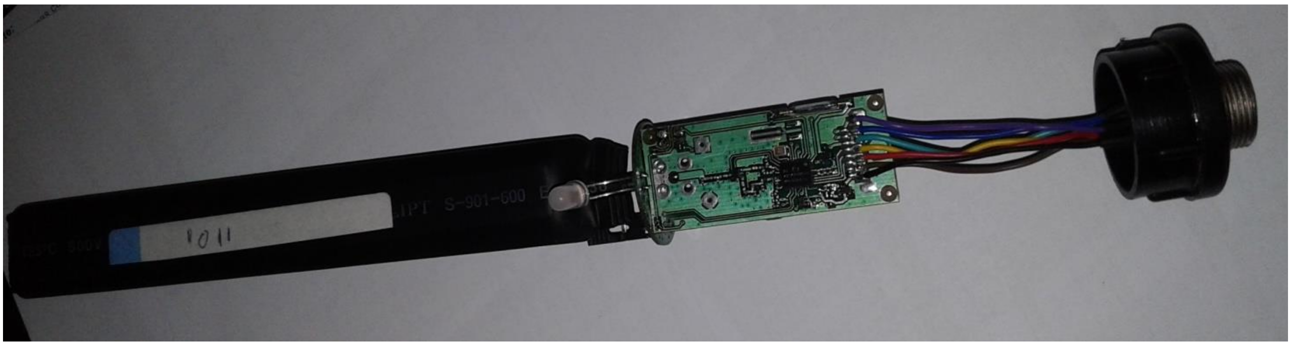


Figure 54: Transponder electronics, wiring, dipole antenna and LED indicator

The foaming compound can clearly be seen in Figure 55. This unit was opened after high pressure washing and approximately 120 hours of testing fitted to a mill. No signs of water ingress were visible and the unit was still in a good working condition.

Figure 55: Transponder electronics, monopole antenna foam potting material

A populated hybrid sensor PCB is shown in Figure 56. The PCB shown is an earlier version where many diodes were used in place of conductor loops. The design was “fine-tuned” during the synthesis phase until a refined version was established. Unfortunately a photo of the refined version PCB was not available during the preparation of this document. It is however functionally the same, only using a lot less diodes as can be seen on the figure. A number of holes are visible on the PCB. The function thereof is to allow the potting material to flow through them in order to provide bonding strength to the board and to anchor it properly inside the liner bolt extended head cavity.

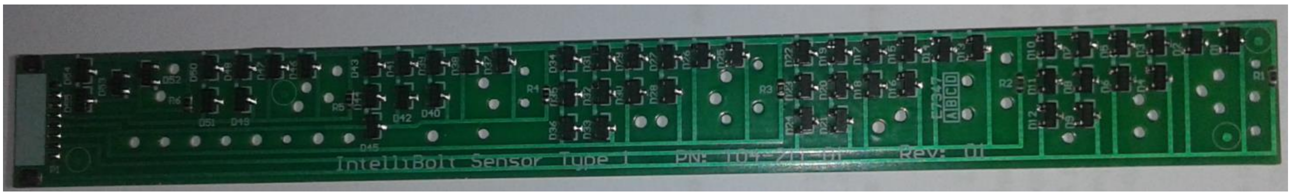


Figure 56: Hybrid sensor

7.5.3 Artefact: host system

The host system can be seen in Figure 57 where it is enclosed in an IP65 housing mounted onto a structure about 10 meters away from the mill. The only connections to the host is a mains feed which is protected in the white conduit tubing shown in the picture. The RF and Wi-Fi antennae are both built into the housing in order to protect them from environmental elements. Two lamps can be seen on the side of the enclosure. One is a red lamp which flashes on a liner sensor level event and the other is a green power indication. These were useful in monitoring the system and to obtain basic indication of system activity.

Figure 58 (on the following page) is a photo of the host electronics, it includes the top portion which is the transponder compatible RF link cape, and at the bottom a BeagleBone Black MCU single board computer. The host was fitted with a dipole antenna as it proved to perform superior to a monopole antenna. Good results were however also achieved by using the monopole antenna. The cape can be seen to include a CR2032 (3 V) battery which is used as backup source for the real-time clock calendar. The cape is further fitted with a relay and IO block for connecting higher power devices such as a flashing red or amber lights to be used as an indicator should critically low liner levels be reached.

Figure 57: Host mounted nearby the mill

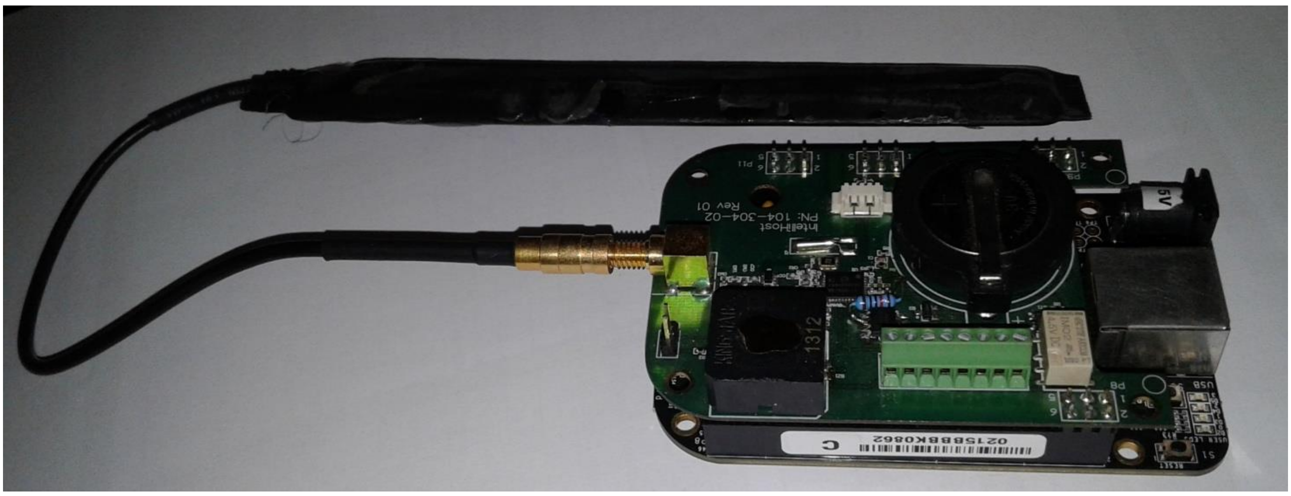


Figure 58: Host electronics with RF module and dipole antenna

7.6 Summary of validation

This chapter provided evidence of verification and validation in the form of validation matrices.

The first set of validation matrices of this chapter show how the mill liner wear measurement system adheres to the requirements as defined in Chapter 3. Not all requirements from Chapter 3 were relevant (as indicated), but all functional and relevant requirements were verified, which implies the actual design is valid in the context of this research.

The DSR validation matrix shows that a relevant and valid research problem was addressed in a systematic manner. The literature search supported the novelty of the design as no similar design was found from the literature search. Finally, the DSR validation matrix shows that individual building blocks were synthesized and integrated to provide a working concept demonstrator.

Final evidence of validation was provided in the form of an actual site test with a fully functional prototype. This prototype included all building blocks, integrated and tested to demonstrate the concept demonstrator's effectiveness.

7.7 Conclusion

In conclusion, this study focussed on the understanding, analysis, implementation, and testing of a real-world telemetric measurement system by utilizing the principles as defined by the Design Science research model. The problem was identified from requirements defined by industry to address shortfalls of existing liner wear monitors, as well as the requirement to have real-time measurement data available for liner wear and wear rate. The design challenges were identified and researched as defined by the DSR process and solutions were synthesised to provide functional artefacts. These were verified and tested, initially in a laboratory environment and thereafter on a real SAG mill at Joel mine in Welkom, South Africa.

All sub-systems performed as per defined requirement to produce a functional concept demonstrator (specifically excluding environmental stress screening and testing for harsh environment as these will form part of an industrialization process that fell outside the scope of this research project). The liner sensors and transponders functioned on a SAG mill providing real-time data as expected.

The primary artefacts that were synthesised and developed are:

- A novel liner wear sensor using a hybrid conductive loop and diode approach;
- An RF transponder with controller and communications interface;
- A host system with internet connectivity to a cloud based user interface (browser);
- An integrated system that provides real-time measurement data.

The knowledge base, or meta-artefacts, that were developed include this thesis, to show how systems engineering (in particular, requirements management) may be used to enrich the DSR research process. It further includes the principle of using a hybrid sensor and sensor interface method that may be used in similar applications where measurements must be made in electrically noisy, semi-conductive, or polluted environments.

Future work includes industrialisation of this measurement system (product hardening), and research and design of real-time sensing equipment for measuring SAG mill pulp-lifters, as well as sensing of “wash through” of the mill drum between liners.

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